The Society of Fire Protection Engineers Series

Fire Safety for Very Tall Buildings

Engineering Guide

Second Edition

SFPE
Engineering A Fire Safe World®

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The Society of Fire Protection Engineers Series

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About SFPE

SFPE is a global organization representing those practicing in the fields of fire protection engineering and fire safety engineering. SFPE's mission is to define, develop, and advance the use of engineering best practices; expand the scientific and technical knowledge base; and educate the global fire safety community, in order to reduce fire risk. SFPE members include fire protection engineers, fire safety engineers, fire engineers, and allied professionals, all of whom are working towards the common goal of engineering a fire safe world.

About ICC

The International Code Council is the leading global source of model codes and standards and building safety solutions that include product evaluation, accreditation, technology, training, and certification. The Code Council's codes, standards, and solutions are used to ensure safe, affordable, and sustainable communities and buildings worldwide.

Preface

The performance history of very tall buildings, while extremely successful, has not been without major incidents causing injury and death. The modern building codes have made major progress in addressing unique issues of design and construction in very tall buildings based on scientific research and lessons learned from catastrophic fires.

From a historic perspective, the model codes included unique provisions for high-rise buildings that evolved over time. These features include separation of egress routes, additional egress shaft requirements, fire department and occupant evacuation elevators, egress markings, stairway structural integrity, and a higher level of structural fire protection. However, the current building codes still may not provide comprehensive performance solutions or adequately address other risks inherent in very tall buildings.

The complexity and unique challenges of today's very tall buildings, coupled with sustainability goals of material, energy, water, and resource savings, have created an environment where comprehensive performance-based solutions have become a necessity. Such is the reason why SFPE and the International Code Council (ICC) published the first edition of this guide in 2013. SFPE would like to thank ICC for its assistance in publishing the first edition of this guide.

The research and practical experience related to the design and construction of very tall buildings advanced substantially since the first edition of this guide was published. SFPE has been monitoring this progress, and the SFPE Task Group on Fire Safety for Very Tall Buildings has made an effort to develop and advance an updated version of this guide. The result is the second edition of the *SFPE Engineering Guide to Fire Safety in Very Tall Buildings.*

This guide is not intended to replace the adopted building and fire codes of jurisdictions; rather, it is intended to complement such codes and serves as an added tool for all those involved in the design, review, construction, inspection, and commissioning of new or existing very tall buildings.

Society of Fire Protection Engineers

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Chapter 1
Introduction

Scope

This guide provides information on special topics that affect the fire safety performance of very tall buildings, their occupants, and first responders during a fire. These topics are addressed as part of the overall building design process using performance-based fire protection engineering concepts as described in the *SFPE Engineering Guide to Performance-Based Fire Protection* [1]. This guide is not intended to be a recommended practice or a document suitable for adoption as a code.

The guide pertains to “super tall,” “very tall,” and “tall” buildings. Throughout this guide, all such buildings are called “very tall buildings.” These buildings are characterized by heights that impose fire protection challenges; they require special attention beyond the protection features typically provided by traditional fire protection methods. This guide does not establish a definition of buildings that fall within the scope of this document and does not intend to apply the definitions found in any code or standard. Rather, it directs the user to perform a risk analysis to achieve a reasonable and adequate solution for the specific building. A description of the elements of a risk analysis is presented in Chap. 7 (Hazard, Risk and Decision Analysis in Very Tall Building Design).

Many building fire risks are exacerbated by height. Challenges associated with height will vary depending upon the type of fire protection features included in the building. These features can include but are not limited to egress, smoke control, structural fire resistance, and suppression systems.

While the focus of this guide is fire safety in very tall buildings, it should be recognized by the building designers that fires may be a consequence of a primary incident, such as earthquakes, floods, tsunamis, hurricanes, tornados, cyclones, and other natural or man-made events. All these events could jeopardize one or more features or systems comprising the construction, means of egress, or fire safety systems provided in the building.

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Additionally, while this guide primarily addresses new construction, designers of existing very tall buildings undergoing fire safety upgrades can benefit from the topics discussed. Existing very tall buildings are addressed in Chap. 22 (Existing Building Considerations).

Purpose

The purpose of the guide is to identify the unique fire safety challenges related to very tall buildings and provide the professionals engaged in the design of these buildings with information on the topics that affect the performance of very tall buildings and their occupants during a fire. By considering these topics, the design professional can prepare a fire protection design report, a fire strategy report, or a fire protection engineering design brief for the project. The guide expects that the design professional will have a fundamental understanding of fire dynamics and is competent in the application of scientific and engineering principles for the evaluation and design of systems and methods to protect people and their environment from the unwanted consequences of fire. The topics identified in this guide are intended to be addressed using performance-based fire protection and engineering concepts and the lessons learned from a historical context.

Background

The impetus for the first edition of this guide [2] was the global increase in the design and construction of very tall buildings. At that time, many very tall buildings used a variety of regulations, codes, and standards, many of which did not contemplate the heights of these buildings.

The World Trade Center terrorist attack on September 11, 2001, caused enhanced interest in the challenges of very tall buildings: those that are taller than what has generally been classified as a "high-rise" building. Among those challenges are:

- Egress and evacuation
- Emergency access
- Communications/situation awareness
- Fire resistance/resiliency
- Reliability of water supply and active fire protection systems
- First responder mobilization

Another factor is the increased number of very tall buildings, resulting from improvements in design technology in areas such as structural design. However, building codes address high-rise buildings but may not adequately address the additional risks inherent with very tall buildings.

This guide builds on the information included in the first edition and emphasizes the importance of taking an integrated approach to the design of fire safety in very tall buildings. An integrated approach looks beyond simply complying with codes and standards and considers how the height of the structure impacts safety and how the various fire safety features in the building complement each other to achieve the building's fire safety goals.

Chapter 2
History

Very tall buildings are not recognized as a special category of buildings in all codes and standards. "High-rise buildings," which are defined by many codes as those 23 m (75 ft) or greater in height from the lowest level of fire department vehicle access, were not recognized as special buildings in codes and standards until the 1970s. Moreover, the term "high rise" was not mentioned until the 13th Edition of the NFPA *Fire Protection Handbook* [3] that was published in 1969 and only in the context of standpipe systems.

The experience with fires in very tall buildings contributed to the development of fire safety provisions for very tall buildings in the model codes and standards. Several fires in recent history brought attention to the fire safety risks associated with very tall buildings. This focus has increased again with several incidents around the world involving facade fires.

Among the significant very tall building incidents are fires at the following buildings:

1. One New York Plaza – August 15, 1970 [4]
2. MGM Grand – November 21, 1980 [5]
3. First Interstate Bank – May 4, 1988 [6]
4. One Meridian Plaza – February 23, 1991 [7]
5. World Trade Center Terrorist Attack – February 26, 1993 [8]
6. World Trade Center Buildings 1 and 2 Terrorist Attack – September 11, 2001 [9]
7. World Trade Center Building 7 (WTC 7) Terrorist Attack – September 11, 2001 [10]
8. Cook County Administration Building – October 17, 2003 [11]
9. Caracas Tower Fire – October 17, 2004 [12]
10. Windsor Tower, Madrid, Spain – February 12, 2005 [13]
11. The Beijing Mandarin Oriental Hotel Fire – February 9, 2009 [14]
12. Shanghai Apartment Tower Fire – November 15, 2010 [15]
13. Lacrosse Fire – November 25, 2014 [16]
14. The Address Downtown Hotel – December 31, 2015 [17]

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15. The Torch – February 21, 2015 [18] and August 4, 2017 [19]
16. Grenfell Tower – June 14, 2017 [20]

While these fires were distinctive, they share common factors. The lessons derived from these factors have had an impact on the global development of codes and standards and are summarized in Table 2.1. The general lessons learned pertain to:

- Unprotected vertical openings
- Inadequate structural fire resistance
- Combustibles in concealed spaces
- Inadequate elevator operations
- Inadequate fire control (e.g., automatic sprinklers, fire barriers)
- Inadequate protection of exit stairways
- Combustible interior finish
- Combustible exterior wall systems
- Redundancy of critical systems
- Inadequate maintenance of fire protection systems and egress components
- Inadequate emergency plan
- Inadequate fire alarm notification

The following paragraphs describe some of these incidents in more detail. The buildings involved may not have met the applicable building regulations at the time of the fire for new construction. In some cases, fire experience demonstrates a lack of compliance with codes and standards at the time of construction or adequate enforcement of adopted regulations associated with post-construction occupancy and operations. Details of these fires and associated buildings are contained in the references. The cited references are not intended to be an exhaustive list of information for the reader.

One New York Plaza, New York, USA – August 15, 1970

A fire occurred on the 33rd floor of the 50-story One New York Plaza office building. Workers from the 32nd floor discovered the fire. Two guards and a telephone company employee took an elevator to the 39th story with the intention of notifying the occupants of the fire. Because the elevator was called to the fire floor by the effects of the fire, the elevator stopped at the 33rd floor. The two guards died; the telephone company employee survived.

Table 2.1 Summary of major lessons learned from major very tall building fires

Incident	Unprotected vertical openings	Inadequate structural fire resistance	Combustibles in concealed spaces	Inadequate elevator operations	Inadequate fire control, e.g., automatic sprinklers, barriers	Inadequate protection of exit stairways	Combustible interior finish	Combustible exterior wall systems	Redundancy of critical systems	Inadequate maintenance of fire protection systems and egress components	Inadequate emergency plan	Inadequate fire alarm notification
One New York Plaza, New York, USA – August 15, 1970		**X**		**X**								
MGM Grand Hotel, Las Vegas, USA – November 21, 1980	**X**		**X**	**X**		**X**	**X**				**X**	
First Interstate Bank, Los Angeles, USA – May 4, 1988				**X**	**X**	**X**					**X**	**X**

(continued)

Table 2.1 (continued)

Incident	Unprotected vertical openings	Inadequate structural fire resistance	Combustibles in concealed spaces	Inadequate elevator operations	Inadequate fire control, e.g., automatic sprinklers, barriers	Inadequate protection of exit stairways	Combustible interior finish	Combustible exterior wall systems	Redundancy of critical systems	Inadequate maintenance of fire protection systems and egress components	Inadequate emergency plan	Inadequate fire alarm notification
One Meridian Plaza, Philadelphia, USA – February 23, 1991					**X**					**X**		**X**
World Trade Center Explosion and Fire, New York, USA – February 26, 1993									**X**			
World Trade Center Buildings 1 and 2, New York, USA – September 11, 2001		**X**							**X**			

Incident	Unprotected vertical openings	Inadequate structural fire resistance	Combustibles in concealed spaces	Inadequate elevator operations	Inadequate fire control, e.g., automatic sprinklers, barriers	Inadequate protection of exit stairways	Combustible interior finish	Combustible exterior wall systems	Redundancy of critical systems	Inadequate maintenance of fire protection systems and egress components	Inadequate emergency plan	Inadequate fire alarm notification
World Trade Center Building 7, New York, USA – September 11, 2001		**X**							**X**			
Cook County Administration Building, Chicago, USA – October 17, 2003					**X**	**X**					**X**	
Caracas Tower Fire, Caracas, Venezuela – October 17, 2004										**X**		

(continued)

Table 2.1 (continued)

Incident	Unprotected vertical openings	Inadequate structural fire resistance	Combustibles in concealed spaces	Inadequate elevator operations	Inadequate fire control, e.g., automatic sprinklers, barriers	Inadequate protection of exit stairways	Combustible interior finish	Combustible exterior wall systems	Redundancy of critical systems	Inadequate maintenance of fire protection systems and egress components	Inadequate emergency plan	Inadequate fire alarm notification
Windsor Tower, Madrid, Spain – February 12, 2005	**X**	**X**			**X**							
The Mandarin Oriental Hotel, Beijing, China – February 9, 2009								**X**				
Shanghai Apartment Tower Fire, Shanghai, China – November 15, 2010								**X**			**X**	

Incident	Unprotected vertical openings	Inadequate structural fire resistance	Combustibles in concealed spaces	Inadequate elevator operations	Inadequate fire control, e.g., automatic sprinklers, barriers	Inadequate protection of exit stairways	Combustible interior finish	Combustible exterior wall systems	Redundancy of critical systems	Inadequate maintenance of fire protection systems and egress components	Inadequate emergency plan	Inadequate fire alarm notification
Lacrosse Fire, Melbourne, Australia – November 25, 2014								**X**				
The Address Downtown Hotel, Dubai, UAE – December 31, 2015 [15]								**X**				
The Torch, Dubai, UAE – February 21, 2015 and August 4, 2017								**X**				
Grenfell Tower, London, UK – June 14, 2017					**X**	**X**	**X**	**X**		**X**	**X**	**X**

Lessons Learned

The consequences of this fire led to improvements, including revisions to the elevator code, specifically:

1. Protection of steel members with appropriate materials
2. Automatic elevator recall
3. Elevator call buttons that cannot be activated by fire or smoke
4. "Fire fighter's service" that allows elevators to be recalled to the "home" floor manually by a key-operated switch at the elevator access lobby and to be operated by a fire fighter from within the car with a key-operated switch

MGM Grand Hotel, Las Vegas, USA – November 21, 1980

A fire at the MGM Grand Hotel resulted in the deaths of 85 guests and hotel employees. About 600 others were injured, and approximately 35 fire fighters sought medical attention during and after the fire. The very tall building, constructed in the early 1970s, consisted of 21 stories of guest rooms above a large, ground-level complex comprised of a casino, showrooms, convention facilities, jai alai fronton, and a mercantile complex. The hotel was partially sprinklered, but major areas including the main casino and The Deli restaurant, the area of fire origin, were not sprinklered. About 3,400 registered guests were in the hotel at the time of the fire. The most probable cause of the fire was heat produced by an electrical ground fault within a combustible concealed space in a waitresses' serving station of The Deli restaurant [5].

Lessons Learned

1. Vertical openings, including seismic joints, stairways, and elevator shafts, must be protected to limit smoke and fire spread between floors.
2. Combustible concealed spaces in fire-resistive and noncombustible buildings should be limited.
3. Automatic elevator recall is needed.
4. Flame spread of interior finish can contribute to rapid fire spread.
5. Stairway doors should allow reentry to floors at not more than five floor intervals.
6. HVAC systems must be protected to avoid distributing smoke during a fire.
7. Large assembly buildings need a pre-fire emergency plan.

First Interstate Bank, Los Angeles, USA – May 4, 1988

The First Interstate Bank building was located in Los Angeles, California. It was 62 stories high and was in the process of being retrofitted with automatic sprinkler protection at the time of the fire. The sprinkler system was, however, not operational at that time. The fire began at 10:25 pm on the 12th story. A maintenance worker took an elevator to the floor of origin and was confronted with intense heat when the doors opened. He subsequently died. Flames spread vertically in the building through a return airshaft and in the space between the exterior curtain walls and the edges of the floor slabs.

Lessons Learned

1. Special precautions are needed for buildings under construction. As buildings are being retrofitted with sprinklers, the sprinklers should be activated as soon as possible (see Chap. 19, Buildings Under Construction).
2. Curtain walls should be designed to limit fire and smoke spread at the joints of exterior walls and floors.
3. Automatic elevator recall is needed.
4. Fire alarm systems should be connected to a monitoring service or directly to the fire department to provide automatic notification of a fire.
5. All stairway doors should be fire-rated doors.
6. Stairway doors should allow reentry to floors at not more than five floor intervals.
7. Very tall buildings need a pre-fire emergency plan.

One Meridian Plaza, Philadelphia, USA – February 23, 1991

One Meridian Plaza was a 38-story office building in Philadelphia, Pennsylvania. The building had a partial automatic sprinkler system, but no sprinklers were installed on the floor of fire origin. The fire began on the 22nd story due to the spontaneous combustion of linseed oil-soaked rags left by painters. The fire department had trouble achieving a water supply from the standpipe system. Because the fire department feared that the building could collapse, they evacuated and suspended fire-fighting operations. The fire continued to spread from floor to floor until it reached the 30th story where it was extinguished by ten sprinklers fed by the fire department connection.

Lessons Learned

1. Very tall buildings need sprinkler protection.
2. Curtain walls should be designed to limit fire and smoke spread at the exterior wall between floors.
3. Combined sprinkler and standpipe risers should be zoned so that pressure-reducing valves (PRVs) are not needed at standpipe hose valves. If installed, annual inspection and testing of the PRVs is needed to achieve reliable operation.
4. Fire alarm systems for very tall buildings should be connected to a supervisory service or directly to the fire department.
5. Primary and secondary power should be routed independently.
6. Special precautions are needed for buildings under construction (see Chap. 19, Buildings Under Construction).

World Trade Center Terrorist Attack, New York, USA – February 26, 1993

On February 26, 1993, a truck bomb was detonated in the garage beneath Buildings 1 and 2 of the World Trade Center (WTC) as part of a terrorist attack. The explosion caused a fire that resulted in substantial damage to the below grade spaces. Smoke permeated the seven towers that comprised the WTC complex. Several stairway enclosures on the lower stories of the complex were damaged by the explosion. Evacuation of the buildings ensued, requiring many occupants to encounter smoke for the descent through the stairways. The explosion disabled many of the fire protection systems and the emergency generators supplying backup power to the complex.

Lessons Learned

1. Generator systems may not provide the needed reliability for providing power for emergency lighting.
2. Key fire safety systems need redundancy and physical separation.

World Trade Center Buildings 1 and 2 Terrorist Attack, New York, USA – September 11, 2001

Commercial aircraft were deliberately flown into the North and South Towers of the World Trade Center complex (Buildings 1 and 2, respectively) in a coordinated terrorist attack. The impacts and subsequent damage resulted in localized loss of structural integrity, loss of exit compartmentation, and loss of fire-fighting water and loss of water to fire suppression systems. While each building withstood the resulting fires for a period of time, each tower ultimately collapsed, killing nearly 3,000 occupants and emergency personnel who were unable to fully evacuate the buildings.

Two significant investigations were conducted, one led by the Federal Emergency Management Agency (FEMA) and the Structural Engineering Institute of the American Society of Civil Engineers (SEI/ASCE) [21] and the other by the National Institute of Standards and Technology (NIST) [9], in association with other government agencies, professional organizations, researchers, engineers, and various agencies within New York City. Several changes were made to the building codes because of these studies.

Lessons Learned

While the events of September 11, 2001, were deliberate terrorist acts, it is appropriate to consider the possibilities and consequences of terrorist events as part of the risk analysis discussed in Chap. 7 (Hazard, Risk and Decision Analysis in Very Tall Building Design) (especially as this incident produced a significant fire that affected the response of the occupant population). Official investigation reports provide much more detail, but key observations from the reports include:

1. Structural framing needs redundancy.
2. Sprayed fire-resistive materials (SFRM) need to adhere under realistic impact and fire conditions, including explosions, as identified in a risk analysis.
3. Structural element connection performance under impact and fire loads must be understood and quantified.
4. Egress systems should be evaluated for redundancy and robustness.
5. Fire protection ratings and safety factors for structural transfer should be evaluated for adequacy.

World Trade Center Building 7 (WTC 7) Terrorist Attack, New York, USA – September 11, 2001

WTC 7 was a 47-story building in the World Trade Center complex. Debris from the terrorist attack on WTC 1 caused structural damage to WTC 7 with resulting fires on multiple stories. Because of the structural damage and the collapse of WTC 1 and 2 interrupted the public water supply to WTC 7, automatic sprinklers in the building were rendered inoperable. Fires burned in the building for nearly 7 hours before it collapsed.

Lessons Learned

1. The reliability of structural SFRM needs to be appropriate to address the risks associated with very tall buildings.
2. Structural system connections need to have fire resistance at least equal to the members that rely on them for support.
3. The reliability of the active fire protection systems should address the greater risks associated with very tall buildings.

Cook County Administration Building, Chicago, USA – October 17, 2003

A fire started in a storage room on the 12th story, spreading through the suite of origin. Fire fighters accessing the fire from a stairway opened doors, which allowed hot smoke and gases to flow into the stairway. For security reasons, the stairway doors were locked from within the stairway, preventing escape except from the stairway exit on the ground floor. Six people died in the stairway, being trapped above the 12th story. As a result of this fire, the city adopted an ordinance to upgrade the fire safety of more than 1,000 existing buildings through a combination of automatic sprinkler protection and other measures.

Lessons Learned

1. A strategy of compartmentation and/or automatic fire suppression is needed to control the spread of fire.
2. Doors need to unlock to allow reentry from stairways that may become compromised.
3. Effective communication with and training of building occupants is important.

Caracas Tower Fire, Caracas, Venezuela – October 17, 2004

A fire originated on the 34th story of the tallest building in Caracas, a 56-story, 220 m (730 ft) high office tower. The fire started around midnight and spread to more than 26 stories for more than 17 hours. The investigation determined that fire pumps malfunctioned, exits were blocked, and elevators were not accessible. The fire was finally brought under control by a combination of military helicopters dropping water on the building and fire fighters' efforts.

Lessons Learned

1. Fire protection systems must be maintained.
2. Codes and standards must be enforced.

Windsor Tower, Madrid, Spain – February 12, 2005

The Windsor Tower was a 32-story concrete building with a reinforced concrete core. Originally, the perimeter columns and internal steel beams were left unprotected, and vertical openings were not protected. There was no fire stopping between the floor slabs and the exterior wall. At the time of the fire, the building was undergoing a multi-year fire protection improvement program consisting of protecting structural steel members, upgrading the curtain wall construction, and installing automatic sprinklers. When the fire started, most of the improvements had been completed below the 17th story. However, some of the curtain wall fire-stopping and vertical opening protection had not been completed. The fire started on the 21st story and spread rapidly throughout the entire building.

Lessons Learned

1. Very tall buildings need sprinkler protection with a reliable water supply.
2. Curtain walls should be protected to limit fire and smoke spread at the exterior wall between floors.
3. Vertical openings, including stairways and elevator shafts, need to be protected to limit smoke and fire spread between floors.
4. Special precautions are needed for buildings under construction (see Chap. 19, Buildings Under Construction).

The Mandarin Oriental Hotel Fire, Beijing, China – February 9, 2009

The nearly completed 160 m (520 ft) very tall building in Beijing caught fire around 8:00 pm, was engulfed within 20 minutes, and burned for at least 3 hours until about midnight. The fire was started by fireworks from an adjacent display or from illegal fireworks ignited in the building. Even though the fire extended across all the floors for a period of time and burned out of control for hours, no large portion of the structure collapsed.

Lessons Learned

1. Fireworks displays should be controlled. NFPA 1123, [22] *Code for Fireworks Display* provides guidance.
2. Combustible components in the construction of a very tall building's facade can pose unreasonable risks for significant fire spread along the exterior of a building. Facade fire spread characteristics must be understood and substantiated by large-scale tests.
3. Special precautions are needed for buildings under construction (see Chap. 19, Buildings Under Construction).

Shanghai Apartment Tower Fire, Shanghai, China – November 15, 2010

During a facade renovation project that was intended to improve the energy efficiency of the 28-story building, a fire was ignited by construction workers conducting welding operations outside the 10th floor elevator lobby window in violation of local regulations. Sparks from the welding operation reportedly ignited construction waste which then ignited combustible scaffold materials on the levels below the welding. The construction waste materials principally included rigid polyurethane (PU) foam insulation board that was being installed as part of the facade renovation project.

Ultimately, 58 people perished as fire spread rapidly up the outside of the building. The fire reportedly spread to the roof within about four minutes and ultimately spread into the building interior on most of the floor levels above the 5th story [23]. The building had fire sprinklers installed only in the lowest four stories. Official accounts of the fire focus principally on the fire ignition and the illegal construction practices; but in review of the floor plan of the building, it is likely that one or both exit stairs became unusable at some point in the fire.

Lessons Learned

1. Combustible components in the construction of a very tall building's facade can pose a risk for significant fire spread along the exterior of a building. Facade fire spread characteristics must be understood and substantiated by large-scale tests.
2. Welding during construction requires proper oversight (see Chap. 19, Buildings Under Construction).
3. Special precautions are needed for buildings under construction. Combustible debris during renovation projects in occupied buildings requires strict control measures.

Lacrosse Fire, Melbourne, Australia – November 25, 2014

A fire started in the early hours of the morning of November 25, 2014, in the 23-story Lacrosse building in Melbourne, Australia. The building was primarily occupied as residential apartments. The point of fire origin is reported to have started on the balcony of Apartment 805. The fire spread vertically via the exterior facade, spreading both downward to apartment 605 and upward. The upward spread affected all apartments above designated as apartments "05" on each floor, up to apartment 2105. It was observed that large amounts of household items were being stored on some apartment balconies, creating a higher fire load. The sprinkler system did not extend to the external balconies of the apartments. This fire caused extensive fire damage to 15 apartments and subsequently water damage to many more. The fire directly affected more than 450 occupants who required immediate evacuation and accommodation. There were no fatalities or serious injuries in this incident.

It was reported that the combined hydrant/sprinkler system performed well and allowed multiple sprinklers to activate while at least one fire hydrant was operating.

Lessons Learned

1. The facade system used on the Lacrosse building should be appropriately addressed, screened, and documented under the code approvals process used for building permits.
2. Apartment balconies should be kept clear of household storage items.
3. Occupiable porches and balconies should be sprinklered in fully sprinklered buildings
4. Sprinkler systems do not prevent fire spread on the exterior of the building, but they can delay fire spread into the interior of a building.

The Address Downtown Hotel Fire, Dubai, UAE – December 31, 2015

The Address Hotel in downtown Dubai suffered a large fire involving most of the 65 stories of the building envelope on the evening of December 31, 2015. It is reported that the fire started due to an electrical short circuit on a spotlight around the 14th floor at about 9:25 pm. The exterior facade system was implicated in the fire spread up the exterior of the building. There was significant fire damage to the exterior and the interior of the building. The sprinkler and standpipes systems were operating, but water storage was quickly depleted as sprinklers activated on multiple floors simultaneously. Fire crews were still fighting the fire, although under control, the day after the fire started. Fifteen people were injured, and one person suffered a heart attack while being removed from the building.

Lessons Learned

1. Combustible components in the construction of a very tall building's facade can pose a risk for significant fire spread along the exterior of a building. Facade fire spread characteristics must be understood and substantiated by large-scale tests.
2. Occupiable porches and balconies should be sprinklered in fully sprinklered buildings.
3. Sprinkler systems can delay fire spread into the interior of a building, but water supplies may become depleted as the demand on the system from fires on multiple floors simultaneously is much higher than the system's design basis.

Torch Tower Fire, Dubai, UAE – February 21, 2015 and August 4, 2017

On February 21, 2015, the 337 m (1105 ft), 87-story building had a fire, damaging 60 stories from a fire that started on the exterior on the 20th story. Local media reported that the fire broke out on the 51st floor of the building. The fire spread upward to the 83rd floor. The strong winds carried flaming debris across the building facade to the 38th floor on the other side of the tower, causing a second fire.

The exterior walls were clad with aluminum composite panels with a thermoplastic core providing fuel and a route for fire spread up the building. An internal automatic sprinkler system prevented serious damage to the interior of the building. Over a thousand residents were evacuated with no fatalities; seven people were treated at the scene for smoke inhalation.

On August 4, 2017, the same building had another building envelope fire that started on the exterior of the 26th floor. Fire spread externally to affect 64 floors, significantly damaging the exterior and, to varying degrees, the interiors of 38 units. Damage to the building interior was again limited due to the presence of sprinklers. Local media reported that 475 people were evacuated from the building; no injuries were reported.

Lessons Learned

1. Combustible components in the construction of a very tall building's facade can pose a risk for significant fire spread along the exterior of a building. Facade fire spread characteristics must be understood and substantiated by large-scale tests.

2. Occupiable porches and balconies should be sprinklered in fully sprinklered buildings.

Grenfell Tower Fire, London, England – June 14, 2017

Grenfell Tower was a 24-story, 129-unit residential building in London, England. Construction of the building started in 1972 and was completed in 1974. The Phase 1 report from the public inquiry into the circumstances leading up to and surrounding the Grenfell Tower fire was published in October 2019 [24].

The building had a plan floor area of approximately 22 × 22 m (72 × 72 ft). It had a central reinforced concrete core, reinforced concrete floors, and concrete columns [25]. Floors 4 to 23 were designed to accommodate residential apartments, with six units on each floor [26]. The building had a single exit stairway, common for buildings of this type, and no fire sprinklers. The building had a dry standpipe riser that could be pressurized during fire-fighting operations with outlets located in the lobbies of Floors 4–23. The building did not have a fire alarm system.

The building was renovated between 2012 and 2016 and underwent substantial changes. The work affected both the outside and the inside of the building. Most significantly, it incorporated the over-cladding the existing building with a new insulation and rainscreen cladding system [27].

A short circuit in a refrigerator started the fire in a unit on the fourth story of the building. The resident of the apartment was awakened by a smoke alarm. The resident notified his neighbors and then called the fire department.

The fire breached the window in the unit of origin and ignited the combustible exterior wall panels, spreading rapidly upward. The fire also spread laterally via the exterior, eventually igniting the facade system on other sides of the building. Many people were unable to escape the rapidly spreading fire. The fire took more than 60 hours to extinguish and involved more than 250 fire fighters. The building's combustible facade and insulation and related installation details were cited as primary factors in the rapid spread. Seventy-two fatalities and 74 injuries were reported.

Lessons Learned

1. Very tall buildings need sprinkler protection with a reliable water supply.
2. Combustible components in the construction of a very tall building's facade can pose a risk for significant fire spread along the exterior of a building. Facade fire spread characteristics must be understood and substantiated by large-scale tests.
3. Multiple means of egress are important elements of building design.
4. Effective communication and training are important to reduce injuries during a fire.

Performance-Based Approach to Building Fire Safety

During the early 1970s, fires in very tall buildings contributed to a growing awareness of the special fire safety challenges of such buildings. This awareness led to the development of a qualitative systems approach for preventing or managing the impacts of fire, which became embodied in the *Guide to the NFPA Fire Safety Concepts Tree*, NFPA 550 [28] (see Chap. 7, Hazard, Risk and Decision Analysis in Very Tall Building Design), and a quantitative systems approach for fire safety design for buildings as described in the US General Services Administration, *Appendix D, Interim Guide for Goal Oriented Systems Approach to Building Fire Safety* [29]. A thorough analysis of the GSA system is contained in an NBS report: “A Theoretical Rationalization of a Goal-Oriented Systems Approach to Building Fire Safety” [30]. References in the report provide an excellent history of the early development in the United States of performance-based approaches to building fire safety. Subsequent discussion on the development of performance-based design (PBD) for fire can be found in a NIST report [31]. The use of a performance-based approach to fire safety design of very tall buildings is important for several reasons, including the uniqueness of the buildings and systems, and the general lack of regulatory guidance specific to very tall buildings.

Chapter 3
Components of Performance-Based Design

The approach to performance-based design varies depending on the building code that applies in the relevant jurisdiction. Where there is no performance-based building code in effect, the design process starts by establishing appropriate performance objectives and acceptance criteria that need to be agreed upon by the stakeholders of the project.

Research conducted into the evolution of performance-based design for fire has shown that several common concepts are entrenched in several guidelines or standards for performance-based/fire safety engineering design [31, 32, 33, 34, 35, 36, 37]. Some of the common concepts include:

1. Identification of site or project information
2. Identification of goals and objectives
3. Development and selection of performance criteria
4. Development of possible scenarios, design scenarios, and/or design loads
5. Development of candidate design options
6. Evaluation of candidate design options and selection of a final design
7. Development of design documentation

The interrelation of these steps is outlined in the *SFPE Engineering Guide to Performance-Based Fire Protection* (see Fig. 3.1) [1]. The relationship between these steps is similar in other published fire safety engineering guidance as well [33, 34, 35].

Very tall buildings demand special consideration, given their unique and highly specialized design requirements, the unusual risks for the occupants created because of the building's height, and consequently the challenges for fire safety design. As the building height and occupant load increase, and the range of uses become more diversified, the design of a very tall building will need to meet a range of performance objectives and acceptance criteria that are unlikely to be covered by a default prescriptive solution by applying a building code solution (even though a building code might give permission to design this way). A performance-based approach should be used, even in jurisdictions where prescriptive solutions exist, to verify the

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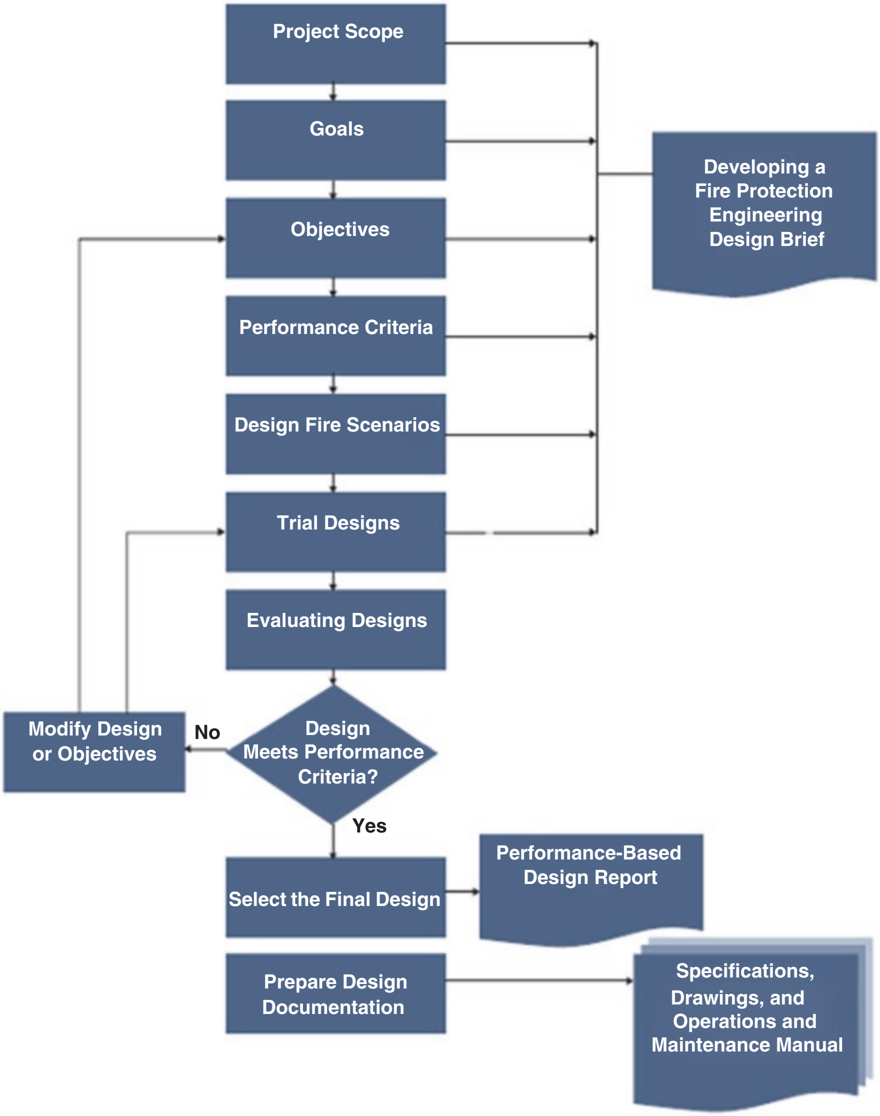

Fig. 3.1 Performance-based fire protection design flowchart [1]

appropriateness of a prescriptive solution for the specific configuration of the very tall building (height, occupancy, mixed use, etc.).

This guide assumes the application of the performance-based design process. One method is outlined above and embodied in the referenced documents. As such, the performance-based design process is not addressed in detail in this document. However, this document addresses certain aspects of the performance-based design process that are applicable to very tall buildings. Issues such as considerations for fire safety goals, objectives, and criteria, as well as specific design features such as egress, structural design for fire, and smoke control, are outlined in topic-specific chapters. In addition, guidance for the identification and treatment of fire hazards and risks particular to very tall buildings are outlined in Chaps. 5 through 8. Evaluation of designs should follow recommendations in the *SFPE Engineering Guide to Performance-Based Fire Protection* [1] or equivalent guidance and is not detailed in this document.

Fighting fires in very tall buildings places unique challenges upon fire department operations. As such, when applying the performance-based concept to the design of a very tall building, one should consider fire scenarios that incorporate the actions and contributions of the fire service (see Chap. 17, First Responder Considerations).

Computer models are often used to evaluate aspects of a performance-based design. These models can range from simple algebraic correlations that can be solved with a calculator or spreadsheet to very advanced computer-based models. The process of determining the suitability of a fire model is outlined in the *SFPE Engineering Guide for Substantiating a Fire Model for a Given Application* [38].

Peer Review

Fire safety designs for very tall buildings that implement a performance-based methodology should be subject to a peer review. Peer review can be defined as a practice of independent and unbiased evaluation of sound engineering principles, judgment, and their proper application in the conceptual approach and technical basis of a work product. The peer review of performance-based designs should follow a well-defined and documented process, such as the process described in *The SFPE Guide to Peer Review in the Fire Protection Design Process* [39]. This guide addresses the initiation, scope, conduct, and report of a peer review.

Documentation

Proper documentation of a performance design is critical to provide a historical record of the design acceptance, construction process, and how to address future changes. Proper documentation will also assure that all parties involved understand what is necessary for the design implementation, maintenance, and continuity of the fire protection design. If attention to details is maintained in the documentation, then little dispute during approval, construction, start-up, and use should occur. The *SFPE Engineering Guide to Performance-Based Fire Protection* provides guidance on the proper documentation [1].

Qualifications for Engineers

For any performance-based fire safety application in very tall buildings, it is critical to ensure that engineers possess appropriate education, training, and experience, as well as appropriate professional certifications and licenses [1]. Requirements governing the use of the term "engineer" or the ability to practice "engineering" vary widely around the world. In some countries, one can call themselves an engineer on graduation with a university degree in engineering. Conversely, some jurisdictions may have very specific governing regulations that specify in detail the knowledge and experience required before legally using the term "engineer" or, with respect to fire, the term "fire protection engineer." In contrast, many parts of the world have no prescriptive or performance requirements governing the knowledge and experience required to practice engineering, or fire protection engineering. Additional information can be found in the *SFPE Recommended Minimum Technical Core Competencies for the Practice of Fire Protection Engineering* [40].

Chapter 4
International Practices

Currently no unified global codes and standards exist for very tall building fire safety design. Many developed countries have local or national codes and standards that address many of the fundamental fire safety principles of very tall building design: fire-resistive construction; active detection, suppression, and alarm systems; and egress, emergency access, and smoke control. These requirements have been developed over time and are often crafted around local and national design and construction practices, historical fire incidents, locally available materials and products, and fire-fighting resources and capabilities. Regulations are also influenced by national and local customs, practices, norms, fire safety knowledge, resource capacities, and underlying socioeconomic, political, and legal environments. These differences mean that acceptable levels of risk, approaches, and systems for achieving fire life safety objectives in very tall buildings can vary between countries (and in some cases even within a single country) that have a long history of constructing very tall buildings. China, Hong Kong, Singapore, and Taiwan, for example, have highly developed regulations for very tall buildings based on their respective local contexts and, therefore, include many provisions not found in North American or European codes.

In some contexts, particularly in emerging economies, little to no regulations specific to fire safety in very tall buildings may exist. In addition, many of these developing countries have limited capacity related to staffing, knowledge, training, financial resources, institutions, and political will to enforce such regulations fully and effectively even if they do exist for very tall buildings. There may also be limitations on the availability, accessibility, and reliability of fire safety resources such as emergency water supplies, fire-fighting operations, fire-tested products/systems, construction materials, maintenance practices, skilled laborers, experienced design professionals, etc. This presents many unique challenges but also provides opportunities to develop new approaches, systems, and products to meet an appropriate level of fire life safety. Addressing these unique circumstances can oftentimes lead to an ad hoc mixture of international best practices, codes, and standards in concert with local requirements and practices, where special care is needed to develop fire

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Table 4.1 International sample of very tall building fire safety codes and standards

Australia – *National Construction Code* [41]
Canada – *National Building Code of Canada* [42]
China – China Fire Code
Hong Kong – Hong Kong Fire Safety Code
Japan – *Building Standard Law* [43]
Singapore – Code of Practice for Fire Precautions in Buildings [44]
United Arab Emirates – Fire and Life Safety Code of Practice [45]
United Kingdom – *BS 9999: Code of practice for fire safety in the design, management and use* of buildings [46]
United States – International Building Code® (IBC®) [47], International Fire Code® (IFC®) [48], and NFPA 5000®, Building Construction and Safety Code® [49]

life safety designs that are comprehensive, sustainable, reliable, and relevant to local conditions. Table 4.1 lists some of the international codes and standards that have requirements for very tall buildings.

Even if a unified code did exist, the uniqueness inherent in very tall buildings, the range of physical environments, and the pace of changing technologies, goals, and perceptions can often warrant the need for new and custom-tailored techniques, concepts, systems, and configurations. This can mean that existing international and local codes and regulations will likely not adequately address the range of unique conditions and evolve rapidly enough to address changes in technologies. As very tall building designs can push the envelope of technology and innovation, approaching fire safety design from a first principles and a performance-based mindset may be more prudent than having a set prescriptive standard.

Key Considerations in International Design

Due to a variety of factors – the increasing complexity of very tall building design, rapid urbanization, growing desire for “world class” facilities in emerging economies, and the globalization of building design and construction industries – international design practice has introduced new opportunities and new challenges to the fire safety design of very tall buildings. This includes new approaches, systems, and equipment for very tall building fire safety. Often, the new approaches blend international design practices with developed and local country regulations, codes, standards, construction practices, and products. While this can result in new advances in fire safety design strategies, construction practices, technologies, products, firefighting operations, fire safety management, etc., it can also introduce new foreseen/unforeseen challenges and uncertainties in how these mixed design practices and new approaches will impact anticipated fire performance.

Integrating international best practices and developed-country codes can be particularly challenging in emerging economies where local capacities and resources are often limited, nonexistent, and constrained. Special care and a holistic understanding of the local context can be critical in developing an appropriate design that not only meets fire life safety objectives but is also sustainable and relevant for the local environment. Some key considerations are:

- What are the local codes, standards, and requirements established by the local authorities having jurisdiction? Are all relevant codes and standards in a format and language that are understood by all design team members and authorities? If not, then accurate translations prepared by professionals proficient in both the local language and the local technical requirements will be required.
- How will the integration of local codes with international practices and developed-country codes impact the fire strategy? Will this impact the overall level of safety provided?
- Are there any underlying socioeconomic, political, legal, and/or administrative conditions that may inhibit or reduce the effective design and/or implementation of the fire safety design? For instance, urban planning issues, security, vandalism, or corruption can impact fire safety design for a very tall building.
- Are there local cultural, social, and environmental factors that require special consideration in applying appropriate data for engineering tools, such as fire effects and evacuation models?
- Are there local cultures, social structures, customs, norms, perceptions, behaviors, or attitudes (such as religious requirements, belief systems, gender roles, smoking practices, and/or permanently blocking doors for ventilation) that should be considered in designing fire control strategy, the evacuation system, occupant notification system, smoke control, or any other human-interfacing designs?
- Do materials and products need to be tested to both local and developed country standards to satisfy various stakeholders? In some cases, products or systems must be tested and designed to local requirements to satisfy statutory requirements while also meeting developed countries' standards to satisfy a project's corporate criteria or insurance requirements. This can be complicated as some requirements can be mutually exclusive.What is the availability of building materials and products appropriate for the design? Many locations are not able to source internationally recognized fire protection products or permitted to use products tested internationally or to foreign standards.
- How will local materials and products that may not be designed to comply with international standards or have not been evaluated to these standards be expected to perform?How will local product, system design, and maintenance standards, which may not have the same performance as international standards and practices, affect the overall level of safety provided?
- What is the availability, quality, and reliability of the local, public infrastructure? Examples include water supplies and electricity. In many developing economies, designers may not be able to rely on public utilities and might, therefore, design elements such as fire protection water supply and emergency power to be self-contained within the building.
- What is the availability, quality, and reliability of the local construction practices?

- Is there a local fire department? What is the local level of fire-fighting capacities and capabilities? Response time, personnel levels, equipment, and hydrants are examples of capacities, skills, experience, and training that are common capabilities which should be considered. In some locations, fire-fighting capacities can be quite limited in performing operations specific to very tall buildings. Designers may need to modify and/or increase fire safety features such as fire resistance ratings and supplemental water supplies and/or provide special training to local first responders.
- How do local road and traffic conditions impact fire fighter access and response times. In some locations, particularly in megacities in developing countries, long response times are not uncommon due to extreme traffic congestion and a lack of emergency lanes (see Fig. 4.1). Designers may need to provide enhancements and/or additional provisions to account for delayed fire-fighting and medical services.
- What is the local level of building operations, testing, inspection, and maintenance? In many locations, the level of building maintenance may not meet developed countries' standards or practices. Designers must take this into consideration and design systems that are simple, reliable, and robust.
- What is the local capacity for plan check, inspection, and enforcement of fire safety designs?

Fig. 4.1 Chronic congestion on roadways can be a common condition in megacities that may necessitate additional fire safety features for very tall building design

Fig. 4.2 Presence of densely packed informal settlements in some international megacities may limit perimeter access and/or local water pressures during an emergency event

Extreme Events in International Very Tall Building Designs

Perhaps the most significant lesson learned from the World Trade Center attack for very tall building designers is that the threat from fire may not be the most critical threat and that a broad range of emergency scenarios must be considered. Most very tall building construction that has occurred since the World Trade Center attack has been outside of North America.

Nonetheless, many of the lessons learned from the World Trade Center attack have been quickly incorporated into very tall building design practices. This has occurred in four key areas.

Structural Hardening

Some buildings are currently being designed with hardened cores that contain emergency system risers and stairways. Enhanced levels of structural fire resistance analysis and/or design are also being adopted whether through advanced performance-based methods, considering a range of normal to extreme fires as the design basis, or more robust forms of fire protection materials or systems. This may also include evaluation of impact loading coupled with complete burnout. Refer to Chap. 12 (Fire Resistance) for further discussion.

Robust and Redundant Life Safety Systems

Current very tall building design typically incorporates more robust and redundant life safety systems including redundant system risers for power, alarm, and fire suppression systems. These features are intended to allow the building to function and to maintain a high level of life safety even in the event of partial system failure.

Egress

In current international practice, the design of very tall buildings' egress systems is based on various principles, including but not limited to phased evacuation, total evacuation, the use of evacuation elevators, occupant relocation, defend-in-place, and the use of areas or floors of refuge (these different approaches are explored in more detail in Chap. 11, Emergency Egress). Extreme events have made clear that full building simultaneous evacuation may be required under certain scenarios. Even if an egress system is not designed for total evacuation, if identified as part of the risk analysis described in Chap. 7 (Hazard, Risk and Decision Analysis in Very Tall Building Design), the performance of an egress system design under similar extreme events should be evaluated.

Fire Fighter Access

Strategies for fire fighter access in tall buildings can vary significantly within larger nations and certainly vary from nation to nation. For example, some codes require a dedicated elevator for fire fighters, accessed through a vestibule. Other codes that require all elevators to have fire fighter emergency controls also require all elevators to be accessed from a vestibule. It is essential to meet with and continually communicate with the local fire services throughout the life cycle design and operations of the facility to develop and implement a design strategy that optimizes local firefighting resources.

Building Materials

Within the past decade, there has been several dramatic and extreme fires involving facade systems on tall buildings, some of which have resulted in tragic losses of life. These have occurred in all regions of the world and have included both completed facilities and those still under construction. The needs and pressures to provide sustainable, energy-efficient, and cost-effective facade systems must be tempered against appropriate levels of fire and life safety.

Extreme Natural Events

Fire and life safety systems can be compromised or lost during extreme natural events such as earthquakes, typhoons, hurricanes, blizzards, tsunamis, or storm surges. At these times buildings have an increased level of risk, which are further increased if the occupants are unable or choose not to relocate to a place of lesser risk. The types of local extreme natural events, their frequency and intensity, and the probable exposure of the building occupants to those risks must be evaluated and addressed as part of the fire protection and life safety process.

Chapter 5
Unique Features of Very Tall Buildings

Very tall buildings have attributes that can adversely affect the fire safety of a building.

Height Beyond Reach of Fire Department Ladders

Typical fire department aerial ladders have a finite reach (recognizing a setback distance from a building). Some building sites provide multiple stories of street access to a building. Therefore, many codes have defined "high-rise" buildings as those having an occupied floor that is a defined height above the lowest stories of fire department vehicle access. Buildings beyond the reach of exterior fire department ladders must have additional protection features because exterior rescue and fire-fighting capabilities will be limited or unavailable for portions of the building above that height.

Furthermore, the lack of exterior access requires fire fighters to access the upper stories of the building by interior means, frequently involving the use of stairways and sometimes using elevators if deemed appropriate under the circumstances. This interior access results in additional physical demands upon the fire fighters and extended time to reach the fire floor.

Extended Evacuation Time

The time necessary for full building evacuation increases with building height (see the *SFPE Handbook of Fire Protection Engineering* [50] and *SFPE Engineering Guide to Human Behavior in Fire* [51] for more information). In the case of very tall buildings, full building evacuation via stairways might be impractical. A "defend-in-place" or "stay-in-place" strategy has been employed in many building designs

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by (1) designing compartments allowing people to remain in place on the floor of alarm, in the case of residential units or on adjacent floors; (2) temporarily evacuating people to areas of refuge on a floor; or (3) moving people to refuge floors elsewhere in the building. Recently, times for full building evacuation have been reduced by employing elevators that have been specifically designed to supplement the egress system of a building. Very tall buildings that have assembly occupancies with large occupant loads on the upper stories require special consideration.

Pronounced Stack Effect

Stack effect is a natural physical phenomenon that occurs in very tall buildings that have pressure differences throughout their heights because of temperature differentials between outside air temperature and inside building temperatures (see the *SFPE Handbook of Fire Protection Engineering* [52] for more information). The effect is pronounced in very tall buildings because of their greater heights. Stack effect causes air to move vertically, either upward or downward, in a building. It can cause smoke from a fire to spread in the building if it is not controlled. As a result, very tall buildings include features such as automatic sprinkler protection and means for smoke control. Sprinklers limit the size of fires and the resulting quantity and energy of smoke which can spread throughout the building. Smoke control, such as openable panels and mechanical systems, can be used to vent, exhaust, or limit stack effect on the spread of smoke throughout the building.

Water Supply Limitations

The water supply needs in very tall buildings can be beyond the water supply capability of public mains and fire department pumpers. Public water supplies have pressures that require supplemental pumps in the building to boost the pressure to a usable level on the upper stories of a building. The building's fire department connection allows the fire department to supply water to the sprinkler and standpipe systems in the event the building's water supply is out of service or inadequate. Above the height achievable by the local fire department's pumps, a building must have the capability to supply water independent of the fire department's pumps. Therefore, multiple levels of pumps and water storage tanks must be provided within the building. Also, because of the potential loss of an external water supply, additional protection features may be considered necessary for such buildings.

Greater Challenges of Mixed Occupancies

Many very tall buildings contain mixed occupancies, involving various combinations of occupancies such as retail, residential, automobile parking, business, public assembly, transportation facilities, health care, educational, childcare, and storage. The fire protection challenges presented by mixed occupancies – such as means of egress and the integration of protection systems – are even greater when they are housed in very tall buildings.

Iconic Nature

Although a building need not be tall to be iconic, very tall buildings generally are considered iconic because they are unusual in height, design, or other features. The iconic nature of the building must be addressed in a risk analysis to determine the measures to protect against willful targeting.

Communication

Very tall buildings have the potential to contain many people, especially if the building has a large floor area. The height and mass of the structure will make communication to people within the building and first responders using radios difficult. Consideration should be given to enhancing the methods used for first responder communication and communication to building occupants. Distributed amplification radio system for first responders is one method for improving first responder communication. Voice communication or mass notification systems will likely be needed to communicate with building occupants.

Chapter 6
Special Features and Attractions

It is common to include special features and attractions within very tall buildings that take advantage of the unique heights and views. The following sections address some of the special features and attractions that have been recently included within very tall building design and outline some of the unique fire and life safety considerations for such features.

Types of Special Features

Many very tall buildings provide a unique experience due to the overall height of the building and therefore the views that are provided. The following is a summary of unique special features that have been included in very tall buildings worldwide.

Observation Decks/Restaurants/Night Clubs/Pool Decks

Observation decks and viewing platforms have become popular for very tall buildings. Often, the observation experience includes both indoor and outdoor spaces and often offers a food and beverage experience. In addition, restaurants, nightclubs, and pool decks have been increasingly popular due to the unique experience that the views provide.

Many times, the demand for these specialized occupancies creates high occupant load spaces that require occupant load monitoring, time ticketing strategies, and/or horizontal exit strategies to address the increased loads. These spaces can be very attractive for use in special events, which can increase the occupant loads to the limit of the egress systems (see Chap. 11, Emergency Egress).

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Glass floors have also become popular due to the unique experience that the transparency provides to the environment below. Floors are traditionally part of the fire-rated structure for the building.

Amusement/Entertainment Thrill Features

As interest in very tall buildings increases for the general public, operators have strived to create unique experiences for patrons that take advantage of the height of such buildings. Often times, the unique experience is aimed at thrill seekers. Thrill experiences include tilt panels that cantilever from the side of the building, ledge walks and roof climbs, zip wires (sometimes between buildings), and specialty elevators or lift devices that provide access to an elevation higher than the roof of the building.

Although less common than observation decks and thrill experiences, some very tall buildings have been designed to include amusement rides, such as roller coasters and observation wheels. The nature of amusement rides, zip lines, and observation wheels include additional safety features that can be more difficult to address in very tall buildings. Most issues will revolve around occupant evacuation when the ride is down or becomes inoperable.

Fireworks

The height of very tall buildings makes them ideal candidates from which to launch fireworks displays. Buildings in Dubai and Taiwan are among more than a few that are designed with the ability to launch fireworks from the building façades and roofs. Recent history shows that launching fireworks within a dense urban area can result in fires in neighboring buildings [14]. Nonetheless, some of today's very tall buildings are still being designed with fireworks launching in mind.

Commercial-grade fireworks are constructed of incendiary and explosive materials; in the United States, they are Class C explosives. Generally, explosives should not be permitted within buildings with large occupant loads, such as those found in very tall buildings. Local codes often mandate that the explosives are stored in stand-alone buildings separated from other buildings in anticipation of a worst-case event. Arguments are made that the fireworks will not be stored within the very tall building, but they do take time to put in place and set up.

Regardless of the semantics, the fireworks will inevitably make their way to the launching locations, which means they must travel through the building. Therefore, a comprehensive risk assessment is needed to be conducted by individuals experienced in handling the commercial fireworks, a blast engineer experienced in evaluating the impact of explosive loads on a building, a fire protection engineer to evaluate the impact of an unexpected event on the building systems, and other professionals as deemed necessary by the risk assessment team. The local fire service should be notified of the presence of fireworks within the building and should be made aware of any fireworks events (date, time, duration, etc.).

At a minimum, the following should be addressed as part of the risk assessment:

- Quality and stability of the fireworks
- Manufacturer recommendations for transport
- Delivery point of the fireworks to the building
- Routes of moving the fireworks through the building
- Potential impacts of unexpected events
- Temporary storage location near launching sites
- Interactions of the launching locations and facade and roof materials
- Capabilities of the local fire authority

Special Life Safety Considerations

The height and nature of the special features can create unique life safety challenges. A critical component in gauging the overall life safety challenges will be coordination between the fire protection and life safety design professionals and the designers/operators of such features so that the unique are adequately addressed. Although many of the amusement rides or devices are governed by design standards, often those standards are specific for the design of the mechanisms of the device or ride, and they do not address rescue and recovery. A fire safety and evacuation plan should be created for each unique circumstance. The evacuation strategies should be reviewed with the local authorities and be coordinated with the operators of the feature (see Chap. 11, Emergency Egress).

Life Safety Systems

For each special feature, the design professional must determine the appropriateness for traditional fire protection and life safety systems, such as sprinklers and fire alarm notification devices. Although sprinkler protection has historically proven very effective in traditional building design, providing sprinkler protection in a moving device, for example, may not be possible. Likewise, the method for occupant notification becomes important. Flashing strobe lights may not be appropriate for a roof climb or edge walk where an occupant could become disoriented.

Amusement rides typically have some interface with the life safety systems to perform overrides should a fire event occur. For very tall buildings, the placement of the ride may impact the override features.

As noted above, observation decks and platforms often include indoor and outdoor spaces. The level of compartmentation for these spaces must be considered.

The compartmentation may be between the observation deck or platform and other areas of the building to minimize the potential effect of fire on the observation areas or may be required for the floor structure itself. Glass floors may need to be fire rated given the construction classification of the building. Although fire-rated glass floors are commercially available, often the assembly is not the preferred method for the designer due to limitations on glazing sizes, thickness of mullions, and clarity of the glass. Alternative methods for achieving a fire rating may need to be explored (see Chap. 12, Fire Resistance).

Fall Hazards

Many of the special features noted in this chapter include devices that cantilever from the building and often include moveable mechanical devices. Consideration should be given to the probability that a component could fall from the device and what that impact might be on occupants or buildings below. Similar consideration should be given to ledge walks and roof climbs regarding the appropriate restraint system for the occupant and the possibility of objects falling from the participating individual.

First Responders: Rescue and Recovery

The location for most of the special features outlined in the section is at the top of the very tall building. This provides access challenges for first responders for rescue and recovery operations. Not only is the travel time to the location increased due to the height; many features include specialty restraint systems or unique vertical movement devices (roller coaster, elevator, observation wheel) that may require specialized knowledge for access.

Consideration should be given to communication challenges that might exist in these unique features. The outdoor features will most likely include a windy environment that make communication difficult, independent of the feature's challenges.

Specialty recovery tools and equipment might be appropriate depending on the functionality of the independent feature. Readily accessible first-aid equipment and stretchers that can be accommodated by the feature may be required within the space or on the roof. Additional consideration should be given to what portions of the feature should be equipped with emergency power sources for rescue and recovery in the event of power failure.

Specialized training will likely be required for first responders for recovery operations. Many jurisdictions employ special response teams specifically trained for high rescue operations. It is likely they will need to train on the specific rides employed on the very tall building.

Chapter 7
Hazard, Risk, and Decision Analysis in Very Tall Building Design

As discussed in Chap. 3 (Components of Performance-Based Design), development and assessment of fire scenarios, design fires, occupant characteristics, and overall acceptable performance can be supported by hazard, risk, and decision analysis. The aim of this chapter is to identify aspects of very tall buildings which may warrant application of hazard, risk, or decision analysis at various stages of design, construction, and operation.

Although fire hazards in very tall buildings are essentially the same as in low-rise buildings of similar uses, specifically related to business, residential, and mixed use, the consequences of a fire have the potential to be more severe given the inherent limitations in egress and access associated with height and the physical aspects of the structure which can affect the hazard such as stack effect and the potentially large numbers of occupants. This is not a new concept; it is why many existing regulations for very tall buildings include more provisions for fire and life safety than those for low-rise buildings of similar use. While such a defense-in-depth approach has resulted in a generally good fire record for very tall buildings, there are several examples of what can go wrong (see Chap. 2, History). Lessons learned from these historic losses highlight the benefits of applying appropriate levels of hazard, risk, and decision analysis to the design of very tall buildings to achieve a high degree of fire safety performance while meeting other project objectives such as operational, financial, etc.

There are a wide variety of hazard, risk, and decision analysis tools and techniques that can be applied to very tall buildings, starting at the feasibility or conceptual planning phase, at various stages of design and construction, and throughout the life of the building. The basic risk assessment process is outlined in Fig. 7.1 [53].

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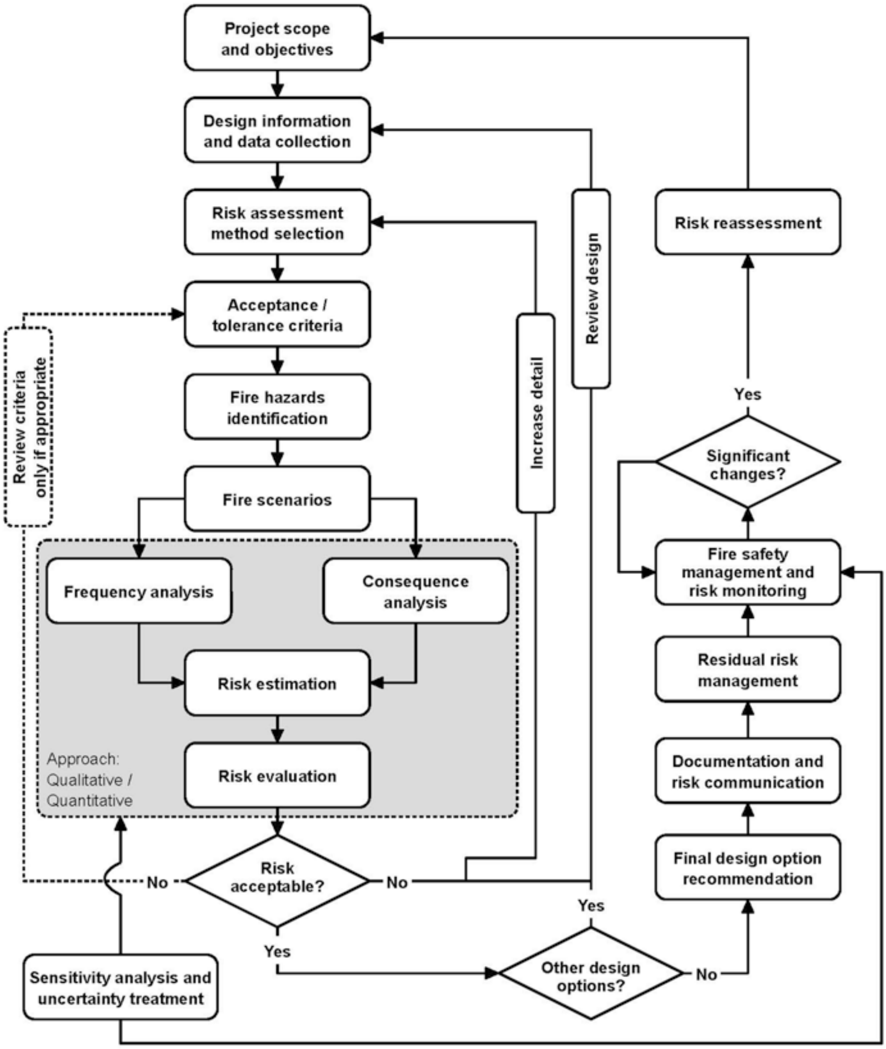

Fig. 7.1 Fire risk assessment flowchart from *SFPE Engineering Guide to Fire Risk Assessment* [53]

Hazards

Fire

During the design of very tall buildings, there may be cases where hazards are introduced or somehow intensified. For example, with a focus on sustainability, there may be additional hazards of concern associated with new materials that may be introduced to address energy performance or other objectives, including facade materials, new thermal insulating materials, fuel cells, photovoltaics, flammable refrigerants, and other such materials. Fires in Busan, South Korea [54]; Shanghai, China [55]; Dubai, United Arab Emirates [17, 19]; and London, United Kingdom [20] associated with combustible facade material installed, or being installed, for energy efficiency upgrades point to a major concern. While new materials for energy efficiency are not unique to very tall buildings, it is likely that energy efficiency will be a significant objective for very tall buildings, and fire hazard assessment should be extended to include these new materials and the expected in-use applications. Facade fires are further addressed in Chap. 13 (Building Envelope/Enclosure). Other new construction concepts are becoming more commonplace. Timber in taller buildings is entering the codes, and architects and owners around the world are considering its use (see Chap. 12, Fire Resistance). Recycled plastics, living walls, and other design features are also becoming more common, and the hazards they pose to a very tall building should be considered.

Tools and methods for fire hazard analysis, as outlined in the *SFPE Engineering Guide to Performance-Based Fire Protection* [1], the *SFPE Engineering Guide to Predicting Room of Origin Fire Hazards* [56], and elsewhere, can be used for facades as for any other fire hazards. For example, simple "what if?" analyses can help identify if a facade is combustible or what happens if it becomes ignited. More structured approaches such as failure modes and effects analysis (FMEA) or fault tree analysis (FTA) can help identify specific failure, such as how the facade might become ignited. Fire effects and other modeling can help assess the development of fire hazards to occupants, contents, and the building. The main point here is to expand the scope of the hazards considered, including fuels, ignition sources, and related factors, seeking appropriate data on the new materials, systems, and hazards to support the assessment and addressing how they affect a very tall building. NFPA has developed a tool for life safety evaluation of the hazards from combustible facades (EFFECT™) [57] in existing buildings, which can be used to help determine the potential risks posed in new buildings.

Technological Events

System failures occur every day. Air-conditioning systems malfunction. Power might be lost to a room or floor of a building or an entire building or group of buildings. An elevator is out of service for routine maintenance. In most cases the interruptions are brief and result in little, if any, detrimental outcomes. However, in a very tall building, interruptions to critical systems can have significant impacts on the building and its occupants. Loss of an elevator servicing the 100th through 140th floors of a building is more than a minor inconvenience, especially if the elevator is intended to serve as part of the egress plan as an occupant evacuation elevator. Likewise, the loss of fire suppression water at the 100th floor is more severe than a similar loss at the 1st floor, which can be more readily reached by responding fire brigade personnel and equipment. Extended power outages can have major implications. Gas or other explosions can result in fire and partial or total building collapse.

Extreme Natural Events

Extreme natural hazard events, such as earthquakes, hurricanes, tsunami, drought, and high wind events, as well as fire exposure from wildland urban interface, pose additional challenges. In these situations, one needs to consider both the primary event (natural hazard) and the secondary event (fire), given the potential for any damage resulting from the primary event. This is particularly important for assessing the availability of fire and life safety systems and their efficacy following the natural hazard event.

For many of these assessments, the fire protection engineer will likely work closely with structural engineers or others focused on the natural hazards evaluation. However, in addition to a focus on structural performance, it is critical to include the performance of nonstructural systems, including power, lighting, piping, HVAC, communication, nonstructural compartment integrity inside the building (passive protection including walls, ceilings, dampers, doors, etc.), and at the exterior boundaries (facade, window, or door openings, etc.). The aim is to estimate the functionality or damage states of the building and systems for assessing post-event fire performance.

For example, fire protection systems can suffer significant damage in seismic events. Reports published following the Northridge and Kobe earthquakes provide some examples [58, 59, 60, 61]. Following the March 11, 2011, tsunami in Japan, the fire and explosions at the Fukushima nuclear power plant, Cosmo oil refinery, and industrial areas of Sendai illustrate the potential for post-earthquake and post-tsunami fire and explosion. An additional challenge in such events is that the initiating event (earthquake, tsunami) can compromise critical infrastructure needed to support fire-fighting operations, including water supply and roadways (for access).

Different challenges are associated with potential climate change. These include rising sea levels (flooding), drought (increased risk of wild land fires, decreased water available for suppression), and increased severity of hurricanes/cyclones (increased wind speeds). As with the above, the focus for the fire protection engineer is post-event fire protection performance of the building. In the case of flooding, issues include location of critical equipment and the ability of emergency responders to reach the building. The water resource issues with drought may lead to a need to have 100% on-site capacity of expected fire-fighting water for the target duration. High winds could result in damage to the building envelope, resulting in loss of compartmentation.

Terrorism

The World Trade Center attack is a clear indication that very tall buildings may be considered targets for acts of terrorism. As with natural hazard events, a key consideration is the operation of the fire and life safety systems following the initiating event. With respect to acts of terrorism, initiating events could include impact, explosion, arson, or chemical, biological, or radiological (CBR) release. While assessment of these hazards may not be within the fire protection engineer's scope, concerns may include the state of the fire protection systems post-event. For instance, the World Trade Center bombing in 1993 disabled the fire alarm, emergency lighting, communications, and many other systems, and the 2001 World Trade Center attack resulted in the loss of passive and active fire protection systems, egress systems, and access for emergency responders. Consideration should also be given to system operation for multiple hazards that can include chemical/biological/radiation management and smoke control.

The US Department of Homeland Security has an array of options to support building owners or design teams considering additional terrorism protection. The Office of SAFETY Act Implementation has a process of vetting and approving products, services, technologies, protocols, and more. They are called QATTs, or Qualified Anti-Terrorism Technologies. The use of SAFETY Act-approved QATTs offers various legal protections. If a project has a particular risk of terrorist attack, it may benefit the owner, designer, and/or builder to investigate options that protect against the risks the project may face [62].

Risk Analysis

As defined in the *SFPE Engineering Guide to Fire Risk Assessment* [53], risk is the potential for realization of unwanted adverse consequences, considering scenarios and their associated frequencies or probabilities and associated consequences. Risk analysis is the in-depth evaluation undertaken to understand and quantify the unwanted adverse consequences. In general, risk analysis is aimed at analysis of what could go wrong, the likelihood of occurring, and the consequences of the event. It involves identification of hazards, identification and specification of scenarios for consideration, estimation and analysis of probability and consequences, combining probability and consequence to obtain an estimate of risk, evaluation of the risk in terms of risk acceptance targets, and taking steps to manage the risk through reducing the probability or consequences of the event, transferring the risk via insurance, or avoiding the risk. The process for fire risk analysis is illustrated in Fig. 7.1.

Risk analysis can be qualitative, semi-quantitative, or quantitative. At the qualitative and semi-quantitative level, matrices for probability and consequence, using descriptive language such as low, medium, and high or numerical values, might be used to reflect a relative ranking of the risk. This approach is found in various fields, such as system safety analysis [63], fire protection engineering [53], and project management [64]. Quantitative risk analysis can take several forms, depending on the type and level of analysis being undertaken. A common approach is the use of event tree analysis (ETA). An event tree is a graphical logic model that identifies and quantifies possible outcomes following an initiating event. An example of a simple event tree is illustrated in Fig. 7.2 [65].

The event tree allows various analyses to be conducted. It allows one to identify and assess the number of safety barriers in a system and what happens if each is successful or fails. By using a logic structure, it allows probabilities to be applied to the successes and failures to develop an estimate of the risk (when combined with the analysis of consequences at each branch termination). It also allows for the analyst to add or remove safety features such as detection, suppression, etc. or to increase or decrease the probabilities of success and failure, to assess the risk reduction contribution of different safety barriers in different combinations and with varying degrees of reliability. For estimating the probabilities of success and failure, one can look to statistics available in the literature, collect data, or look to expert judgment. Tools such as FTA can be used for each system to both identify current reliability and to identify how reliability can be increased.

For example, in the simple event tree in Fig. 7.2, Item C is "fire suppression system successful" with the probability of success at 0.85. If the details of the fire suppression system were known, one could construct a fault tree to identify where and how the system might fail. Examples could include a valve closed or not monitored and infer ways to increase the success. This can include monitoring the valve at a constantly staffed location or sounding a local alarm if the valve is closed.

In addition to being tools for estimating risk, given the ability to consider the safety barriers in place to mitigate an initiative event, and the ability to add or modify safety barriers to assess outcomes, event trees can be useful tools for decision-making with respect to fire safety alternatives in a building (and other safety measures as well).

A major challenge for any risk analysis is establishing the risk acceptance (tolerance) levels for the design. These are typically set by the owner in consultation with other stakeholders. For any complex process, a full risk characterization process is

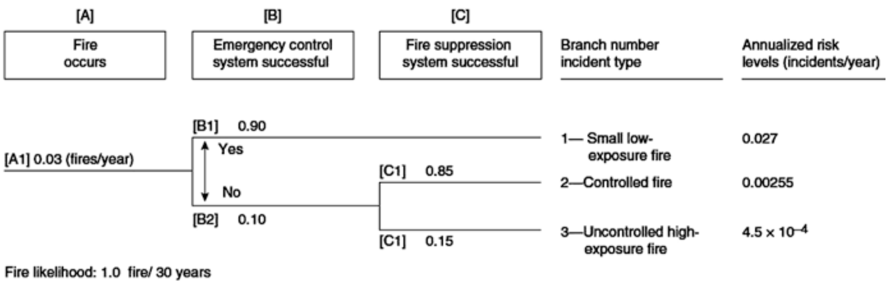

Fig. 7.2 Example of a simple fire event tree [65]

suggested [66, 67]. The aim is not to address the issues of what can go wrong, how likely that is, and the resulting consequences but, more specifically, which consequences, and at what levels, are tolerable. This must address challenging issues of tolerable fire size, tolerable losses of people, property and mission, and the circumstances of such losses.

Setting risk acceptance levels will be the benchmark against which all fire protection system requirements are measured in the risk analysis process. If risk to life values are not set, and surrogates such as extent of fire spread are used, risk thresholds might reflect factors such as the maximum allowable area or volume of a compartment or floor for fire containment and the duration of such containment, the probability and acceptable extent of horizontal fire spread, the probability and acceptable extent vertical fire spread is acceptable, and the acceptable levels of toxicity and exposure times for products of combustion in various parts of the building. While modeling of fire effects, structural analysis, and evacuation modeling may be used to support such analysis, establishment of the criteria considering associated uncertainty and variability will be the critical factor in assessing the acceptability of designs.

Decision Analysis

Decision analysis reflects formal processes for helping individuals and groups reach decisions by structuring decision problems and assisting with the challenges of addressing multiple objectives. Decision support tools can range from qualitative to quantitative, much like hazard and risk assessment. At the qualitative and semi-quantitative end, simple consensus processes can be used, with or without ranking of options. Decision trees, which are much like event trees, can be used to decide between options, using probabilities and consequences (or costs) in combination. More intensive approaches exist for multi-criteria problems [68, 69].

A good starting point for identifying and choosing fire protection measures is the Fire Safety Concepts Tree (FSCT) [28] (see Fig. 7.3). The FSCT provides a structure with which to analyze the potential impact of fire safety strategies against defined fire safety objectives. While it is not a decision tree and cannot incorporate probabilities or be quantified in the same way as a decision tree, it can be used to identify gaps and areas of redundancy in fire protection strategies as an aid in making fire safety decisions.

Regarding costs, several tools may be appropriate, including return on investment analysis, cost-effectiveness analysis, benefit-cost analysis, and life cycle cost analysis [70]. It must be recognized that, in any case [71, 70], no building design can be protected against all risks. Whereas risk analysis aims to help identify the risks and the tolerable levels of the stakeholders, a cost analysis will identify the costs involved with different protection options, not only during construction but also as long-term costs associated with the operation of the building.

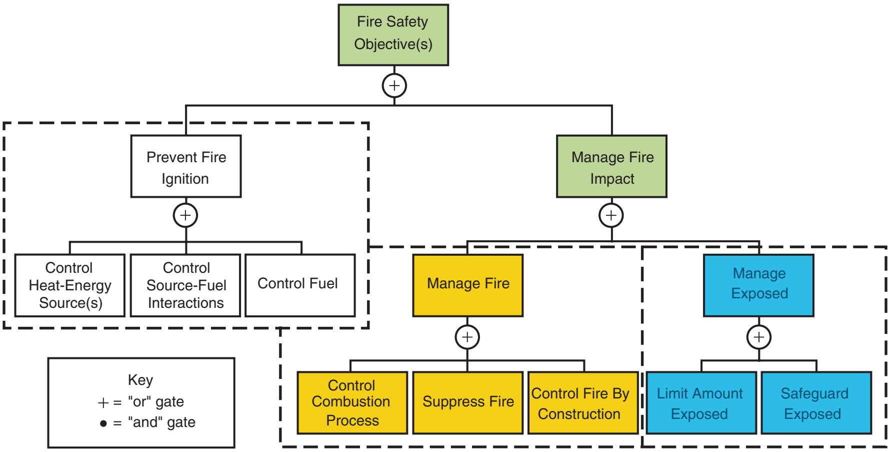

Fig. 7.3 Top branches of the Fire Safety Concepts Tree [28]. Reprinted with permission from NFPA 550-2017, *Guide to the Fire Safety Concepts Tree*, Copyright © 2017, National Fire Protection Association, Quincy, MA. This reprinted material is not the complete and official position of the NFPA on the referenced subject, which is represented only by the standard in its entirety

Uses and Applications of Hazard, Risk, and Decision Analysis for Very Tall Buildings

Tools and methods of hazard, risk, and decision analysis can be applied at various stages of very tall building design, construction, and operation. A performance-based design process as outlined in Chap. 3 (Components of Performance-based Design) includes the following applications.

Fire Strategy Development

A fire strategy for a building typically outlines key aspects of the building, fire hazards, fire safety systems, and related approaches aimed at helping to address the fire safety challenges of concern. In some cases, the fire strategy might be developed to address alternates to a regulation or might be needed for a completely performance-based approach. The fire strategy will be part of a Fire Protection Engineering Design Brief (FPEDB) as discussed in the *SFPE Engineering Guide to Performance-Based Fire Protection* [1] or equivalent fire safety engineering guide. A fire safety strategy should include the rationale for the selection of pertinent fire protection/life safety features to be incorporated into the building design. Topics to be addressed in the fire strategy for a very tall building can include, but are not limited to, the following:

- Alternate methods of construction, engineered solutions, or performance-based design provisions used in the building design, including documentation of all modeling performed
- Reaction to fire properties of materials of construction and the fire performance of construction assemblies
- Passive fire resistance design, including structural fire resistance ratings and fire-resistive rated separations
- Interior finish requirements and compliance plans
- Egress system design, including the use of horizontal exits, phased evacuation zones, length of time to accomplish the evacuation approach used, and unique exiting configurations
- Fire suppression system design, including sprinkler design densities, unusual fuel loads, special suppression systems, and fire pump arrangements
- Fire alarm system design, including zoning, special detection provisions, and emergency communication system configurations
- Smoke management system design, including design approaches, pertinent design calculations, and integration with fire suppression and detection systems
- Facility emergency and standby power
- Hazardous materials and methods of protection for them

As noted above, use of the FSCT [28], application of the risk characterization process, and other decision analysis methods can be useful in framing the key issues and developing initial strategies.

Fire Safety Goals and Objectives

One of the most important stages of a very tall building project is establishing the fire and life safety goals and objectives, in conjunction with other objectives for the building, and developing a corresponding set of acceptance and performance criteria that will be used to assess the suitability of the protection design. Key considerations in developing goals, objectives, criteria, and acceptance targets for very tall buildings include the following:

- The building will house many occupants who are also distributed over many different floor levels in the building.
- Occupants will have limited evacuation options (all occupants must descend to ground level to escape).
- The building needs to remain standing for the time necessary to protect occupants in place or to safely evacuate them.
- The fire and other emergency responders will have limited access, as most occupants and fire locations will be above the reach of local fire-fighting equipment.
- There can be a wide range of initiating events (natural hazards, deliberate events, etc.) and associated consequential damage, associated with the longer design life usually assigned to very tall buildings.

- Possible accidental or technological failures could have a disproportionate impact on fire and life safety in a very tall building.

This translates into considerations for fire protection system availability, reliability, efficacy, redundancy, and resilience that includes:

- Systems required to manage fire impacts should have a low probability of failure, including electrical, mechanical, and fire protection (active and passive)
- Redundancy should be considered where the potential for single points of failure is identified.
- Sufficient emergency power is available to address all critical functions.
- The structure and systems have sufficient resiliency to withstand the initiating and postulated fire events identified as a concern for the building.

For the above, tools and techniques of hazard and risk analysis, particularly reliability, availability and maintainability analysis, failure modes and effects analysis, and fault tree analysis, may be helpful.

Fire and Egress Scenario Development

As outlined in the *SFPE Engineering Guide to Performance-Based Fire Protection* [1], identifying the hazards and building and occupant characteristics can help in selecting the mitigation strategies. A key element of the characterization process involves the application of hazard and risk assessment techniques for a range of issues, including the following:

- Identifying the fire hazards and their likelihood of occurrence
- Identification of potential fire scenarios of concern, grouping possible fire scenarios into clusters of reasonably possible scenarios to be used for fire and life safety analysis
- Characterizing the occupant population in terms of risk factors such as age, ability to evacuate, language, occupant load and distribution, familiarity with the building, whether they will be sleeping in the building, and their perception of risks associated with the environment
- Characterizing evacuation scenario parameters, such as pre-movement behavior actions and times, movement times, exit selection, and related parameters

Tools such as fault tree analysis (FTA) and event tree analysis (ETA) can be useful in coupling potential fire hazards to event development and response given a range of potential mitigation measures. In this way, these techniques can be helpful for evaluation of designs as well. Such analyses can also account for the expected reliability of installed mitigation measures.

Fire Size and Structural Response

Following the World Trade Center attack on September 11, 2001, and partial collapses of other very tall buildings, such as the Windsor Building in Madrid, there has been a focus on structural system resilience to fire. As detailed in sections that follow, the potential mitigation approaches are wide ranging, including designing for full burnout and increasing the effectiveness of suppression systems to reduce the likelihood of fire becoming a significant structural threat. In helping to assess the potential fire threat (likelihood and severity) and consequences (likelihood and severity), risk assessment techniques are needed and can be applied within deterministic or probabilistic fire engineering analysis frameworks. In deterministic analyses, risk assessment methods can be useful for quantifying likely fire threats for use in structural response modeling. In stochastic analyses, the likelihood of fire threats and unacceptable structural performance can be assessed probabilistically [72], which may be useful for very tall buildings where the acceptance level for the probability of structural failure is set at a more stringent level than average.

Multi-hazard Extreme Event Analysis

In addition to fire, very tall buildings face a number of event-related loads, in some cases dependent upon the building location, including high winds, seismic activity, and deliberate (terrorist) attacks. For some of these events, fire may be an integral concern, either concurrent with the event or in a post-event damage condition (such as a post-earthquake fire or post-blast fire). Where these scenarios are a concern, risk assessment techniques can be beneficial, especially considering the low probability yet high consequence potential of some events or event combinations. Several resources exist for assessing and designing for extreme event considerations, including single and multiple events [73].

Evaluation of Possible Mitigation Measures

As noted above, there is a wide variety of potential mitigation measures which can be considered in very tall buildings. When considering how the selections of mitigation measures will work together in providing the level of protection desired, risk analysis techniques can be helpful, including event tree analysis (ETA) as mentioned above. The *SFPE Engineering Guide to Performance-Based Fire Protection* [1] outlines how classical risk analysis and risk binning techniques can be used for evaluation of design options. Various other techniques for assessing risk reduction through various fire mitigation strategies, including Bayesian network analysis, are also available. Risk-cost-benefit analysis techniques can also be useful in weighing options and optimizing the balance of costs and benefits based on likely scenarios and system performance.

Identification and Selection of Evacuation Strategies

There are various strategies one might consider for protecting occupants from fire in very tall buildings, including protect-in-place, phased partial evacuation, phased full evacuation, full simultaneous evacuation, use of refuge floors, occupant self-evacuation elevators, fire fighter-assisted elevator evacuation, and combinations thereof. Risk assessment can be helpful in assessing the options available, such as the nature of the occupants and their likelihood to stay in place or try to evacuate or to use stairways versus elevators or the reliability of systems required for achieving the target level of performance for fire and life safety systems.

Emergency Response

Risk assessment and management techniques can be helpful for emergency personnel in planning responses and managing fire ground operations. Understanding the mitigation measures that are in the building, the availability of those systems within the building, and evacuation systems provided can be crucial in assisting appropriate first responder response decisions. Based on the type of information required by the emergency organizations for a range of possible events and scenarios, a risk-informed approach to response planning should be developed. This risk approach can help to identify whether types of sensors, camera locations, additional communication and control equipment, and related resources should be installed in the building to help manage an event.

Chapter 8
Integration of Building Design and Systems

Proper systems integration is important in any building design, but given the range of challenges associated with very tall buildings, it is crucial that all systems work together as planned. The cause of fires and resulting loss are usually due to several factors failing or not operating as designed to mitigate the risks.

At a high level, the first recognition is that the people, building, and fire are interrelated and influence one another (see Fig. 8.1).

Core building systems are designed to support the structure, provide necessary environmental conditions for occupants, and provide acceptable access and use by occupants. These systems should be designed giving due consideration to occupant risk perceptions, expected responses, and protection desired. Building systems should be evaluated to verify that they will operate in an integrated manner to provide the intended outcome.

Cultural customs, economic practices, social implications, and reliability of systems must be considered as part of the design. Questions such as the following issues must be addressed when developing the protection concepts for the project:

- Fire department response time
- The number of expected fire department response personnel, both day and night, and available equipment
- The water supply and its reliability
- The maintenance program for the fire alarm systems in the building
- The maintenance program for integrated core building systems
- The nature and anticipated response of building occupants

In most very tall buildings, there may be multiple occupants' needs or uses within the same structure. There may be condominium floors, above hotel floors, located above office floors which are all located above retail and restaurant floors. Each of these different types of occupancies may have separate mechanical systems, separate elevators, and separate building entrances. Working with the design team, the fire protection engineer will need to assist the coordination of the stairways, fire alarm zones, sprinkler zones, standpipe zones, voice communication zones, smoke

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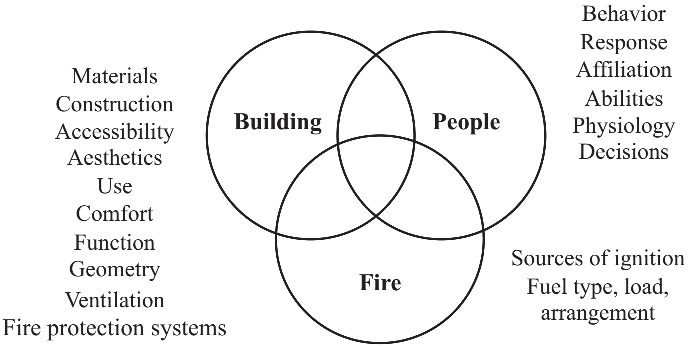

Fig. 8.1 Building life safety design framework related to a fire event [74]. Courtesy of Interscience

control HVAC zones, lighting, emergency power, elevators, and building automation. The security features in the building will also need to be reviewed. For example, coordinating the structural movement requirements of a building with the firestop details for the head of wall firestop joints to ensure the connection (of the fire-rated wall to the fire-rated floor) will be capable of maintaining the movement designed into the building. The coordination of these core building zones and systems is critical in designing such that in the event of an emergency, the building will work cohesively to maximize the safety of the occupants and the effectiveness of the emergency responders.

On all projects of these types, it is important that the coordination and operation of the life safety and fire protection systems be discussed and reviewed with the local authorities. As they will review and approve the project submittals and building commissioning and respond to potential fire scenarios in the building, it is critical that the local fire brigade be a part of the design process. In many cases, numerous entrances, elevator lobbies, and fire department connections are required in these buildings for appropriate response and actions when an alarm occurs.

After design and installation, the life safety and fire protection systems must be commissioned to confirm that they are operating correctly and will perform their intended functions. This will include testing on both normal and emergency power and via actual alarms from the various portions of the building.

In many projects, records are maintained of the approvals and design concepts used in the construction of a very tall building. These records are important when future revisions are being considered so that the life safety and fire protection systems are not adversely affected. They are in addition to the fire safety plan which provides a description of the systems in a building and the actions to be taken by supervisory staff and the maintenance requirements.

After a building is occupied, it is important that the life safety and fire protection systems be maintained and the staff be trained on actions to take in the event of an alarm. This is required to increase the probability that these integrated systems will continue to operate as intended as well as to minimize the potential for the systems themselves becoming a source of ignition. For these reasons, the operators of the building, the maintenance staff, and the security staff become the final part of the project team to ensure the ongoing life of the integrated safety systems in the building. Building management can see systems are adequately maintained and necessary training and procedures are in place so that a prompt and efficient response to fire and other emergencies can occur. As time progresses, much of the storage and coordination of information will be done using building information modeling (BIM). Currently, BIM is widely used in building design and construction, but its capabilities extend well beyond into maintenance and operations – all a part of integrating system.

Interrelationship of Operation of Systems

At a more specific level, combinations of systems required to operate simultaneously need to be designed and tested in that manner. For example, if a strategy is to provide phased evacuation to areas of refuge from which occupants will be evacuated by elevators, the integration of detection, communication, smoke management, elevator control, signage, and related systems need to be designed and tested to determine if the desired outcome is achieved. This requires coordination of zoning of alarm, automatic suppression, smoke control, and notification zones so that the building systems are working together to help inform and protect the occupants.

Supervision of one system by another, and reporting of system status, may be necessary to demonstrate that performance of the integrated system will be achieved. For instance, a detection system activation can result in activation of smoke exhaust, closes doors, pressurizes areas, sends elevators to specified stories, and sends appropriate messages to occupants in various locations. A major aspect of testing system integration is to document that required functions work end to end during systems' commissioning.

If elevators are proposed to be used for vertical egress or for movement to areas of refuge during an emergency condition, it is necessary to consider protected vestibules and elevator shafts. This must be coordinated with the fire alarm systems to make occupants aware of situations in the building.

Emergency Response and Control of Systems

In very tall buildings, the control of safety systems may be from a centralized, staffed control room. Ideally, this control room is in the vicinity of the primary fire department access point to the building. Consideration should be given to provide secondary control points at a secondary location with a computer to provide access to first responders.

Lower stories of very tall buildings can have larger floor plates than typical upper stories and may include various mixed uses. For example, there may be a rapid transit system beneath the building, and the lower stories of the building might be a large podium, thereby negating the ability of the fire department vehicles from reaching even the lower stories of a tower. Clearly, the source of fire risks should be addressed regarding the protection methods to be provided.

Given the various uses with very tall buildings, it may be necessary to have several fire department response points such as retail entrance, office entrance, hotel entrance, and residential entrance. The integration and testing of the systems in the control room(s) should be completed prior to partial occupancy of portions of the building. Note that it will be necessary to provide the proper protection for these control rooms based on location and anticipated use during an event.

The Building as a System

Various tools are available to a design team to identify fire risks and to address protection measures to properly mitigate these risks in a very tall building.

The fire protection engineer should take a step back and review the objectives (Chap. 3, Components of Performance-Based Design), given the specific risks associated with this specific building (see Chap. 7, Hazard, Risk and Decision Analysis in Very Tall Building Design). It may be beneficial for the design team to review the systems reflected in the Fire Safety Concepts Tree [28].

Fire Safety Goals and Objectives

As discussed in performance-based design guidance [1], fire safety goals and objectives identify fire performance targets for a building. As outlined in these guidance documents, there are many potential means to address fire safety goals and objectives. A principal objective of all fire codes and regulations is to use prevention to reduce the risk of a fire occurring. Prevention of fires relies on human actions, selection of equipment to reduce ignition hazards, proper installation techniques, as well as implementation of planned maintenance of equipment and systems. As prevention of fires cannot be guaranteed, it is generally considered necessary to incorporate active systems (such as automatic sprinkler protection) in conjunction with passive protection by building elements (exit stairway enclosures, fire separation of hazardous spaces, fire-rated structural elements) to limit the effects of a fire, should it occur, while providing options for protection and evacuation of the occupants. Fire fighter safety should also be a consideration in this exercise.

The design team – and more specifically the fire protection engineer – will need to concentrate on the interaction of all systems within the building so that incipient fires are limited in size to meet the building's fire safety objectives. To achieve this, the fire protection engineer will need to be fully integrated into the design team so that fire safety is taken into consideration from the initial design concept to final delivery of the building and occupancy. The fire protection engineer will also act as a liaison between the design team and other building stakeholders.

The relationship between building systems and building structure is required to be considered with respect to the fire risk and the capabilities of the occupants. When considering the building as a system, the following is an example of the interrelationship of the building occupants, the building, and the building systems.

- At the very start of a project, the occupancies and their expected fuel loads are required to be established. This information is necessary to determine the fire risk and the type of fire that could be expected within the building. Consideration must also be given to potential future occupancy changes that may be known. It will also establish the use of each area of the building and the types of occupants expected.
- After establishing the expected occupancies and fuel load types, it is necessary to identify the potential ignition sources in the building. While there are obvious sources, such as human carelessness or cooking hazards, building hazards such as poorly maintained equipment, must also be considered. Construction and tenant fit-up is another significant cause of fires in occupied buildings that must also be addressed.
- The likely fire scenarios must be agreed to by the fire protection engineer and the building official at the start of the project when performance-based design is used in establishing the types and level of fire safety and fire protection to be provided.
- Standard operating procedures and maintenance programs should be developed and implemented to maintain these expected performance-based objectives.

Once the fuel load, types of materials, and potential ignition sources have been established in a building, the actual structure must be evaluated. The means by which a fire resistance rating is provided to a structure is required to be reviewed (see Chap. 12, Fire Resistance).

The fire resistance will be determined either by the local building code regulation as a minimum or by use of fire modeling in a performance-based design using the expected fuel load and heat release rate of materials expected in the building. When performing this analysis, it is necessary to remember that collapse of a building is not acceptable, neither are system failures caused by any extended timeframe in the fire resistance strategy. As such, it will be necessary to consider other safety features in the building such as elevator protection and use, duration of fuel supply for emergency power, and voice communication for instructions to occupants. The operations of these systems, among others, should match the timeframe desired for fire resistance in the building. While fire resistance often has units of time, these times do not necessarily correspond to actual building performance during a fire.

Integrating Evacuation Strategies

In evaluating the methods used for evacuation of occupants, it is necessary to keep options open for the emergency responders to select the best approach to evacuate the occupants. For example, it is important to consider design simplicity that will aid first responders' efforts under emergency conditions as buildings may differ within a city. The fire protection engineer should also consider the local first responder's experience with emergencies in relation to very tall buildings. This is important where the local fire responders do not respond to frequent emergencies with these buildings.

In very tall buildings, emergency responders may choose to evacuate only the floor of alarm or may also evacuate the stories immediately above and below the floor of alarm to remove the occupants in immediate danger of a fire. The method of evacuation may depend on the source of the alarm, the type of event (fire or mass notification), whether an actual fire has been confirmed, and the activities occurring in the building. As well, the time of day can play a role in choosing how to evacuate the occupants. If an alarm occurs during night hours when there may be fewer occupants in the building, the emergency responders may choose a partial evacuation or may choose to do a complete evacuation of the building.

If a partial evacuation is chosen, the areas being evacuated should consider the zones used for smoke control systems in the building. The smoke control zones should also consider the zones of the fire alarm system, zones for the voice communication system, and the phasing for partial occupancy of the building. These may also coincide with the elevator shafts and the stories being served. In very tall buildings, there will likely be several banks of elevators which serve different stories. This information needs to be coordinated during the design phase so that partial evacuation can be done easily.

Chapter 9
System Reliability

System reliability is always important, but it is critical in very tall buildings where access for manual suppression is limited and failure of key systems has the potential to result in trapping occupants or cause building collapse. In a very tall building, it is even more important to consider the reliability of the systems as they work together, not just individually. The fire protection components overall create a "system," and it is the reliability of this overall "system" that must be considered, as well as the reliability of its component parts.

There are different strategies for assessing reliability. One is to include system and component reliability data into a quantitative risk analysis. Another is to consider defense-in-depth, with multiple layers of protection aimed at having backup measures in case the primary measure fails. The use of redundant or fault-tolerant systems could be feasible as well. The specific approach will depend on the project goals and the systems used. Chapter 7 (Hazard, Risk and Decision Analysis in Very Tall Building Design) describes various approaches to evaluate hazard and risk.

Depending on the systems used, there are several approaches that could be taken to provide a high degree of reliability. For electrically powered systems, measures such as providing multiple primary power feeds, onsite standby and emergency power, and looped, cross-zoned, and physically protected circuits can increase reliability. For suppression systems, multiple sources of water supplies and duplication of distribution systems (external to building and dispersed within the building), multiple risers, alternating sprinkler branch lines supplied from separate risers, looped systems, and other such measures might be considered. For passive systems, increased fire resistance ratings of assemblies, fail-safe opening protectives, and related measures such as protection of service penetrations through fire separations around riser shafts could be considered. Procedures for modifying passive systems, such as tighter control of work procedures for any post-occupancy building services alterations using an internal "permit process" for alterations involving rated walls and floors, should be implemented. For elevators for occupant self-evacuation, additional measures are needed to protect against water or smoke entry into shafts or

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equipment rooms. These systems may require redundant controls and informational displays for waiting passengers, and other measures may be appropriate.

There are a variety of risk and hazard assessment tools that can be applied to help identify potential failure modes (e.g., failure mode and effects analysis), results of component or system failure (e.g., fault tree analysis), and impact of failures on the success of fire protection system performance (e.g., event tree analysis). Reliability, availability, and maintainability (RAM) analysis is a helpful tool in assessing the expected in-use performance of systems. As used here, "reliability" is a likelihood of an item working after a predefined time. "Availability" refers to the likelihood that at item will be operational at a predefined time, and "maintainability" refers to the downtime because an item may not be operational due to inspection, testing, or maintenance [75]. RAM analysis can help make informed decisions on reliability and redundancy of systems needed to meet targeted performance levels, considering downtime that will occur and informing which systems need to be available under various circumstances. Single point of failure (SPOF) analysis aims to identify single points or nodes within a system that, if compromised, result in failure of the complete system. This can then inform the need and systems/locations within the building for increasing reliability or adding redundancy or resiliency into the system. A simple example is having the water supply for the building provided by a single main, where a breach of the main line would result in no fire protection – water for the building.

The reliability, availability, and maintainability of systems need to be considered from planning through operation stages of the building. At the planning stage, factors such as reliability of utilities (power, water, etc.) should be considered. The analysis should consider the appropriateness of the utility infrastructure in supporting the building, especially if the building is to be constructed in a currently underdeveloped area. This will not only affect decisions about the base requirements but also for internal backup and emergency systems (power, lighting, communications, water, etc.). During operation, the reliability of utilities can affect maintainability and availability of systems. Again, this may have an influence on backup systems and on maintenance and emergency planning.

Mechanical systems that are only intended to operate during an emergency can frequently be neglected both by building managers and maintenance staff and are often overlooked during regular inspections by personnel from the local jurisdiction. Mechanical ventilation or smoke extract systems, stairwell pressurization systems, emergency power generation systems, elevators for emergency responders, and fire hoses and cabinets are among the examples of such systems which can and have been neglected. Whenever possible, systems which have a dual purpose and are used on a regular basis should be selected. This allows building management to become immediately aware of any malfunction and (because of the need to provide normal services to building occupants during normal times) provides motivation to promptly repair malfunctioning equipment. Additionally, the mechanical systems that are intended to operate during an emergency shall be operationally tested at reasonable intervals during the year to assure the systems' ongoing operational capabilities.

Chapter 10
Situation Awareness

Very tall buildings are becoming increasingly complex. These buildings are cities unto themselves, some with overall building populations reaching into the tens of thousands. Providing building occupants accurate information about an emergency increases their ability to make more appropriate decisions about providing for their own safety.

Threats to an individual's safety can be either real or perceived. The occupants' perceptions are developed based on available information. In an emergency, occupants will make risk-based decisions about how best to provide for their own safety based on the information they receive from a wide range of sources and the individual's perceptions of the situation. In a very tall building, if the information is incomplete or conflicting and consequently those perceptions are not accurate, the decisions may be detrimental to their safety.

Shortly after September 11, 2001, the risk perceived by very tall building occupants was that very tall buildings can collapse. Given that news today is transmitted instantaneously to smartphones via the Internet and social media, occupants of a building can become aware of a fire occurring in their building before the fire department can arrive and take control of the incident. Lacking any other specific information output from the building life safety systems, building occupants receiving the outside information will begin to make decisions based on their perceived risks. Those decisions can put occupants into an unsafe situation.

Awareness of one's surroundings, and whether the emergency has rendered part of or all those surroundings hazardous for evacuation, is critical information needed by very tall building occupants to make appropriate decisions during an emergency. In the circumstance of needing to evacuate a very tall building, not having awareness of the situation or one's surroundings can be catastrophic. Drills should be enacted in accordance with the evacuation strategy for the building.

Situation awareness in an emergency has three distinct components [76]:

1. Determine what information is needed for occupants to make a good decision given the situation.

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2. Determine the potential sources from which information can be obtained.
3. Determine the most effective manner to communicate that information.

Situational Information

During an emergency event in a very tall building, building occupants will benefit from information with which to make the critical decisions about how they will respond. Some of this information, such as information about the means of egress plan employed in the building, can be provided in advance of the event. Other information will be specific to a given event and can only be provided during the event.

The *SFPE Engineering Guide to Human Behavior in Fire* [51] contains information about considerations related to managing the movement of building occupants that is centered around situational awareness of the developers of the egress systems. It discusses models related to the design of new buildings as well as existing buildings.

The risks associated with life safety and fire protection strategies need to be considered, coordinated, and balanced as the designs of life safety and fire protection systems are selected so that the fire protection systems work to minimize the risks to occupants given the life safety systems. The design of the means of egress for any very tall building is not necessarily the same as that used in another. In a very tall building, the risk to building occupants increases if one of the egress routes becomes unusable or the occupants are unaware of the range of available alternative egress routes.

There have been several variations on the stay-in-place or defend-in-place strategy employed in developing the egress systems from very tall buildings throughout the world. Building occupants may or may not be familiar with their surroundings. Regardless, they need to be aware of the designed egress strategy to make good decisions. Chapter 11 (Emergency Egress) provides a detailed discussion on the types of egress strategies that may be used in a building. In non-transient-type occupancies, egress strategy information can be shared with occupants at various times throughout the year and emphasized through fire drills. In all occupancies, real-time data regarding the egress strategy used in the design of the specific building can be shared with building occupants during an emergency event through the one-way voice alarm system in combination with strategically posted evacuation plans. Providing this information can increase the efficiency of evacuation.

For example, some jurisdictions mandate the use of refuge floors periodically throughout the height of all very tall buildings. The intent of this concept is that occupants nearby the floor of origin will evacuate down to the next refuge floor below and harbor in this protected environment. From there, they can take elevators or continue using stairways, if needed, to complete their egress. However, building occupants need to be made aware of this strategy. Providing real-time information about the egress system using communication systems is critical in such a situation. Designers of egress strategies for very tall buildings should also consider the consequences if occupants do not follow the assumed egress strategy because of real-time information they have received about an emergency, and as a result they decide they will be safer to abandon the as-designed egress protocols.

Recent advances in evacuation technologies make situation awareness even more critical. Historically, building occupants have been directed not to use elevators in a fire emergency, to use only the stairways. As technologies have improved, the design community has used elevators to reduce the amount of time required for evacuation, especially where full building evacuations may be needed. While conducting drills that incorporate all the evacuation systems will help the building occupants understand how those systems can be used, there will inevitably be occupants in the building who were not present for the drills.

Other useful information that can be communicated to buildings occupants includes the location of the fire incident and whether the incident has disabled any of the building systems. In buildings that may have only two stairways, it would be important to know if one of those stairways is unusable for egress because the fire department is using that stairway to attack the fire.

Information Sources

People use all their senses to obtain information to understand the situation they may be facing. However, research indicates that during emergency situations, decisions made will be based largely on past experiences [51]. Since most people have not had the opportunity to face an emergency such as a fire in the building they occupy, they will not be able to rely as much upon experience (or intuition) and should rely more on evaluating information made available to them at the time. In the absence of timely and accurate information, a good decision becomes less likely.

People receive information from numerous sources [51]. In the case of a fire within a building, systems designed to provide information to the occupants are one potential source of information that are built into the building. In addition, several sources of information from outside of the building are usually readily available via smartphone and will be more compelling to many building occupants. Through their smartphone, they can receive phone calls, instant messaging, emails, social media posts, and Internet news information, all of which will be updated more frequently than live instructions issued from a one-way voice alarm system. In the absence of live communication from an authoritative source, such as the fire department on-scene commander, the outside sources of information may be more influential than desired.

Fire drills can be a valuable source of information for building occupants on the means of egress strategies and the location of fire-protected egress routes used within the building. Fire drills can be used to train non-transient building occupants on the locations of primary and alternate egress paths, especially when those may include elevators for evacuation assistance.

Fire detection and alarm systems are a principal source of information during an emergency incident. They are important systems relative to detecting the presence of products of combustion, notifying response teams, and providing information to building occupants. Another source that can provide information about the environment of the building is security cameras, and video can be used for both security and fire detection. Recent editions of some codes have required the installation of cameras in the stairwells for very tall buildings. The intent of requiring these cameras is that the emergency personnel can monitor conditions within the stairwells and direct building occupants away from areas that are crowded or otherwise not suitable for evacuation.

One-way voice communications systems are provided for very tall buildings so that the occupants can be made aware of a fire situation within the building and directed to use the egress systems provided. Now, with the prevalent use of horizontal exiting and the anticipated growth in the use of elevators for evacuation, it will become more critical to notify occupants and share real-time information on the availability of egress system components during an emergency.

Two-way communication systems have traditionally been provided in specific locations within very tall buildings. In the past, these systems were specifically intended for fire department use because the radios they carry had operational difficulties over long distances. As outlined in Chap. 17 (First Responder Considerations), more and more fire departments are mandating the installation of radio signal amplification systems so that the communications tool fire fighters typically carry (i.e., portable radios) will work throughout the building. Consequently, the two-way systems may no longer be provided for fire department use. However, given their overall value to building occupants, it is advisable to consider providing such a system for use by building occupants. Areas of refuge are typically required to have two-way communication systems for building occupants to provide information. However, they are only credible tools if they connect the occupants to a constantly attended location staffed by properly trained personnel. Future developments could include the use of social media or other methods that will allow individuals within the building to provide information about what they are experiencing to emergency personnel.

Effective Information Delivery

Effective delivery can be divided into two components, the system(s) used to convey the information and the content and presentation of the information itself. Details of design concepts associated with voice systems are fairly well developed and will not be addressed at any length in this chapter as they can be found in other resources [77, 78, 79].

However, proper delivery is important. Many voice alarm systems are arranged to operate automatically with pre-recorded or synthesized voice messages. Manual voice announcements are often left up to front desk security guards who are not regularly trained for operating under a stressful condition. In particularly complex structures, the building staff may be better for making live voice announcements to occupants near the emergency since they understand their building. The calm, reassuring voice of the fire department can also have impact upon those having to navigate a complex egress system during an incident.

The level of knowledge and training of building staff can have a significant impact upon the effective delivery of situation-specific information. Intended operation of voice alarm signaling systems needs to be determined early in the design process because it may dictate design decisions.

The value of having a predefined, rehearsed, emergency management plan cannot be overstated. Persons trained and experienced in emergency situations are shown to make quicker, better decisions in crisis situations [51]. Building staff responsible for taking charge during an emergency within the building should train with all shifts of the responding fire department, including the shift command personnel, not just the fire inspector who coordinates these activities on behalf of the fire department.

Egress plans can provide significant amounts of information if presented in the proper manner. Making them a part of building wayfinding systems is one way to be able to keep the information in front of building occupants on a regular basis and can be especially helpful when the building is used by many transient occupants. An example of such a case is the wayfinding systems that are used in the meeting room levels of large hotels and conference centers. Most of these wayfinding systems will identify key egress components and egress paths.

Printed/posted wayfinding systems are being replaced by digital diagrams that are easily and remotely changeable. It is reasonable to expect that, at some point in the future, digitally based wayfinding systems may be used to provide real-time evacuation information and direction in emergency situations based on input from the fire alarm and security systems. Being able to tell building occupants in a live verbal and visual message that an exit may be unusable for evacuation can better inform the occupants and help influence desirable decisions that can positively impact the outcome of an emergency incident.

Chapter 11
Emergency Egress

The development of an appropriate and effective egress strategy is considered one of the key fire safety aspects of any very tall building design. As occupants increase their vertical remoteness from the point of discharge to a public right of way, the time taken to evacuate the building will also increase. Above certain heights, the vertical distance to be traveled by an occupant may subject them to additional risks when adopting the traditional method of evacuation using only stairways. In such instances, the proposed egress system may require re-evaluation to consider alternative strategies such as relocation or refuge in addition to examining what role elevators can play in enabling timely occupant egress from very tall buildings.

The acceptability of the egress system design for a very tall building is an evaluation that should be conducted in collaboration with the building's design team, the project's stakeholders, and the local approving authorities. The solution finally adopted will depend upon the building's design, its intended use, and its location, among many other factors. In many instances, these buildings will require some form of engineering analysis to be conducted to determine the time taken to evacuate the building, either fully or partially, under a series of given scenarios. Guidance on methods to conduct such analysis is provided in a number of sources, including the *SFPE Engineering Guide to Human Behavior in Fire* [51], *SFPE Handbook of Fire Protection Engineering* [80], and others [81, 82, 83].

This chapter highlights some of the options available to a building designer/fire protection engineer for decreasing occupant evacuation times or providing building occupants with safe places to rest or seek refuge remote from the fire event. While the building designers/fire protection engineers may not elect, upon consultation with other stakeholders, to implement all these techniques, this chapter provides descriptions that are intended as "tools" to be adopted, as appropriate by designers to meet their overall performance goals and objectives of the egress design for their given project.

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Design Considerations for Very Tall Buildings

While the design of all buildings must account for a range of egress considerations, several are specific to very tall buildings, and others gain importance as the building height, and consequently its occupant load, increases. These are discussed in greater detail in the following sections.

Fire Safety Goals and Objectives for Egress

The primary goal for any fire related egress design is to provide appropriate facilities to allow occupants to move from the area of hazard to a place of relative safety, from which access to a place of ultimate safety can be achieved.

The concept of areas of relative safety is important for very tall building egress design, because escape to ultimate safety (i.e., a location outside of the confines of the building at street level) could take a considerable amount of time to achieve. As such, stairways, separate fire compartments, areas of refuge, etc. are all examples of places of relative safety. Prior to accessing a designated place of relative safety, people are potentially exposed to the fire and therefore considered at risk. Consequently, fire safety features, such as limitations on travel time or distance, govern within this period and terminate upon entry to the place of relative safety.

When considering a holistic egress plan for a very tall building, it is often beneficial to consider the time taken to complete certain actions (such as reaching the entry door to a protected egress stairway) more so than the distance required to complete them – as is traditionally specified within the prescriptive building codes. While this concept is quite commonly accepted, in certain countries, the practice of designing a building's egress system around a travel time, instead of a travel distance limitation, is less familiar to many designers. As stated previously, travel distance limitations (and hence travel time limitations) are usually taken to terminate upon entry into the buildings' protected egress system – typically the stairways. Even when the vertical egress components are efficiently designed, and people descend relatively unhindered within the stairways, the time taken to reach ground floor increases in proportion to the building's height and will be further increased due to the onset of fatigue for evacuating occupants of varying fitness levels. In these cases, a time-based approach to egress may be more appropriate than a traditional distance-based approach, and this time parameter may form an integral element of the chosen egress goals or objectives for the building under consideration.

As with all buildings, very tall or not, the escape objectives for the design should be able to be achieved without the need for external assistance from first responders or building management, whose arrival may be delayed for reasons beyond their control. Such assistance therefore acts as an enhancement to the fire safety design, but an acceptable level of safety within the building's design should not depend upon such external assistance.

It should be noted that the goals and objectives of a building's egress design are not always complementary with the goals and objectives of other building systems, for instance, building security. Collaboration between the project's fire protection engineer and security consultant early in the planning stages of a project will allow the design team to address any areas of potential conflict such as reentry to non-fire floors from stairways, lobby security devices such as turnstiles that could impede egress, procedural conflicts, or other items that may arise. The overall egress approach should be discussed with the building operations staff and fire officials early in the design process, particularly if nontraditional approaches are planned.

Evacuation Scenario Identification

There are several ways in which the fire safety egress goals and objectives for a project can be combined into an overall emergency plan that suits the particular use and occupant characteristics of a building. The following will predominately focus on the issues surrounding very tall building design.

Besides incidents of fire, there may be a range of conditions or events which warrant the evacuation of a building, either in part or completely to maintain occupant safety – for example, seismic events, explosions, chemical or biological agent releases, power failure, extreme weather conditions, etc. While it is not the intent of this guide to address evacuation because of these non-fire-related occurrences, many of which are not mandated by code, the advice and principles contained herein will assist in forming an appropriate egress plan in such instances. It is therefore important that the fire protection engineer and members of the design team responsible for considering such events (security/risk consultant, for instance) coordinate their approaches early in the design process since the evacuation provisions for a non-fire threat may conflict with those required for fire safety (not evacuating vs evacuation, for instance). Where appropriate, those evacuation procedures for fire and non-fire-related scenarios should be fully combined and integrated into an overall life safety design to provide occupant evacuation procedures that are common to as many circumstances as possible, thus enabling increased levels of familiarity in all emergency conditions for the building's occupants.

Traditional fire safety design usually assumes a single fire source and does not routinely consider the potential for multiple, simultaneous fire locations – for example, as a result of arson. The vertical nature and the slender aspect ratio of very tall building design give increased opportunity for single fire locations to pose a threat to multiple egress routes than in other building types. If multiple egress route failures are thought to be an appreciable risk within the building under consideration, then an egress design considering a greater occupant load per stairway may be an event scenario which is considered. This may be true for buildings adopting a central core design where exit stairways may be on the limit of the minimum width and separation requirements.

While effective design against arson, in terms of space planning of egress arrangements, could be a never-ending process, close coordination with a project's security consultant should be initiated to establish an agreed-upon threat level that may warrant more than the standard single fire location approach.

Human Behavior

There have been numerous studies completed of human behavior in fire conditions [51, 83, 84]. A general finding is that occupant and occupancy characteristics can vary significantly among a variety of different building uses – examples of such characteristics include:

- Building population and density
- Groups or lone individuals
- Building familiarity
- Distribution and activities
- Alertness
- Attention to social media such as texts, email, and real-time information
- Physical/cognitive abilities
- Role/responsibilities
- Commitment to task
- Focal point
- Gender
- Culture
- Age
- Prior fire/evacuation experience
- Clarity of egress path legibility

These aspects of human behavior affect both occupants' recognition of, and response to, fire cues and their ability to affect an evacuation [51].

The pre-movement time of any evacuation occurs after fire-related cues have developed but before occupants have decided to begin their evacuation. The psychology processes that influence this pre-movement period is cue validation and is resolved by an overlapping decision-making process. During cue validation, our brain will process all information as follows [51]:

1. Receiving the cue (sense the cue)
2. Recognizing the cue (identify the cue)
3. Interpreting the cue (give meaning to the cue)

The time delay associated with cue validation will depend on the variety of characteristics of the evacuation scenario, such as the occupancy type, the nature of warning systems, the evacuation procedures, and the nature and number of cues given at the time of a fire.

Cues that should be considered and assessed relative to the occupant group(s) in a building include:

- Visual, olfactory, sensory, and audible fire cues.
- Building notification or public address systems.
- Cues from people alerting others, including from social media outside the building.
- Cues from building service disruptions. This can include, but not be limited to, shutting down of various building systems and power failure.

The cues for those close to the origin of the fire will likely be different to those in another area of the building. Also, the effectiveness of cues will vary with respect to all the occupant characteristics.

For design purposes, one or several cues may be applicable to an occupant group. Given the selection of appropriate cues, the reaction for the cues and time for validation of the cues must be established using available research data, case histories, decision models, or engineering judgment. Various guidance documents on human behavior aid in this area via discussion and reference to many literature sources and case studies that illustrate time delays associated with cue validation [51]. Four of the nine "principals" of human behavior listed in the CIBSE Guide: Fire engineering [63] that address the importance and potential impact of the time delay include:

- Deaths in large-scale fires attributed to "panic" are far more likely to have been caused by delays in people receiving information about a fire.
- Fire alarm and communication systems cannot always be relied upon to prompt people to move immediately to safety.
- The "start-up" time (i.e., people's response to an alarm) can be more important than the time it takes to physically reach an exit.
- Much of the movement in the early stages of fires is characterized by activities such as investigation rather than escape.

Closely tied to the cue validation process are the decision-making processes that can contribute further to the delay before evacuation. The pre-movement decisions may occur with or without the validation of cues. The cues may be ambiguous and result in an occupant's decision to seek new information or simply to decide to ignore the cues which may be based on the inaction or complacency of other occupants. Some engineering guidance documents [83, 85, 86] have published tables of pre-movement times for various occupancies, and context-specific data can be found in other sources [87, 88, 89]. The sources cited can be useful but should be used with care because the pre-movement times are generic and based on broadly subjective views. The context-specific literature and background sources may serve as the best sources for pre-movement delay times.

Occupant evacuation, unless in the direct vicinity of the fire, can be a slow process with many occupants reluctant to be the first to leave. However, in the aftermath of the World Trade Center attack, there has been an increased focus on occupant evacuation and responses to alarm conditions. An increased level of seriousness, and a heightened level of awareness, to building fire alarms and evacuation drills was experienced by many – more so for the occupants of the tallest and most iconic buildings in the world's major cities. Social media allows multiple methods of instant communication and therefore the ability for information to spread rapidly throughout a building.

This increased level of awareness could lead to behavioral factors that influence the egress plan chosen. For instance, the use of refuge floors within buildings (discussed later in this chapter) requires close coordination between building fire wardens/management, fire safety systems, and first responders to appropriately direct occupants to the place of refuge. It is possible that not all building occupants will respond in a compliant manner when requested to remain within the building during a fire event – some might attempt to totally evacuate the building irrespective of the instructions given. If an occupant wishes to evacuate, there is little that can be done to prevent this, even if this compromises the building's fire strategy and potentially slows the evacuation from floors in the immediate vicinity of the fire. While such actions may not be in the majority, an appreciation of such non-compliant actions may be an appropriate safety factor to include within a very tall building's egress design.

In addition to response to cues, there are aspects of human behavior that can affect their travel time throughout a very tall building. Several items that should be considered include [51]:

- Occupant mobility
- Occupant mobility as affected by group dynamics
- Number and distribution of occupants
- Nature of floor and wall surfaces
- Egress path geometry such as stair treads and risers
- Egress path width restrictions (doors, stairs, corridors)
- Training or staff guidance
- Understanding of the egress path

The above factors that affect considerations on distance and speed are defined from a review of either occupant characteristics or building characteristics. The designer or engineer may need to consider each factor explicitly or be prepared to justify why a factor is not relevant to the analysis at hand.

Occupant Functional Limitations [51, 80, 90, 91]

When selecting an evacuation strategy for a very tall building, the procedures and building features that challenge occupants with functional limitations require specific consideration. Functional limitations include visual, hearing, mobility, upper extremities, cognitive, and other impairments of temporary or permanent nature. Such impairments may impact the evacuee's behavior or require an additional response and behavior of others in the building. Such impairments may include, but are not limited to, the following:

- Mobility impairments, e.g., wheelchair and walking disability
- Temporary functional limitations, e.g., injured and broken limbs
- Visually impaired and the blind
- Hearing impaired and the deaf
- Physically limited – asthma, heart condition, and obesity
- Cognitive impairments

Within the context of building egress, such functional limitations can result in slower moving speeds on stairs or an increased likelihood of frequent rest stops required for the evacuee.

While these impairments should be considered for all buildings, their impact can be compounded when the buildings are very tall. Over a significant number of stories, this has the potential to significantly increase overall evacuation times. Regardless of any acknowledged impairment, the increased stairway descent distance that accompanies increased building height automatically increases the proportion of building occupants who would not be confident they could evacuate without physical difficulty. Thought should therefore be given to adopting evacuation procedures for occupants of reduced mobility or fitness as would be adopted for those who are more traditionally mobility impaired such as those in wheelchairs.

Security and Fire Safety [73]

By their very nature, very tall buildings create landmark structures within cities. This can result in an increase in the property's security risk profile, which subsequently requires unique security solutions to be included within the design and operation to create an acceptable level of risk.

If not given appropriate consideration early in the design, standard security strategies such as vehicle standoff and access control can be at odds with fire safety requirements to gain rapid access to buildings for first responder vehicles and personnel. Given the increased security considerations for many very tall buildings, which often contain tenants for which security is a key consideration of their business model, the early collaboration of a project's fire safety engineer and its security consultant is considered essential.

Such collaboration enables solutions to be developed that can enhance, and not constrain, the overall fire safety design of the project – for instance, the use of combined fire and security control/command centers and the use of CCTV to monitor evacuations.

The typical security, smoke control, and egress strategies of very tall buildings rely on compartmentation created by closed fire doors at stairs and residential corridors. Self-closers for such doors are a very effective tool and should be evaluated by the designers. In buildings relying on this approach, occupants should be trained in the importance of closed doors at stairs and residential corridors.

Understanding Evacuation Times

To better understand the time taken to evacuate a building, a timed egress analysis can be conducted. Such analyses are typically associated with fire events and are often used to demonstrate that the evacuation of the occupants is completed before conditions become hazardous to the occupants. The analysis typically undertaken compares a Required Safe Egress Time (RSET) versus the Available Safe Egress Time (ASET) [51].

Why a Timed Egress Analysis?

The taller the building, the more occupants it can accommodate, resulting in an increased time to evacuate. Occupancies contained in very tall buildings are the same occupancies that can be found in lower-rise buildings such as commercial offices, residential apartments, and assembly occupancies. In low-rise buildings, the time to evacuate may not be considered critical. Placing these same occupancies further from the level of exit discharge increases the time for evacuation. The question is: when is a timed egress analysis necessary? Should it be undertaken for all very tall buildings? If one is completed, what is an acceptable result? The answer to these questions may depend upon various factors. Further discussion of this is provided within the Full/Total Evacuation section.

Egress Plan and Timed Egress Analysis

The evacuation strategies in very tall buildings for events such as fire often rely upon some form of partial evacuation. Partial evacuation means that only those people immediately threatened will be evacuated at one time; thus the evacuation process will be relatively quick. During such evacuations, occupants may be relocated to a place of safety within the building or evacuated to a place of safety outside the building at ground level. In either case, the need for a timed egress analysis for a partial evacuation is generally not critical though this depends on the type of design fire being addressed. Of greater interest are those evacuations that go beyond the initial three to five affected floors. They may begin to slow the evacuation process, for buildings where the stairway width is based on the occupant load of a single floor. Although this approach assumes that the occupants of different floors will arrive at a point in the stairway at different times, this approach breaks down when too many floors evacuate simultaneously. This effect can be studied with a timed egress analysis.

Elevators

A timed egress analysis can be beneficial if elevators are being considered as part of the evacuation process. Properly protected elevators can assist in reducing the time for evacuation, and a timed egress analysis will help to quantify this and assist in establishing the number of elevators to be used for such purposes.

Timed Egress Analysis Tools

There are many egress models available, each based on different assumptions concerning person-to-person and person-to-object interactions, with each containing varying levels of functionality (see Fig. 11.1 for a visualization of an egress model). An evaluation of many of these software tools has been produced by the National Institute of Standards and Technology (NIST) [92, 93], and it is included in the *SFPE Handbook of Fire Protection Engineering* [94]. A dedicated review of the use of evacuation models for very tall building applications is also available [95]. In addition, surveys on the evacuation modeling market as well as a user's experience and needs are available in the literature. This provides some insight into what is expected of egress models in the future. It should be noted that the characteristics of evacuation models rapidly evolve (in response to the engineering environment and user requirements); therefore, potential users are encouraged to not fully rely on those reviews and to check contemporary information concerning their capabilities.

Fig. 11.1 Example output from egress simulation software [96]. (Courtesy Movement Strategies, a GHD Company)

Where appropriate model functionality is available, such models can be used to represent scenarios of interest specifically related to the building, the procedure, and the population and then quantify the outcome of an evacuation. For instance, such egress models can be used to first populate a building with the appropriate design population. These occupants can then be assigned characteristics, either as a group or individually, such as movement (walking) speed, reaction/pre-movement time, tolerance to queuing, etc. [97, 98, 99, 100, 101, 102]. This population can then move to a place of designated safety through the building design being examined.

Review of Evacuation Model Characteristics

An important factor when assessing the capabilities of evacuation models for their use for very tall buildings is their ability to represent the egress components included in the evacuation strategies under consideration and the behavioral aspects associated with evacuation decision making, that is, their ability to represent key scenario factors. This means that models should be able to simulate both horizontal (e.g., corridors, exits, refuge floors, sky bridges, etc.) and vertical (e.g., stairs, elevators, etc.) egress components as well as the behavioral factors associated with human decision-making and route choice. A set of specific issues concerning the simulation of very tall building evacuations are discussed here, including movement and behaviors in different egress components such as stairs, occupant evacuation elevators (OEEs), etc., and route/exit choice in case of multiple egress options available (stairs vs OEEs).

Evacuation models allow the representation of complex behaviors and their impact on the evacuation process. This is a significant advantage compared to the use of simpler hand calculations which mostly represent the physical factors related to pedestrian evacuation movement. Assuming that the structure can be represented to a satisfactory level of detail, the use of a computational evacuation model may also reduce the likelihood of human error. Representing a tall structure in manual calculations can be a challenge given the complexity and scale of the structure. This representation, and the representation of the movement between different components within the structure, can pose significant challenges to the practitioner, somewhat reduced in computational approaches. However, that is not to say that computational tools automatically produce a credible representation of the space and evacuee response – and therefore still require expert scrutiny.

When simulating movement speeds on stairs, it is essential that the data the model is based on and the assumptions within the model match the expected conditions within the building. The models may not match the conditions that are expected within the very tall building that is being modeled.

The model that is selected for simulating the movement of people must be validated for use in very tall buildings. Much of the data that is used as the basis of movement speeds was collected for occupants traveling between two stories or for evacuation drills of buildings that were typically less than 15 stories. Extrapolating that the same trends in movement speeds will apply for the longer travel distances in very tall buildings may not be realistic. This is especially true if the model uses the same average speed for all occupants as some populations travel at much slower speeds than the average values.

In simulations of very tall buildings, small differences from reality that occur on each floor can make a large difference in the final total egress time due to the same small change being made many times. These include issues related to the geometry of the stairs as well as the behaviors of occupants.

Stairs consist of a series of treads connected to landings. For the treads, taller riser heights can lead to fewer steps per floor but can also increase fatigue. With data that is developed based on 18 cm (7 in) riser heights with 28 cm (11 in) tread depths, other stair configurations could result in different movement speeds. For the landings, a critical variable is the travel distance. While some models calculate the travel distance on the landing with people moving at 90° angles, people walking in arcs matches observed behavior. This leads to shorter travel distances on stairs, and occupants may travel a shorter path when the stair turns to the right (in locations where people walk on the right).

Occupants traveling down stairways interact with each other, and these interactions could significantly impact the total time required for evacuation. For example, people may choose to only walk on one side of the stair to leave the other side open for emergency responders or people in greater need of assistance. When this type of behavior occurs, the total evacuation time will be significantly increased as the width being used for evacuation is much less than what is typically simulated. Similarly, how people defer to individuals entering from the floor could alter the time required to clear the floor or the speed within the stair. This deference behavior has been seen to vary based on several key variables.

The direction of travel will also make a difference in the accuracy of the simulation model. Most of the data that is used applies to occupants descending the building. In very tall buildings, travel in the ascending direction may also be required. This could be the case for travel up to a refuge floor or sky bridge. These speeds will be different from the descending speeds, and fatigue has been observed after fewer stories of ascending compared to descending.

Concerning OEE modeling, to date, there are both models that are specifically dedicated to the representation of elevators as well as general-purpose pedestrian evacuation models which include OEE simulations. The main issue with the tools that are dedicated to performing vertical transport evacuation modeling is that the simulated human factors are generally homogeneous and simplified (i.e., all occupants in the populations generally use the OEE in the same way and no complex decision-making is represented). In addition, because those models are designed to represent movement through elevators, their interactions with horizontal egress components are represented implicitly (i.e., the horizontal and vertical movement components are not connected, and the interactions are manually devised). This is generally solved modeling "trip inefficiency" (i.e., additional time needed to pick up latecomers) or representing arrival rates. In contrast, genera-purpose evacuation models generally explicitly represent the behavioral choices considering the interactions between horizontal and vertical egress components.

Modeling OEEs is based on the representation of their:

- Kinematics – accelerators/deceleration and speed
- Physical features – maximum load, number, and type of doors
- Operational features – opening and closing times, and floor dispatch strategies
- Behavioral factors – usage of the elevators, waiting times, behavioral itineraries, and elevator loading time

Evacuation models may represent all these factors or a subset of them. Depending on the needed level of resolution in the modeled scenario, the evacuation model will need to represent those factors explicitly (through a dedicated input setting) or implicitly (through another input which can account for the impact of those variables).

The decision-making process linked to the use of elevators in case of availability of multiple egress components can also be addressed in the model input calibration process. In fact, an important factor to be considered while simulating very tall building evacuation is the percentage of agents willing to use the elevators in relation to the floor on which they are initially located. This is linked to the time occupants are willing to wait for elevators before redirecting their movement toward the stairs and the occupants' perception of relative risk when using elevators or stairs for fire egress. Experimental datasets on this issue are available in the literature, and they can be used by model users to calibrate this input. Those datasets are based on different types of data-collection techniques. This can include behavioral intention surveys, online or on-site questionnaires; and their limitations should be assessed prior to their application. The calibration of this input should also consider the expected number of people with disabilities in the building and the evacuation strategy. Total evacuation or presence of refuge areas are examples of evacuation strategies that should be considered as this might increase the actual number of elevator users. In addition, evacuation models often provide the opportunity to represent not only the evacuation outside of the building but also phased evacuation or other strategies which make use of refuge floors. Similarly, it is possible to represent strategies which account for a proportion of building occupants using other alternative means of egress such as sky bridges.

The reliability of the results produced by evacuation models is a combination of the model functionality, data availability, and user expertise. This combination needs to be examined through model calibration and testing to ensure model performance and increase output credibility. It should also be noted that the time required to set up and run the scenarios depends on the building and scenario complexity. For instance, the procedures employed might be phased or vary according to different sub-populations. Very tall building evacuations may also require the simulation of many occupants, thus computational aspects should play an important role in the selection of a suitable model.

Specific factors of the evacuation process in very tall buildings may require careful user consideration. The first factor is the simulation of the impact of physical exertion experienced by the evacuating population and how it can impact the evacuation process due to the reduction in walking speeds along traveled distances. This is particularly important in very tall buildings given possibly long travel distances to reach a safe place and the fact that most evacuation models do not currently model this explicitly. The effects of group dynamics also need to be considered. In fact, as shown during the WTC evacuation, the formation of groups during descending stair evacuation can play a significant role. Model users may also need to represent the impact of the actions of staff and the behavioral interactions among people in the building. This is particularly important for people with disabilities because some evacuation models can represent different assisted evacuation procedures.

Evacuation models allow the representation of different evacuation strategies and test the impact of different design and procedural solutions. Given their ability to represent stairs, OEEs and other egress components such as refuge floors and sky bridges that are typical of very tall buildings can be considered a powerful tool to compare different approaches and behavioral scenarios. For example, considering total evacuation strategies, evacuation models give the opportunity to compare evacuation strategies including (1) the sole use of staircases for evacuation; (2) the combination of staircases and OEEs; (3) the impact of other means of egress that can include refuge floors, sky bridges, etc.; and (4) different human responses/actions during the evacuation process. In addition, one can evaluate different elevator dispatch strategies and their possible impact on evacuation times. This includes the study of elevator zoning such as which floors elevators are serving, the use of "lifeboat" elevators such as shuttle elevators serving only given floors, and the impact of the type/characteristics of OEEs themselves. These variables can be studied in isolation or in combination with other physical or behavioral aspects such as route choice based on resulting simulated waiting times.

In conclusion, evacuation models are a useful tool to study very tall building evacuation strategies, but they require human behavior data for their calibration and a careful evaluation of the model inputs to provide reliable outputs.

As is apparent, several computational egress tools exist. Other non-computational approaches (models) exist. They do not all have the same capabilities or make the same assumptions. They are typically employed to address two objectives: to familiarize participants with the procedure in place or assess the performance of this procedure. Egress tools typically address the latter. The following models are included here as they may assist in meeting these objectives [103]:

- Computational egress tools (as described above)
- Egress drills – a preplanned simulation of an emergency evacuation for a specific incident scenario. In conjunction with other events (see below), drills may be used to improve the performance of the occupant population and/or staff present and active during an emergency and measure the extent of this improvement.
- Virtual/immersive environment/serious gaming – participants are "located" within a virtual space allowing them to actively make decisions in response to the conditions faced, interact with it, and perform actions (either through control of an avatar or through acting directly).

- Laboratory experiment – exposure of participants to a physical/psychological condition (ideally reflective of an evacuation) in a controlled artificial environment to assess performance of a specific task given the manipulation of this environmental condition.
- Tabletop exercise – involves participants in a simulation of the decision-making process in response to the exercise scenario to test the effectiveness of the procedure tested and their part in it.
- Mental rehearsal – individual attempts to visualize expected decisions, tasks, and desired outcomes before the situation is experienced.
- Hot/cold debriefing – a review of the events, decisions, and outcomes produced during the event, including those involved and those monitoring the event.

Drills are typically performed based on the fire/building regulatory requirements applicable to the jurisdiction in question. Given political, social, and environmental developments, there are hazards (both fire and non-fire) that may require an emergency response. Examples of these events include evacuation due to terrorist attacks and/or severe weather events. As with all models, drills represent a cluster of simplifications, and much of the model's value relies on the nature and extent of these simplifications. Ideally, a typical occupant population, the safety staff, and the procedures expected during a real incident should be present during the drill, allowing more confidence in the similarity between the drill and reality. Indeed, the potential for this similarity is one of the strengths of the egress drill model – as it potentially involves actual members of the target population in their host environment that represent conditions that might be experienced by a subpopulation of evacuees in a real incident. It is apparent that where these elements are in place, the drill "model" can potentially approximate real-world conditions, at least in the initial phases, where incident development and evacuee exposure are at a minimum.

Evacuation models (specifically the performance of drills) may observe or affect performance at several different organizational and procedural levels:

- An individual act – operating a fire extinguisher
- An individual role – a floor warden
- A group defined within the procedure – floor sweepers
- The interaction between different groups – security staff and wardens
- The planned procedure – phased evacuation
- The interaction between different procedures – the emergency evacuation and a security procedure
- The building performance – the time for occupants to reach a place of relative safety, or the time for the entire population to be evacuated
- Multiple external agencies responding to the incident – the fire service and police service
- Multiple building and locations involved in the incident(s)

At each of these levels, performance may relate to the recall, accuracy, and time of completion of the task in question. It is apparent that the evacuation process from very tall buildings carries an inherent complexity such that these levels of performance and these indicators of performance are difficult to examine in full. In addition, egress drills pose several challenges given that they involve human subjects moving within a building currently in use. These include the following:

- Resources are needed to design, organize, execute, and analyze an egress drill. There is a cost to them related to the loss of functionality of the building.
- Attempting to reproduce credible real-world conditions may place those involved at undue risk of injury. A key consideration in the conduct of drills is weighing the risks posed to participants with the potential insights provided/training benefits provided. There is a cost associated with the drill related to the increased risk of injury to participants related to the drill scenario and the individual movement abilities.
- Evacuee observations require some form of building instrumentation to collect the needed data at the level of refinement needed to identify the underlying dynamics. This is not always possible to complete at the desired level of detail or scope.
- Typically, the existence, frequency, or nature of the drills are not monitored or scrutinized by authorized third parties. Therefore, it is not always possible to ensure that drills are conducted as expected to ensure the credibility of the data collected or the training provided.
- Drills are performed periodically with each drill representing an instance of a scenario – a single data-point from within a distribution of outcomes that might reasonably be expected for a scenario.
- Given minor perturbations in the initial conditions, a scenario may possibly be repeated several times over a period. It is unlikely that drills will be performed in sufficient number or scope to be genuinely representative and reliable of the range of scenario outcomes that might reasonably be expected.
- Given the challenges posed by the drill's organization, it may be difficult to ensure that those involved are subjected to training for all the tasks that they may be expected to perform in a real incident.

These challenges are apparent in all structures. Such challenges are amplified in egress dress conducted in very tall buildings – given the increased scale and complexity of the scenario. Given this, it might be prudent to complement the drills of alternate means of enhancing performance or measuring this performance.

Evacuation Strategies

A variety of evacuation procedures and methodologies are available for use by a building's fire protection engineer. The appropriate selection of such a strategy is one which provides the required level of safety for the building occupants and best meets the other stakeholders' design objectives. A selection of the egress strategies widely used in building design are highlighted below [104].

It is not possible to definitively state which egress strategy should be adopted for all very tall building designs, as this can only be derived from the performance objectives identified at the outset of the design. Some strategies are better suited than others to very tall building design as is described within the relevant commentary below.

Simultaneous Evacuation

Simultaneous evacuation involves the simultaneous broadcast of an alarm signal or notification to all floors and the consequent evacuation of all building occupants on all floors, egressing at the same time. This strategy is the norm for many building types, particularly those with relatively few floors/occupants, but is not appropriate for all buildings. It might be adopted for very tall buildings in non-fire scenarios.

The use of a simultaneous egress strategy does not give any preference to those occupants within the immediate vicinity of the fire and places the maximum demand on the egress system, particularly the stairways, as they are used by the maximum number of people simultaneously. Because of this, egress components designed to accommodate simultaneous evacuation generally require greater width than those provided for other evacuation strategies. This is usually particularly undesirable in very tall buildings because this reduction in leasable floor area is magnified by the large number of stories over which it occurs.

Simultaneous evacuation is not typically adopted for fire evacuations within very tall buildings because it causes large-scale disruption for what could be a relatively small fire event or even a false alarm. This form of evacuation also has the greatest potential to cause queuing within both the stairways and on the building floors, which can increase the escape time from the fire floor where people are directly at risk. This potential for the greatest number of people to be exposed to long queuing times is also potentially the most disruptive and distressing for occupants in very tall buildings, caused by the increased anxiety of the long queue-waiting times after receiving notification to evacuate.

For buildings located within dense urban environments, which represents a large proportion of very tall buildings, the use of a simultaneous egress strategy can have an effect beyond the initial evacuation. Occupant dispersion away from a building requires consideration as the simultaneous evacuation of a very tall building can create people movement issues within the immediate vicinity when possibly thousands of occupants simultaneously exit the building. This not only has the potential to slow the discharge of evacuees from the building's exits, which has negative impacts on the occupant flows within the stairways, but also has the potential to slow the first responder's response to the incident by causing large crowds and blockages within surrounding roads inhibiting vehicle access to the building's designated fire service attendance points.

For any building type, the point at which a simultaneous evacuation begins to hinder, and not enhance, the level of safety within a building is difficult to determine, and it is left to the judgment of the project's design engineers to assess the benefits and/or drawbacks of this form of evacuation procedure for their specific application.

Phased Evacuation

Most very tall buildings will adopt some form of phased evacuation regime (sometimes referred to as "staged," "prioritized," or "sequential" evacuation).

Such an approach has the advantage of only evacuating those people in the immediate vicinity of the fire, which allows those people in direct danger to make most efficient use of the egress provisions available to them. Others may evacuate afterward reducing the loading on the available egress routes and ensuring that at most risk evacuate first. Additionally, for small fires or false alarms, the level of disruption to the building can be kept to a minimum, enabling day-to-day operations to resume in the shortest possible time. At the exterior of the building, in a real fire condition, the first responders will have clearer approach routes and fewer people to manage around the site, which enables them to respond to any developing incident quickly and efficiently.

Those occupants within the zone being evacuated are given an appropriate warning signal, while those outside the evacuation zone are either notified of a developing incident and told to remain in place and await further instruction or are given no warning at all and continue their normal day activities unaware of any incident. The decision upon the extent of occupant warning past the initial evacuation zone is determined on a case-by-case basis by first responders on the scene and their assessment of the severity of the incident.

The typical phased evacuation philosophy adopted within many medium-height buildings and above is the initial evacuation of the fire floor + a number of stories above + a number of stories below the fire floor. Other floors "stay-in-place" and do not evacuate. Local codes of practice and opinion may differ on how many stories below the fire floor require to evacuate in the first phase; however, between two and three floors (i.e., fire floor + floor above or fire floor + the floor above and below) is common practice. Phased evacuation needs to be designed carefully and in conjunction with other fire safety systems, especially in those very tall buildings where a single fire compartment may include multiple floor levels.

With a large proportion of the building's occupants remaining in place, and potentially unaware of a developing fire incident, the building's fire-resistant compartmentation has a greater level of importance in the success of the phased strategy compared to the simultaneous approach. This is because it is important that people located outside the initial evacuation zone are unaffected by the incident until those within the affected zone have evacuated.

While the above two or three floor phased evacuation approach is reasonable in theory, the reality is that during an emergency the evacuation is unlikely to be as orderly as the designated two or three stories only. With the advent of multiple methods of instant communication (mobile phones, text message, email, real-time messaging, social networking apps, etc.), the ability for information to spread rapidly throughout a building is becoming increasingly likely – particularly in very tall buildings where a single tenant may occupy multiple stories and occupants across those stories may be well known to one another. It is very likely that some occupants on non-fire floors will choose to evacuate, ignoring messages to remain in place. The designer should, if appropriate, consider evacuation scenarios where the baseline two or three-floor evacuation scenario has an appreciation of occupant overflow from stories outside the initial zone of evacuation to account for an increased number of evacuees due to uncontrolled communication. It is not possible to prescriptively define how, or to what extent, such an appreciation should be applied; however factors of safety by increasing the total building population per floor may be acceptable under certain circumstances. This could result in exit capacities greater than those required by the governing code.

In residential buildings, phased evacuation requires sections of the occupant population to remain in place until they are required to evacuate – at which point the alarm system will sound in their apartments/floor. This assumes that the building provides sufficient protection at their location (remote from the fire origin) to allow them to delay their movement until the specified time.

Defend-in-Place

Occupants of the area of fire origin (e.g., apartment) are assumed to evacuate to a place of safety (inside the building or outside the building), and all other areas, either on the same level or above/below, remain in place. The compartmentation of the fire floor provides a defense for occupants in other portions of the fire floor. The defend-in-place approach requires a good level of fire and smoke-resistant compartmentation between adjacent evacuation zones, and in the case of an apartment building, this requires each individual residence to be constructed as its own fire compartment. It also requires the occupants to have confidence in the protection and then remain in place. Egress route capacity may be designed to only accommodate a fraction of the population assuming that the majority defend in place.

Progressive Evacuation

Progressive evacuation is the same as the previously described phased evacuation, except that the occupants of the evacuation zone are evacuated to a safe area within the building remote from the fire location (as opposed to escaping directly to outside). From this safe place, occupants will either remain or, if threatened further, be relocated to an alternative safe area with the building – hence the “progressive” nature of an occupant’s evacuation. People are only evacuated from the building to the exterior as a last resort. This evacuation strategy is also sometimes referred to as staged evacuation.

The relocation of occupants can either be horizontal – to an adjacent compartment on the same floor – or it could be vertical to a dedicated region further down the building from the fire floor, i.e., a refuge area/floor.

The architecture of very tall buildings (relatively small footprints of an open plan nature) is rarely conducive for the use of horizontal relocation, and therefore the vertical form is generally considered the only appropriate method. One notable exception to this is the sky bridge connecting the twin towers of the Petronas Towers building in Kuala Lumpur, Malaysia. The sky bridge allows occupants within one tower (during its evacuation sequence) to cross over to the other tower (which is not evacuating) to use the egress stairways in the non-evacuating tower. In the case of a fire event, such an approach is advantageous in a single tower evacuation mode; however, it provides little benefit in instances where the simultaneous egress of both towers is warranted, such as in the event of a security threat.

The evacuation of mobility-impaired occupants usually adopts this progressive movement approach (by relocating them to areas of refuge) even if the remainder of ambulant occupants evacuate in some other manner.

Full/Total Building Evacuation

In very tall building design, the horizontal portion of egress is usually relatively short, and it is the period which people are within the protected stairways which becomes the dominating factor in an occupant's time for total evacuation. While people within the stairways are at a significantly reduced level of risk from fire and smoke, the building's ability to structurally resist the developing fire over time plays an increasingly important factor.

The fire resistance period for a structural element tested under the standard fire exposure tests may not correlate with how a complete structural system will react, and how long it will survive, in a real fire condition.

An evacuation of Taipei 101 in Taiwan in 2004, prior to the building's official opening, gave a total evacuation time in the region of 2.5 h when using only the egress stairs. To reduce this time, at the direction of the local fire authority, the egress strategy was modified to incorporate the use of elevators from the upper floors which resulted in a reduction in the overall evacuation time to the region of 1 h [105].

Hybrid/Combined Strategies

While on the macro-level, a phased evacuation procedure is the predominant strategy for a large proportion of all very tall buildings, the likelihood of this being the sole evacuation strategy for the building is unlikely.

Many modern very tall buildings contain more than one occupancy type, and therefore a subset of the overall phased evacuation procedure may also be present. For instance, a very tall all mixed-use building containing office, residential, hotel, assembly uses, etc. may have a separate evacuation strategy for each occupancy type; however, this will be part of the overall phased evacuation approach for the entire building.

It is common design practice to share the vertical egress components among the various occupancies present – by doing so, egress strategies are also mixed. While the egress design will need to adopt the requirements of the most onerous occupancy present, other challenges in such instances may still be evident. Particular attention should be given to the interface between adjacent occupancies and hence adjacent evacuation strategies.

Most very tall buildings, in some way, often capitalize on the views experienced from their upper stories by providing features such as external observation decks or internal/external dining experiences. The challenges of a potentially large assembly occupancy (whose occupants may be unfamiliar with the building and may contain a greater age range than a typical office's occupants) near the topmost story within the building, from where evacuation will take the longest, require additional thought within any such fire safety strategy.

Design Features Affecting Evacuation Times

Methods are available for reducing the amount of time required to evacuate a building during a fire event. Some of these methods involve physical systems, whereas some may require management strategies or a combination of both. The selection of such methods requires consideration that each works to appropriately complement one another [104].

Components of Egress

Exit Discounting

Many fire safety codes determine egress capacity from a floor on the basis that one of the exits available to occupants could become compromised because of a fire occurring in a location which blocks the use of that exit. In such cases, the remaining exit or exits are then required to serve the total occupant load of the floor (i.e., an n-1 approach).

This approach, adopted by several European fire safety codes, offers a level of redundancy should an exit be lost in the event of a fire. While many fire safety codes do not require such an approach, it is perhaps a concept that should be considered for certain very tall building designs. Such an approach, while increasing the level of redundancy within the design, may have a detrimental effect on the efficiency of the building's egress system design. If adopted, this efficiency reduction may be offset by deploying additional egress solutions such as elevator evacuation (see section in this chapter on "Elevator Evacuation"). A risk analysis as described in Chap. 7 (Hazard, Risk and Decision Analysis in Very Tall Building Design) should be performed to determine whether this approach is adequate or if another strategy is needed.

Horizontal Stair Transfers

The competitive nature of very tall building design has necessitated that architects continually push the boundaries of very tall building design. One aspect of this is the variation in the vertical nature of many very tall buildings. Staggered or offset floors, creating leaning towers, are becoming increasingly common in very tall building design.

For the fire safety engineer, the challenge often lies in the fact that compliant travel distances and stairway separation are required on all building stories, but where a floor shifts, with respect to the vertical stairway locations, this can sometimes be challenging.

To maintain cost efficiency, and constructability, inclined or stepped stairways (mirroring the exact geometry of the tower) may not be an appropriate method of addressing such design challenges. Instead, a series of straight vertical runs of stairways can be provided which horizontally connect to one another at transfer floors.

At such floors, horizontal transfer corridors (fire passageways) will connect the two stairway portions, allowing evacuees to transfer between the two stairways, in an equivalent level of protection to that of the stairway (in terms of fire resistance and pressurization).

As an evacuee, it may be somewhat of a surprise when evacuating down a stairway to find that it suddenly terminates and leads into a horizontal corridor above the level of exit discharge. To prevent potentially confused occupants from exiting the egress system at this point, thought should be given to limiting access points into the transfer corridor. Ideally, the corridor will contain no access points, which maintains its level of protection and prevents occupants from leaving the protection of the corridor. Additional exit signage, reaffirming and reassuring evacuees as to the direction of escape, should also be provided to improve occupant situational awareness.

Effective Wayfinding/Exit Signage

As with any building, the provision of appropriate fire safety signage is a crucial feature in facilitating a smooth and efficient egress strategy.

Within very tall buildings, with the repetitive nature of the continual downward motion of descending multiple stories, occupants can lose an appreciation of their progress toward safety and be unaware of how many stories they have descended. For this reason, repeated information within the stairway, such as fire safety signage and stairway level identification, can reassure occupants and give people a metric with which to benchmark their progress to safety at ground floor level. Where facilities such as refuge rooms or floors are present, these should be clearly identified by signage to encourage their use (see Fig. 11.2).

The ability of occupants to negotiate a building's egress system under power failure scenarios should perhaps be considered with a very tall building egress strategy. There are several approaches that can be used to address this. Methods of supplementing the primary power source for emergency lighting include redundant power sources or the use of photoluminescent markings (see Fig. 11.3) [106].

Egress Discharge Locations

With the large numbers of people potentially evacuating from a very tall building, it is essential that people discharge to locations where they are safe both from the effects of a fire and from hazards above such as falling glass. Egress discharge also should not interfere with vehicle access routes to the building for the fire service. Key to enabling this is the implementation of a building management plan to move evacuees from the perimeter of the building to appropriate assembly areas in locations remote from the building.

While considered fundamental in any fire strategy for the interior of a building, the adequate separation of exterior exit discharge points at the street level is equally important. While theoretically, the discharge of an occupant to the exterior of the building is moving away from the fire threat someway above them, the close proximity of final exits at street level creates the potential for a single point of failure which may, or may not, be fire related which could be the case if exits are blocked by a parked vehicle or large numbers of evacuees.

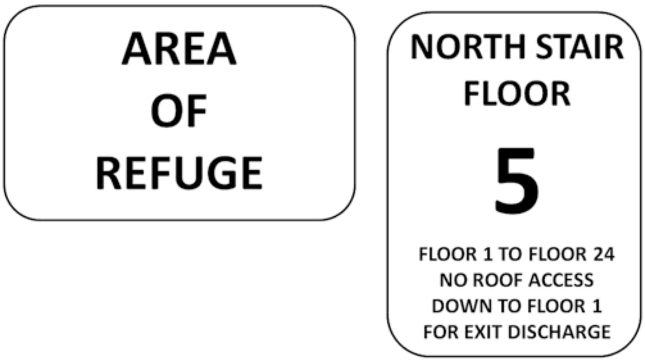

Fig. 11.2 Example of signage provided within egress stairways

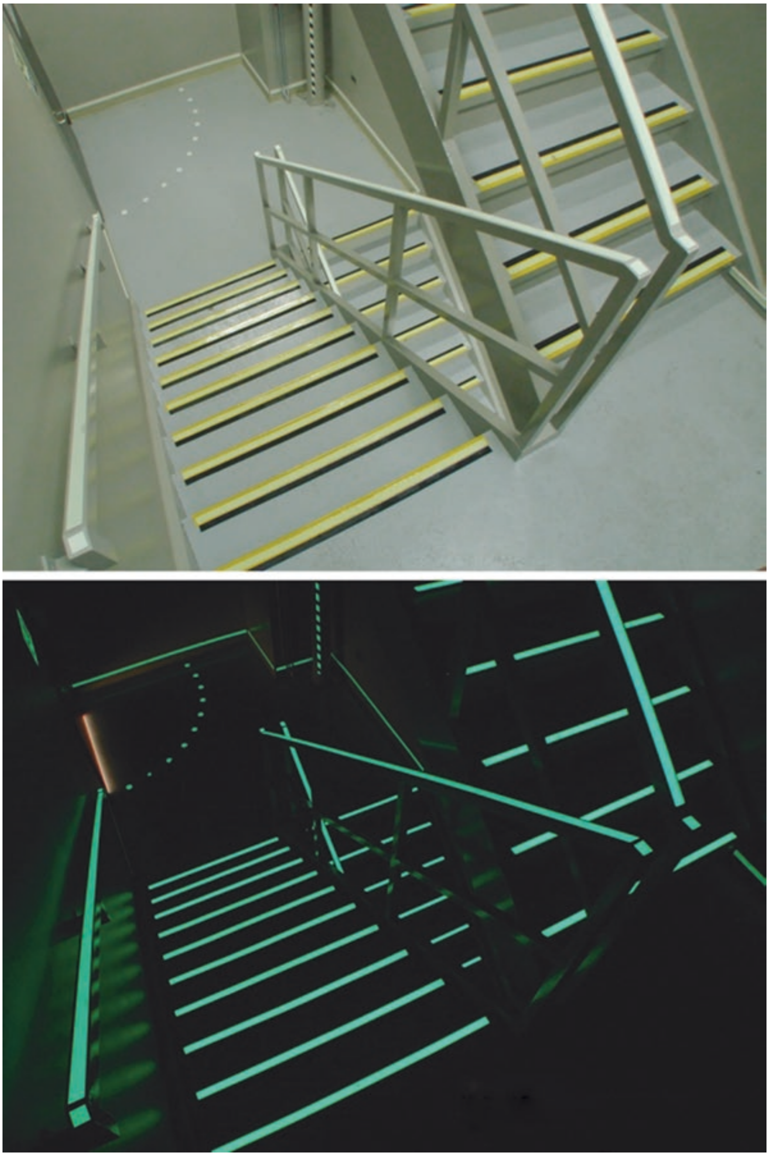

Fig. 11.3 Egress stairway with photoluminescent markings. (Copyright 2021, National Research Council of Canada on behalf of Her Majesty the Queen in Right of Canada [106])

Some very tall buildings are not free-standing entities but are connected in some way to a low-rise function, e.g., a tower as part of a shopping center, transport interchange, or other forms of podium accommodation. In such instances, it is conceivable that egress from the tower above may discharge onto these low-level functions similar to a podium/plaza area where occupants discharge to an area that is not truly at street level. Where this occurs, the important aspect of any such design is that occupants are appropriately protected from any risks below, for instance, smoke discharge locations, and that egress from the podium/plaza areas can be readily achieved without affecting the ongoing egress within the tower portion of the building.

Elevator Evacuation

Properly protected elevators have been recognized by some prescriptive codes as a means to assist with occupant evacuation since at least the 1970s [107]. While the early use of elevator evacuation was typically under the manual control of the fire department, in the late 1980s and 1990s, various government and industry groups began to encourage the use of elevators to evacuate building occupants, particularly those with disabilities [108, 109, 110, 111]. A collection of references detailing these early studies in the use of elevators for occupant evacuation were compiled by Bukowski et al. [112].

Within the United States, such a strategy adopted a system of recall, as detailed below. While this terminology is specific to the United States, the principle is adaptable to many countries. Currently, many buildings operate elevators under a recall system that involves two phases:

Phase I recall: Elevators automatically relocate to the predefined fire department access level.

Phase II recall: Elevators are placed under the control of the fire department, for their use, in performing fire-fighting operations or assisting with occupant evacuation.

As security concerns drive designers to consider a wider range of emergency scenarios for very tall buildings, the use of elevators for the evacuation of building occupants is likely to become more prevalent. A number of very tall buildings already use elevators for evacuation in some form [113]: the Stratosphere Tower [114] in Las Vegas, the Petronas Towers in Kuala Lumpur, Taipei 101 in Taiwan [105], and Burj Khalifa in Dubai. 181 Fremont Street in San Francisco [115] is the first new building to follow the modern iterations of NFPA 72 and ASME A17.1 with explicit requirements for occupant evacuation elevators (OEE) and occupant evacuation operation (OEO).

There are several roles that elevators can play in a building's fire safety strategy:

- For use by the fire department in fire-fighting operations. This reduces counterflow conditions in stairways as fire fighters ascend to the floor of the incident without affecting the physical condition of the fire department personnel.
- For use by fire fighters to shuttle equipment from the fire department access level to the bridgehead on the level of incident.

- For use by the fire department to assist in rescue operations.
- For use by disabled occupants for evacuation or others unable to use the stairways.
- For use by all, or a portion of the general building population, for evacuation.

Depending on the needs of a particular building, elevators may be used for several of these roles. No matter what the specific use, there are several design considerations that should be considered, including safety and reliability of the elevators, coordination of elevator controls and building safety systems, education of the building population and first responders, and communication to evacuating people during a fire.

Safety

To safely use an elevator for evacuation, several criteria should be considered. Fire and smoke should be kept out of the elevator system (i.e., elevator shafts, cars, lobbies, and any adjacent stairways), water should be kept away from elevator cars and machinery, redundant power supplies should be provided, and features should be made for the rescue of occupants of a stalled car if a failure does occur. A number of these items are addressed in NFPA 101® [116] and the IBC® [47].

For the purposes of limiting the spread of fire and smoke into an elevator during evacuation, one should consider the entire system, including:

- The elevator shaft/hoistway/car
- The elevator lobbies on any floor connecting to the elevator
- The stairway(s) attached to the elevator lobbies
- The exit area between the elevator at the level of exit discharge and safety
- The availability of normal and standby power to the elevator and its controls is critical to the use of the elevators for evacuation.

Available literature suggests a range of options for providing a fire separation between the elevator evacuation system and the rest of the building [117]. This could include a fire-resistant separation or a combination of a fire-resistant separation with automatic sprinklers. In addition to physical separation, measures will be needed to prevent the migration of smoke into the elevator evacuation system. Whether this is accomplished through physical separation, pressurization, smoke exhaust, or other means, a safety feature is to install smoke detection in elevator cars, at the top of elevator shafts, in elevator machine rooms, and in each elevator lobby. Activation of any of these smoke detectors should recall the affected elevator to the level of exit discharge. However, this will take the cars out of service for evacuation.

Whatever the means of providing fire and smoke separation from the elevator evacuation system, it is crucial that performance criteria be set such that occupants waiting in the elevator lobbies will be protected from untenable conditions for a period long enough to undertake an evacuation. Design of these areas should consider the number of people that may be housed in these areas as well as the needs of disabled building occupants.

Another safety/reliability consideration is the possibility that water from sprinklers or fire department suppression efforts could affect elevator machinery. The elevator cab doors could also be affected by water, causing them to become inoperable and preventing egress. To prevent water infiltration into an elevator evacuation system, the following methods could be considered [114]:

- Construct shaft enclosures and any penetrations in such a way that water accumulating on the inside wall cannot spill over into the elevator shafts/machine rooms (e.g., by installing a threshold or an upward-sloped floor adjacent to the lift landing doors).
- Provide drainage sufficient to manage the flow of water from fire department hoses and activated sprinklers.

Controls and Operations

The controls used to operate elevators in very tall buildings are complex and require planning during the design process. Elevator cars should be provided with an emergency call system that will allow riders to call for help if the elevator cars malfunction. The fire control/command room can be used to monitor the movement of each elevator and respond to any request for assistance.

The controls used to run elevators used in evacuation require interface with the building fire protection systems. As the height and complexity of a building increase, it may be necessary to pre-program automated control responses into the elevator systems. Controls should be programmed differently for emergency situations where the intended use of the elevators has changed. Decisions as to what functions are appropriate in different situations should be informed by a risk analysis, as discussed in Chap. 7 (Hazard, Risk and Decision Analysis in Very Tall Building Design). Whereas in normal conditions elevator occupants usually control the elevator to the desired floor (by an elevator control panel within the car), there may be benefit in an emergency scenario of having dedicated egress elevator operators (a trained member of building security staff, for instance). While this reduces by one the room for evacuating occupants within the elevator, the increased efficiency of the evacuation may compensate for this.

The power and control system for the elevators must be carefully designed to be robust and function under many possible fire scenarios. Physical and fire protection for the wiring should be considered.

A thorough discussion of controls for evacuation elevators is provided by Bukowski et al. [112], and some of the major concepts are outlined here. Some control functions that should be considered during the design of an elevator evacuation system are:

- When smoke/fire has penetrated to a portion of an elevator system (shaft, lobby, machine room, etc.), that elevator should be recalled to the level of exit discharge and taken out of service for egress purposes.
- The fire department should have the ability to route elevators as needed to fit their suppression/rescue plan for the building.
- Consideration should be given to minimizing the number of starts and stops required for an elevator during an evacuation. Certain stories can be designated for elevator evacuation, and elevators can be run in an "express" mode.
- Priority should be given to collecting occupants from the fire floor and other adjacent floors. Once the fire zone is emptied of occupants, the elevator evacuation can serve other floors. The demand can be determined through elevator call requests or occupant-sensing devices in the cars and/or lobbies.
- An elevator can be designated for fire department use and remain clear of evacuating occupants. This could be at the request of the fire department during an event, allowing more cars to be used for egress until the fire department arrives.

Communication

In addition to algorithms designed to operate the elevators for egress, other tools that communicate the availability and location are necessary. The following are some key pieces of information that will give the building occupants and fire department more confidence in the use of the elevators [112].

- Displays in the lobbies indicating if elevators are available for egress and the approximate wait time
- Ability for occupants to communicate from the elevator lobbies with the fire command center
- Status of elevator system for emergency responders in the fire command center

Training

Training of the building occupants and the fire department will be a key requirement to successfully implementing an elevator evacuation system. For decades, people have been told not to use elevators during an emergency, and in most buildings they still should not. The few buildings that do harden their elevator systems for use in an evacuation will need to make their occupants aware of how they should use the elevators in an emergency. A major aid to the education of a building population in the use of their elevators is providing voice communications and illuminated signs during an emergency event. Fire crews must also be trained in the use of elevators for evacuation. However, since the responding fire crew may not always be the one planned, the fire fighter interface and the elevator evacuation system itself must be intuitive.

The following issues should be considered when developing a training plan for use of elevators in evacuation [112]:

- Building occupants need to practice unconventional procedures. Distribution of the plan to occupants is insufficient by itself.
- The system cannot be expected to work properly in a fire emergency without periodic exit drills. Repeated instruction is important because very tall buildings experience a changing building population.
- Occupants of elevator lobbies should be taught to anticipate long waits and to understand when the wait time is too long. They should know that evacuation to grade may be quicker in the elevator, but that conditions become untenable, so the stairs may be a safer place.
- A means of receiving feedback from fire drill participants should be implemented.
- Training should not be restricted to a classroom setting; it should include a walk-through of the steps required of evacuating occupants.
- Separate and more regular training should be provided to employees who staff the control room.
- Voice and visual communication to elevator lobbies from a fire command location should be provided.
- The fire department should be made aware that taking elevators out of service unnecessarily will increase egress times.

Maintenance

Elevators used for occupant evacuation are as critical as other fire safety systems, such as sprinklers, and care needs to be taken to maintain the elevators in working condition. Generally, elevators will need regular maintenance and repair. Maintenance and repair should be considered when planning the evacuation strategy for a building. This should limit the number of elevators taken out of service at any given time.

The level of smoke and fire protection of the lobbies and their size must be determined during the initial building design. These factors must be made available to those owners and designers who in the future will be responsible for tenant improvements and other changes. The useable size of the lobbies has a direct effect on the number of occupants who can remain in the safety of the lobby, awaiting elevator service. The egress plans for the building should overtly state the minimum lobby size and the method of its calculation, so that changes do not reduce it below the minimum.

Supplementary Escape Equipment

Following the events of September 11, 2001, many products began to emerge that were designed to provide supplementary provisions for escape of very tall building occupants without the use of traditional stairways. The use of such devices may be inappropriate for very tall building evacuation, and they are not recommended as a permanent alternative to the use of stairways or elevators. It is not expected that these would form an integral part of any fire strategy other than in exceptional circumstances.

At one point about 50 years ago, during a period of global growth in the construction of high-rise buildings, helicopters were successfully used to evacuate occupants from the roof in several notable high-rise fires. A detailed discussion of the use of helicopters for egress is included in Chap. 24 (Aerial Vehicle Platforms).

Methods for Protecting Building Occupants in Place

Some evacuation strategies make use of safe areas to which building occupants can be relocated. These may be designed to provide temporary refuge/resting locations as people exit the building or to hold people for the entire duration of an event within the building. Several methods of achieving these options are discussed below. To make use of any of these strategies, it is important that a structural analysis of the building design is also completed to demonstrate that the integrity of the building and its systems can be maintained during design fires/events under consideration.

For many incidents, particularly those in very tall buildings, precautionary relocation of building occupants in stories adjacent to an incident will occur. Frequently, many of those stories can be re-occupied shortly after extinguishment of a fire.

Evacuation of the Mobility Impaired

The traditional view of mobility impairment is that of occupants confined to wheelchairs or similar devices. However, there are a variety of conditions outside of the commonly considered mobility-impaired definition that may require an alternative egress plan to be sought, for example, those with temporary disabilities such as those with broken limbs and sports injuries and those who are pregnant.

Adequate provisions for the evacuation of mobility-impaired occupants are a fundamental requirement in all buildings – whether tall or not. In very tall buildings, however, where there may be an extended time before outside support arrives to assist these occupants, special consideration for their protection may need to be considered.

Areas of refuge for such occupants can include protected elevator lobbies, stairway landings, or any other protected space. These must be sufficiently sized to accommodate mobility-impaired occupants. Unless a "protect-in-place" approach is used, these spaces should be considered temporary refuges and not a location where a disabled person can be left unattended.

Refuge Spaces

Refuge spaces can be provided to create "safe spaces" within the building where occupants can await assistance, periodically rest as they descend, or wait for an evacuation elevator (if this forms part of the building's evacuation strategy). Such refuge spaces may occupy part or all of a building story (in which case they are often termed "refuge floors") and should be sized appropriately for the occupant load requiring to use them in an emergency. Regulatory requirements for refuges vary. This will lead to differences in the size and design of the refuge space (or indeed refuge floors) to range across jurisdictions along with their role in the evacuation plan [118].

The use of refuge spaces may be appropriate for buildings of exceptional height or special occupancy conditions but should be used with caution and with implementation of strategies or design elements which eliminate the life safety issues highlighted within this chapter.

The extent of refuge space used in an evacuation is not easy to predict accurately because it depends on several factors, such as the location and time of a fire incident, the extent of subsequent fire spread, the building's occupancy type, the length of time it takes for the fire emergency to be officially under control, and the nature of the emergency communications/alarms systems within the building.

Where refuge spaces are provided, human behavior is an area of uncertainty with both overcrowding and non-use being potential outcomes. Assuming a refuge space is appropriately utilized, it should be recognized that the space effectively becomes an assembly occupancy, whereby subsequent evacuation of the refuge could create crowd management issues due to many occupants competing for access to a limited number of evacuation routes (stairs and elevators).

Prescriptive fire safety codes in a few cities/countries around the world that include Hong Kong, Singapore, Korea, and India mandate dedicated refuge floors in buildings over a certain height, typically located by separating adjacent refuges by a specified number of stories from one another. For instance, the *Indian National Building Code* [119] requirement for refuge floors, albeit not whole floors, is at least every seven stories. The size of the refuge is based upon a percentage of the habitable area of the floors between adjacent refuges. The Indian refuge model is different from those in other parts of the world in that the refuge rooms (to give them a better description) are not a mandatory part of the building's fire strategy (although it is mandatory that they are provided). An evacuation regime is chosen for the building, for example, a phased evacuation, and if an evacuee becomes fatigued during that evacuation, they can stop and rest in the refuge room (which is directly accessed from the stairway enclosure).

Regardless of the exact design of an area of refuge, the following features should be considered to increase its effectiveness during an emergency. These include but are not limited to:

- The refuge space should be sufficiently sized to appropriately accommodate the number of people expected to occupy the space during an emergency condition.
- Provide two-way communications for contact between occupants and emergency responders and building management.
- Sanitary facilities.
- Source of drinking water.
- Seating facilities.
- Appropriate instructional/directional signage.
- Emergency power for lighting and refuge floor amenities.
- Ventilation/HVAC design that is reliable for the expected duration of an event and designed to maintain a smoke-free environment for the duration of the intended use (see note below).
- Proper integration with building fire safety systems, maintenance procedures, and procedures for evacuation and emergency response.
- Contain or have access to an elevator.

Some of these requirements will affect the building power supply system and are discussed further in Chap. 17 (First Responder Considerations).

The natural ventilation of refuge spaces, where two or more sides of the building facade are open to the atmosphere, is a design concept that is suggested in some building codes that advocate refuge floors. Several papers have studied the reliability of this concept and cited issues of smoke contamination of the refuge space via these exterior openings [120, 121, 122]. Where refuge spaces are enclosed, HVAC systems need to be designed to maintain a reasonable level of comfort within the space when occupied to its maximum design capacity.

A study of human behavior related to use of areas of refuge in a number of US government office buildings was conducted by Levin and Groner in the 1990s [123]. This study found that intended users of refuge areas would accept the concept if properly implemented. It was found to be important that information is provided to the building occupants regarding the specific hardware features of the areas of refuge (smoke control, communications, etc.) and, when areas of refuge are intended for long-term staging that seating is provided, that vision panels are provided in doors.

Another alternative to the concept of providing dedicated refuge spaces is designing reentry for occupants evacuating onto floors that are below the fire floor. If this strategy is adopted, stair doors for reentry should be regularly spaced (e.g., every three to five stories) and their use for reentry be clearly labeled on the stairway side of the doors.

A final consideration that may be appropriate for areas of refuge in some buildings is their level of structural isolation. If the building could be subject to threats that could result in partial building collapse, the structure of areas of refuge could be designed to be independent of other portions of the building or provided with redundant structural reinforcement that could make them more resistant to harm during a partial collapse of a building. Structural considerations should also be noted; Chap. 12 (Fire Resistance) discusses the impact of extended egress on fire resistance, which is applicable to refuge spaces, or stay-in-place and defend-in-place zones.

Sky Lobbies

An efficient elevator strategy is one of the most important aspects of very tall building design. The design of many modern very tall buildings is governed by its ability to move people from street level to their level of work or accommodation in a reasonable time period. This can be a challenge at times of the day when there is a peak flow of people either leaving or entering the building.

Technologies with respect to elevator strategies for very tall buildings is advancing to cater for taller buildings. Double-decker elevators, destination control, and express elevator zones are all methods of reducing elevator wait times.

Often integral to this strategy is the use of sky lobbies, areas (or even whole floors) where transfer between various elevator groups can be achieved to reach the desired floor. These sky lobby areas may share a level with mechanical equipment and may even have additional occupant facilities to act as a mini destination as observed with cafés and light retail facilities. Given the familiarity of these spaces to the building's population (as people are required to transfer through these spaces daily), their alternative use as a refuge area in a fire condition may be an appropriate function, particularly for use as a refuge area. However, the design must also consider the potential for a fire to start at the sky lobby level.

Impact of Emergency Responders

In all complex building designs, the engineer should consult with the local fire department to understand their operational procedures and how they could impact building evacuation. While the operating procedures/access strategies of any local fire department could influence egress performance, some degree of counterflow will occur during fire department intervention process, whereby evacuees who egress downward pass fire fighters traveling upward.

A fire department access strategy which adopts protected fire fighter elevators can be more efficient because the occurrence of counterflow is vastly reduced compared to an approach where the fire department accesses the fire floor purely by the stairways. The use of dedicated fire-fighting elevators is becoming increasingly common within many international codes. This strategy allows the rapid vertical movement of fire-fighting equipment and personnel throughout the building.

Within many buildings, fire department standpipes and hose reels/hose racks are located within the stairway, either on the full or half landing. When setting up a fire-fighting bridgehead within the stairways, congestion may be experienced. A common method for reducing the effect of equipment within the stairway, which is adopted within several countries within Europe, is the location of the standpipe outlets within a protected lobby/vestibule between the stairway and the occupied space – thereby reducing the presence of hose lines within the stairway. If connected to the fire floor, this has the advantage that the fire doors into the protected stairway remain closed (as opposed to being held open by a charged fire hose) which assists in the effectiveness of the stairway pressurization system.

The New York City Fire Department (FDNY) considers counterflow by defining a single stairway within a building as their attack stairway. If it is necessary to further evacuate occupants above the fire floor following the initial evacuation, fire fighters direct occupants to the other (non-attack stairways). While this addresses the difficulty of fire department access when people evacuate using the attack stairway (not to mention evacuees obstructing fire-fighting operations), the building evacuation time may be increased.

Evacuation Management

Due to the complexity associated with evacuation and relocation of occupants in very tall buildings, creating and implementing an evacuation plan is an essential element of a building's fire safety strategy. Building codes typically do not mandate how a building is to be evacuated, but there is often a requirement for certain buildings, such as very tall buildings, to develop fire safety and evacuation plans. These types of plans likely include elements such as egress routes, the basic evacuation strategy (phased, simultaneous, defend in place, etc.), employee procedures, procedures for assisted rescue, and operation procedures for systems such as emergency voice communication [104]. An egress strategy can be developed using a risk analysis such as described in Chap. 7 (Hazard, Risk and Decision Analysis in Very Tall Building Design).

Very tall buildings are likely to have large populations, which can be challenging to manage in terms of occupant reaction and the need to respond during a fire or other emergencies. Therefore, building owners/managers need to take the lead role and work with the local fire department and emergency responders to establish the most efficient regime for the building. In certain countries or cities, every very tall building is required to have a fire safety director to manage egress planning and associated evacuation training. Even if not mandated by code, this approach can be beneficial for all very tall building projects.

Development of Egress Plan

Egress plans should be documented in the fire protection design report. The building's stakeholders should participate in its development. In the case of a very tall building, there may be many stakeholders, such as the owner, property manager, fire safety director, occupant and tenant representatives, and building engineers. The emergency responders such as the police and fire department should be involved.

When developing the plan, several factors should be considered, for example:

- What are the anticipated credible events?
- How is a fire detected or how it is determined that a hazard exists?
- How are occupants alerted?
- How are the building owners/managers alerted?
- How are emergency responders alerted?
- How will occupants, building owners/managers, and fire department personnel interact? Will they interfere?
- Where will the occupants go when exiting the building – will it affect the fire department?
- How are occupants being accounted for during and after an evacuation?
- If elevators are used, do the evacuation features automatically activate? Do they need be activated manually, and if so, who makes the decision on site to activate?

These factors may seem straightforward for a single fire in a building; however, other events such as a chemical release may not have automatic detection and notification to the fire department and might require a different response strategy such as protect-in-place, or relocation to other stories, in lieu of a building evacuation strategy. Being prepared for a variety of events provides more flexibility for the egress plan.

Implementation

Several factors affect the implementation of an egress plan. Much of it comes from the leadership. Building occupants should understand that the senior leadership see planning and implementing egress plans as a priority and that it is important for occupants to take the process seriously. Otherwise, during an event of fire, wardens will not be as effective, and strict adherence to the plan might be optional or unnecessary.

Changes and Absentees

Changes in layout of a building, introduction of new tenants, or changes in fire wardens should all be addressed. Also, fire wardens could be absent during an event, along with people designated to assist those with a disability.

Occupancy Types

Occupant familiarity plays a major role in the execution of a successful egress plan. Office or residential occupants, for instance, are likely to be familiar, to a degree, with a building's escape routes and egress procedures, whereas for a hotel occupant (who is likely to be unfamiliar with their surroundings due to the short duration of their stay), the use of fire wardens providing clear evacuation information to occupants becomes more critical.

Assisted Evacuation

People with any sort of physical, mobility, or cognitive impairment will likely require assistance during evacuation. This assistance may simply be from a fire warden or other assigned staff that make sure the occupant reaches a place of safety to await further assistance or rescue.

Chapter 12
Fire Resistance

Maintaining structural stability and limiting the spread of fire/smoke throughout the duration of a credible, structurally severe design fire scenario (e.g., total burnout) are important requirements to satisfying overall fire life safety objectives for any very tall building design. These requirements are intended to provide sufficient time for building occupants to exit the building or reach a place of relative safety with minimal fire exposure, enable fire-fighting and search-and-rescue activities, and limit fire exposure to people and buildings in the surrounding area. While these functional requirements apply to buildings of all sizes, they are of paramount significance for very tall buildings as the consequences of failure of compartmentation or partial-/global-collapse due to fire pose a disproportionately greater risk to a larger number of people, fire fighters, surrounding buildings, and the community at large. These requirements are also critical as the time and the level of effort required for building evacuation and fire-fighting operations can be significantly greater as buildings get larger, taller, and more complex.

The significance of fire resistance in very tall buildings, however, is more complicated than just the potential for increased consequences of failure. Very tall buildings, by their nature and scale, often include unique architectural and structural design features (see Fig. 12.1). This includes but is not limited to:

(a) Large complex atria
(b) Large open floor plates
(c) Large structural members
(d) Long structural spans
(e) Complex structural systems and geometries
(f) Innovative structural components (e.g., damping systems, base isolation systems)
(g) Innovative use of structural materials (e.g., mass timber, very high-strength concrete)

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Fig. 12.1 Shanghai Tower, China – nine cylindrical buildings stacked atop each other with innovative double-layered facade twisting as it rises to reduce wind loading

(h) Coupled gravity and lateral load-resisting systems
(i) Non-homogenous structural systems such as large-scale concrete-filled steel hollow sections and composite steel-concrete-braced frames
(j) Modular construction

These features not only introduce unique fire/smoke hazards but can also complicate structural fire responses that might not be envisioned by prescriptive methods of evaluating and designing for fire resistance (see the International Building Code) [47]. If these structural fire responses are not properly assessed through structural analysis, they can present unknown risks to the stability of the structure and/or integrity of compartmentation in the event of a severe fire and to life safety, property protection, the environment, and other performance objectives.

Thus, special consideration should be given to the increased consequences of failure, additional resources needed for egress and fire fighting, introduction of unique structural and architectural features, and other aspects of very tall buildings (see Chap. 5, Unique features of Very Tall Buildings) that present new hazards and/or features that may not be adequately addressed in current prescriptive codes and standards. This should include a deliberate evaluation of the underlying levels of quality, strength, effectiveness, durability, safety, and resilience of the proposed fire resistance design in addressing the complex challenges specific to the project. The following list identifies some of the key challenges with very tall buildings that designers should evaluate to determine appropriate levels of fire resistance. These challenges are discussed in greater detail in this chapter:

- Increased complexity and interrelationship of performance objectives
- Increased risk associated with stacking and concentrating large numbers of people, assets, and other resources in a single building (the "exposure landscape") where access to outside and emergency response resources is remote and might be restricted to one direction, thus requiring travel toward and through the fire hazard
- Increased demands on time and physical effort for building egress and firefighting operations
- Limitations of prescriptive methods of fire resistance design (i.e., standard fire tests) to accurately represent structural performance in severe fire conditions
- Identifying methods for analyzing, evaluating, and determining appropriate levels of fire resistance (e.g., standard methods, performance-based approaches, analytical metrics)
- Impact of unique architectural design features (e.g., large atria, large open floor plates) on anticipated fire hazards and design fire scenario(s)
- Impact of fire temperatures on unique structural systems and material responses

These considerations may warrant an increase in the required level of fire resistance and/or more resilient structural detailing than is prescribed in codes for structural components and fire compartmentation systems, as well as the need to adopt advanced, performance-based structural fire analysis techniques (i.e., explicitly quantifying the fire loading and its impact on the structural response) to demonstrate that desired performance objectives are satisfied. Higher levels of performance may need to be provided to address issues such as resilience, reliability, business continuity, property protection, community investments, and national security.

Performance Objectives for Fire Resistance of Very Tall Buildings

Because of the concentration of resources and societal significance often associated with very tall buildings, the consequences of fire in a very tall building have an increased impact on life safety, property protection, and a variety of societal values (e.g., economic, cultural, political). Meeting the goals and performance objectives which are additional to life safety may be necessary and prudent in developing a fire resistance strategy in very tall buildings.

Development of the specific performance requirements will result in part from a hazard and risk assessment (see Chap. 7, Hazard, Risk and Decision Analysis in Very Tall Building Design for an overview of hazard and risk assessment). A major component of this development will be an evaluation of the comprehensive set of values and objectives identified by all stakeholders. As the fire protection engineer or designer, it is essential in the design process to engage all stakeholders. These stakeholders can include but are not limited to the owner, design team, authorities, insurers, future tenants, public representatives, and general public who communicate the unique fire risks in very tall buildings and to establish a holistic set of performance objectives collaboratively.

This dialogue among key stakeholders will vary depending on the project brief, design needs, and local context. However, the following list provides some sample questions or concerns that directly relate to and impact on the fire resistance design of very tall buildings and should be discussed at the early stages of the design:

- What are the key performance goals and objectives for the very tall building (e.g., in addition to life safety)?
- Do the building owner and their insurers have additional performance objectives beyond the minimum for life safety (e.g., limit damage/deformation, property loss, or business disruption) particularly as very tall buildings are substantially high-value assets?
- Do other stakeholders have additional performance objectives that may impact the fire resistance design (e.g., environmental considerations, sustainability goals, energy demands, material requirements)?
- Does the egress plan for the building change the performance criteria for the structure and/or compartmentation during a fire event (see section Impact on Fire Resistance of Extended Time and Effort for Egress and Fire-Fighting Operations)?
- How are fire fighter activities going to be conducted (see section Impact on Fire Resistance of Extended Time and Effort for Egress and Fire-Fighting Operations)?
- How would the surrounding community be affected? What level of safety needs to be provided for the public or community in the vicinity of the building?
- What level of fire damage/loss is acceptable?
- What is an acceptable level of downtime for repair?
- What level of local collapse (if any) is acceptable given different fire severity levels?
- What level of resilience in fire should be provided?
- What level of analysis is satisfactory to meet the desired performance objectives?
- What is the best approach (e.g., semi-quantitative, advanced quantitative analysis, fire testing) to understanding the structure's real performance in fire?

- What fire scenarios (fire size, severity, location, number of stories affected) are reasonable for design?
- Does the structural design for other load cases and/or hazards improve or reduce fire performance? Are there ways of evaluating the fire resistance design through an all-hazards analysis, as opposed to designing in isolation that would provide value (e.g., increased safety, robustness, efficiencies) to the project?
- Should multi-hazard scenarios be considered (i.e., post-earthquake fire events)?
- Should extreme events or malicious acts (e.g., terrorism, arson, simultaneous fire incidents) be a design consideration?
- Should a threat and risk assessment be conducted to develop suitable design/mitigation measures?

Refer also to Chap. 4 (International Practices) for additional considerations based on international design practices that may also be relevant and critical for the fire resistance design of very tall buildings.

Impact on Fire Resistance of Extended Time and Effort for Egress and Fire-Fighting Operations

In very tall buildings, it is not uncommon for the egress strategy to rely on either an implicit or clearly defined defend-in-place strategy (see Chap. 11 (Emergency Egress) for more information). Occupants may be expected to remain on floors above the floor of fire origin that are not yet impacted by fire or smoke or may be directed to refuge areas for an extended period (hours) while emergency responders conduct fire-fighting, search-and-rescue, or evacuation operations. As buildings get taller and more complex, the demands on first responders for undertaking these efforts can be significantly greater than in low-rise buildings. Prescriptive fire resistance levels for compartmentation and/or structural stability may not account for the increased effort and complexity faced by first responders. That is, prescriptive hourly ratings do not directly translate to exposure (of structure to fire) in real time and thus may not provide sufficient levels of protection to resist total burnout or to safeguard fire-fighting operations. This presents obvious risks to both building occupants awaiting assistance or further instruction and first responders performing emergency activities.

Similar challenges to occupant and first responder safety are also present where total building evacuation is implemented by design or during the incident. The cumulative effect of large numbers of persons from multiple floors, traveling great vertical distances, will require significant physical demands and time to perform where traditional forms of egress (i.e., exit stair enclosures) are employed. In some of the tallest buildings, evacuation could take up to 2 hours or more, particularly if occupant egress is slowed by the counterflow of emergency responders using the

Fig. 12.2 Simultaneous use of stairwells by occupants and fire fighters. (Photo credit: NIST)

same egress elements for operations (see Fig. 12.2). Refer to Chap. 11 (Emergency Egress) for further discussion and possible design alternatives to reducing this risk.

The increased demands on time and physical effort for managing building occupants, as well as undertaking first responder activities, will likely require performance-based approaches where those increased demands are more explicitly considered in determining appropriate levels of structural fire stability and compartmentation. The specific needs will depend on the adopted strategy for egress, as well as local emergency operations for the range of potential fire and non-fire events anticipated for the building. It may also warrant evaluation of the reliability, durability, and robustness of fire resistance methods adopted (e.g., passive versus active systems, material choices, fire resistance ratings, structural detailing for ductility and resilience). This is discussed in detail later in this chapter. Special consideration will need to be given not only to individual components/assemblies of compartmentation (e.g., floors, walls) and associated structural support elements but also to the global stability of the structure. This could mean modifying the fire resistance requirements and structural detailing for compartmentation and structural stability that are different from the prescriptive codes, to achieve the desired performance given the unique features and conditions of the building.

The design should address the following points:

- Egress strategy

- – Does the egress plan for the building change the performance criteria for the structure and/or compartmentation during a fire event?

    Evacuate occupants on the floor of fire origin and the floors adjacent to the floor of fire origin only? How long will this take?

    Stay/defend-in-place or areas of refuge

    - Does the fire resistance of floors and adjacent walls need to be enhanced where they are protecting areas of refuge?
    - How long will it take before emergency responders provide assistance?
    - If long wait times are anticipated, should refuge areas be supplied with basic survival resources? If so, what are those resources and in what amounts? How is this managed over the lifetime of the building?

    Total building evacuation? How long will this take? How does fire-fighting access impact egress times?

- – How does the fire load to the structure, range of credible fire scenarios, and egress strategy influence the fire resistance design (both compartmentation and structural stability)? Do the levels of fire resistance provide appropriate protection for the "real-time" impact of fire in achieving performance goals?
- – Is the total egress time longer than the time for complete burnout of the fire load?

- Fire-Fighting and First Responder Operations

  - – How are fire fighter activities going to be conducted?
  - – How does this impact the fire resistance design of the structure and compartmentation?
  - – How does time and level of physical effort to conduct operations influence the structural fire resistance and compartment (i.e., floors, vertical egress elements)?
  - – How does the fire load to the structure, construction materials, facade design, and connectivity of floor openings influence how fire resistance is designed for first responders? Do the levels of fire resistance provide appropriate protection for the "real-time" impact of fire in achieving performance goals?
  - – Should enhancements to durability, resiliency, and/or robustness be considered?

- What methods of fire resistance will be adopted?

  - – Does the fire resistance rely on sprinklers to protect areas of refuge?
  - – How does the structure provide adequate fire resistance when ignoring the effectiveness of sprinklers?
  - – Do the levels of fire resistance provide appropriate protection for the "real-time" impact of fire in achieving performance goals?
  - – What level of quality, strength, durability, resiliency, and/or robustness is provided by the method of achieving fire resistance?

– Does the fire resistance of the structure need to account for the possibility of fire traveling across a single floor and/or spreading vertically to one or more floors? How is this affected by the facade design and materials or internal connection between floors?

Considering the factors above, it is increasingly likely that for very tall buildings, fire resistance of the building will need to consider the “real-time” impact of fire not just on structural stability and compartmentation but also on the project-specific functional life safety needs for egress and fire-fighting operations. Traditional methods of fire protection, based on hourly ratings, do not translate to real fire durations and/or structural fire performance in evaluating these objectives. This will mean assessing very tall buildings in both the temperature domain (i.e., behavior and characteristics of real fire scenarios) and the strength/resilience domain (i.e., structural fire performance), to achieve the confidence necessary to avoid structural instability, breach of compartmentation and associated functional needs for egress and fire fighting.

Methods to Determine Fire Resistance

Fire resistance is generally defined as the property of a building element or assembly to maintain its structural stability and integrity to fire, and for some assemblies (such as wall and floor-ceiling assemblies) also to serve as a barrier to fire spread (thermal insulation and integrity), for a minimum specified period when exposed to a standard fire curve (see Fig. 12.3) [124, 125, 126, 127, 128, 129].

Once the performance objectives for the project have been agreed with all relevant stakeholders, an acceptable approach for determining, evaluating, and demonstrating the fire resistance of the building should be determined. Two general methods are available for assessing fire resistance: (1) prescriptive approach or (2) performance-based structural fire engineering.

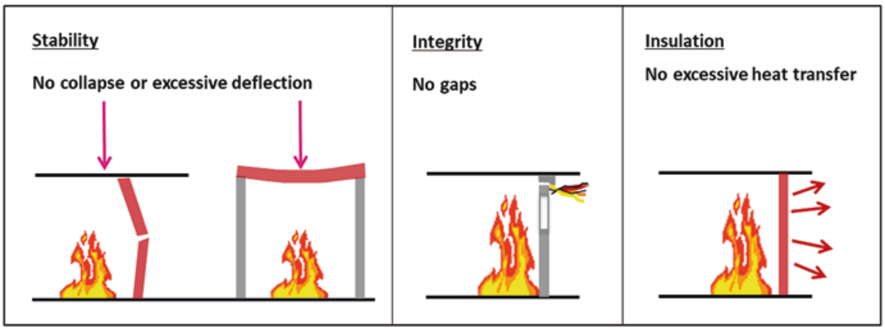

Fig. 12.3 Typical components defining fire resistance of structural and nonstructural building elements

Prescriptive Approach

The simplest and most common approach to assessing fire resistance is through prescriptive rules found in building codes, which specify hourly fire resistance rating requirements depending on the type of occupancy, numbers of stories, and floor area of the building. These fire resistance periods are derived from standardized fire tests (e.g., ASTM E119 [124], NFPA 251 [130], ANSI/UL 263 [124], CAN/ULC-S101 [126], BS 476:20 [127], EN 1363 to 1366 [131, 132, 133, 134] ISO 834 [128], or AS 1530 Part 4 [129]) where prototype elements and assemblies (columns, beams, floors and walls, etc.) are subjected to a specified time-temperature curve and evaluated against standard acceptance criteria for stability, integrity, and/or insulation. Fire-tested elements and assemblies are documented in prescriptive tables (e.g., Chap. 7 of the IBC [47]) and fire resistance catalogs and/or online databases (e.g., UL Product iQ™ [135]). Rules, guidelines, and correlations are also available to evaluate a limited range of variations from tested assemblies (e.g., IBC [47], ASCE/SFPE/SEI 29 [136]).

While standard fire resistance testing is an integral part of the regulatory system, it is well documented in the literature that they are primarily comparative thermal tests and not intended to be predictive of actual structural performance under real fire conditions [137, 138]. This is because of the numerous limitations of the standard fire exposure (e.g., no cooling phase, infinitely heating) and physical test setup (e.g., not full-scale, unrealistic boundary conditions). Because of these limitations, the hourly fire resistance ratings are not indicative of a specific duration that a building element, assembly, or global structure will withstand collapse in an actual fire [138]. As an example, Fig. 12.4 illustrates the large range of real fire exposures that may be more or less severe than the standard fire exposure with respect to rate of heating, peak temperature conditions, total energy output, and duration. Figure 12.5 illustrates the modest scale of the physical test specimen limitations (e.g., 3 m (10 ft) for columns, 4 m (13 ft) x 5 m (16 ft) for floor systems, and 3 m (10 ft) x 3 m (10 ft) for walls).

The reader is encouraged to review the extensive literature on the details of these limitations and the implications these have on structural fire resistance design of all buildings, not just very tall buildings. Table 12.1 provides a list of some of the key limitations common for all buildings.

These limitations, while a concern for all buildings, can have disproportionate impacts in very tall buildings due to the size, scale, and complexity of architectural and structural features often associated with these structures. For example, it is well understood that in real building fires, structural elements/systems can undergo significant thermally induced expansion/contraction forces (axial and bending), geometric elongation/shortening, and thermal curvature throughout the heating and cooling phases of the fire. These effects are a function of several factors: member length, cross-sectional profile, applied loads, boundary conditions, fire duration, peak temperatures, heat transfer to structure, etc. So, as member spans tend to be longer in very tall buildings (particularly in floor systems), the magnitude and

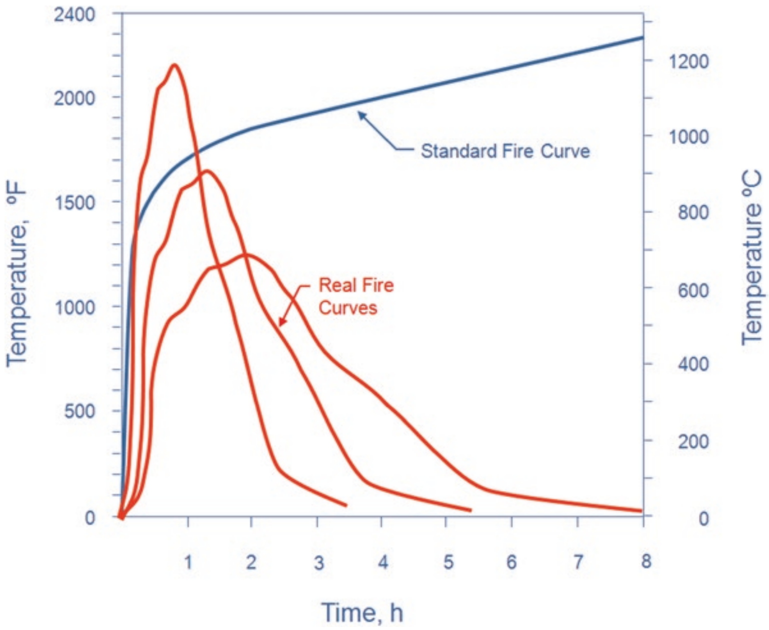

Fig. 12.4 Standard fire curve vs real fire curves

complex interaction of thermal expansion/contraction forces and thermal bowing/elongation/shortening can be exacerbated, markedly impacting global structural fire performance compared to that experienced in small-/medium-rise structures. The larger member sizes can also result in element/system behaviors and/or failure mechanisms in fire conditions not observed in smaller structures, let alone relatively small-scale fire tests.

In addition to the limitations of the standard fire tests which are common to all buildings, very tall buildings can have unique design features not well captured by standard fire resistance tests. These include unique structural systems (e.g., combination gravity-lateral load-resisting systems), innovative elements (e.g., base isolators, dampers), complex connection details, and uncommon structural materials (e.g., mass timber, high-strength concrete). Very tall buildings can also have unique architectural features (e.g., geometrically complex interior spaces, large open floors and multi-floor openings, mixed fuel loads/uses and varying ventilation conditions, and unique/complex facade structures) that can significantly alter the characteristics and behavior of fire compared to standard fire exposures. These conditions and features result not only in numerous fire exposure profiles and distributions but also unique structural and nonstructural mechanical responses to thermal exposure variations on one or multiple floors simultaneously.

For example, very tall buildings often incorporate large, horizontal and vertical compartments. In the event of fire, these large compartments typically result in a range of spatial-temporal distributions of temperatures across the structure

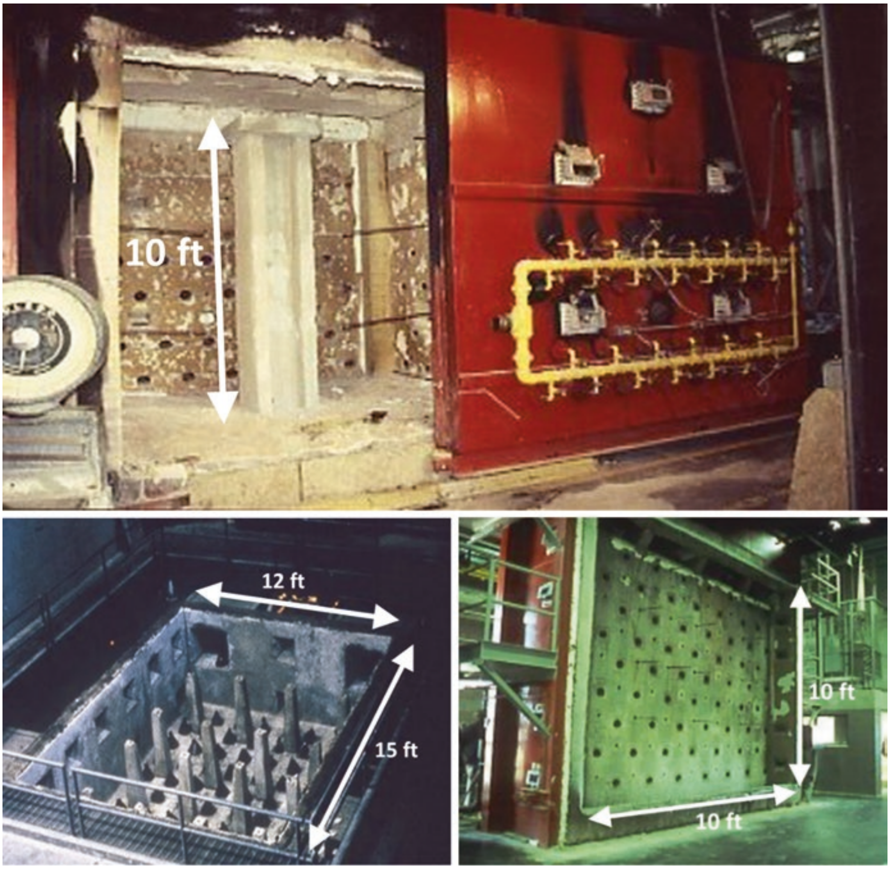

Fig. 12.5 Typical standard furnace test configurations for columns (top), floors (bottom left), and wall systems (bottom right)

simultaneously. These variations can have a significant impact on the performance of the structure, due to differences in thermally induced expansion and contraction forces, degradation of mechanical properties, and interactions of structure and materials in different stages of heating/cooling phases. These phenomena can compound and/or offset ambient stress states. This may highlight significant weaknesses in the ambient structural design (e.g., unanticipated load combinations and interactions, unplanned deformations and/or displacements, premature failure of connections and/or elements from high axial forces, etc.) or inherent strengths (e.g., load redistributions, alternative load-carrying mechanisms, structural and fire protection redundancies, etc.). These possible detrimental or beneficial frame responses cannot be predicted or quantified using single-element fire resistance tests under the standard fire curve, as they are specific to the interactions of numerous project design features (e.g., fuel load characteristics/distribution, ventilation conditions, interior geometries, structural design, structural systems,

Table 12.1 Key limitations of standard fire resistance tests for all buildings

Fire exposure limitations	Physical limitations
Indefinite heating	Limited to relatively small spans and/or dimensions of a subassembly
No cooling phase	Limited or no loads applied to structural elements and/or assemblies[a]
Not representative of all fires	No load-interaction tests (e.g., beam-columns)
Only representative of small compartments	Single elements only (columns, beams, floor/ceiling systems, walls)
Unrealistic heat transfer conditions	No tension element tests (e.g., rods, cables, braces)
No spatial distribution of temperatures; only fully developed, post-flashover fire conditions	No testing of 2D or 3D systems
	No consideration for continuity of systems
	No member interaction
A "pass" under the standard fire test only measures peak structural temperatures during the "official" heating phase, ignoring the continued heating of the structure due to thermal lag after the test has been completed	No testing of connections
	No consideration for restraint (e.g., lateral, in-plane, boundary conditions)
	No failure criteria based on structural mechanics (e.g., deflections, deformations, strains, stresses)
	No assessment of structure performance when peak structure temperature is reached (i.e., after "official" heating phase is completed), therefore no certainty that "pass" result is associated with maintaining structural stability

[a]Load-bearing floor, roof, wall, and/or beam assemblies are often tested with limited loads (not at full design load). Structural columns have typically been tested without any loads and subjected only to thermal acceptance criteria. Non-load-bearing assemblies are tested without any applied loads

compartmentation designs, etc.). Many of these effects can also breach compartmentation (e.g., separating walls and floors, stair enclosures, shaft walls) if they are not explicitly considered as part of the design.

Given the numerous limitations of the standard fire test and the combination of unique, complex architectural and structural features found in very tall buildings, it may no longer be prudent to rely exclusively on prescriptive methods of fire resistance design. Compared to short-, medium-, and standard high-rise buildings, very tall buildings lack the history of structurally severe fire incidents to verify full-scale fire performance of the unique features inherent in their design. This lack of real fire history increases the uncertainty and risks associated with relying on standard tests for fire resistance design. The consequences of structural failure and breach in compartmentation are also disproportionately higher for very tall buildings and thus may demand a higher level of confidence, reliability, and certainty in explicitly quantifying the structural response to fire compared to other buildings. This is also linked to the increased time and level of effort required for building evacuation and fire-fighting operations, or stay-in-place strategies, that would also require a more definitive understanding of the actual performance of the structure in credible fire conditions. There may also be additional performance objectives for very tall buildings beyond life safety (e.g., extreme events, business continuity, property protection) that may not be reasonably addressed using prescriptive approaches.

Because of the complex nature of very tall buildings, appropriate methods of assessing and designing fire resistance of the structure and compartmentation features should be evaluated and agreed with all relevant stakeholders. The final design basis may consist of a combination of methods at different scales of analysis, to obtain a more comprehensive understanding of the structure's performance in fire conditions. This may mean that certain portions of the project that reflect traditional forms of construction and exposure (e.g., MEP spaces) warrant prescriptive methods, while other portions require alternative methods to achieve the desired performance objectives.

Performance-Based Structural Fire Analysis

Where the agreed performance objectives and/or the unique aspects of very tall buildings are outside the relevant application of standard fire tests, consideration should be given to adopting a performance-based structural fire analysis as the basis for the fire resistance design of the structure.

Structural fire engineering is a performance-based approach to design and analyze structural systems under realistic fire conditions and to use this understanding as the basis for determining an appropriate level of fire resistance. The fire severity is characterized by the amount of fuel load in an enclosure, fire compartment or fire cell (an occupancy-dependent, time-dependent variable), the availability of ventilation to a fully developed fire (given that it reaches this state; ventilation is typically related to the number of frangible elements on the perimeter, such as glass windows), and the geometry of the enclosure/fire cell in terms of height and volume. These factors determine the key fire severity measures, which are (i) the temperature of the fire environment and (ii) the length of time that this heated environment exists.

This type of approach typically involves the evaluation of realistic fire scenarios in and around the building, calculation of the heat transfer from the design fire(s) to the structural elements, and quantification of the structure's response for the duration of the design fire(s). This contrasts with the prescriptive requirements, where the actual fire hazards and response of the structure to the fire are not quantified or explicitly understood.

Various types of structural fire analysis are available to the designer, ranging from simple single element checks to sub-models to advanced nonlinear finite element models. The design fire(s) basis and the level of analysis should be agreed with the designer, owner, local authority, insurer, and other relevant stakeholders. For very tall buildings, special consideration should be given to assessing the performance of the structure using an advanced nonlinear finite element model.

• ***Single-Element Analyses***

The analysis of single structural elements in isolation from the rest of the structural frame has formed the basis for structural fire engineering for many years, mainly because it is comparable with standard fire tests and excludes calculations based on nonlinear response of a whole frame or a subassembly to fire. This approach is a simple, first check of the capacity of a structural element at elevated temperatures.

This type of analysis typically involves an assessment of the load-bearing capacity of an element at elevated temperature (considering thermal degradation of material properties) with the applied load at the fire limit state. Single-element analyses, by nature, do not consider the effects of three-dimensional restraint or load redistribution on the performance of the structural element. The influence of thermal expansion or restraint is not usually addressed. The benefits of alternative load-carrying mechanisms (e.g., catenary action) are neglected. An example of the output from time-dependent heat transfer calculations that might be used for single-element analysis are shown in Fig. 12.6A and 12.6B.

Design tools for performing single-element analyses can vary in complexity and include empirical correlations, look-up tables, nomograms, hand calculations, or simple computer models. Various single element methods are available in several references such as the *SFPE Handbook of Fire Protection Engineering*· [137],

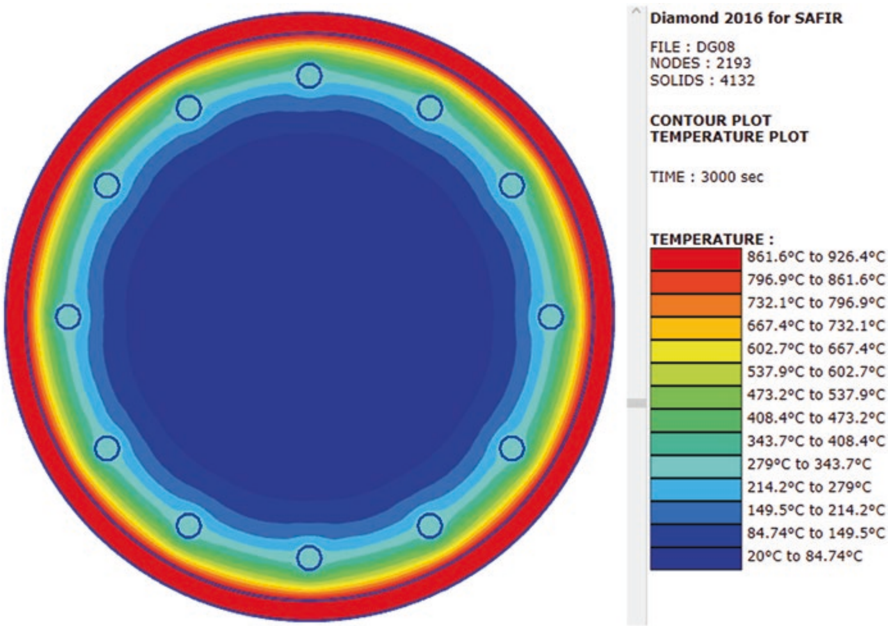

Fig. 12.6A Sample temperature contours from 2D heat transfer analyses, a composite steel-concrete column. (Courtesy: Holmes Fire)

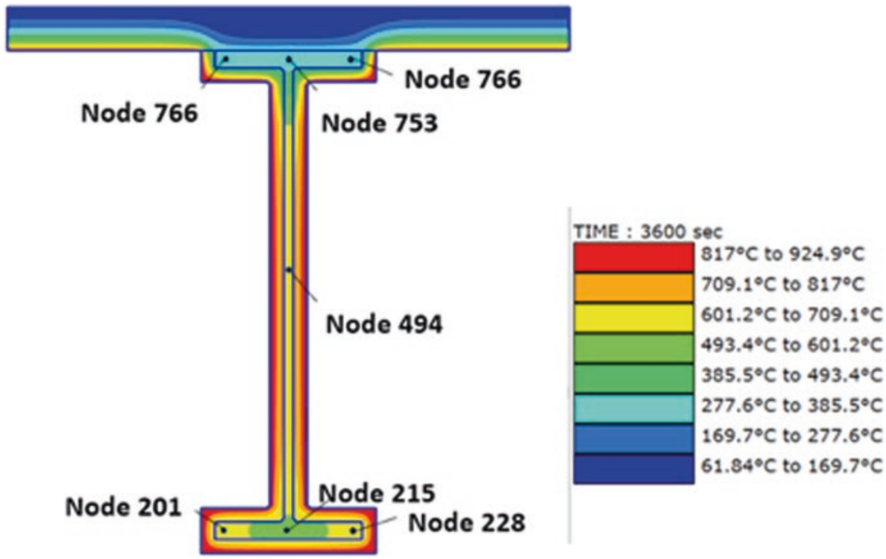

Fig. 12.6B Sample temperature contours from 2D heat transfer analyses – an insulated steel beam with concrete slab. (Courtesy: Jensen Hughes)

ASCE/SFPE/SEI 29 [136], Eurocodes [37], BS 5950-8 [139], BS 8110 [140], AS 4100 [141], AS/NZS 2327 [142], NZS 3404 [143], etc.

- ***Advanced Analysis***

Following the Cardington tests in the United Kingdom [144], research and development worldwide has led to an improved understanding of structural performance in fire. This has led to the development and use of more advanced performance-based structural fire engineering techniques, as an alternative to the traditional prescriptive approaches and/or single-element methods.

Advanced analysis techniques can include varying degrees of complexity in assessing the design fire and quantifying the performance of the structure in fire conditions. The types of analysis methods can include slab analysis, 2D frame analysis, sub-system 2D and 3D analysis, element removal analysis, or whole structure 3D finite element analysis (see Figs. 12.7A, 12.7B & 12.7C). In contrast to most single-element methods, advanced analysis can consider the effects of thermal expansion, alternative load paths, secondary load-carrying mechanisms, nonlinear material response, large displacement response, and connection performance.

An advanced structural fire analysis may involve the following design aspects:

- Identify additional performance criteria and objectives with all relevant stakeholders that are relevant to the greater level of information about the structural performance in fire (see Chap. 7, Hazard, Risk and Decision Analysis in Very Tall Building Design).

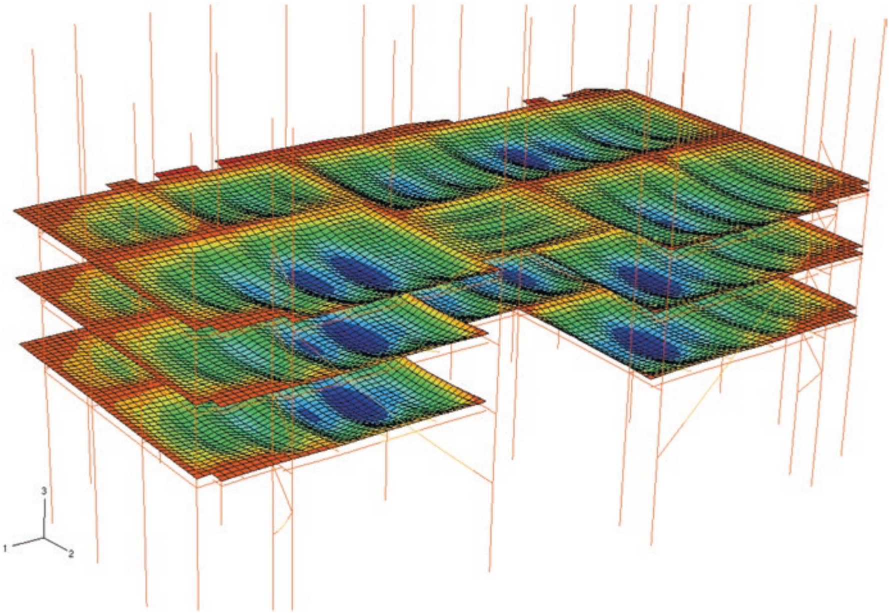

Fig. 12.7A Sample performance-based finite element model of representative worst-case multi-floor fire. (Courtesy of Arup)

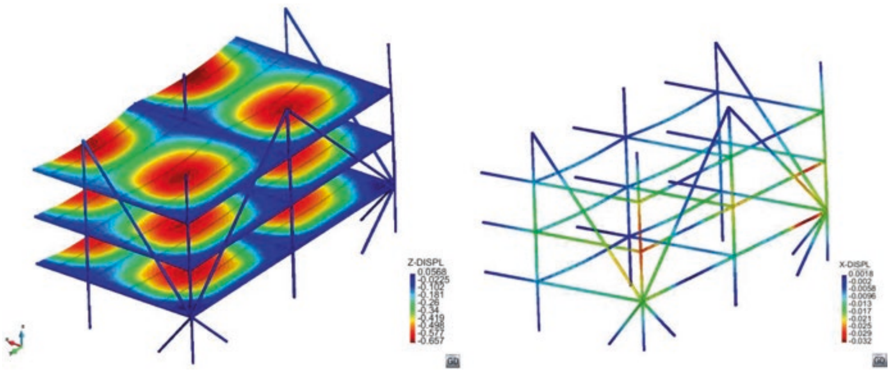

Fig. 12.7B & 12.7C Sample performance-based finite element models of representative, worst-case multi-floor fires. (Courtesy: Holmes Fire)

- Identify credible worst-case fire scenarios based on building use, geometry, combustible contents, worst-case ventilations conditions for structure, and presence of fire safety systems (e.g., multi-story fires, traveling fires, etc.). SFPE Standard S.01 provides guidance on selecting fire scenarios for structural fire engineering analysis [145].

- Identify an appropriate method of fire analysis. Refer to “Fire Scenarios” sections for detail.
- Undertake a heat transfer analysis to determine the thermal impact to structure, including cooling phase (e.g., 1D, 2D, or 3D spatial-temporal analysis, lumped capacitance, finite element thermal model). SFPE Standard S.02 provides guidance on calculation methods to predict the thermal performance of structural and fire-resistive assemblies [146].
- Identify representative portions and key critical elements/systems and connections of the structure.
- Consider dead and live load combinations in the fire limit state (e.g., 0.9 or 1.2 DL + 0.5LL + 0.2S) [147] (where DL = dead load, LL = live load, and S = snow load). Pay attention to load combinations in the specific country where the building is located.
- Assess the structure for stability, fire separation, and other performance criteria for the duration of the design fire scenario(s) to satisfy the performance objectives.
- Assess the response of the structure(s) for the duration of the agreed design fire scenario(s) during both heating and cooling phases. Include thermal and mechanical properties with elevated temperatures (i.e., thermal expansion, material degradation, and inelastic response).
- Consider the potential need to redesign structural members, connections, and other structural/nonstructural details to account for thermal expansion/contraction forces, large displacements/deformations, and other fire-induced responses.
- Consider the effects of spalling for concrete structures (if present).

Guidance on performing advanced structural fire analyses can be found in several resources, for example, the *SFPE Handbook of Fire Protection Engineering* [148]; Eurocodes [37], [149]; [150] ASCE Manual No. 114. [151]; *Structural Design for Fire Safety* [152]; Steel Design Guide 19 [153]; ASCE Manual No. 138 [154]; ASCE Manual No. 78 [155]; ACI 216.1-14 [156]; ASCE/SEI 7-16, Appendix E [147]; examples publication [157]; ANSI/AISC 360-16, Appendix 4 [158]; examples publication [159] and Designers’ Guide to EN 1991-1-2 , EN 1992-1-2, and EN 1994-1-2 [160]; etc.

Metrics for Performance-Based Structural Analysis

Depending on the type of structural fire engineering analysis adopted, specific performance metrics will need to be established to demonstrate that stability, integrity, and compartmentation throughout the full duration of the agreed design fire scenario(s) for life safety objectives are satisfied. These metrics, in addition to any other metrics for performance goals beyond life safety, should be discussed and agreed with all relevant stakeholders. Consideration should be given to the impact on compartmentation features (e.g., floor-to-floor separations, egress elements, shaft enclosures) as a result of the response of the structure to fire.

Sample performance metrics for an advanced 3D, nonlinear structural fire analysis of steel framed buildings are provided below.

Stability

- The primary structural systems (columns, beams, connections, load-bearing walls, lateral load-resisting system) should maintain the applied design loads in the fire limit state for the full duration of the fire (including cooling).
- Metrics for stability may include:
  - Limitations on deflections.
  - Strains are within reasonable limits for slab reinforcement and structural steel in fire conditions.
  - Stresses are within the limit of the relevant material properties at elevated temperatures.
  - Connections forces are within reasonable rotation and ductility limits for fire conditions.

Integrity

- Limit the passage of smoke and flame through floor-to-floor separations and through fire separations protecting fire-rated escape routes (stairways, cores, elevator, etc.) and essential systems (e.g., for HVAC smoke management, fire protection, elevators, and emergency power generation and distribution).

  Metrics for integrity may include:

- Limitations on deflections.
- Strains in slab/fire barriers/fire walls are within acceptable limits for fire conditions.
- Rotations in slab/fire barriers/fire walls near supports and cores are within acceptable limits for fire conditions.

Compartmentation

- Fire separations (e.g., walls and floor systems) should limit temperature rise on the unexposed side.
- Thermal bridging is limited.
- Metrics for compartmentation may include:
  - Thermal transmission is limited to the unexposed side of the fire separation.

– Strains in slab/fire barriers and fire walls are within acceptable limits for fire conditions.
– Rotations in slab/fire barriers/fire walls near supports and cores are within acceptable limits for fire conditions.

Fire Scenarios to Consider in Fire Resistance Design

Unlike design basis fires for smoke control systems, which relate to the incipient and growth phases of a fire, design basis fires for structural fire resistance are concerned with fully developed post-flashover fires (i.e., a scenario where sprinklers fail to operate or are not effective in limiting fire growth or when fire fighters do not intervene to control and/or suppress the fire). This is when the fire has moved past the growth phase and all combustible contents in the compartment are burning. It is during this phase of the fire and during the cooling phase when a structure can be affected. The peak temperatures, duration of peak conditions, and overall fire severity are a function of combustible fuel load and amount of ventilation (or openings). In very tall buildings, the amount of combustibles may be no different than for low-rise buildings. However, the amount of ventilation (i.e., windows), particularly for very tall buildings, is often higher. This can result in higher peak temperatures in a post-flashover fire scenario.

Various methods are available to the designers to determine post-flashover events/conditions, e.g. [161]:

- Zone models (SFPE S.01 [145]; Pettersson, Magnusson, and Thor [162]; Babrauskas and Williamson 1978 [163]; Ozone [164]; SFIRE-4 [165]; Eurocode [37])
- Standard fire curves (e.g., ASTM E119 [166], ISO 834 [128], BS 476:20 [127])
- Parametric temperature-time curves (e.g., Babrauskas method [167], Eurocodes [168], Lie's model [169], Mäkeläinen's model [170], etc.)

In some cases, adopting a uniform post-flashover fire scenario as the basis for design may not always be the correct approach [167]. For example, in very large open spaces (such as atria, large area open plan office layouts) or where the structure is located external to the facade, which can often occur in very tall buildings, a fully developed fire exposure is unlikely. A suitably severe localized fire, traveling fire, or external fire may be more appropriate for design. Methods are available to designers to determine localized and/or traveling fire scenarios which include:

- Localized fires (e.g., Eurocodes [37] , SFPE S.01 [145])
- External fires (e.g., Law method [171], *SFPE Handbook of Fire Protection Engineering* [172], Eurocodes [37])
- Multi-zone fire models (e.g., CFAST [173], Ozone, B-Risk [174])
- Computational fluid dynamics (e.g., FDS [175], SMARTFIRE [176])

Because of the size, scale, and unique design aspects found in very tall buildings, the potential fire scenarios may be different than those typically observed in low-rise buildings or assumed by standard fire tests. Consideration should be given to conducting a fire risk assessment where unique design features of the very tall building result in a fire scenario that challenges the agreed performance criteria for the building (see Fig. 12.8). Table 12.2 provides some sample fire scenarios that are relevant for very tall buildings.

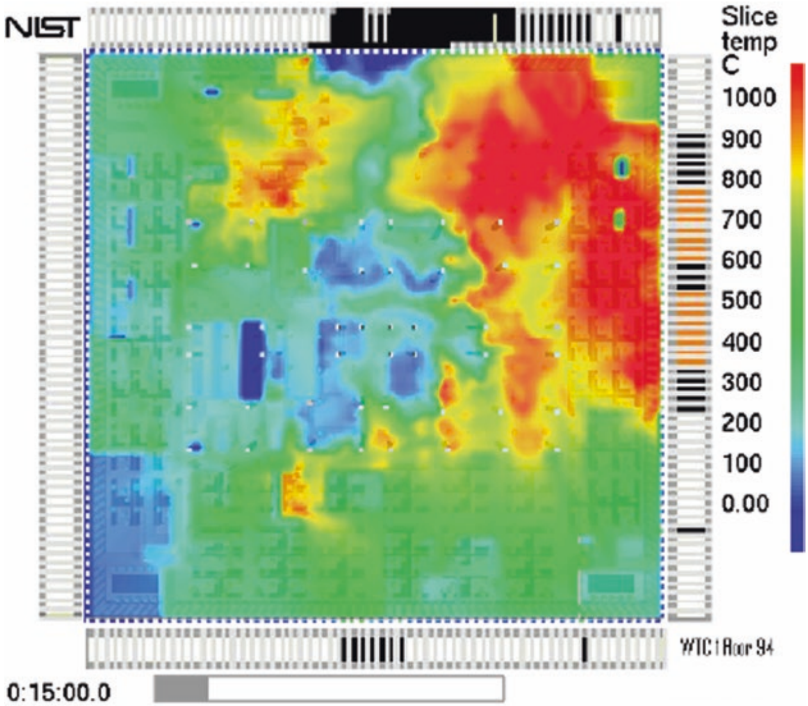

Fig. 12.8 Complex spatiotemporal distribution of elevated temperatures due to a large open floor plate (e.g., traveling sires) that may need specific consideration in very tall building design [9]

Table 12.2 Relevant fire scenarios for very tall buildings

Potential fire scenario	Unique aspect of very tall buildings
Traveling fires[a]	Large open floor plates Complex multiple floor openings
Multiple floor fires	Complex atria Complex multiple floor openings Consequence of external vertical fire spread (see Chap. 13 (Building Envelope/Enclosure)) Delayed fire fighting due to remoteness of floor

[a]Fires that burn locally and move across a floor plate over a period of time in large compartments [177]

Consideration of Cooling Phase

The cooling phase of a fire is a critical period, which can last several "hours to days" in the response and performance of a structure in fire conditions. During the heating phase of a fire, a structure is affected by thermal expansion, material degradation, reduced stiffness, and material weakening that can lead to a range of structural responses (e.g., local damage, elastic deformations, plastic deformations, large displacements, etc.). As the structure cools, it thermally contracts, tending to return to its original shape. If a joint, for example, has been allowed to freely rotate and expand during heating, it may freely rotate and contract during cooling [178] [179].

However, if joint components have impacted structural elements or buckled during the heating phase, then during the cooling phase, when the structure tries to thermally contract and return to its original position, high tension forces can develop. In some cases, where a joint is not designed to resist these forces or has insufficient ductility, joint failure can occur. This may be a critical issue in very tall buildings where specific connections are integral to overall structural stability (e.g., nodes of mega braces) and large transfer girders and trusses.

The effects of the cooling phase on the performance of key connections must be considered in the design (e.g., provide enough ductility or tensile force capacity). For steel-concrete composite structures, some requirements for structural detailing to provide resilience and ductility to resist fire-induced deformations are given in Section 7.9.5 in AS/NZS2327-2017 [142].

High Challenge Fire Hazards

Areas with high fuel loads should be identified and addressed when assessing structural fire resistance. Examples include rooms containing liquid or gaseous fuel storage, lithium-ion energy storage, significant paper storage, rack storage, retail storage spaces, and multi-story car stacking systems and routes for or shafts containing piped liquid or gaseous fuels.

The overall fire performance of the structure can be affected by the fire resistance surrounding individual hazards. If not properly considered in a performance-based structural design, individual hazards could cause failure of a fire separation or a structural element, with potential to affect structure remote from the fire or lead to progressive structural failure.

It may be necessary to provide a greater level of thermal insulation for these areas with high potential fuel load. Alternatively, these areas should be addressed individually within the structural fire model. Designers should be aware that even in a prescriptive-based fire resistance design, the fuel load and fire hazard of some of these spaces may exceed that represented by the standard time-temperature curves used in the standard fire test. More information can be found in Chap. 5 (Unique Features of Very Tall Buildings).

Coupling of Gravity and Lateral Load-Resisting Systems

In very tall buildings, the coupling of gravity and lateral load-resisting systems also becomes more essential for economy of scale and performance. This results in increased use and reliance on combinations of structural systems (e.g., shear-wall frame systems, shear truss-outrigger braced systems, framed tubes, tube-in-tube systems, bundled tubes, truss tubes, mega-braced tube structures, cable stiffened towers, etc.). New forms of structural systems serve multiple functions and satisfy the unique structural challenges faced by very tall buildings. This may mean that the fire resistance level of a structural system may need to be increased beyond that normally specified in building codes for low-rise buildings due to the importance of maintaining global stability. For example, some very tall building designs include major transfer trusses, beams or floor systems, or structure configurations that are essential to the overall stability of the building. The fire resistance of these structural elements may need to match the level of fire resistance applicable to the main structural frame compared to the requirements for a more conventional height building.

The various structural systems that are coupled in very tall buildings frequently consist of mixed structural materials (e.g., steel-concrete composite systems) which can behave differently at elevated temperatures. These differences in material behavior can lead to thermally induced forces, internal stresses, deformations, displacements, and other incompatibility issues that are not considered when using prescriptive fire resistance approaches. For example, a steel diagrid member filled with concrete will experience a complex interaction of thermo-mechanical responses over the course of a fire event. Early in the fire, the steel outer tube (which has a high thermal conductivity relative to concrete) will heat more rapidly and expand against the cooler, interconnected diagrid structure but also relative to the concrete infill with which it is acting compositely. This will result in a complex history of interactions of restraining forces and strains in the various 3D structural system elements and at the local steel-concrete interfaces. These thermal expansion forces and interactions can be significant, resulting in a variety of responses (e.g., inducing high axial forces in the steel leading to yielding or buckling early in the fire debonding of the steel-concrete, shear failure of the concrete). Consideration should be given to the effect of differing material thermal properties of gravity and lateral resisting systems that are coupled in very tall buildings.

Structural Systems for Reducing Drift and Other Lateral Accelerations

In general, for buildings taller than approximately 30 stories, lateral stiffness to address drift and lateral accelerations such as wind and seismic become an increasing concern. Traditional lateral resisting systems, such as moment frames, for

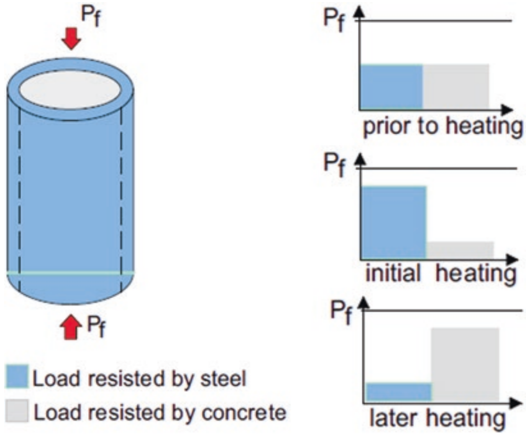

Fig. 12.9 Simplified example of a concrete-filled steel diagrid element and the response of the materials over the course of a fire with respect to axial forces. This does not account for a variety of other complex structural system and material responses that may also occur

low- to medium-rise buildings, are too flexible or less efficient as building heights increase. More sophisticated structural systems can stiffen the damping that is intrinsic in a structural frame and thereby reduce both drift and accelerations. In addition to stability objectives, these damping systems may also be used to minimize joint sizes at the exterior facade systems and therefore may also be integral to limiting floor-to-floor fire spread. Oftentimes, supplementary damping systems or components may be integrated into the overall structural design to help mitigate lateral accelerations in a cost-effective manner.

The structural fire resistance of these supplementary damping systems may need to be considered if they are an integral part of the overall global stability system of the building, where failure of the components/systems themselves or support to these systems would have a dramatic effect on structural stability or floor-to-floor compartmentation. Further complicating design considerations is the need to balance fire protection of these systems with the need to allow free movement for other load cases (e.g., wind, seismic, etc.) and other operational objectives. For example, base isolation systems may require several feet of lateral movement to accommodate seismic accelerations. However, most common fire protection methods (e.g., spray-applied fire-resistant materials, board protection, etc.) are not designed to accommodate this level of movement. In this case, performance-based structural fire engineering approaches will likely be required to determine an appropriate design that can satisfy both operational seismic needs and fire safety requirements. Thus, it is important that the nature and range of performance needs of supplementary damping systems be fully understood such that appropriate fire resistance is provided.

Damping systems exist in many different forms, and each requires a unique fire-resistive response. Tuned mass dampers and pendulum or sliding types require attention to be certain the structure supporting the damper or pendulum does not fail. Viscoelastic dampers depend upon the performance of special elastic pads, which may fail under extreme heat. Viscous dampers utilize special fluids contained with cylinders, which may also be subject to failure under extreme heat. Tuned

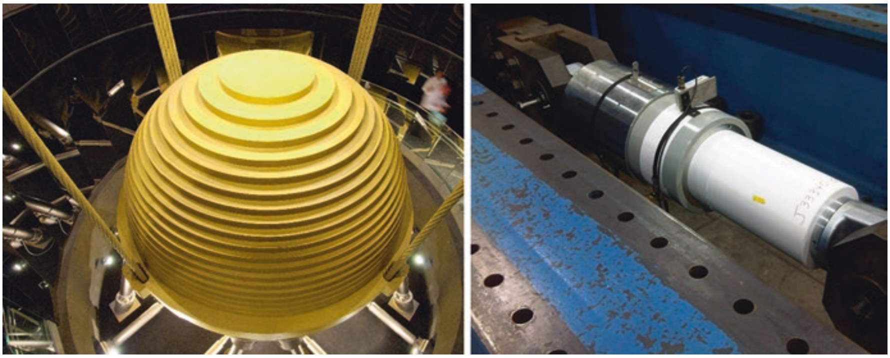

Fig. 12.10 Examples of wind-damping systems typically found in very tall buildings. (12.10A, left) Tuned mass damper. DJ Anderson from Nagoya, Japan, CC BY-SA 2.0 https://creativecommons.org/licenses/by-sa/2.0, via Wikimedia Commons, (12.10B, right) viscous damper. Courtesy of Arup

sloshing dampers and tuned liquid column dampers usually utilize water as the primary medium but also have exceptional weight, and therefore their support system must be protected from collapse due to fire (Fig. 12.10).

Given the variety of systems, consideration needs to be given on how fire will affect the material response of these systems locally and globally and what level of fire resistance or protection is appropriate to maintain global stability and other performance objectives. Issues with providing approved/tested systems that meet fire resistance requirements while also allowing for necessary building movements can be a practical challenge and will require discussion with local authorities.

Consideration for Timber: Combustibility

In recent years developments in the manufacturing of timber structural components utilizing new systems have resulted in a rebirth in interest in the use of these mass timber systems for tall buildings. The fire design approach for mass timber buildings is very different depending on whether the timber is fully encapsulated (so the timber is proven – for the full duration of the fire – not to char to the detriment of adequate strength) or whether the timber is at least partly exposed (e.g., some parts encapsulated, some parts exposed, or fully exposed). For timber structures of any height, if the structural timber is partly exposed to the fire, the vulnerability of using a combustible material for the structural system requires special consideration when assessing the fire resistance necessary to maintain structural stability, as well as other potential influences on the enclosure fire dynamics, internal flame spread, and external flame projection.

Mass timber structures can achieve high levels of fire resistance, owing to formation of char on exposed surface timber. However, this combustion and charring come at the expense of physical destruction of a portion of the cross section of the structural element and the irreversible reduction of the load-carrying capacity of the structure. Depending on the gas temperature within the enclosure, fire duration, pyrolysis and charring, and loss of strength can also occur when the timber structure is located behind external linings, depending on the lining's effectiveness to shield the timber structure from the fire. The reduction in load-carrying capacity continues for as long as the structure continues to be heated. To limit the extent of loss of strength of a timber structure in fire, it is therefore important to quantify when the fire can be assumed to be extinguished and the structure has subsequently cooled to an extent which stops any further structural heating or charring.

The depth of charring and damage to the timber structure is linked closely to the thermal conditions within the enclosure (magnitude and duration of heat flux received by the structure) and the duration of timber exposure to the actual fire (as distinct from a duration of exposure in a furnace for a standard test method). The heating of the timber section, charring of surface timber, and consequent degradation of the strength and physical loss of material of a timber structure may continue during the fire decay phase, potentially for a considerable time after the time at which the peak fire temperature occurs. The nature of the decay phase of the fire is therefore critical for timber structures. This has implications for both performance-based assessment of structure using design fires and for the interpretation and application of fire resistance ratings based on the standard fire test. Designers should carefully consider the depth of the char layer used for design purposes, to account for the fire exposure time, the thermal penetration, and the associated loss of strength due to heating and dehydration.

Empirical correlations for required levels of fire resistance ratings are developed and typically evaluated for noncombustible structures. Designers should consider the effect of this shortcoming, including the energy balance discrepancy for combustible structures tested according to the standard fire curve and the influence of the contribution to the fire severity of burning the structure, when assessing a fire resistance rating for timber structural elements in very tall buildings.

Where the characteristics of the fire and the response of the timber structure are assessed using performance-based design, the design fires which are used to assess the impact on loss of strength of the timber structure must also include the contribution to the fire load from the combustion of timber surfaces involved in fire and the effect this has on the overall enclosure fire dynamics.

Where the timber structure is exposed to the fire (i.e., not encapsulated by an insulative fire protection material), the interaction between the enclosure gas temperature, incident heat flux, fire duration, and the sacrificial charring of mass timber becomes an even more significant issue. If exposed to the fire, mass timber structure (particularly elements with large surface area, such as walls/floors) contributes to the fuel load, fundamentally altering the fire dynamics within the fire compartment by increasing the actual duration and/or intensity of the fire.

Where designers are relying on establishing compliance with prescribed levels of fire resistance (e.g., from prescriptive codes, which have been developed for application to noncombustible structures), additional caution is needed where the mass timber structure is exposed to the fire or where the lining might fail before burnout. This is because the prescribed levels of fire resistance are unlikely to account for the contribution of additional fuel from the charring timber.

For structures using glued cross-laminated timber (CLT), an additional risk during fire attack is the potential for adhesive line integrity failure, resulting in a sudden increase in exposed surface area of uncharred timber. This uncharred timber adds additional fuel load, often relatively late in the fire's time history (e.g., causing secondary flashover events to occur). Some codes include rules to prevent the use of CLT that is vulnerable to adhesive line integrity failure. In very tall buildings, designers should consider the benefits of specifying CLT that is not vulnerable to adhesive line integrity failure, even though local codes might not formally prescribe this.

For timber structures, the vulnerabilities listed above are greatest when the fire intensity and fire duration are not accurately quantifiable. As the height of timber structures increases, the effect of fire on the structural load capacity and the influence of duration of the fire decay phase on the depth of damage to the timber structure must be carefully considered.

Until the full influence of the fire decay phase on timber fire and load resistance is more clearly understood and quantified, designers should expect that tall mass timber structures might be more appropriately protected from fire by encapsulation with an effective fire protection system, with less reliance on the inherent fire resistance contributed by the slow degradation of the timber section (e.g., encapsulation may provide a more reliable strategy for maintaining structural stability). The encapsulation system must be capable of staying in place restricting pyrolysis of the concealed timber with a time until (encapsulation) failure greater than the full duration of the fire or else delaying the onset of mass timber involvement until a time that is sufficiently late in the fire that it would not result in a secondary flashover. This is increasingly necessary for buildings where there needs to be a high level of confidence that the strength of the fire-affected structure is sufficient to support the structural loads, including foreseeable lateral loads, that may need to be resisted before the fire-damaged structure is repaired.

Documents are available that provide guidance for evaluating various challenges with design for tall mass timber buildings.

FPRF – Fire safety challenges of tall wood buildings, Phase 1 [180]
Fire safety challenges of tall wood buildings – Phase 2: Task 1, literature review [181]
Fire safety challenges of tall wood buildings – Phase 2: Tasks 2 and 3, development and implementation of cross-laminated timber (CLT) compartment fire tests [182]
Fire safety challenges of tall wood buildings – Phase 2: Task 4, engineering methods [183]
Fire safety challenges of tall wood buildings – Phase 2: Task 5, experimental study of delamination of cross-laminated timber (CLT) in fire [184]
Design fires for open-plan buildings with exposed mass-timber ceiling [185]
Fire testing of rooms with exposed wood surfaces in encapsulated mass timber construction [186]

Compartment fire testing of a two-story mass timber building, US Forest Products Lab FPL-GTR-247 [187]

Consideration for Concrete Spalling

During heating free and chemically bound water in the concrete matrix begins to rapidly vaporize resulting in a buildup of internal pore pressure that eventually leads to deterioration and breakdown of concrete at the surface. If there is insufficient porosity in the matrix for vapor to escape, small to large sections of concrete will separate from the substrate – a phenomena known as spalling. This can occur in varying degrees. In fire conditions, spalling can be progressive (due to a gradual rise in temperatures) or explosive in nature where there is a sudden loss of large portions of the concrete, potentially exposing the reinforcement beneath the surface.

This phenomenon can be caused by different mechanisms [188]:

- Increased pore pressure
  - As a concrete element heats, the free water and physically bound water begin to evaporate. At the surface layers of the concrete structure, this water vapor is generally able to escape via the pore structure in the concrete matrix. However, in deeper layers, water pressure increases, inducing stresses perpendicular to the exposed surface. This pressure is maximum at a critical thickness and drops to zero at the external surface.
- Increase in compression forces
  - As the concrete surface increases in temperature, thermal expansion forces that are restrained from moving began to induce axial and flexural restraint forces. This results in higher compression forces near the surface of the concrete element and tension forces further inside.
- Internal cracking due to difference in thermal expansion between aggregate and cement paste
- Cracking due to difference in thermal expansion/deformation between concrete and reinforcement bars
- Strength loss due to chemical transitions of the concrete matrix during heating
- Very rapid heating to high temperatures

In general, spalling is rare and/or minimal in normal concrete strengths when exposed to cellulosic fires (i.e., fires involving wood, paper, furniture, etc.) which is most common in residential and commercial buildings. However, for high-strength concretes (e.g., greater than 8,000 psi (or 55 MPa) in ACI codes, or greater than 50 MPa in Eurocodes), spalling is more likely. This is due to the dense, low porosity matrix of high-strength concrete which limits the free movement of water vapor pressure and steam as the concrete is heated. This can lead to high pore pressures that result in explosive spalling and the loss of a significant portion of the concrete element. Similarly, rapid heating rates and very high temperatures of a hydrocarbon fire can also cause explosive spalling even in normal-strength concrete.

Where high-strength concretes or fires with rapid heating ratings or extreme peak temperatures are anticipated, consideration should be given to mitigate the effects of spalling. This can include the use of suitable fiber reinforcement (e.g., polypropylene fibers), sacrificial concrete layers, thermal barriers, or fire-resisting concrete [149, 150].

Consideration for Fire Protection Material: Robustness

In very tall buildings, a higher level of resilience and robustness may need to be considered as part of a strategy for increased confidence in achieving adequate fire resistance for the structure. This translates to the materials and structural fire protection systems used to protect the structure. More robust fire protection materials and systems may be warranted due to the disproportionate impacts of partial or global collapse of the structure, the increase in times and effort for building occupants to egress, the increase in time and effort for fire personnel to conduct firefighting activities, or the iconic nature of some very tall buildings to malicious acts.

Robustness of the structural fire protection may be a function of several factors requiring consideration, such as the quality, durability, and strength of the material or the proper design, construction, application, and/or installation of the product, assembly, or system. For example, concrete may be a physically more robust fire protection material with respect to durability, damage, long-term maintenance, etc., in comparison to a friable sprayed fire protection material or gypsum board, in situations where the latter is more susceptible to physical impact, contact with water, or abrasion during maintenance. Composite concrete and steel systems (such as concrete-filled sections or concrete-encased steel sections) provide the robustness benefits of both materials. The advantages of a more robust fire protection material or system need to be reviewed in the context of other factors in the design (e.g., constructability, weight, impact on program time and cost, aesthetics, sustainability, etc.), to identify an appropriate solution.

Accordingly, the specification of structural fire protection should address the following points:

- Does the material which is providing thermal insulation have sufficient quality, hardness, and durability for the anticipated environment, application, and duration of use?
- Is the applied fire-resistant material, assembly, or system prone to being altered or removed during future tenant improvements or degrade over time?
- Is the applied fire-resistant material, assembly, or system vulnerable to degradation or attack from non-fire-related effects such as lack of water proofing, mold, or mildew, rodent, or insect attack? Does the structural fire resistance system rely on components that will be changed over the life of the building under normal

tenant improvement scenarios? If so, what safeguards are necessary so that future building designers and owners can maintain these systems?

- Will the materials and/or assemblies providing structural fire protection or compartmentation be subject to periodic maintenance and inspection?
- What is the quality, reliability, and skill of the manufacturer and/or installer of the protection product, assembly, and/or system?
- Does the level of robustness of the structural fire protection material, assembly, and/or system require enhancements due to concerns over malicious acts?
- Has the property thickness, density, and adhesive qualities of sprayed fire-resistive material (SFRM) been verified? Standards are available to qualify these properties [189, 190, 191, 192, 193, 194].

Refer to Chap. 11 (Emergency Egress) for further discussion on robustness of the emergency egress system(s).

Post-fire Assessment

After a severe fire, post-fire material testing should be conducted to assess structural condition and worthiness. In addition to the impact of heat, consideration should also include the impact of water (from the fire suppression operations) on the materials, especially those which are more porous, such as timber, gypsum board or spray-applied fireproofing, and to a lesser degree concrete. While this is true for most buildings, it is critically important for very tall buildings. A fire analysis may be required to determine the gas temperatures to which the structure was likely exposed. Consideration should be given to replacing structural elements that were exposed to severe fire temperatures unless material testing deems otherwise.

Post-earthquake Fire Risk

The occurrence of fire following an earthquake is a potential concern for all structures in seismic regions, not just very tall buildings. Water supplies, automatic sprinkler systems, emergency power, and fire department intervention may be limited or disrupted after a major earthquake. However, for very tall buildings, because of the potential remoteness of the fire floor from grade level, it may take more time for emergency fire-fighting activities to occur. This may mean that the consequences of a fire in a very tall building have more impact after an earthquake than a fire in a low-rise building. A fire on the upper floors could go unchecked for several hours and spread to multiple floors. Consideration should be given to the impact of a fire on the performance of the structure post-earthquake. Additional considerations for the design of fire protection of critical seismic systems or other mitigations may also be prudent, such as automatic gas shut-off valves to reduce potential for easily ignitable fuel sources. This may consist of a post-earthquake fire risk assessment, structural fire analysis of various fire scenarios (e.g., fully developed post-flashover fire over a single floor, multiple floor fires, traveling fires, damaged structure fire event, etc.), or providing additional fire safety provisions to mitigate fire ignition or spread, etc.

Chapter 13
Building Envelope/Enclosure

Recent Fire Incidents and Lessons Learned

In the last two decades, severe fires involving combustible facade systems and combustible architectural features of the facade and roofs have become more prevalent and have demonstrated the potential for rapid fire spread over multiple stories of very tall buildings resulting in loss of life as well as significant losses to property and businesses.

These fires have predominantly occurred in residential buildings, with several incidents also occurring in hotels and office buildings. The fires are characterized by fire spread, both visible on the exterior and concealed within the cavity spaces of exterior wall/facade systems. In those cases where lives have been lost, it is often as a result of fire propagating to the building interior through openings in the exterior enclosure of the building such as windows, doors, utility lines, and similar penetrations causing fire spread through both the interior and exterior of the building.

Three widely publicized fires in recent years include the Lacrosse Fire in Melbourne on November 25, 2014; Address Downtown fire in Dubai on December 31, 2015; and the Grenfell Tower fire in London on June 14, 2017. Details of these fire events and lessons learned can be found in Chap. 2 (History).

The combustible materials contained within the facade systems have been predominantly decorative metal composite material (MCM) cladding panels (with solid plastic cores) or foam insulation and in some instances both. However, there are a range of other combustible materials utilized in facade assemblies which also may contribute to fire spread, and therefore, this chapter is not limited to MCMs or foam insulations but provides an overview of facades as a multicomponent system. It should be noted that subsequent investigations of these incidents typically find

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Building enclosure (or *envelope*): all materials, components, systems, and assemblies that, collectively, provide shelter and environmental separation between interior and exterior or between two or more environmentally distinct interior spaces within the same building or structure

Fire Safety for Very Tall Buildings, The Society of Fire Protection Engineers Series, https://doi.org/10.1007/978-3-030-79014-1_13

multiple contributing factors such as materials and assemblies not complying with applicable building regulations or lack of enforcement of those same regulations.

Combustible materials in facade systems are generally subject to restrictions by building and fire codes to limit fire spread on the exterior of the building. However, a lack of understanding or enforcement or other issues in the construction industry supply chain have meant that some building facade systems procured and installed globally have combustible material content that has not been restricted or otherwise tested, evaluated, and approved for use. This applies not only to the building enclosure system but also to materials used as decorative features on the building enclosure (Fig. 13.1).

Fire Safety Goals for New Construction

A basic principle of fire safety for very tall buildings and a requirement of most national codes is to contain fire spread to the compartment of fire origin, typically the floor of fire origin. Fire containment is one of the fire safety measures which allows for phased evacuation of very tall buildings and for fire fighters to enter a very tall building to fight a fire on the upper floors and to prevent collapse of the structure.

Fig. 13.1 Left, Grenfell Tower fire in 2017 (London); right, Address Hotel fire in 2015 (Dubai)

Containment of a fire to a single story is achieved in the interior of a very tall building through layers of fire safety measures including detection and alarm, sprinklers, smoke control, interior fire-fighting equipment, noncombustible materials of construction and fire-rated separating construction. However, if the active fire safety systems fail, fire containment relies upon noncombustible materials of construction and fire resistance-rated elements of separating structures (walls/ceilings/floors), opening protectives, and fire stopping of joints and penetrations to limit the fire size to the contents of the room or floor.

Interior fire suppression systems are not designed nor intended to control fire spread via the exterior of the building. Therefore, control of exterior vertical and lateral fire spread has historically relied on the materials of construction and detailing of the building envelope design. Combustible materials in facade systems are therefore either not permitted or restricted to limit fire spread on the exterior of the building. Materials of construction in a roof system are also restricted although to a lesser extent. A roof, by definition, sits on top of the upper most story and is not expected to contribute to fire spread vertically unless it is adjacent to or presents an exposure to a combustible facade system or feature.

This chapter sets out guidelines and points to consider when developing a building envelope design for a tall building to limit vertical and lateral exterior fire spread and prevent a breach of internal compartment boundaries by an external fire involving the building envelope system.

Facade Types

The terms used to describe external walls, exterior walls, cladding, and facades vary internationally. For the purposes of this guide, facade systems or exterior wall systems are used interchangeably and are intended to mean the entire buildup of materials and components comprising the exterior wall enclosure of the building. When the term cladding is used, this refers to the outer aesthetic skin of a facade or exterior wall system and not the entire system. The terms facade assemblies or exterior wall assemblies are used when describing a representative sample of a facade or exterior wall system to be tested in large-scale fire tests (e.g., NFPA 285 [195]).

Facade systems on most very tall buildings fall into three recognizable categories:

1. Curtain wall: As the name suggests, a curtain wall is defined as a lightweight, non-load-bearing exterior wall system that is "hung" from a base building structural frame and intended only to provide environmental separation between interior and exterior and protection from the effects of weather, including positive and negative wind pressures. It often consists of an extruded aluminum frame supporting glass alone or a combination of glass and a variety of other semi-opaque or opaque products or materials; curtain wall systems are manufactured in two ways:

(a) Stick-built or knockdown ("KD") systems: individual components that are fabricated off-site and shipped as a "kit-of-parts" for assembly in the field. KD systems often utilize extruded aluminum framing members and associated glazing accessories that are shipped in bundles and installed in the field onto the base building structural frame. Glass and/or semi-opaque or opaque wall panels are then installed in the field onto the curtain wall framing and weathered-in as either a fully sealed, barrier-type wall system or internally drained system with end dams, zone dams, and weeps.
(b) Prefabricated unitized systems: fully assembled curtain wall panels that include both glass and semi-opaque or opaque wall panels with insulation, joint sealant, and internal flashing as necessary that are assembled off-site and then delivered and hung on the base building structural frame and weathered-in as either a fully sealed, barrier-type wall system or internally drained system with end dams, zone dams, and weeps.

In both stick-built or knockdown (KD) and prefabricated, unitized curtain wall systems, the weight (dead load) of the curtain wall is transferred to the base building structural frame at alternating floor lines, with live ("wind") load anchors installed at one or two floor lines below depending upon location, exposure, and design intent.

Hybrid systems such as "cassette wall" systems also exist and include prefabricated, unitized curtain wall panels installed in the field onto or within a pre-installed, stick-built framing system.

2. Window wall: The components and materials that comprise a window wall system are often substantially the same as those that comprise a curtain wall system. However, unlike a curtain wall system that is hung from one floor line and designed to extend downward across one or more floor lines below, a window wall system is field-constructed and supported individually at each elevated floor line as an "infill" wall consisting of glass or a combination of glass and a variety of different opaque wall systems and assemblies.

In this type of construction, slab edges are typically allowed to remain exposed (warmer climates) or are clad in a semi-opaque or opaque product or material and insulation (all climates), often to simulate the appearance of a continuous curtain wall.

3. Veneer wall: A veneer wall system is similar to a window wall system in that it is also field-constructed and supported at each floor line and can include components and materials designed to function as part of a barrier-type wall system or an internally drained and, in certain instances, pressure-moderated or fully compartmentalized, pressure-equalized rainscreen. Common veneer wall types in very tall buildings include:

(a) Clay brick masonry exterior cladding supported on structural steel shelf angles at each elevated floor line and restrained laterally by corrosion-resistant wall ties to a reinforced concrete masonry or steel stud backup wall, installed over an internally drained wall cavity with a continuous layer of exterior sheathing and air barrier behind rigid or semi-rigid insulation.

(b) Architectural metal panel exterior cladding over a pressure-modulated or fully compartmentalized, pressure-equalized exterior wall cavity with semi-rigid or rigid insulation over a continuous layer of exterior sheathing and air barrier.

(c) Architectural precast concrete exterior wall panels prefabricated off-site and then delivered, installed, and supported at each floor line and weathered-in with one or two lines of joint sealant between panels to form a barrier-type exterior wall system with insulation including within or otherwise applied on the inboard side of the precast concrete panels after installation. Depending upon surface treatment, architectural precast can function as either a barrier-type exterior cladding or a "reservoir" cladding with a storage capacity for moisture that will shed water upon initial contact and allow for evaporative drying over time.

(d) EIFS or ETICS installed in the field as an exterior wall covering system, over exterior sheathing, and cold-formed steel studs or directly over reinforced masonry infill.

In new construction, concerns associated with exterior facade systems and fire protection involve the combustibility of the exterior cladding materials, vapor barriers, and underlying semi-rigid or rigid insulation.

Each of these facade types can be constructed of materials or have characteristics that can propagate or impede fire spread on the exterior of a very tall building. These facade systems and their characteristics in relation to the propensity for fire spread are described in the following sections.

Curtain Walls

A curtain wall can be "stick (assembled on site)" or "unitized (prefabricated)" and requires the facade system to be supported by structural elements that extend from the structural floor plate to the framing elements of the facade system.

These systems are commonly constructed from glass and aluminum which are typically considered to be noncombustible with insulation and membranes at the spandrels only. Timber framing is also possible but should be avoided in very tall buildings.

Fire spread beyond two stories is unlikely with a conventional curtain wall system as there is no cavity and materials of construction are usually noncombustible or any combustibles are limited to a spandrel area. If the curtain wall contains vertical framing elements which link the spandrels, then noncombustible materials should be used.

With this type of facade design, a void space commonly appears between the floor system and the spandrel of the facade assembly as shown in Fig. 13.2. The

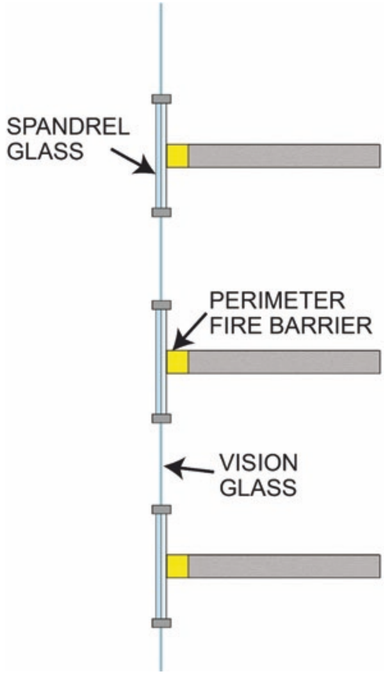


Fig. 13.2 Curtain wall hung off flab edge

void space at the slab edge introduces a risk of fire spread from floor to floor. Typically, such void space conditions (Fig. 13.2) are sealed with a material or system to prevent the interior spread of fire from one story to the story above. This requires some form of a joint system or "perimeter fire barrier system." These are discussed in later sections of this chapter. When the edge of the floor slab has irregularities in its distance to the curtain wall, issues can arise in the performance of the joint system. This can be important when the joint gap exceeds the specified gap of the selected joint assembly (Fig. 13.3).

Double-Skin Facades

Double-skin facades are a variation of a curtain wall system. The basic components of a double-skin facade system involve the use of an outer glazed curtain wall, usually with ventilation openings; a cavity (usually ventilated) with varying depths; and a second inner curtain wall of glazed units, sometimes also ventilated.

There are wide variations possible for the design of these double-skin facades. Design variables include the ventilation scheme (passive or active), use of louvers, motor-operated openings or fans, shading devices, horizontal or vertical partitions within the cavity, and operable windows on the inner skin of the double facade.

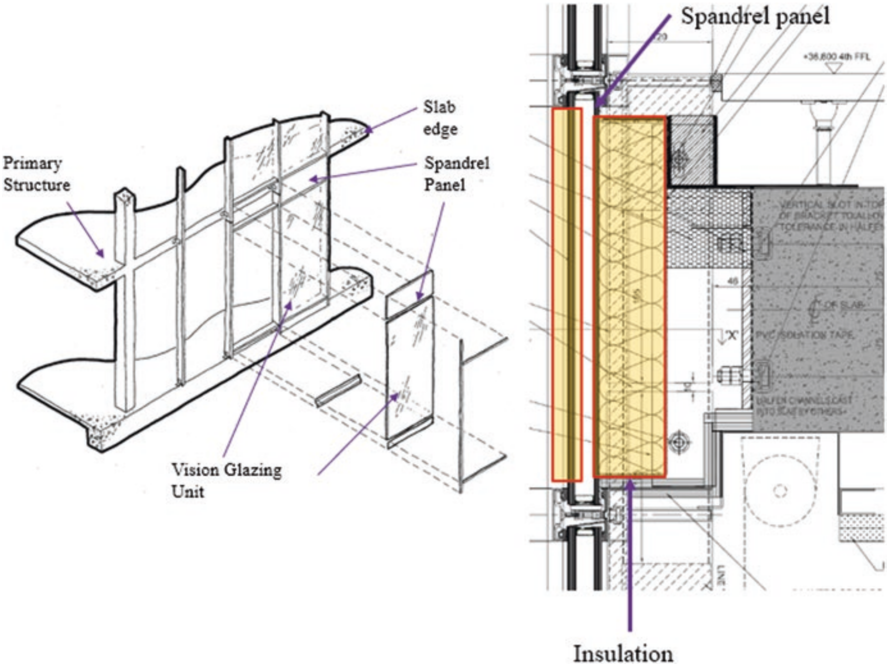


Fig. 13.3 Typical curtain wall detail at slab to facade interface including the perimeter fire barrier system (Courtesy of Arup)

Depending on the local climate, the double-skin facade concept may be used in different ways. For example, in winter climates, the air cavity can be isolated, and the system is used as a triple-glazed system with the air in the cavity acting as a transparent insulator. In hot climates, air inlets and outlets may be opened to develop a stack effect (hot air rises) allowing hot air to be released at the top of the cavity and replaced by fresh air from the lower regions of the cavity. Within the air cavity, sunshades can be used to absorb and reflect solar heat energy which can promote an even higher temperature differential for the stack effect to take place within the cavity. As a result, cooling cost for inhabited areas is reduced and human comfort increased.

Designers should consider the materials of construction of these passive systems and sunshades as they are fundamentally a part of the facade and may provide a route for fire or smoke spread (Fig. 13.4).

Built-Up Walls with a Cavity

A built-up facade system is supported directly on the structural floor slab edge. Therefore, there is no joint between the slab edge and the facade system.

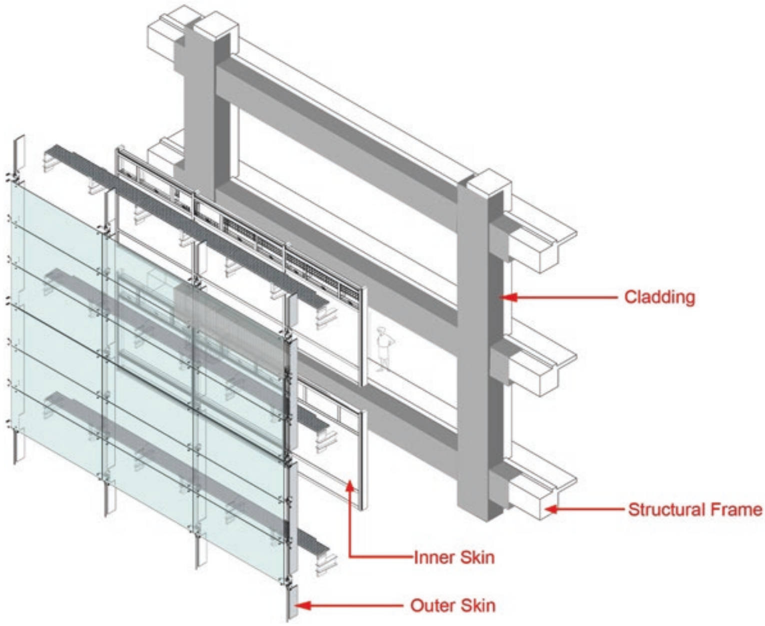
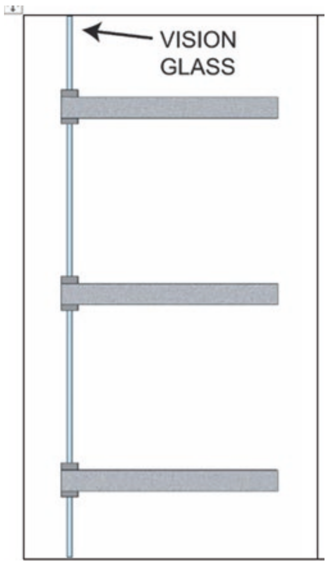


Fig. 13.4 Double-skin facade system (Courtesy of Arup)

Fig. 13.5 Built-up system supported on slab edge



The primary materials of construction include an outer cladding, insulation, and membranes as well as the facade system framing and any vision glass/glazing (Fig. 13.5).

A rainscreen system or "cavity wall" is a wall system installed over a largely open, unobstructed air space or drainage cavity. Such cavity or rainscreen wall assemblies rely upon a partially or fully concealed air space and drainage plane to resist bulk rainwater penetration which is also used to improve the thermal performance at the building enclosure. An opaque rainscreen system is tied back to a supporting substrate (concrete wall, blockwork wall, or cold-formed steel-framed gypsum board system) with or without insulation or punched windows (see Figs. 13.6 and 13.7). In this case a cavity is created between the rainscreen and the supporting substrate.

The insulating layer can be located either inboard or outboard of the internal drainage plane depending upon the geographic region and climate in which the building or structure is to be located.

The materials and configuration of these facade systems can influence their ability to propagate fire spread. If combustible, the cavity in a rainscreen provides a route for flame spread within the depth of the facade system that may require a fire-rated or noncombustible cavity barrier. Cavity barriers are discussed in more detail in this chapter.

Built-Up Walls Without a Cavity

A built-up facade system is supported directly on the structural floor slab edge; therefore there is no joint between the slab edge and the facade system.

The primary materials of construction include an outer cladding, insulation, and membranes as well as the facade system framing and any vision glass/glazing. The presence of combustible materials and the configuration of these facade systems can

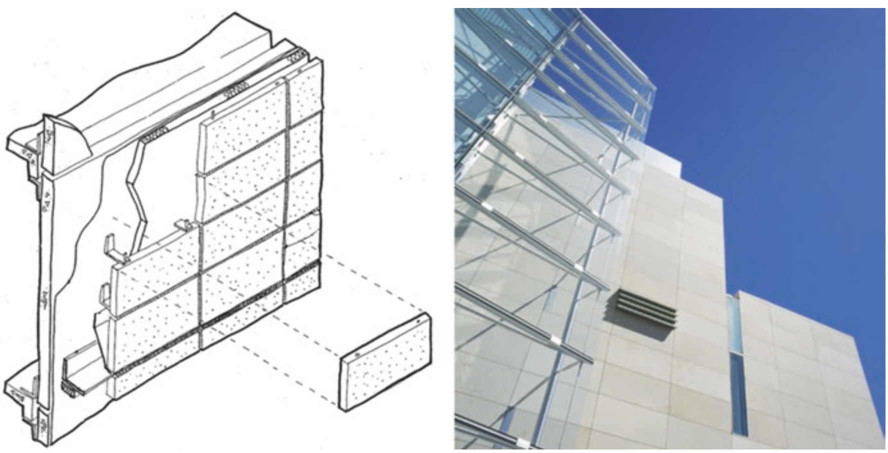


Fig. 13.6 Rainscreen facade system on solid wall (Courtesy of Arup)

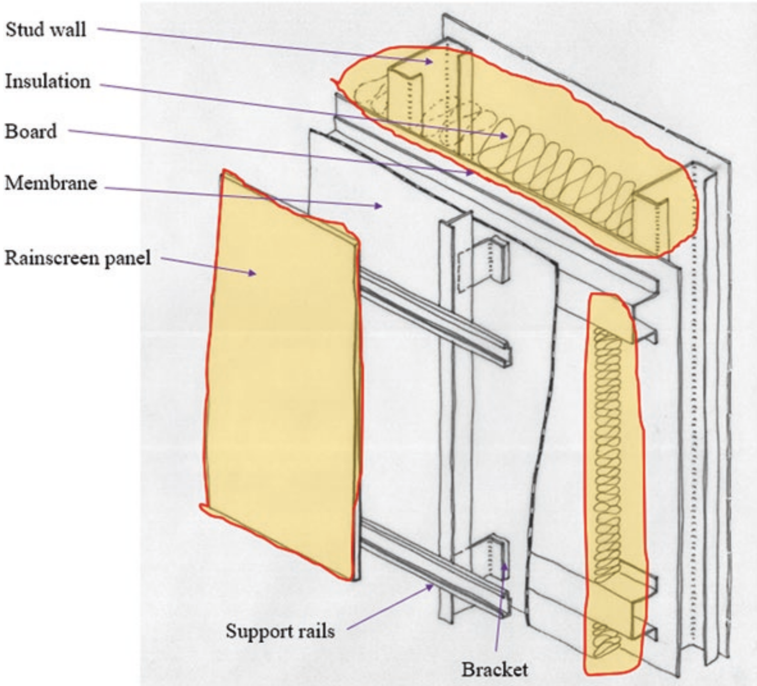


Fig. 13.7 Rainscreen facade system on cold-formed steel-framed gypsum board stud wall. The stud wall could also be blockwork or a concrete shaft (Courtesy of Arup)

influence their ability to propagate fire spread although there may be no air space or cavity.

Pre-cast concrete panels are commonly used in this type of facade system (see Fig. 13.8).

Exterior insulation and finish systems (EIFS) and external thermal insulation composite systems (ETICS) are also a form of a built-up facade. These systems are typically made of foam plastic insulation (several centimeters) encapsulated in a proprietary mesh and a thin (a few millimeters) render system (cementitious screed). They are commonplace in the Americas and Europe although they tend to be used more on low- to mid-rise buildings. EIFS/ETICS with a mineral wool insulation is also available. In some model codes, a thermal barrier is required between the interior of the building and the combustible foam insulation. Figure 13.9 shows a typical EIFS assembly.

It is important to "back-wrap" the glass fiber reinforcement mesh around the EPS or XPS insulation. The glass fiber reinforcement mesh needs to be adhered to the outer face of the gypsum sheathing at the top and bottom of the walls and at vertical edges, at re-entrant corners, and at the ends of the wall.

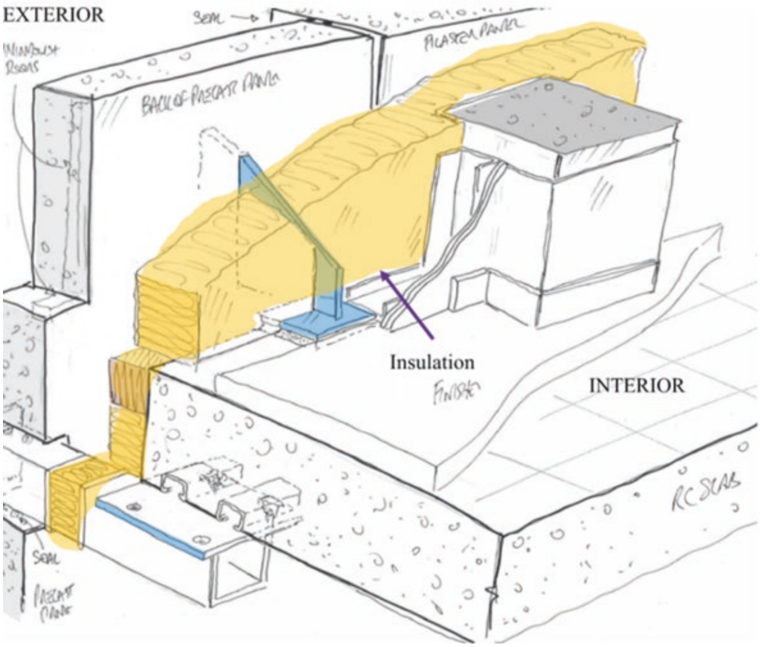


Fig. 13.8 Pre-cast concrete panel facade system without a cavity (Courtesy of Arup)

Mechanisms of Fire Spread

Based on review of reported fire incidents and existing research [196], the following are key initiating fire events and mechanisms of fire spread specific to the building enclosure.

Fire Initiating Events

- Interior fire (pre-flashover or post-flashover) spreading to exterior wall system via external openings such as windows
- Interior fire (pre-flashover or post-flashover) spreading to exterior wall system via internal openings including cavities and concealed spaces
- A fire starting inside the cavity due to electrical wiring or similar within the cavity.
- Exterior fire exposing a nearby wall system resulting in ignition due to radiant heat and/or flame impingement
- Exterior fire spatially separated from exterior wall system resulting in ignition due to radiant heat

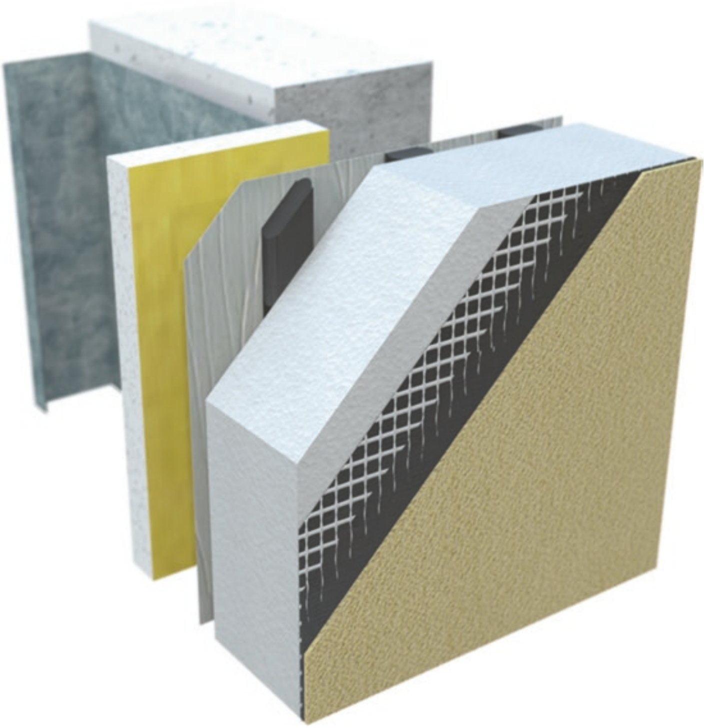


Fig. 13.9 Typical EIFS configuration. Courtesy of EIMA

Mechanisms of Fire Spread After Initiating Event

- Fire spread to the interior of the story above via openings such as windows causing secondary interior fires resulting in multi-story fire spread sometimes called the “leap-frogging” effect
- Fire spread via combustible materials found on exterior balconies
- Flame spread over the external surface of the wall
- Flame spread within an internal cavity/air gap
- Heat flux impacts cause degradation/separation of noncombustible external skin resulting in flame spread on internal core of the skin
- Secondary external fires initiated at lower (ground) levels arising from falling burning debris
- Secondary external fires initiated on adjacent property arising from falling burning debris

Figures 13.10, 13.11 and 13.12 illustrate some of these fire exposure mechanisms at work.

A ventilation-controlled fire is represented in Fig. 13.10 based on the scenario of a fire burning in a building without the benefit of control by sprinklers. The fire

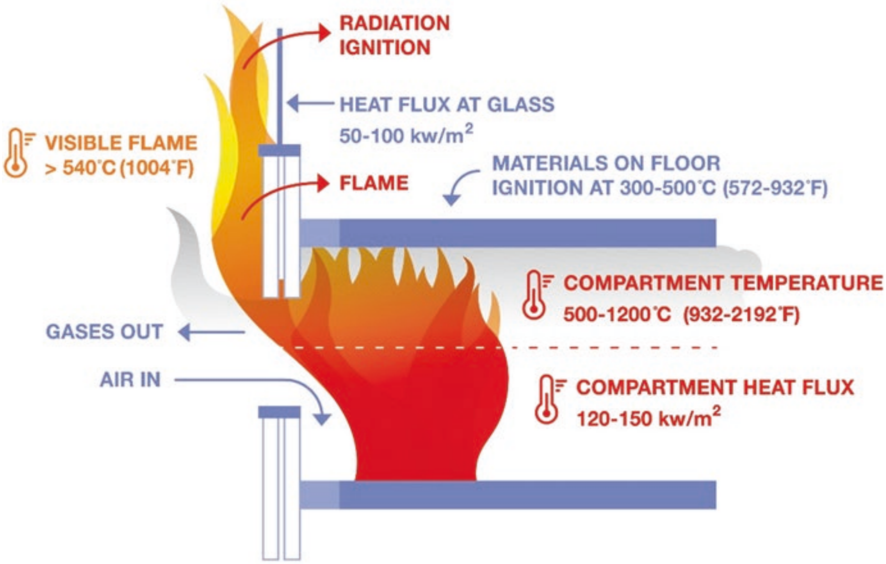


Fig. 13.10 Exterior wall and floor fire exposure mechanisms from a fire starting within the building [197] (Courtesy of Arup)

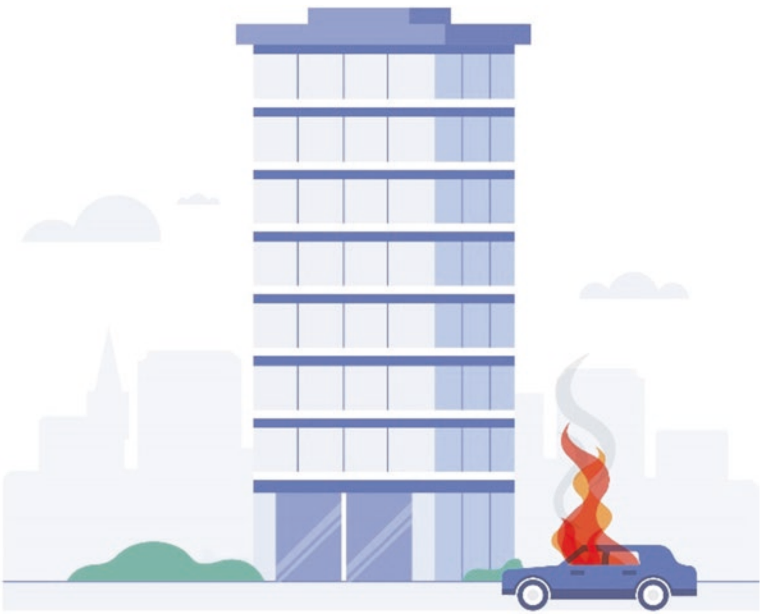


Fig. 13.11 Exterior wall and floor fire exposure mechanisms from a fire starting at the base of a building (Courtesy of Arup)

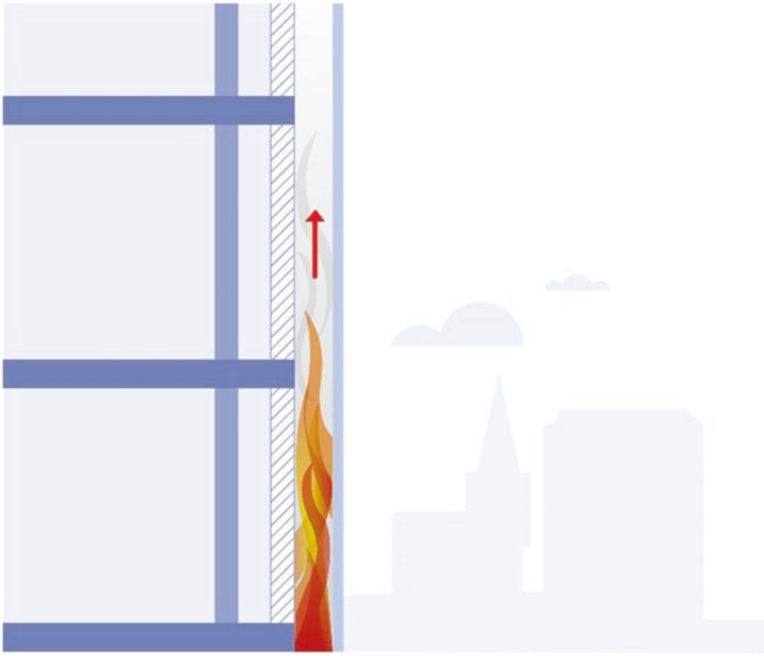


Fig. 13.12 Exterior wall and floor fire exposure mechanisms from a fire starting in the cavity of a facade system (Courtesy of Arup)

breaks the window glazing, permitting hot gases to flow out the top portion of the opening. A portion of the hot gases are unable to burn inside the room due to limited air (ventilation controlled) but, upon movement to the exterior, encounter sufficient air entrainment, allowing the hot fuel gases to burn outside the building.

The flame projection and temperature profile will be a factor of window area and height, room geometry, fuel contents and burning rate, and wind velocity and direction. Building interior areas and facade systems can be attacked by fire in three principal ways. Figure 13.10 illustrates the potential temperature and heat flux characteristics of a fully developed, compartment fire without the benefit of suppression from an automatic sprinkler system.

As a result of this fire exposure, the integrity of the exterior wall system may be attacked and threatened as follows:

- Inside – Flames and fire gases in the building attack the interior surfaces and details of the building enclosure, window framing, and associated perimeter fire barrier materials.
- Outside – Flames and hot gases projecting from fire-broken glazing or other openings directly impinge on the window framing and the exterior face (convection) of the building enclosure. Flame impingement on the facade system may ignite combustible components of the facade system if not appropriately isolated/protected. If these combustible components are also vertically connected

over multiple stories of the building, then fire spread past compartment floors may occur.

- Outside – Flames projecting from fire-broken glazing or other openings radiate heat to and through glazed surfaces or through other openings to building contents and furnishings on the floors above or adjacent.
- Within the facade cavity – Flames may break into a facade system cavity via weaknesses around window frames as an example.
- Burning brands and falling debris ignite other parts of the building enclosure or items stored on balconies on the building of fire origin or properties below or adjacent.

A fuel-controlled fire is represented in Fig. 13.11 based on the scenario of a fire burning at the base of a building. The fire can ignite the facade system either by direct flame impingement or radiant heat exposure without the benefit of suppression from an automatic sprinkler system unless they are installed in the soffit of a balcony.

As a result of this fire exposure, the integrity of the exterior wall system may be attacked and threatened as follows:

- Outside – Flames and hot gases projecting from fire directly impinge on the exterior face (convection) of the building enclosure. Flame impingement on the facade system may ignite combustible components of the facade system if not appropriately isolated/protected. If these combustible components are also vertically connected over multiple stories of the building, then fire spread past compartment floors is likely.
- Outside – Flames projecting from the fire radiate heat to and through glazed surfaces or through other openings to building contents and furnishings on the floors above or adjacent.
- Within the facade cavity – Flames may break into a facade system cavity, and if they encounter combustible materials the fire can continue to grow and spread.
- Burning brands and falling debris from the facade system ignite other parts of the building enclosure or items stored on balconies, etc. on the building of fire origin or properties below or adjacent.

A ventilation-controlled fire starting in a cavity is represented in Fig. 13.12 based on the scenario of a fire starting in electrical cabling or similar within the cavity. The fire can ignite the facade system by direct flame impingement without the benefit of suppression from an automatic sprinkler system.

As a result of this fire exposure, the integrity of the exterior wall system may be attacked and threatened as follows:

- Within the facade cavity – Flame spread may bypass compartment floors within the facade cavity and break out to the exterior and/or interior of the building.
- If flames break out of the cavity, then the fire spread mechanisms already shown and discussed in Fig. 13.10 and Fig. 13.11 could evolve.

Building Enclosure Design Considerations

Exterior building walls and curtain walls are often a relatively complex combination of components that can include masonry, composite panels, aluminum frames, vision glass, spandrel panels of glass, metal or stone, metal back pans, weather resistant membranes, insulation, gaskets, sealants, and anchors or connectors of steel or aluminum.

They provide shelter to the building interior from weather effects, prevent moisture accumulation in the building fabric, maximize thermal performance, control sunlight, provide an acoustic barrier, and are often a key component of the architectural vision for a building as illustrated in Fig. 13.13.

Factors in facade design that impact the building enclosure's resistance to vertical and lateral fire spread include:

- Combustible components of the enclosure – material considerations for cladding on the outer skin, insulations, vapor barriers, framing, and other components
- Joints and cavities – ability of perimeter fire barrier system or cavity barriers to remain in place during fire exposure
- Double-skinned facades

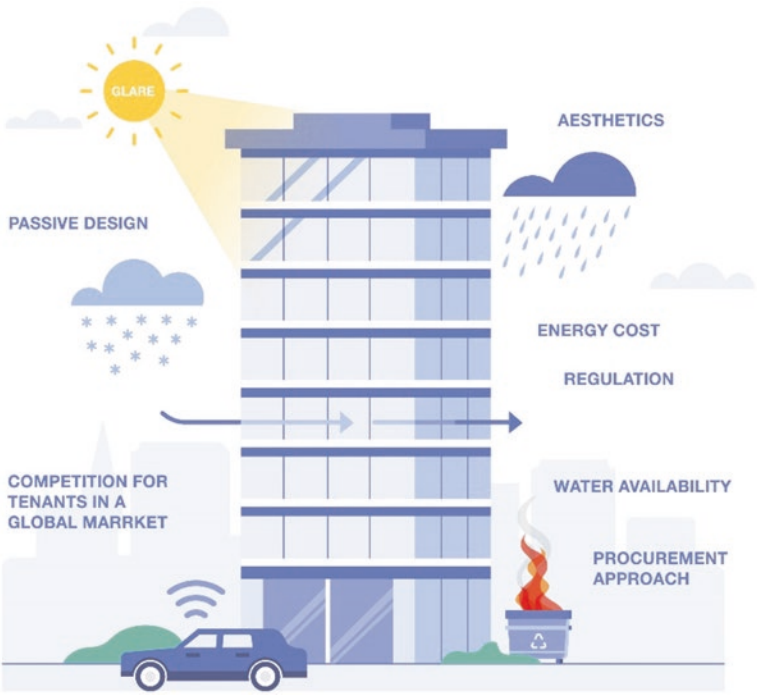


Fig. 13.13 Competing aims of a building enclosure design (Courtesy of Arup)

- Full-height or partial-height vision glass systems and nature of the glass used to construct the glazing system
- Geometry (twisted, staggered, sloped), exterior vertical or horizontal projections including spandrels that may deflect or enhance flame behavior and windows
- Balconies and building exterior appendages
- Specialty facade systems – LED display screens, photovoltaic (PV) systems, or vegetative walls

These topics are discussed further in the following sections.

Combustible Components of the Enclosure: Material Considerations

The materials used to construct a facade system are a critically important consideration in the relative risk that the facade poses to fire spread vertically and horizontally on the building face. From the 1980s forward, to reduce energy losses from buildings, the regulatory requirements for noncombustible exterior walls have been modified to allow for the use of combustible materials such as foam plastic insulation in exterior walls. The desire for lighter weight construction and a reduction in the use of solid aluminum saw the advent of MCM, high-pressure decorative exterior-grade compact laminates (HPL), and others.

Some jurisdictions use the term limited combustible to define materials that are combustible but have passed certain code-mandated fire tests such that ignition and combustion are substantially more difficult.

If the building envelope uses combustible or limited combustible cladding or insulation systems, consideration should be given to performing a risk assessment allowing for the limitations of large-scale testing, local construction quality, local building regulations, possible interior or exterior fire exposures, reliability of fire safety provisions, and other risks. When warranted by the risk assessment, a key objective of the facade design would be to prevent fire to spread a significant distance horizontally or vertically over more than one or two stories. Material fire testing of each element and large-scale fire testing of the facade system(s) may need to be utilized (and may be required) to justify any very tall building facade system containing combustible or limited combustible materials (see Section "Fire Testing of Designs" for the limitations of fire testing).

Cladding

Although the building enclosure of very tall buildings is often constructed primarily of metal and glass materials, it is also common to find facades that use architectural cladding systems comprised, in part, of combustible materials.

Cladding is the outer skin of the facade system and is visible from the exterior of the building. Cladding does not usually provide significant insulation properties but may be used in conjunction with insulation materials and open-air cavities to provide a more effective thermal barrier.

Often the facade of very tall buildings is mostly glazing, but for facade systems comprising large opaque areas, there is a whole range of materials available for use as cladding. A selection of these is shown in Table 13.1 along with their classification as combustible or noncombustible.

Table 13.1 Materials available for use as cladding along with its classification as combustible or noncombustible

Example cladding material	Noncombustible or combustible	Commentary
Glass reinforced concrete (GRC)	Noncombustible	Polystyrene is often used as formwork for pre-cast units and if left in place poses a significant risk and should be removed
Solid metals such as aluminum, copper	Noncombustible	
Stone	Noncombustible	
Pre-cast concrete	Noncombustible	
Terracotta	Noncombustible	
Ceramics	Noncombustible	
Aluminum composite panels (ACPs)/ metal composite materials (MCMs)	Combustible core between thin metal sheets	The core of ACPs/MCMs can be specified to have improved fire performance. Many of the proprietary MCMs contain fire retardants and minerals in the core to improve the fire performance of the core. Each product is proprietary with a different mix of fire retardant/mineral which means one ACP/MCM product may not behave the same as another. All these still contain some quantity of combustible binder, and even the highest-performing MCM should be evaluated for whether it should be used at all on a very tall building with consideration for large-scale testing, local construction quality, exposures, and other risks Large-scale fire testing of the facade system(s) would be required, and the hazard posed by the cladding should be evaluated based on risk
Glass reinforced polymers (GRP)	Combustible	These materials can be treated to achieve limited combustibility but as with MCMs, they all pose a risk of fire spread and should be evaluated for whether it should be used at all on a very tall building with consideration for large-scale testing, local construction quality, exposures, and other risks
High pressure laminates (HPL)	Combustible	
Timber	Combustible	
Cross laminated timber (CLT)	Combustible	

Insulation

Insulation is critical in some countries to meet the thermal resistance/transmission requirements for exterior wall assemblies (i.e., walls and facades) established by the energy conservation regulations. Insulation in walls may be materials such as fiberglass/glass wool, mineral wool, or foam plastic materials with generally higher insulating capabilities. The common insulating materials are listed in Table 13.2.

Table 13.2 Common insulating materials

Example insulation material	Noncombustible or combustible	Notes
Fiber glass/glass wool (w/o facing)	Noncombustible	Least insulating
Mineral wool (w/o facing)	Noncombustible	Mineral wool is a fibrous thermal insulation material manufactured from molten rock or slag. To obtain the same U-value as a foam plastic, the insulation must be 16–33% thicker. However, this material is noncombustible and therefore may be more appropriate for the facade of very tall buildings
Expanded or extruded polystyrene	Combustible	Polystyrene drips and pools are highly flammable and should not be used on very tall buildings
Polyurethane (PUR)	Combustible or limited combustible	These materials can be treated to achieve limited combustibility, but they all pose a risk of fire spread. It should also be noted that these materials are proprietary with different mixes of fire retardant which means one foam plastic product may not have the same behavior in fire as another Large-scale fire testing of the facade system would be required, and the hazard posed by the facade system should be evaluated based on risk
Polyisocyanurate (PIR)	Combustible or limited combustible	
Phenolic	Combustible or limited combustible	
Proprietary insulation made of a blend of phenolic and PIR	Combustible or limited combustible	
Silica aerogel	Noncombustible	Silica aerogels are noncombustible and allow a very thin insulation, due to their very low heat conductivity. Compared to mineral wool, insulation layer thickness can be reduced by 50%
Other proprietary insulations	Combustible or limited combustible	New products are being introduced to the market in response to previous fires and evolving regulations. These should be evaluated by a qualified fire safety professional

Membranes

To control air, water, and vapor penetration from the exterior to interior spaces, various types of polymer-based thin membrane or sheet materials are seeing more common use in modern buildings. Air barriers are used to resist air leakage (ingress and egress), water-resistive barriers (WRBs) provide resistance to bulk-water penetration, and vapor barriers serve to retard or resist moisture vapor transmission.

Membranes perform an important role in preventing moisture from entering the building, and they are often connected and/or continuous throughout the building envelope. Their location within the depth of the facade system depends upon the local climatic conditions and building science/design principles in context of the membrane's properties and function. Consideration should be given to the type of membrane materials used, their vertical and horizontal extent, and whether they need to be continuous over the height of the facade system. There should be a balance between protecting the building from moisture and increasing the fire load in the facade system.

Where combustible or limited combustible materials are used, the reaction to fire performance characteristics should be carefully reviewed by a qualified fire safety professional as the fire test may not represent the proposed installation and therefore perform differently than during the test. For example, the test orientation may not be the same as the proposed facade system, or the backing material used in the test may not be the same as that proposed in the facade system, etc. Oftentimes a material that appears to be suitable for use was tested in a horizontal position but when used in a vertical orientation performs differently.

A large-scale fire test of the project specific facade system(s) should be considered or may be required by the building regulations where the membranes are combustible or limited combustible. See Chap. 12 (Fire Resistance) for the limitations of fire testing.

Framing

Framing of a facade system is typically aluminum or may be of steel where the strength and stiffness of steel are required locally. Timber framing is also an option but should be evaluated for the risks related to very tall buildings and the combustible nature of timber.

Gaskets, Sealants, and Thermal Breaks

Gaskets, sealants, and thermal breaks are essential to the performance of a facade system and are typically a small proportion of the overall facade system when compared with cladding, insulation, and membranes. For this reason, the material selection for these elements should focus on their primary performance criteria which is to seal the joints and interfaces of the facade system. Because the aluminum framing components of a curtain wall have a high thermal conductivity, it is common practice to incorporate thermal breaks of low conductivity materials and reduce the temperature transmission via the aluminum components. PVC, neoprene rubber, polyurethane, and polyester-reinforced nylon are materials used to create the thermal break for improved thermal performance.

Fire Barrier Systems at the Envelope-Floor Intersection

The intersection of floor slabs with the exterior wall are potential weak points or paths for flame spread within facade systems. These were discussed in relation to each facade system type in the earlier part of this chapter.

The potential weak points are typically at the joint or interfaces between the facade system and the floor slab, at the structure around window frames, in cavities, or between different facade systems on the same building. These issues are solved by designing them out or by treating them with tested and certified fire-rated cavity barriers and perimeter fire barriers.

Perimeter fire barrier systems or fire stopping is usually required by building regulations, tested in a standard furnace, and listed for their application. They can be tested for their fire resistance in a small assembly in a standard furnace or as part of large-scale fire tests of the project-specific facade system(s).

The small-scale assemblies cannot replicate the movements and failures of a complex facade system, so they should be used with caution. The stability of a fire barrier system between the slab edge and facade needs to be carefully considered at the time of design. If they are permitted to fail with the facade system, then this is less of a concern. If they are required to remain in place after the facade system has failed, then the spandrels and transoms need to be robustly detailed and may need to be tied back to the fire-rated slab. The spandrel should be fire-rated if the perimeter fire stopping is to remain in place when the facade system fails.

Cavities in Facade Systems

Cavities other than between the slab edge and facade system can exist within the facade system (e.g., rainscreens) or within fins or other architectural features. These vertically continuous gaps pose a path for fire spread over the height of a building, bypassing rated floor assemblies. Horizontal cavities may also exist and may need to be considered if fire-rated compartment walls are present and critical to the building performance (e.g., hospitals). The risks of fire spread presented by cavities in exterior wall assemblies and facade assemblies can be evaluated in full-scale assembly tests.

Proprietary open-state cavity barriers are available to allow ventilation throughout the cavity until a fire occurs. The open-state cavity intumescent barrier is intended to seal the gap once flaming or hot gases cause the intumescent to react. The installation of cavity barriers and the workmanship of the contractor are critical to gain benefit. If they are not properly tested, specified, or poorly installed, then the cavity will not be entirely sealed providing a path for flames and hot gases. Intumescent products can degrade with time. The manufacturer should provide evidence of the expected service life of the intumescent product depending upon their location (interior or exterior) and when they should be replaced.

Double-Skinned Facade Considerations

Double-skinned facade or curtain wall systems include systems where two glazed walls are separated by distances typically less than a meter but can be larger. There are several issues to consider when a double-skin facade is used. The double-skin facade concept poses conditions that impact fire and smoke spread that are not encountered with single-skin or more common curtain wall designs. The risk of fire and smoke spread through such double-skinned façades introduces concerns arising from the fact that should flame break through the inner facade it would then be confined within a long, tall shaft-like space as shown in Fig. 13.14. The dynamics of the flame and radiant heat exposure for this case is potentially more severe than a flame freely flowing to the open atmosphere. Other types of double-skinned facades may reduce the risk of fire spread, particularly those using a partitioning scheme within the cavity of the double-skinned facade.

Vision Glass Considerations

When full-height vision glass systems are used, flame extension and heat flux to the window areas above can be greater than that for curtain walls using a spandrel panel design. A spandrel panel design can limit the flame extension and reduce heat flux to the story above by providing an opaque surface to block the heat transfer. Glass used in curtain wall assemblies may be one of several types – float glass which may be heat strengthened or tempered glass or laminated or wired glass. Vision glass can be single, double, or triple glazed and is typically assembled into an insulating glass unit (IGU). Vision glass may also be tinted to provide a heat-absorbing quality or coated to provide a heat-reflective capability. All these features can impact the performance of glass under fire exposure; however, little is currently known about the fire performance of the wide variety of IGUs that are possible.

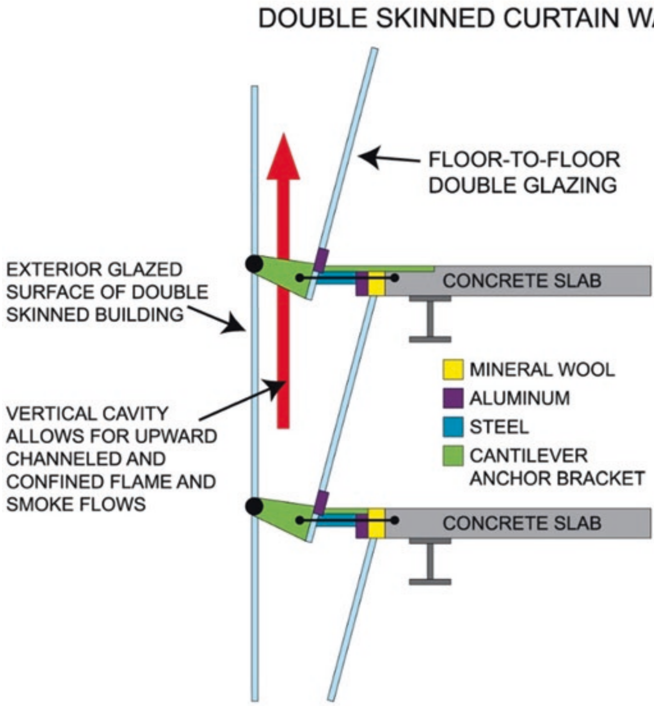


Fig. 13.14 Vertical cavity and potential fire spread route [197]

Geometry, Exterior Projections, and Windows

Many articulated facade designs veer from the more traditional continuous vertical facade surfaces of the past, often using curved surfaces and rotated floor plates that complicate the facade connections and hidden details of fire barrier assemblies. Such new designs can result in orientations and arrangements that either allow for more direct flame exposure or diminish the threat of direct flame contact. Regardless of the facade orientation and arrangement, wind conditions may reduce or exacerbate the flame and temperature exposure.

Building geometry and exterior projections of the facade system or building structural elements can have a beneficial or detrimental effect on flame length extension and heat flux exposure to building enclosure elements above the fire compartment. This can be particularly important if operable windows or ventilation openings are used. Of course, any such opening can allow the unrestricted passage of flames and hot gases from a fire on a floor below into the floor above. The position of the window or ventilation opening relative to the expected flame extension is important in assessment of the fire spread risk.

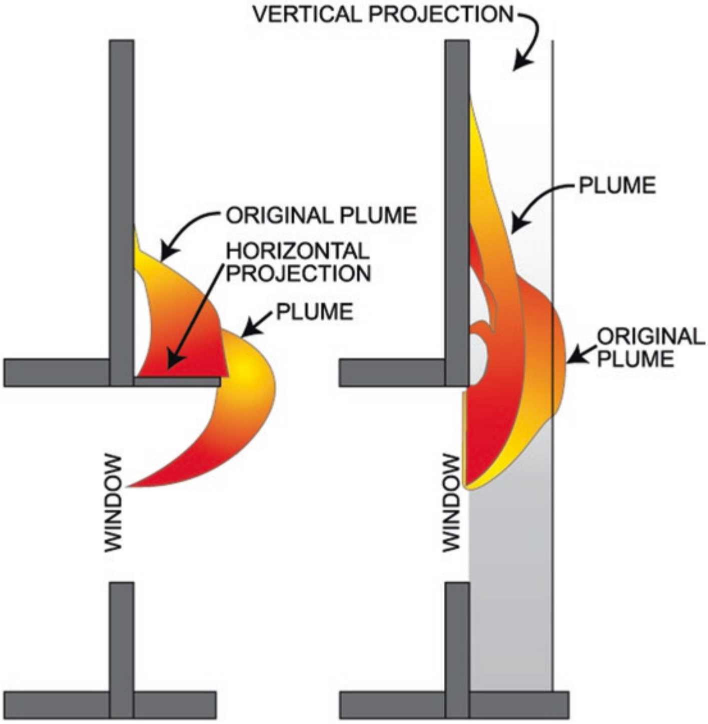


Fig. 13.15 Impact of horizontal and vertical projections on window plume [197]. Based on Oleszkiewicz [198]

Exterior building detailing or articulations incorporated as elements of the facade or, which perhaps, are due to the structural floor plate changes can impact the flame projection and associated heat exposure to the façade. Work done at the National Research Council of Canada [198] showed the extent to which a horizontal projection located above flames issuing from a window can be effective at reducing the flame exposure. This work also showed that vertical exterior elements could increase the vertical projection of flames along a façade. Figure 13.15 illustrates the change in fire flame position and extension due to a horizontal projection above a window and vertical panels located at each side of a window.

In terms of hazard reduction or increase, Fig. 13.15 illustrates how the deflection of the flame by a horizontal projection reduces the heat transferred to the wall above the burning compartment. Conversely, the vertical projections increase the heat transfer to the wall. The increase in heat flux with vertical projections installed is due to the restriction of lateral air entrainment, which forces a lengthening of the gas plume as it seeks to entrain more air for combustion.

Balconies and Building Exterior Appendages

Design elements of a building such as balconies, terraces, or other extensions outside the building envelope can pose a fire spread hazard due to combustible fuel loads that may be present. In Fig. 13.16, the residential very tall building has balconies with vegetation and a vegetative wall. The size of fire that may occur on a balcony will depend upon the fuel but also the ventilation. Figure 13.16 shows balconies with and without lids or enclosing walls. Enclosed balconies may behave more like a compartment resulting in ventilation-controlled fires with potentially longer flame lengths and higher temperatures than a fully open-air balcony.

The risk of fire spread via the combustible contents of articulated elements of the building or vertically around the facade via the mechanism of flame leap poses potential concerns for very tall buildings. Noncombustible construction of the facade system provides more freedom for the inclusion of planters, vegetative walls, or balconies. Sprinklers can also be added to balconies to help control a fire.

Fig. 13.16 Example of a vegetative wall (Darsheni, CC BY-SA 3.0, via Wikimedia Commons)

Use of Combustible Materials for Decorative Purposes

Two well-publicized fires involving materials used for decorative or aesthetic purposes have demonstrated potential fire safety issues associated with these products, as well as difficulties associated with fighting fires involving these products. These fires include the Borgata Water Club fire in Atlantic City [199] and the Monte Carlo Hotel fire in Las Vegas [200].

In 2007, the Atlantic City Fire Department responded to a fire at the 41-story Water Club Tower finding MCM panels composed of 3 mm aluminum sheets bonded to a 6 mm polyethylene core in flames. The back sides of the panels were covered with 18 mm polystyrene insulation.

The panels were used as a decorative finish on a structural frame set approximately 2 m (6.5 ft) distant from a concrete sheer wall that prevented major fire extension into the building. This fire resulted in large pieces of aluminum flying off the MCM support structure and upward flame spread from the 3rd to 38th floor. Fire department personnel indicated that the fire was of relatively short duration having subsided 10–15 minutes after fire service crews began their engagement at the building [199]. The Water Club Tower fire is an example of building designers using MCM panels and polystyrene insulation in a creative, but nonstandard way that did not fully consider the fire risk implications.

In the case of the 32-story Monte Carlo Hotel and Casino in Las Vegas, Nevada, exterior wall/facade system features were the fuel source for a fire reportedly started by work activities on the roof. The exterior facade system consisted of an EIFS used to clad flat areas of the building from the 29th to 32nd floor.

Materials that were not part of the EIFS system were installed to add decorative cornices between the 28 and 29 levels and at the top of the 32nd floor. The investigation report [200] cites the non-code compliant decorative elements consisting of expanded polystyrene (EPS) with a polyurethane resin as the primary reason for fire progression. Also, although the EIFS was found to have a non-compliant thickness of lamina, it was observed to burn only in the area of fire exposure [200]. In summary, the decorative EPS features were not code compliant and formed into components of relatively large thickness (200–900 mm) which provided the primary fuel for this fire incident. The EIFS contribution to this incident was limited.

Specialty Facade Systems: LED Display Screens, Photovoltaic (PV) Systems, and Vegetative Walls

The building envelope can also be formed or covered with other systems such as LED display screens, photovoltaic (PV) systems, or vegetative walls. All of these are combustible, and although they may not be part of the building fabric, they are a route to fire spread and need to be considered and evaluated for the potential fire spread risks.

The fire safety issues associated with each of these are listed in Table 13.3.

Table 13.3 Fire safety issues associated with different facade systems

Type of specialty facade system	Fire safety considerations
Photovoltaic (PV) systems and panels	PV panel installations present both an ignition source and a fuel source that can lead to significant fire event. One of the fire safety considerations for PV panels is how the panel and its mounting system impact the combustibility of the overall roof system or associated facade system. Many solar panels include a backing of combustible plastic that will contribute combustible content for fire spread if ignited
LED display systems	LED screens, panel, or mesh systems installations present both an ignition source and a fuel source that can lead to a significant fire event LED systems include plastic-insulated wiring and other plastic components that will contribute combustible content for fire spread if ignited
Vegetative walls	Vegetative walls should be irrigated to keep the plants and soil wet. Consideration should be given to the type of containers used – combustible or noncombustible materials. Vertical connection of the vegetative wall over more than a couple of stories should be avoided. Large-scale fire testing of the proposed facade system may be required if the extent of vegetative wall is substantial. A risk assessment should be undertaken to establish if the irrigation system needs to be part of the fire safety systems, i.e., provided with a reliable water and power source

Fire Testing of Designs

To comply with building regulations, building envelope systems in high-rise buildings must be noncombustible or, if combustible, pass a series of fire tests to show that the proposed facade system assembly is designed to limit flame spread vertically and horizontally across multiple floors. Where combustible components are proposed, generally the materials must meet the requirements for small-scale fire tests of the component materials and large-scale fire test(s) of the actual proposed facade system(s) for the project. The large-scale tests are intended to mimic two or more floors of a building with a fire starting in the lower floor and breaking out through an opening or window. Building regulations vary from country to country, and these statements may not apply to every jurisdiction, but the risks due to vertical and horizontal fire spread are the same everywhere. Examples of language regarding the required tests can be found in the relevant codes and are summarized by White and Delichatsios [196].

Fire testing of the building envelope systems falls into four main categories:

1. Reaction to fire tests of the constituent materials
2. Fire resistance testing of perimeter fire barrier systems with or without fire-rated spandrels or the entire glazing system if the facade is to be fire rated
3. Large-scale fire testing of the exterior wall assemblies and/or facade assemblies
4. Large-scale testing of the roofing system

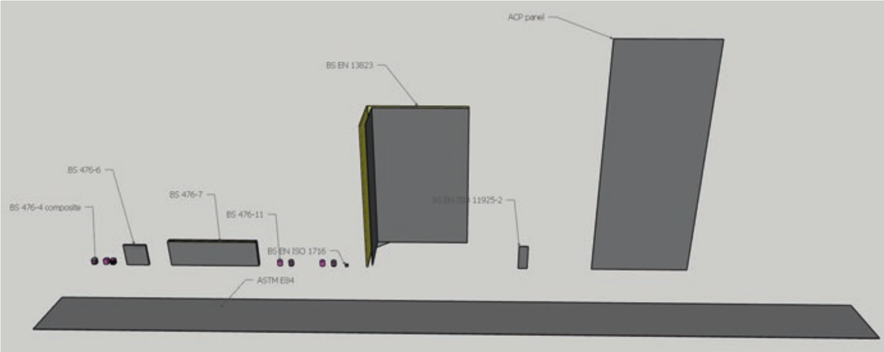


Fig. 13.17 The various scales of reaction to fire test drawn against a typical facade cladding panel (Courtesy of Arup)

These are discussed further in the following sections.

Fire resistance testing of the exterior wall assemblies may also be required if the building is near a neighboring plot/building. Fire resistance testing is addressed elsewhere in this guide.

Reaction to Fire Tests of the Constituent Materials

Material tests typically consider ignitability, flame spread, and combustibility. Noncombustible generally means a material will not ignite or burn. Local building regulations will typically include prescriptive definitions and performance requirements or limitations to classify materials as noncombustible. Some jurisdictions define limited combustible materials. A limited combustible material is one that will ignite and burn but has passed certain code-mandated fire tests such that ignition and combustion are substantially more difficult.

Figure 13.17 illustrates the range of sample sizes that are tested in reaction to fire tests compared with a typical facade cladding panel. These small-scale fire tests are intended to characterize the fire performance of a material, but they do not replicate a real fire involving a facade system.

Fire Resistance Testing of Perimeter Fire Barriers With or Without Spandrels

Perimeter fire barriers with or without fire-rated spandrels should be tested in large-scale mock-ups of the facade system. ASTM E2307 [201] (see Fig. 13.18) and EN 1364–4 (see Fig. 13.19) [202] are examples of these tests. These are the only tests

Fig. 13.18 Sample ASTM E2307 [201] fire test (Courtesy of Thomas Bell-Wright International Consultants)

that reflect the stiffness of the facade system during a fire exposure and its ability to hold the perimeter fire barrier system in place. Both tests expose the perimeter fire barrier system to a standard fire exposure representative of a fully developed compartment fire. Fire rated expansion joint systems tested between two concrete or blockwork slabs/walls may not be representative of design conditions where a facade system interfaces to the perimeter floor slab.

Fire Resistance Testing of Fire-Rated Facade Systems

Fire resistance testing is conducted in a furnace, typically 3 m x 3 m (9.8 ft. x 9.8 ft) to a standard fire exposure as defined by ASTM E119, EN 1364–3, or equivalent. In terms of test size and fire exposure, it is the same standard furnace test as that described for load-bearing elements of structure in Chap. 12 (Fire Resistance). As a facade system is usually non-load bearing, the test specimen is not loaded and pass/fail is based on insulation (temperature transmission) and fire integrity. The tested assembly must match the proposed facade system design. The applicable building code and overall building fire safety strategy identify if the building's exterior wall

Fig. 13.19 Sample EN 1364–4 fire test [202] (Courtesy of Efectis)

enclosure requires a fire resistance rating. In the model building codes, there are numerous provisions that stipulate if and where exterior walls require a fire resistance rating.

Large-Scale Fire Testing of the Facade System

When limited combustible materials are used as part of the facade system design, then a combination of reaction to fire testing described above and large-scale fire testing is relied upon to justify the design. The full-scale fire tests must adequately

Fig. 13.20 Sample NFPA 285 fire test (Courtesy of Thomas Bell-Wright International Consultants)

replicate the actual facade systems on the building which means that more than one test may be necessary for a project.

There are many forms of these large-scale fire tests in use around the world including NFPA 285 [195], ANSI/FM 4411 [203], and ANSI/FM 4880 [204] in the United States, ISO 13875-2 [205] internationally, Australia's AS 5113 [206], BS 8414 [207] in the United Kingdom, and several throughout Europe (e.g., SP 105 [208] in Sweden, LEPIR 2 [209] in France) although the European community is looking at harmonizing a test for use throughout Europe. Figures 13.20 and 13.21 show a NFPA 285 fire test rig and a BS 8414 test rig, respectively.

The size of the fire, size, heat flux and details of the test rigs (height, width, return wall or not, windows or not), duration of the test, measurements taken during the tests, and pass/fail criteria vary from test to test. While there are many differences, most of them involve a test rig that represents two floors of a building, a fire source at the base of the test rig and/or in a room in the lower part of the test rig. The test standards typically require the testing laboratory to measure flame height at the top of the test rig and flame spread horizontally along the test rig. They also measure temperatures achieved within the facade system, on the surface of the facade, and within the rooms behind the façade. Pass/fail is based on a maximum flame height or horizontal projection and maximum temperatures within the facade system or floor above the fire.

Fig. 13.21 Sample BS 8414 fire rest (Courtesy of Thomas Bell-Wright International Consultants)

It should be noted that the large-scale standard fire tests of facade systems are relatively simple empirical tests of a complex facade system with a single result of pass or fail. The reasons for a facade assembly comprising combustible or limited combustible materials passing or failing one of these tests is not well understood by academics or industry. Even experts from test laboratories, consultants, and academia find it difficult to predict test success or failure. There are no correlations to predict a pass/fail, for example, the industry does not know the impact of cavity width on fire performance, and it could be that there is an optimum cavity width which propagates flames. For this reason, relying on large-scale fire testing for very tall buildings requires careful consideration, and engineering judgments should be avoided. Furthermore, there is no certainty that a facade assembly passing one type of standard fire test will pass other tests.

It is also important to note that for the results of the large-scale test to be relied upon, the actual facade system(s) on the building must match the tested facade system. This means several fire tests may be required, and the project team must make sure the facade system is not inadvertently altered due to late changes or poor construction practices.

There are noncombustible materials that can achieve desired aesthetics and U-values for thermal insulation and should be considered for all very tall buildings, especially in areas where construction and quality or thoroughness of inspection is less consistent.

Fire Testing of the Roofing System

Roof covering systems are tested by evaluating the propensity for surface flame spread and penetration by burning brands. Roofing systems are generally subject to well-established fire test procedures. One such fire test is ASTM E108, Standard Test Methods for Fire Tests of Roof Coverings [210], which is conducted to classify (i.e., Class A, B, or C ratings) a roof covering's relative resistance to exterior fire exposure. The maximum flame spread is 6 feet for a Class A rated roof, 8 feet for Class B, and 13 feet for Class C. The slope of the test specimen is pre-established, and since steeper slopes are more of a challenge, the rating applies to the maximum slope passed. For roof assemblies with combustible decks (wood, plank, tongue, and groove), ASTM E108 requires two additional fire tests: (1) an intermittent flame test, in which the flame is turned on and off at a specific schedule during the duration of the test, and (2) the "burning brand test," which measures the ability of the roof assembly to resist surface flame spread and penetration of the roof covering resulting from flaming embers.

Roof assemblies using above-deck foam plastic insulation are typically required by model codes to install a thermal barrier (e.g., ½ inch gypsum board) between the deck and foam plastic insulation unless the roofing systems meets the requirements of fire tests evaluating the performance of the roof assembly when exposed to a below-deck fire exposure. Examples of such tests are FM Approval Standard 4470 for Class 1 Insulated Steel Deck Roofs [211] and UL 1256 Fire Test of Roof Deck Constructions [212]. These tests are used to evaluate the contribution of the roof assembly components to allow fire spread below the roof deck into a building.

If the roof comprises decorative add-ons (e.g., a crown), then the add-on should meet the same requirements as the facade system. The lower fire test standards for a roof structure are not appropriate. This is especially true where the roof add-on and the facade system are continuous.

Installing roof mounted solar panels above a roof assembly changes the fire dynamics of a roof fire and can negate the rating for the roof assembly by itself. Adhesive used below the PV panel and re-radiation can significantly add to fire spread. Solar panels should be tested as part of the roof assembly.

Certification

Certification of fire test performance is provided by third-party organizations accredited in accordance with ISO/IEC 17065 [213] and a suitable scope of accreditation. Third-party certification of products and assembly designs provides confidence that the recognized product and/or assembly is representative of actual manufacture and the product/assembly that was tested.

Risk Assessments

If combustible or limited combustible materials are used in a design, then fire testing and certification as described earlier may be important to understanding the facade design or enclosure fire performance. There may circumstances where a project-specific risk assessment should be undertaken by a qualified fire safety engineer/professional as part of a holistic fire safety program for the building. A risk assessment can be particularly useful in the evaluation of a facade on an existing building.

Several factors to consider in a risk assessment of a facade system design and particularly upward fire spread at the building facade include, but may not be limited to, the following:

- Fire hazard – fuel loads, ignition sources, materials of construction, continuity of combustibles, or materials of construction over the height of a building
- Security threat assessment scenarios
- Automatic sprinkler systems' reliability
- Extent of the automatic alarm system
- Robustness of egress provisions
- Fire department/brigade response capabilities
- Building height
- Building occupancy considerations – e.g., office, residential, hospitals, and mercantile
- Building compartmentation features
- Building evacuation strategies
- Compartmentation

In response to the many major facade fires internationally, the NFPA Research Foundation funded development of a risk assessment tool, EFFECT™ (Exterior Facade Fire Evaluation and Comparison Tool), specifically aimed at existing buildings with combustible facade systems. The primary objective of EFFECT™ is to evaluate the potential risk of vertical and horizontal flame spread beyond the story of ignition. While not intended to be used for design of new buildings, the methodology and background report describe the key issues to be considered in any risk assessment of facade systems and address the issues listed above except a security threat assessment [57].

Security threat assessment scenarios should consider the impact of any damage scenarios on the performance of the buildings fire protection features and, specifically, the sprinkler systems. The survivability of sprinkler system features and water supplies may be critical to prevent a major fire spread event that results from a security threat scenario.

EFFECT™ primarily addresses residential and commercial office buildings [57]. Other occupancy considerations that may impact the assessment of vertical exterior fire spread risk are:

- Assembly occupancies – They have large and potentially dense populations of occupants. Often these occupancies are found at the very top stories of very tall buildings.

- Hospital facilities – These are facilities in which occupants can be expected to require assistance from staff and are physically not capable of relocating to lower levels or to the building exterior. This may be the most critical situation that deserves consideration of the exterior fire spread risk. Horizontal exits, where a floor is subdivided into two fire areas, are often used in hospital facilities and can be a mitigating factor in the risk assessment for hospitals or other occupancy groups.
- Very tall buildings – These are buildings with large occupant loads and long total evacuation times (e.g., > 1 h). In an unsprinklered, very tall building fire scenario, fire spread by vertical means, whether exterior or interior, may unnecessarily subject a large number of occupants to adverse conditions from a single fire event.

While sprinkler systems will not prevent vertical fire spread on the exterior of the building, their role in protection of very tall buildings is so important that the following sections discuss these specific systems.

Sprinklered very tall buildings have a very successful record of life safety and property protection performance. These systems are critical to the fire safety of very tall buildings as they are designed to control a fire until the fire department can respond. For this reason, many modern building codes do not require fire resistance-rated spandrels or flame deflectors at the building facade in fully sprinklered buildings. Significant reliance on sprinkler systems becomes exceedingly more critical for very tall buildings. As the height of buildings increases, so does the complexity of sprinkler systems with an integrated network of piping zones, valves, pumps, power supplies, and water supply tanks. Many components are required to be operational and operated properly for the sprinkler system's success.

Sprinkler system maintenance can be a major maintenance activity for today's very tall buildings and is key to successful performance. A recent analysis [214] of data from the National Fire Incident Reporting System (US data) indicates that for all building types, sprinklers failed to operate in 7% of structure fires. The identified reasons for these failures were 65% of the systems were shut off, 16% were defeated by manual intervention, 11% were due to lack of maintenance, 5% of the systems were the wrong type, and 3% were due to damaged system components. These failure rates may or may not be applicable to new very tall buildings, but it is important to note that human error is the primary factor. Consequently, it is important for buildings with complex sprinkler system design to have features and redundancies that can overt issues of human error and maximize sprinkler system reliability (e.g., electrical supervision of components).

Sprinkler system designs can be enhanced to improve their reliability. Gravity feed systems that do not rely solely on electric pumps and emergency power supplies can assure that pressure is available to supply sprinklers. Also, piping schemes that use riser cross-connections or feeds from alternate floors can provide additional assurances that a single closed valve does not negate sprinkler water flow. Electrical supervision of valves and other sprinkler components has long been recognized to be the most important feature to monitor sprinkler operational status. The value of sprinklers was observed in the One Meridian Plaza incident where ten sprinklers supplied by fire department pumpers are reported to have stopped fire spread after burning for 19 h. If buildings' sprinkler systems can be designed so that successive floors cannot be turned off with a single valve, then a significant level of redundancy to protect against vertical exterior fire spread can be maintained.

Fire department response capabilities should be factored into the vertical exterior fire spread analysis for very tall buildings. Prior incidents in unsprinklered buildings demonstrate the difficulty that large, capable fire departments may have for buildings 60 stories or less in height. Many of the new class of high-rise buildings will double or triple this height. An important question in this regard is, "Does the local fire department have the response capabilities and response plan to handle an unsprinklered fire in a very tall building?" If the answer is "no," then, again, great reliance is shifted to the automatic sprinkler system.

Chapter 14
Suppression

Controlling the growth and spread of a fire in a very tall building is of paramount importance, and there are several systems needed to contribute to this goal. Compartmentation and fire-resistive construction are key elements in the ability of a very tall building to limit the impact of a fire, but they can only limit the growth and spread to the amount of fuel contained within the boundary of the fire barriers forming the compartment. Controlling the fuel load within fire compartments is typically accomplished by both compartmentation and the use of active fire suppression systems.

As observed in numerous fire events, one of the most infamous being the One Meridian Plaza fire in Philadelphia, PA (see Chap. 2, History), fire sprinkler systems are critical in the ability of a very tall building to limit the growth and spread of a fire in a very tall building. Sprinkler design codes and standards used throughout the world provide the designer with guidance in the basics of designing and installing sprinklers within buildings. However, they do not focus on some of the challenges associated with designing and installing sprinklers, and related systems, in very tall buildings.

Risk Assessment

The design team will need to consider the risks imposed by the individual project and how those risks may impact the design of the building's fire suppression systems. For example, if the project is being built in a geographical area where the water supply is not reliable, then provisions will likely need to be made in the project to provide a fire protection water supply for the building's sprinkler operations. The water supply should be of sufficient capacity to support fire department operations, and allow for complete building evacuation.

Today, for most very tall buildings, sprinkler systems are designed based on evaluating the occupancy classification of the intended use of the building and using a

Fire Safety for Very Tall Buildings, The Society of Fire Protection Engineers Series, https://doi.org/10.1007/978-3-030-79014-1_14

prescribed design discharge density that is commensurate with the occupancy classification to determine the overall amount of water needed to suppress a fire in this anticipated occupancy. This is an abridged approach to assessing the fire hazard and designing the suppression systems to control or suppress the potential fires associated with such hazards. The sprinkler designer will need to consider the results of the risk analysis performed early in the life of the project design (see Chap. 7, Hazard, Risk and Decision Analysis in Very Tall Building Design) to identify design parameters that need to be incorporated into the overall project.

Fire Strategy

The fire suppression systems for a typical office or residential occupancy are generally intended to control the fire, anticipating the fire department to be summoned to finalize the task of extinguishment, if necessary. In this case, the fire sprinklers serve two primary purposes, that of detecting and notifying of the presence of the fire and that of controlling its growth and spread until fire department arrives. Therefore, it is important to involve the local fire department as a stakeholder early in design so they can share their operational approaches and best practice design considerations that are likely to shape the overall design of the suppression systems they may ultimately be using to fight a fire in the building.

On the other hand, if the fire department in the location of the project is expected to be challenged in fighting a fire in such a unique structure, then the designer may consider increasing the design discharge density. Increasing the design discharge density gives the system the ability to discharge sufficient quantities of water to more likely extinguish the incipient fire rather than to merely control it. For very tall buildings, this may be a preferred strategy since the response times within the building may be delayed due to the building's height.

Meanwhile, in areas of the world where water supplies may be severely limited and perhaps are not available to support standard fire sprinklers, alternative active fire suppression strategies must be considered. One such alternative strategy may include the use of water mist technology. Water mist operates on similar principles as standard sprinklers, where water is released into the fire compartment is converted to steam, removing energy from, and reducing temperatures within, the fire compartment. Water mist uses water droplets that are much smaller than those issued by standard fire sprinklers (50 microns compared to greater than 1000 microns), significantly reducing the water demand. However, water mist systems are quite different than fire sprinkler systems in that the water mist systems must be designed in strict accordance with proprietary guidelines that the water mist system manufacturers have developed through conducting fire suppression tests using their equipment. Comparable to fire sprinklers, water mist systems are specific to the occupancy being protected, and water mist is often used in protection of some higher hazard areas (like emergency generator rooms, etc.). Many of these system manufacturers have systems that are specifically engineered and locally approved for the fire loads anticipated in the occupancies most often found within very tall buildings, those being office and residential occupancies. It is a technology that is prevalently used throughout Europe. Costs and maintainability are key considerations for the use of this alternative technology.

Other strategies for controlling fire growth may be developed to address the unique nature of a project, and those strategies likely involve other systems as described in other chapters of this guide. Coordinating those strategies with the design and arrangement of fire suppression systems may be necessary.

Reliability

Appropriately designed, installed, and maintained fire sprinkler systems can be remarkably reliable. A 2017 study identified the five leading reasons for failure of sprinklers in the United States [214] as follows:

- System shut off prior to fire ignition.
- Manual intervention that defeated the system.
- Discharged water did not reach ignited combustible materials.
- Insufficient water discharged to protect the hazard.
- Lack of maintenance.

Three of these five top reasons were among the top five in a similar 1970 study, indicating the issues have not generally changed in 50 years [215].

Given the importance of sprinklers or fire suppression alternatives in providing protection within very tall buildings, the system designer should consider redundancies and system enhancements to directly countermand these reasons for system failure. Implementing one or more of these enhancements will increase the reliability of the sprinkler systems. Features to enhance the system reliability may include:

- Multiple points of supply for floor sprinkler or suppression alternative systems
- Alternating floor supplies from different risers
- Electronic supervision of floor control valves
- Rigorous control of system isolation, frequent maintenance, and inspection programs
- Gravity source of water supply for sprinklers or suppression alternative systems
- Cross-connecting standpipe/sprinkler risers at multiple points vertically with control valves arranged to permit shutdown of one riser without shutting down the other
- Re-evaluating appropriateness of sprinkler or suppression alternative system design and arrangement upon tenant changes

Improving the reliability of system operations and components enhances the effectiveness of the suppression systems. Multiple water supplies, redundant fire pumps, looped systems, and other backups will improve reliability. Ongoing and frequent maintenance and inspections will also improve reliability.

Using one, or a combination, of these enhancements will improve the operating reliability of the sprinklers. The designer will need to consult the fire strategy to determine the level of enhancement that is needed for a given project.

System Documentation

The strategy employed in designing fire suppression systems for a given project is unique. Therefore, the design approach to be used in designing the systems for the project needs to be documented so that the building owner and future architects and engineers who may be designing modifications and alterations are aware of key system design concepts. The fire strategy, as described in Chap. 7 (Hazard, Risk and Decision Analysis in Very Tall Building Design), is one potential medium that can be used to document all the decisions going into the design of fire protection water supply, suppression, and standpipe systems.

Key Issues

Most of the issues surrounding suppression systems in very tall buildings have to do with the water supply, the pressure problems that result from elevating the water to extreme heights, and the building's reliance on the need for fire pumps to elevate the water within the building.

Water Supply

Availability and dependability of the municipal water supply will dictate overall on-site storage needs. Some very tall buildings are planned in locations that will eventually become a city. However, there may be no public utility infrastructure in place. Very tall buildings cannot wait for a water supply of adequate duration to arrive with the rest of the city, and therefore appropriate on-site storage needs to be considered.

Primary water supplies will need to consider sprinkler and standpipe demands. In most buildings, the water supply system is generally designed for the larger of either the sprinkler or the standpipe demand. This is predicated on the understanding that the fire department will respond in emergency situations and is able to supplement the water supply for the two systems. However, because fire department apparatus will generally not be capable of reaching the top of the building, fire protection systems in very tall buildings need to be designed to be essentially self-sufficient.

In a very tall building, the designer should consider providing a system capable of meeting the combined demands of sprinklers and standpipes. Discussions with the fire department will provide better understandings of their anticipated tactics for deploying hose streams, which will help the designer to identify necessary flow rates and pressures needed. This will drive the determination of the standpipe system demands.

Many property insurers have established their own required site water supply requirements, including storage duration. Therefore, it is in the best interests of the building owner and the building design to reach out to the anticipated building insurance early in design to obtain the pertinent information that could impact the designed amount of stored water.

Primary and backup water supplies should be considered. If the municipal water supply is reliable, considerations should be given to at least two connections to the city water mains, preferably from two separate mains. In addition, on-site water supplies from storage tanks should be considered as a backup source. These storage tanks should have sufficient capacity to meet the fire design strategies.

Reliability of the water supply will also be a key consideration for very tall buildings. Since the fire suppression and standpipe systems will depend upon pumps for moving water up to the top of the building, backup pumps, gravity-based storage supplies, or both may be considered to enhance the reliability of the water supply system. Figure 14.1 depicts one approach for providing a gravity-based water storage system for building sprinklers.

Durations to be used to determine water storage capacities will vary depending upon the fire strategy and will need to be discussed and agreed upon with the local fire department. One approach is to provide a water supply sufficient to maintain sprinkler water flow for a duration equivalent to a full building evacuation. This approach could result in a need to store large quantities of water, which will impact structural design and architectural planning. Another approach would be to provide water sufficient to accommodate system operation until local fire department deployment can be achieved. This approach is likely to result in much less water storage requirements than the aforementioned approach. The water storage issue needs to be addressed in the overall fire strategy and then discussed, resolved, and agreed upon with local fire officials early in the design of the building since finding locations within the building for water storage tanks late in design will be extremely challenging.

In seismically active areas of the world, a secondary water supply within the building may be required by local codes in anticipation of a potential disruption to the municipal water supply to the fire protection systems. If the water supplies of the building are generally self-sufficient (i.e., not reliant upon a constant connection to a municipal water supply), there is little need to consider additional storage in case of severe seismic events since the planned water supply likely meets or exceeds those requirements. Nevertheless, it is important to keep seismic design considerations in mind with the development of the water supply system design.

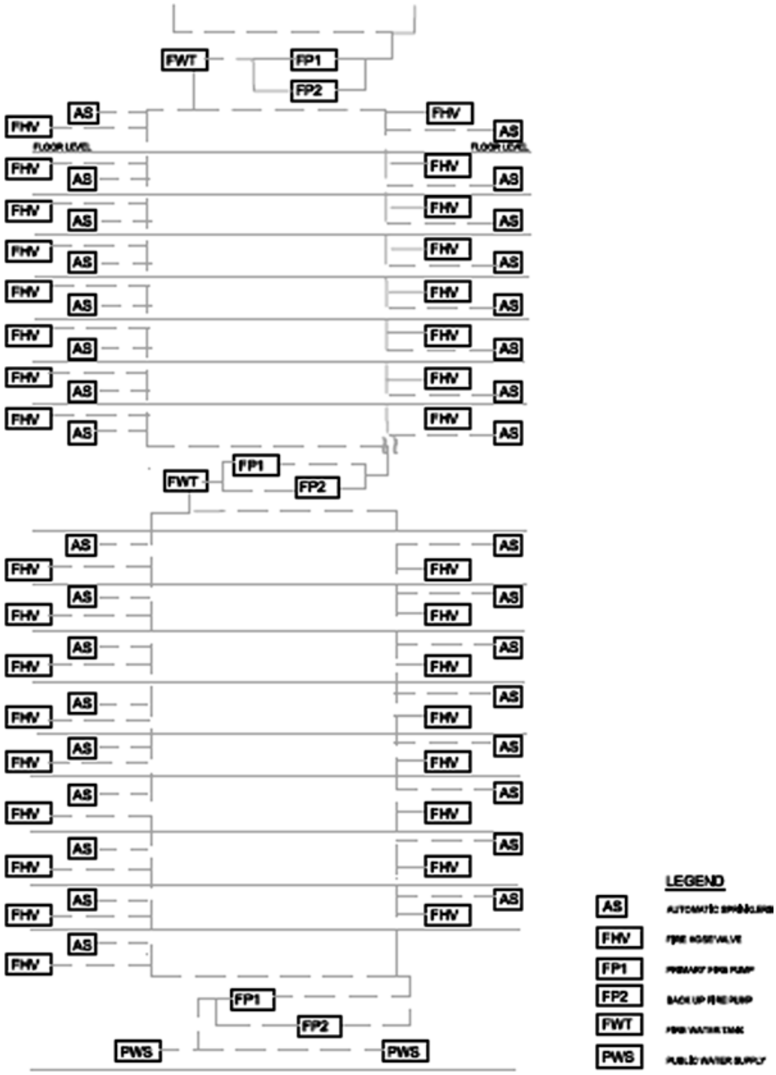


Fig. 14.1 Example of a Gravity-based water storage system for sprinklers

Pressure Control

Sprinkler and standpipe system components are typically limited to maximum working pressures of approximately 1200 kPa (175 PSI). Components with higher working pressures are available. Combined with city water pressures and booster pump pressures, system components in very tall buildings can be readily exposed to pressures exceeding their maximum typical working pressures. Designers need to consider this issue as they develop their designs of the standpipe/sprinkler riser systems. Establishing the heights associated with vertical zoning is a critical consideration directly related to controlling pressures within the zone.

There are several means to conceptually design the pressure zones in a sprinkler and standpipe piping system. Vertical zones of piping can be designed so that the entire zone of piping maintains pressures less than the 1200 kPa (175 PSI) working pressure. However, the express risers feeding such vertical zones located high in the very tall building will need to be designed to accommodate pressures more than 1200 kPa (175 PSI).

Another alternative is to permit the risers to maintain higher pressures than the normal 1200 kPa (175 PSI) maximum working pressure but then design the floor sprinkler piping and equipment to realize the normal maximum working pressures of 1200 kPa (175 PSI). In this case, equipment is needed to modify or reduce the pressure so that the floor piping and equipment realize working pressures not exceeding their designed maximums. The final approach is to design all system components for the maximum anticipated system working pressures, making sure to not exceed the maximum working pressure of the designed equipment. Typically, a combination of the first two options is used to control pressures in very tall buildings.

Using devices designed to modify (or reduce) pressures on parts of the system is common in very tall buildings. These devices generally fall into two categories, ones that operate in both static and dynamic (or flow) modes and those that operate only in dynamic mode. Those that operate only in dynamic mode, such as flow-restricting orifices or pressure-restricting valves, will permit a static pressure that may exceed the maximum working pressures of typical system components. Pressure-regulating (or reducing) valves (PRVs) are often used because they can regulate pressures in both static and dynamic modes. It is recommended that the designer considers both static and dynamic pressures when choosing pressure-reducing equipment. This will ensure that the equipment is suited for the pressures likely to be realized in that portion of the system.

PRVs function based on the use of a heavy-duty spring. Being a mechanical device, they require periodic maintenance and testing to be sure they continue to operate as intended. Without proper maintenance and testing, they have been known to failure. See discussion in Chap. 2 (History) on One Meridian Plaza fire.

Another means to control pressures within sprinkler and standpipe systems is based upon the use of variable speed driven fire pumps. Normally, fire pumps run at a relatively constant, rated speed, at which point they deliver a given flow rate at a given pressure. In a variable speed driven pump, the speed of the pump motor is varied based upon the demands of the system. Such systems use controllers and pump motors specially designed for variable speed arrangements.

Flow Control

After the collapse of the World Trade Center Towers, one factor identified to have affected the ability of the fire department to fight the resulting fires in the towers was that the planes flying into the building compromised the building standpipe systems by shearing the risers. This resulted in loss of the entire standpipe system and a loss of the system to feed water to other fire protection systems. Component manufacturers responded by developing a valve that is designed to automatically shut down, or close, when there is an excessive flow (meaning beyond that for which the system is designed to flow) combined with an excessive loss of pressure on the system. These devices are commonly referred to as automatic breach control valves.

The intent is to strategically locate automatic breach control valves (ABCVs) on the building fire protection risers so that loss of a riser would not render the rest of the fire protection (sprinkler or standpipe) system unusable. A riser could be lost for several reasons (including significant damage to the building), but a more common reason that a fire protection riser would be lost is the failure of a fitting or device (possibly due to water hammer). An ABCV in the right location could help to minimize the amount of the system that is out of service until the repair is completed.

Because of the nature of the ABCV operation, the operational pressure and flow design range are quite challenging to determine without adversely affecting the operation of the fire protection systems. For instance, if the operational flow (with a margin of safety to allow for extra sprinkler operation or additional or excessive hose streams operation) and pressure are not properly identified or the ABCVs are not properly exercised and maintained (see the previous discussion on maintaining pressure reducing valves), operation of the ABCV could result in compromising the flow of water to the fire protection systems downstream of the valve. While ABCVs are an ideal way to increase the overall reliability of the fire protection systems in very tall buildings, other system design features (such as redundant risers) might provide equal or better reliability without the potential for malfunction when needed. The use of ABCVs should be carefully considered and their locations properly identified so that their use does not adversely impact the normal operation of the suppression and standpipe systems.

Fire Pumps

Pumps and other piping system components (including the device into which the fire department would supply additional water) have practical limits on their maximum working pressures that vary depending on the component considered but can reach up to 4200 kPa (600 PSI) for fire pumps. The system designer must design the overall system to not exceed the maximum working pressure of the system component having the lowest design working pressure when designing and specifying the pumps and components for the overall system. For very tall buildings, fire pumps will inevitably need to be located on several stories as the tower rises to keep moving water up the building. Precisely which stories will be are based on the overall building design, the maximum working pressure limitations of the system components, and height of the building.

Reliability of local electrical power supply will also dictate the need for backup power supplies. It is important to maintain a reasonable separation of the backup power supply from the main power supply and that proper protection for pump emergency power supplies is provided. The intent is to reduce the potential that a single reasonably anticipated event is unlikely to disable both power supply pathways. Consideration for impact of the increasing severity and frequency of natural events adversely impacting local electrical power supplies is becoming a normal design for backup power supplies.

Backup pumps should be considered for each pump zone used in the system to get the water to the top of the building. The rationale is that if any one pump in the system design were to fail, most of the building above the failed pump will be left without water, especially where local fire department apparatus is incapable of pushing water up to the highest parts of the building. To enhance the reliability of the water supply system, the backup pump is typically located in a separate room enclosure from that of the primary pump. Both pumps and their respective controllers and power transfer switches should be located within rooms whose walls are designed to be fire-rated assemblies. Backup pumps are important because the upper stories are reliant on the operation of pumps located on lower stories to serve the pumps supplying water to these stories.

Standpipe Systems

Fire suppression systems in very tall buildings typically include both automatic sprinkler and standpipe systems. The automatic sprinklers will detect and control or extinguish a fire, whereas the standpipe systems feed the fire hose lines for fire department responding personnel. Responding personnel will connect their hoses to standpipe valves located within the building to enhance and promote extinguishment of the fire or use hose already in place on hose reels or racks. These valves and hose reels are typically located within the stairwells or corridors and are served by both building fire pumps and responding apparatus.

Due to the height of very tall buildings, local fire department apparatus may not be capable of supplying sufficient pressures to feed hose lines in the building. The designer should discuss the suppression strategy with the local fire department prior to designing the standpipe systems. Where building fire pumps are used solely to feed these systems, redundancy of the fire pumps to enhance reliability should be considered in the design.

Due to the height of very tall buildings, multiple standpipe pressure zones are likely. As noted in the pressure control section above, standpipe zones are also regulated by pressure. Hose valves are typically limited to 1200 kPa (175 PSI) as well. However, a standpipe pressure zone can also be limited to 2400 kPa (350 PSI). Where heights require higher pressures, multiple standpipe pressure zones need to be employed. These zones can be supplied by express risers exceeding 2400 kPa (350 PSI). Hose valves should not be connected to those portions of the system that exceed 2400 kPa (350 PSI).

Water Hammer

There are various mechanisms by which water hammer can occur in a system. The classical type of water hammer is the rapid closing of a valve in a piping system to stagnate a flowing fluid or a rapid start-up of a pump delivering a fluid to a voided section of pipe. A type of water hammer mechanism that is especially important to consider as part of a fire suppression system design for very tall buildings is one induced by column separation and rejoining.

Column separation and rejoining refers to the phenomena where the liquid drains away in a section of pipe resulting in the formation of a very low, near vacuum, pressure void. The void volume is occupied by low-pressure saturated vapor corresponding to the fluid temperature. As an example, water at 21 °C (70 °F) has a saturation pressure of only 0.36 psia. Column separation and rejoining is susceptible in any piping configuration that changes 9.1 m (30 ft) or more in elevation, which is especially true for systems that employ the use of standpipes.

For piping that changes elevation by 9.1 m (30 ft) or more, it is important to evaluate if a possibility exists for the liquid to drain down from high elevation during normal and abnormal modes of operation. Abnormal refers to, for example, an unanticipated pump trip and restart. Additionally, will the drain down result in column separation and the formation of a low-pressure void? If so, then a subsequent restart of the flow into that voided space will lead to column rejoining and a potential water hammer resulting in high pressure and forces on the piping.

Water hammer mitigation strategies should consider passive and active aspects of the design that prevent the liquid drain down. If a drain down cannot be designed away and has the potential of occurring, then additional design features should be implemented to dampen the severity of the water hammer, such as the use of vacuum breakers or accumulators. Such features will result in the injection of noncondensable gas into the voided space, thus resulting in a noncondensable gas-water water hammer rather than a steam condensation-induced water hammer.

Facilities for Testing

Adequate facilities to test and maintain the equipment used in pressurizing or controlling sprinkler and standpipe system pressures need to be provided as a part of the entire building system. Every fire pump and pressure control device used in the building needs to be operated at capacity on a periodic basis to maximize the potential it will work when needed. This means that water needs to flow, which means appropriate systems and facilities need to be put in place to accommodate the necessary testing and maintenance. The One Meridian Plaza, fire described in Chap. 2 (History), is a primary example of the failures that may occur when mechanical systems are not periodically operated as designed.

Buildings that use PRVs as a regular part of the design for controlling pressures in the floor systems or fire hose valves must provide a drain riser that is sized to accommodate a full flow through the PRV to permit proper maintenance and testing. Demands for floor sprinklers and hose streams will vary from one location to another, but it is highly likely that the drain riser will need to be at least 100 mm (4 in) in diameter. Likewise, provisions need to be made for handling this water. Discharging the drain into a tank sized to accommodate 30 min of water flow will likely not be adequate for testing hundreds of PRVs.

Designing drain systems for the full flow of fire pumps requires careful consideration. Running fire pumps in churn once a week for 15 min may not sufficiently test the pump. Fire pumps need to be operated at full flow to properly evaluate whether they are operating as intended. Oftentimes the on-site water storage tanks are used to test these systems to allow for the drain to come back to the tank. Designed properly, this arrangement can be used to conserve water. Consideration needs to be taken in the design of these closed-circuit testing systems to avoid overheating of the pump.

Water conservation should be a consideration in the development of designs of drain systems. Being able to recycle fire protection water is critical in many areas of the world. Creating the piping and storage tank arrangements necessary for water conservation will need careful consideration.

Chapter 15
Detection and Alarm

Fire alarm systems are intended to provide notification of fire events within the buildings in which the systems are installed. They provide early warning notification to building occupants and notification of fire events for both on- and off-site emergency response personnel. They also provide control of fire safety functions for fans and dampers to reduce smoke spread, recall and shut down elevators, and control fire doors.

Fire detection is provided through initiating devices such as heat detectors, smoke detectors, flame detectors, multi-criteria detectors, and other fire-related detection devices. Fire alarm systems also monitor extinguishing systems such as automatic sprinklers, gaseous agents, and other extinguishing agents. Recognition of a fire event can also be provided by building occupants via manual fire alarm stations. All these input devices provide an indication that a fire event may be present within a facility. These input functions also serve to initiate specific output functions (see Fig. 15.1).

Output functions include occupant notification, emergency response notification, fire safety functions, and annunciation of input device type and location. Occupant notification can occur throughout the building or within selected zones as required for building evacuation concepts. Emergency response notification can be transmitted directly to the fire department but typically occurs through a third party or by on-site personnel responsible for monitoring the fire detection and alarm system.

Fire/smoke damper and fire door closure are often used to compartmentalize buildings areas to limit the spread of smoke and fire. Fire safety functions also include elevator recall for fire safety service use and building occupant safety, along with shutdown in the event of a hoistway or machine room fire. In very tall buildings, the elevator may be used for evacuation purposes. Occupant evacuation elevator operation requires close coordination between the sequences for the elevators and the fire alarm system. Included in these requirements are a dedicated smoke zone for the elevator lobby and real-time signage for the elevator cars.

There are many brands and models of fire alarm systems available. For very tall buildings, addressable systems using networked panels are a common practice.

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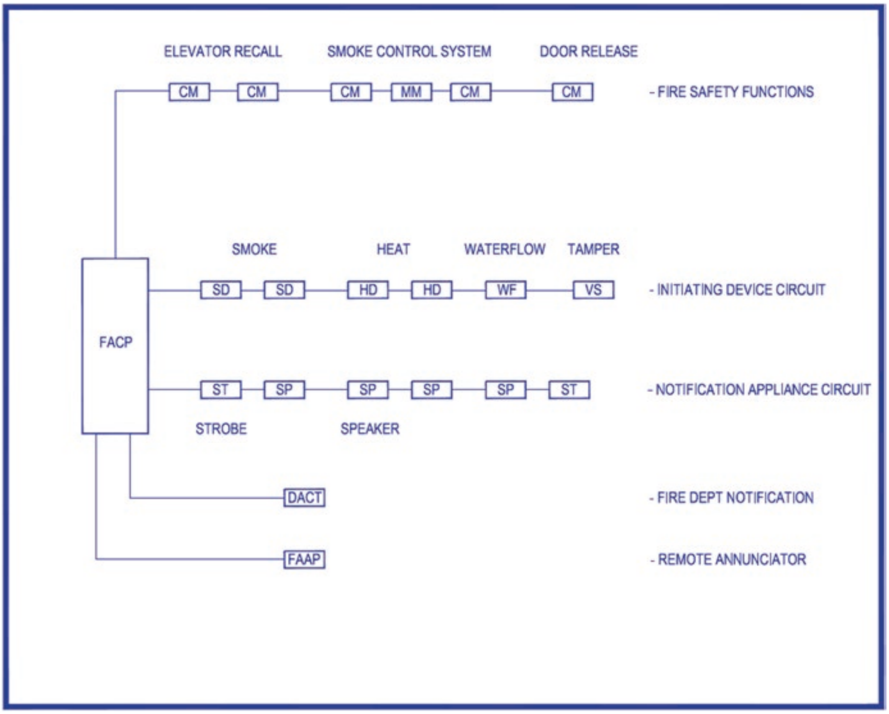

Fig. 15.1 Typical fire alarm system configuration (Courtesy Allyn Vaughn)

Addressable systems allow for a variety of initiating devices to be placed on a common circuit and allow for individual annunciation of the device. This reduces the number of circuits needed relative to a conventional zoned system. These intelligent initiating devices provide discrete information on the device type and location. This aids response time in that the exact alarming device location is displayed at the panel rather than having to survey the incident area. For very tall buildings, this can reduce response time.

Networked systems use multiple panels to distribute circuits and power supplies throughout the building while still allowing for common control and annunciation areas. They can also be configured to allow for control of specific areas if part of the network is disconnected or malfunctions. For very tall buildings, this can be beneficial since panels can provide localized controls if connection to the overall system is lost due to a fire or other events.

Reliability/Robustness

Because the primary function of a fire alarm system is to provide early warning of fire events, its role in a very tall building is crucial. System reliability is important to the building fire strategy. Because many very tall building evacuation strategies incorporate partial evacuation, the ability to communicate to building occupants is important. The fire alarm system must remain operational during events to facilitate this communication.

In the design of fire alarm systems for very tall buildings, the designer should consider the potential for loss of service to certain building areas. How that impacts the overall fire strategy will dictate the amount of redundancy or robustness to be included in the system design. Items to consider are:

- The number of stories being served by an individual panel
- Whether a networked or main/remote system should be used
- A reconfigurable network design versus a standalone degraded mode
- Quantity of primary control panels and their locations
- Required notification for multiple occupancies/events

For very tall buildings, panels are typically distributed throughout the building with a certain number of stories served by each panel. That number varies depending upon design criteria and system limitations. Most systems can easily serve five to seven stories, but even three stories pose a challenge for certain panels. An odd number of stories is generally used, since that allows the floor the panel is located on to be served by the panel while allowing for a certain number of stories directly above and below the panel.

By limiting the number of stories served by a panel, should that panel be damaged, only those stories served by the panel will be impacted. Consideration should be given to limiting the stories served by an individual panel based upon building height. If the building is very tall, it might be beneficial to reduce the number of stories to no more than three per panel. While this will increase the cost of the system, it will also increase the overall system reliability.

Most multiple panel systems are wired with redundant circuitry to increase system reliability. Redundant circuitry will allow the system to operate should there be a fault on a circuit, such as an open, short, or ground.

Consideration should also be given to system configuration. Networked systems allow for each panel to be standalone and serve as a local control panel while sending required signals to other networked panels. Should the network be impacted, a typical system will allow for only that portion of the compromised system to be affected, keeping the remainder of the network operational. This can allow for those areas to be covered by a system capable of basic operation, even though the overall system is not operable (see Fig. 15.2).

Some systems are designed using a control panel that is connected to remote panels in the field. These systems rely on the main control panel to perform all output functions, while the local panels are used to provide local circuits and power supplies. These systems do not allow for the local panels to continue operating should communication to the master panel be lost. For very tall buildings, this approach may not be consistent with the overall fire strategy developed. Instead, it may make sense to network multiple control panels or nodes distributed to provide coverage through very tall buildings.

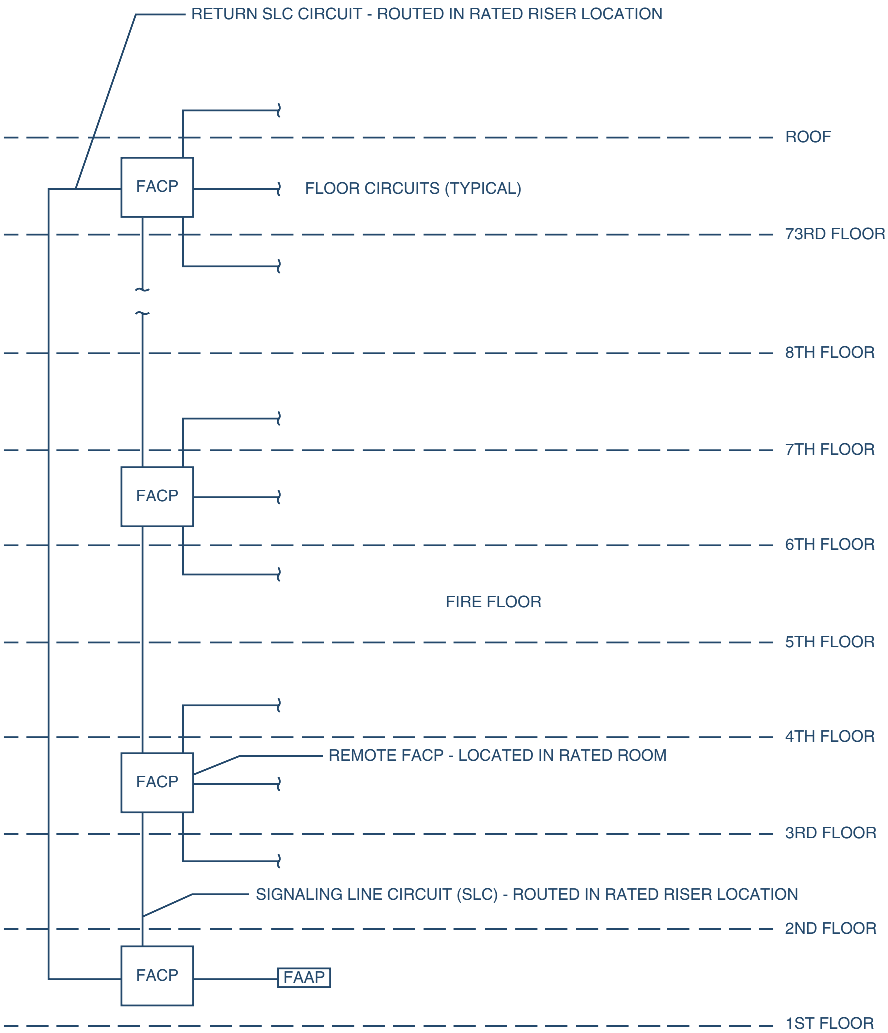

Fig. 15.2 Distributed fire alarm panels with redundant signaling line circuit (Courtesy Allyn Vaughn)

Most networked systems will reconfigure under fault conditions. Depending upon the fault, they may automatically reconfigure to continue operating. This fault can vary from a partial loss of network signal to a complete loss of signal between panels.

When a complete loss of signal occurs, most systems can reconfigure to allow communication between the panels that are still interconnected. This can be useful for very tall buildings since portions of the building will not be completely lost if a break occurs in the network circuit. In addition, most systems are capable of defaulting to a degraded mode that sounds evacuation signals to the story served by the panel if all communication is lost to the remainder of the system. This would allow for at least an evacuation of the stories covered by the panel should an event occur within the building with loss of communication.

Most very tall buildings require some type of fire command center for first responder personnel to access the building life safety systems. When a very tall building has a large footprint and/or multiple towers, it should be determined in the fire strategy and system design whether multiple command center locations should be incorporated. This would provide additional levels of redundancy should the primary command center be blocked or impacted by an event. If this condition occurs, responders and on-site personnel can assemble at an alternate location to monitor and control the life safety systems.

Survivability

For very tall buildings, a large portion of the fire alarm and emergency evacuation system will likely be in non-fire areas. Therefore, it is important to consider system operability during fire and emergency events. For very tall buildings, it is important to have a system operate in non-fire areas even though a fire may impact a portion of the system. Designs can include measures to improve the survivability of the fire alarm system panels and circuits within the building. Some of the design considerations include:

- Protection of panels from fire
- Protection of fire alarm circuits from fire
- Configuration of fire alarm circuits
- Shielding of panels

Consideration should be given so that an attack by a fire within an evacuation zone does not impair the evacuation system operation outside the zone. This will allow system operation and communication to occupants even though a fire may impair other portions of the system.

Some of the design considerations to improve the system to survive a fire event may include panel and circuit protection. It might be desired to locate remote network panels in fire resistance-rated rooms so that a fire event on a floor that contains a remote panel does not impact on the system elsewhere. It may be practical to consider locating the panels in rooms having a fire resistance rating similar to that of the floor assembly. This would provide the same level of protection afforded by the floor assembly to the fire alarm control panel.

Circuit protection, especially for vertical circuits (risers), should also be considered. Since remote panels in very tall buildings will be located on various stories, the circuits that interconnect these panels will run vertically within the building. As with the protection of panels, consideration should be given to the riser protection. This can easily be accomplished by routing them in the same rated enclosures as with the panels and by rating rooms or enclosures that contain just the riser circuits. This will provide protection of the circuits that connect remote panels, as well as devices and appliances on stories, from a fire event.

Selection of circuit classes for fire alarm systems should be evaluated for very tall buildings. Fire alarm circuits are categorized in classes which provide requirements for operation under certain fault conditions based on the communications capability. Basic circuit configurations include those that operate up to the fault condition, such as an open circuit, whereas enhanced circuits operate under single fault conditions. In very tall buildings, consideration should be given to enhanced circuit design for risers and laterals.

Enhanced circuit design will allow portions of the system to continue to operate even though other portions may be impaired. By using enhanced circuit design, the system survivability is increased. Many of the systems allow enhanced circuits to be routed in the same raceways, which allows for increased reliability without significantly impacting overall costs.

In addition to pathway classification, the engineer will need to select the survivability level. Survivability levels have been added to building codes such as NFPA 72® National Fire Alarm and Signaling Code® [216] to provide options to protect the riser and circuits based on customer needs/risks. It is possible to utilize several survivability levels in a very tall building. Depending on the strategy used, the riser may be at a higher level of survivability than the circuits on the individual stories.

Risers interconnecting panels should be designed to incorporate enhanced levels of survivability, whereas horizontal circuits to initiating devices and notification appliances could be either basic or enhanced depending upon the implemented fire strategy concepts.

Risers interconnecting panels should be designed to incorporate enhanced levels of protection, whereas horizontal circuits to initiating devices and notification appliances could be either basic or enhanced depending upon the implemented fire strategy concepts. Enhanced circuit methodology involves the interweaving of basic circuits such that alternating devices are on a separate circuit. This can be done for notification appliances so that if one circuit is impacted, some coverage is still provided by the alternate circuit (see Fig. 15.3).

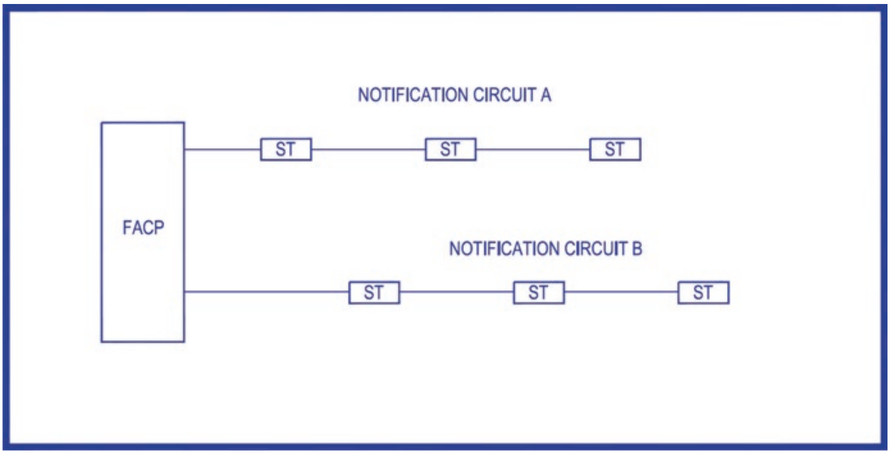

Fig. 15.3 Alternating notification circuits (Courtesy Allyn Vaughn)

Another consideration for protection of fire alarm equipment is to protect the panels located within the room. Shielding of the panels can be done to prevent water damage, as well as locating conduit entries only in the sides and bottom of the panel enclosure and not on the top. This will reduce the potential impact to the electronic equipment inside the panel from water that may otherwise seep into the enclosure from penetrations on the top.

Nuisance Alarms

The primary benefit of a fire alarm systems is to provide early warning of a fire event. This allows for evacuation to occur before conditions escalate while summoning emergency response personnel to the building within an appropriate timeframe. When alarm systems experience nuisance alarms, building occupants can start to ignore evacuation signals thinking that it is just another false alarm. For a very tall building, nuisance alarms can have a detrimental impact to the fire strategy and evacuation schemes.

Maintenance of devices is critical to limit and/or avoid nuisance alarms. A regular maintenance and inspection program that includes the cleaning and/or replacement of detectors should be implemented, especially in very tall buildings. This will limit the number of alarms within a building while improving system integrity. Because a very tall building often relies on defend-in-place or partial evacuation strategies, occupants cannot afford to ignore alarm signals thinking they are false alarms.

Voice Communication

Very tall buildings employ voice communication systems to alert building occupants of fire or other emergency events. They can provide evacuation signals through tones, pre-recorded messages, and/or live voice messages from monitoring and response personnel. With partial evacuation systems, they are particularly helpful in providing evacuation messages to the fire areas and instructions to other areas about the fire event to improve the building occupants' situational awareness. Consideration should also be given to enhancing the methods used for first responder communication and communication to building occupants. Distributed amplification radio systems for first responders is one method for improving first responder communication. Voice communication or mass notification systems is typically used as one method to communicate with building occupants. E911 capability on commercial cellular devices will soon include GPS X, Y, and Z positioning capabilities using a commercial distributed antenna system (DAS), aiding first responders in finding building occupants. The same DAS would also serve as part of a mass notification system.

One of the drawbacks of pre-recorded and live voice messages is the language to be used. Many very tall buildings are developed in multi-cultural populations where there is not just one language spoken. Consideration should be given to the use of multiple language pre-recorded messages that account for the primary languages spoken in the region.

While it is difficult to address all languages, the primary ones should be used. This can be done by having pre-recorded messages sequence through the various languages repeating the same message.

This also applies to those who may be providing live messages. They should be trained in multiple languages, or else adequate staff should be on hand to address the multiple languages required for voice evacuation. This should be considered when developing the overall fire strategy.

Voice communication systems are often integrated into the fire detection and alarm systems, sharing the control panels used for the detection system. For very tall buildings, amplifiers are distributed in the building inside of remote panels. Audio circuits are driven from these amplifiers to the building speakers.

Pre-recorded or live messages can be sent to multiple areas of the building depending on how many channels the system has. Multiple channel design in very tall buildings can be beneficial for use of the non-simultaneous evacuation strategies (see Fig. 15.4).

The audio circuits interconnecting panels can be either single or multiple channels. A single-channel system will allow all messages or tones to be routed to active circuits. Essentially, only one message or signal can be broadcast on the system at a time. Multi-channel systems allow for different messages to be sent to different areas as part of the overall building fire strategy.

Because of the size of very tall buildings, it is often desired to send evacuation messages to the fire area while also sending informational messages to areas adjacent to the fire area. This could serve to alert occupants that a fire may exist in the building and that occupants from the fire floor will be relocating to their area and to be prepared to receive these people. However, this may cause individuals on the non-fire floors to evacuate, so care must be given to message content.

Pre-recorded or live messages can be sent to multiple areas of the building depending on how many channels the system has. Multiple channel design in very tall buildings can be beneficial for defend-in-place or partial evacuation strategies (see Fig. 15.4).

Visual Notification

In certain portions of the world, fire event audible annunciation is accompanied by visual notification from devices such as strobes. These provide event notification through flashing lights – often imprinted with the word “FIRE.” They are used to inform the hearing impaired of an event so they can take necessary action.

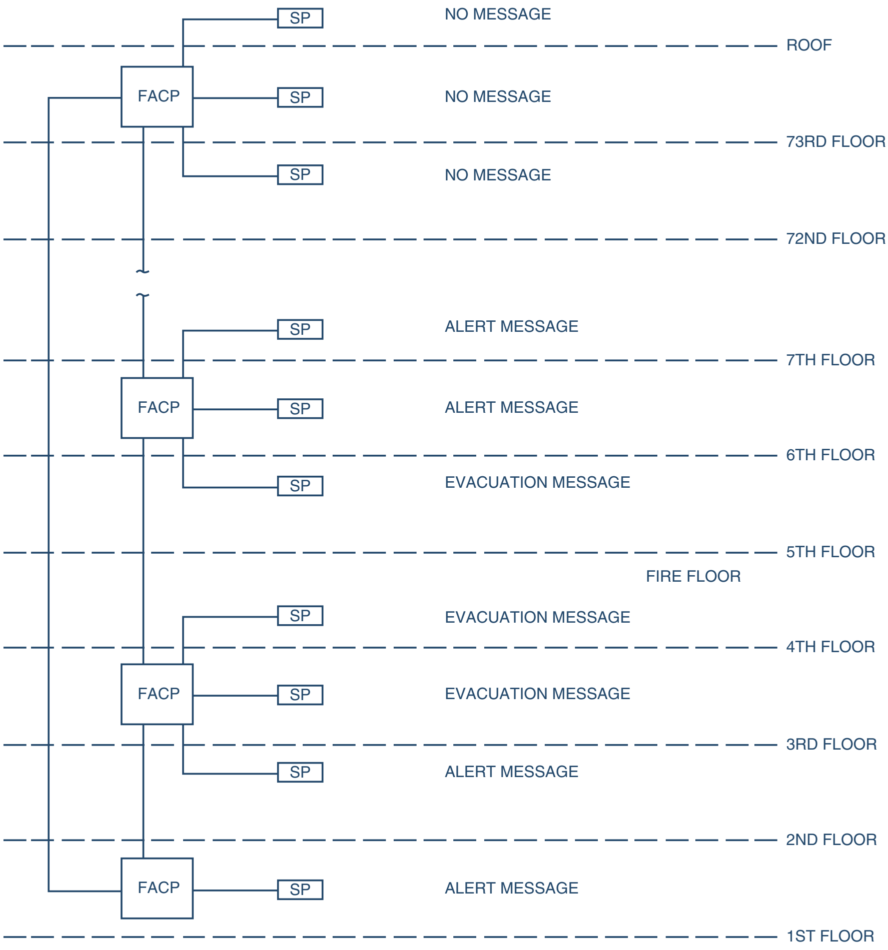

Fig. 15.4 Partial evacuation concept (Courtesy Allyn Vaughn)

Unfortunately, they do not provide specific information on events as with live audible messages.

For fire alarm systems, strobes are used primarily to alert occupants of fire conditions. While the devices cannot provide specific instructions, they are useful in alerting occupants of an event so they can seek assistance from other occupants who are not hearing impaired.

In addition to strobes, textual visible appliances can be used in fire alarm systems. These appliances can be connected to the fire alarm system to provide specific generic instructions to building occupants, similar to pre-recorded messages. They can be beneficial in very tall buildings where additional information is needed for those who may be hearing impaired.

Textual displays are also common in mass notification systems. Mass notification systems are used to alert building occupants of any event, not just a fire alarm. Strobes and textual displays can be combined with the fire alarm and mass notification systems to provide an integrated notification system.

For very tall buildings, event notification to building occupants is critical in the overall fire strategy. Since an event may be isolated to a small building area, occupants in other areas are remote from the event and may not be aware of the ongoing situation. By providing notification to all building areas on a selective basis, occupants can be made aware of the incident while not impeding actions in the incident area.

Mass Notification

As the building owner is more and more challenged with having to address not only common space responsibility but also external and internal risks both from the tenant and the public, mass notification should be considered as part of the overall life safety plan. Many very tall buildings use partial evacuation or defend-in-place evacuation strategies; mass notification systems can be a benefit in providing building occupants incident information. All modalities of communication should be considered when providing notification/instruction. In addition to audio, text, and graphical means of notifying occupants, simultaneous, parallel messaging should be considered to reinforce the nature and urgency of an emergency. In-building notification systems are used to provide information and instructions to people in a building using audible and visual signals, text, graphics, and other communication methods. These can include textual display boards as noted above, fire alarm or other speaker systems, paging devices, and smartphones.

In-building mass notification systems provide benefit to the overall fire strategy for very tall buildings. They can be used to alert occupants of certain building areas that an event is occurring remote from their location. They can provide specific instructions through a variety of methods that may not be readily available or employed by the fire detection and alarm system. These diverse modalities are useful in the variety of evacuation schemes as they can be designed to integrate with any concept. Mass notification systems should be considered in very tall buildings as part of the overall egress plan. For example, how do you notify personnel from Tenants B and C (stories 20 and 22) if there is an event on story 21 in Tenant A's offices? There is a common interest with providing unified communications and action plans for a very tall building.

The engineer will need to define what are core building systems, what systems are provided by the tenant and how they will interact, and where they will overlap. Interlinking this information in the initial life safety engineering design becomes a critical part of the comprehensive design (Fig. 15.5).

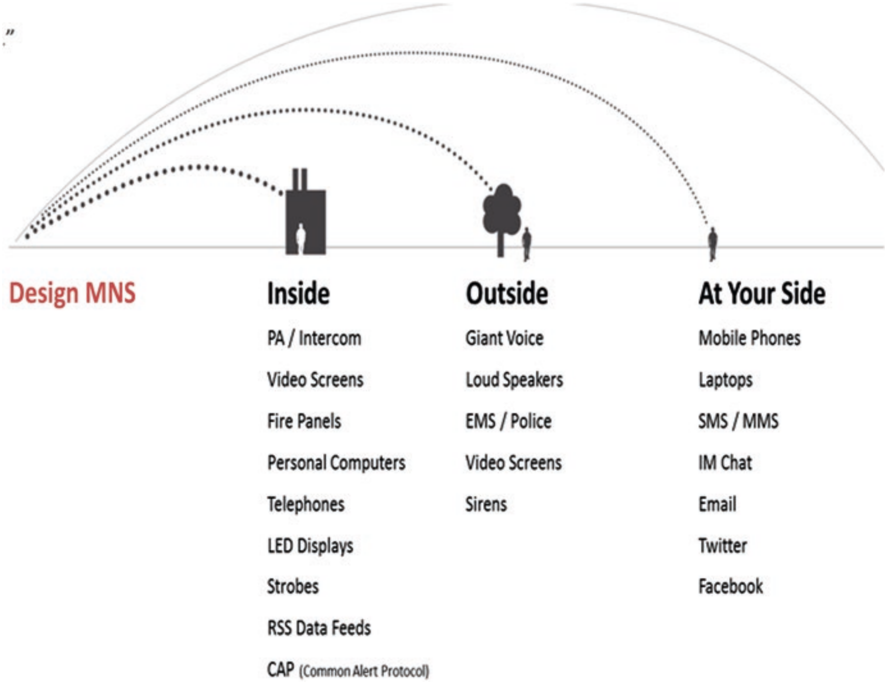

Fig. 15.5 "Inside, Outside, At Your Side" model. Courtesy of Siemens

Chapter 16
Smoke Control

Removal of fire byproducts (heat and smoke) from a fire in a building is even more critical in very tall buildings, especially when the building facade has no operable window openings and egress of some number of occupants would typically have to pass through the level of fire origin. The forces that drive the movement of heat and smoke are addressed, and considerations for the design development of smoke and heat exhaust ventilation systems (SHEVS), otherwise referred to as smoke control in many parts of the world, are detailed herein.

Smoke control is incorporated in the overall fire strategy in many different building types, independent of size. However, the matter of smoke spread and smoke control is a little more complicated in very tall buildings. Their inherent geometry, occupant distribution, the physics of smoke flow, and the characteristic design features such as extensive networks of shafts, complex ventilation systems, and spatial interconnections make such a structure potentially more vulnerable to smoke spread and the consequences thereof. Refer to the *SFPE Handbook of Fire Protection Engineering* [52], the *Handbook of Smoke Control Engineering* [217], the *Fire Protection Handbook* [218], or the *ASHRAE Handbook* [219] for specific details.

Consideration should be given to the desired performance goals for the structure. Once the goals are developed and criteria are set, an appropriate smoke control strategy can be implemented. Several different smoke control strategies are possible, incorporating one or more of a variety of design features. Features that might achieve the goals vary from the simple, passive reliance on smoke barrier walls and floors to the complex, the utilization of air handling systems to develop pressure differentials which restrict smoke spread from a fire zone. A sprinkler system can similarly be thought as an effective smoke control feature because it restricts fire development, limiting smoke production and reducing buoyancy, thereby reducing smoke spread.

However, even sprinkler-controlled fires can continue producing smoke, albeit at a reduced rate, until final extinguishment is accomplished by the fire brigade or fire department. Without any floor-by-floor smoke barriers, smoke from sprinkler-controlled fires driven by stack effect can spread to adjacent floors. Such smoke

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could also damage property in other areas of a building, a potential concern for owners. In such instances acceptable limits of property damage should be included as a performance objective. A very tall building equipped with a sprinkler system might meet the local code requirements for minimizing smoke spread, but the owner's performance goals may require a higher level of performance.

The smoke control strategy for a very tall building might necessitate going beyond the applicable codes and requiring input from stakeholders. Occupant life safety, the most common goal for smoke control systems, is often one of the design goals. Consequently, the type of egress plan – phased, defend-in-place, etc. – might influence the smoke control design. In some cases, additional smoke control goals such as fire fighter safety (stair or fire fighter lift smoke protection) and property protection might also need to be considered. These goals need to be reviewed and established before developing the smoke control strategy. The design solution needs to address the nature of the building, its relevant occupant characteristics, the stakeholders' performance objectives, and, lastly, reliability.

Factors that Influence Smoke Control in Very Tall Buildings

"Smoke control" is not a special system meant only for unusual structures (underground buildings, theaters, sporting arenas) or unique geometries (atria or shopping malls). Smoke control is more a part of the holistic approach to fire safety in a building, established by the integration of one or more building characteristics, features, or systems.

For example, the provision of automatic fire sprinklers can be considered a fire safety feature or system which provides a form of smoke control. Throughout a variety of buildings, one finds several features that could be deemed "smoke control": smoke detectors installed in air handling systems to provide shutdown to prevent smoke recirculation, smoke-resistive floor construction to minimize the smoke spread between floors, and the provision of self- or automatic-closing cross-corridor doors which close building sections from impending smoke intrusion down a corridor.

Smoke control concepts can provide a means to address different egress strategies. A stay- or defend-in-place concept, or similarly phased evacuation, would likely necessitate one or more forms of passive or active smoke control, whereas the evacuation times of very tall buildings may necessitate an active type of system to protect the vertical egress pathways (see Chap. 11, Emergency Egress).

Because of their nature, very tall buildings have complicated smoke spread potential. Their inherent geometry creates stack effect challenges; their multi-use and multi-tenant space programming and their characteristic design features such as extensive network of shafts and services create create special vulnerabilities. Building height, high occupant loads, and significant evacuation time also pose smoke spread challenges not normally seen in other types of buildings.

These challenges require a thoughtful, strategic approach. Consideration needs to be given to a broader palette of concerns from occupancy considerations to construction details. The possible solutions are also numerous: from passive to active smoke control including features such as, but not limited to, smoke barrier walls and floors, stairway pressurization systems, pressurized zoned smoke control provided by the air handling equipment, addressable smoke dampers, fire alarm activated doors, and more. The solution or solutions chosen should address the nature of the building, its uses, its occupancy, relevant occupant characteristics, and, above all, reliability.

Factors that influence smoke control in very tall buildings include:

- Stack effect
- Wind effect
- Piston effect
- Building environmental control systems (HVAC)

Stack Effect

Stack effect is the natural flow of air within the building due to temperature differences between the inside and outside. This natural flow of air can spread smoke via inadequately protected elevator, HVAC, plumbing, or similar shafts via unprotected openings or unsealed penetrations and other gaps in construction. The taller the building, the greater the stack effect. Because of stack effect, a very tall building's height makes it inherently more vulnerable to smoke spread than shorter buildings.

This flow of air can spread smoke via unprotected floor openings, unsealed penetrations in floors or shaft walls, and other gaps in construction. The effect is correlated positively with height and is of greater concern in very tall buildings, particularly in climates with extreme temperatures. The greater the temperature variation between the interior and the exterior of the building, the greater the stack effect. When the exterior temperatures are low, the heating of a building causes a natural flow up and throughout the building (see Fig. 16.1). The cooling of a building in an otherwise hot climate can cause a reverse stack effect, causing smoke, once cool having drifted far afield from the point of fire origin, to lose its buoyancy which is further drawn down through a building by the reverse stack effect (see Fig. 16.2). The stack force is present in a building whether there is a fire or not. In naturally ventilated buildings or in temperate climates, where the inside temperatures are similar to the exterior temperatures, stack effect is less pronounced.

Analytical equations have been developed to describe the stack effect for simple uniform buildings with simple shafts [217]. The equations can be extended to buildings with multiple shafts, provided the shafts are similar to each other. The analytical methods are not suitable for buildings which have shafts of varying heights and varying geometry. Computer network models have been developed to address the design of pressurization systems in complex buildings with shafts of varying heights and geometries [220]. An advantage of network models, such as CONTAM, is that

Stack Effect

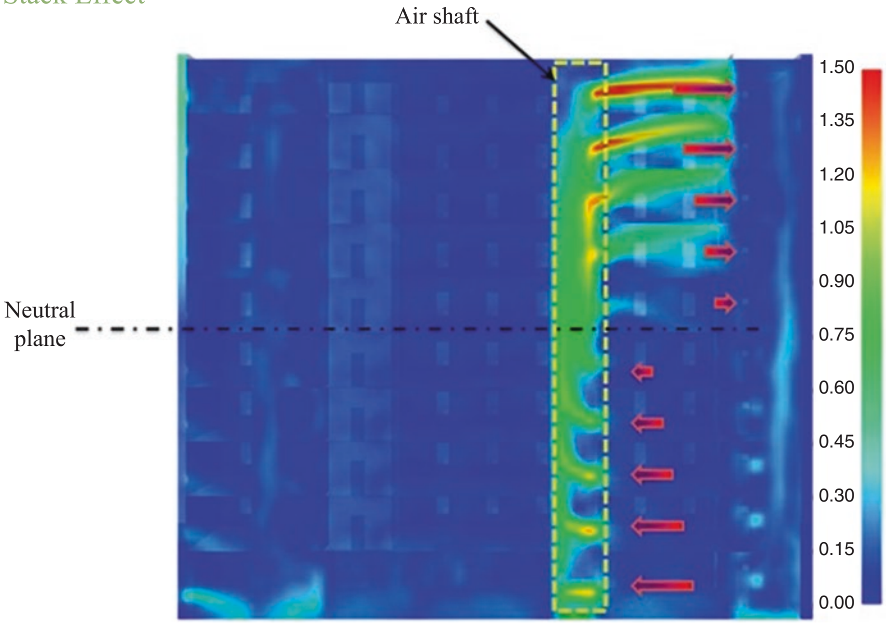

Fig. 16.1 Illustration of the forces generated by stack effect

Reverse Stack Effect

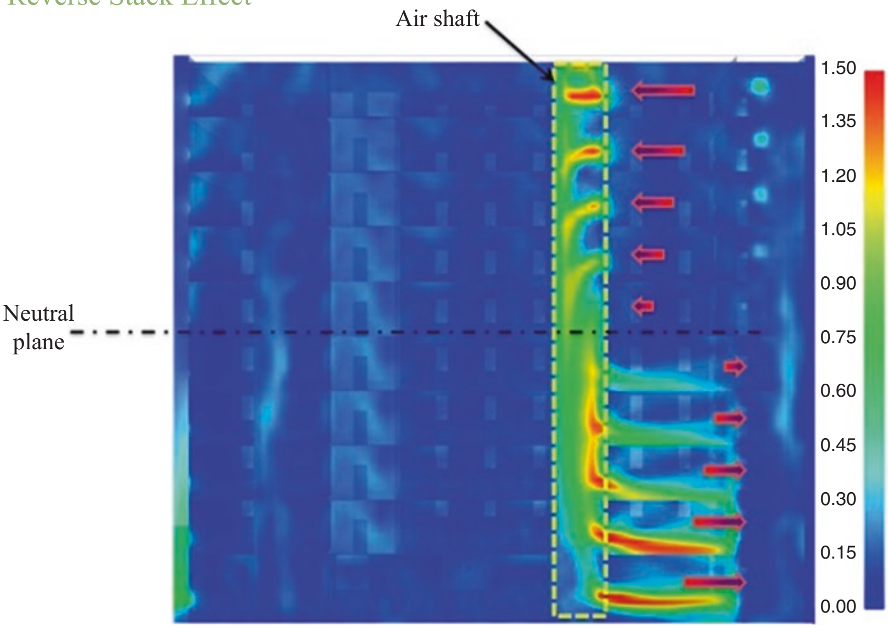

Fig. 16.2 Illustration of the forces generated by reverse stack effect

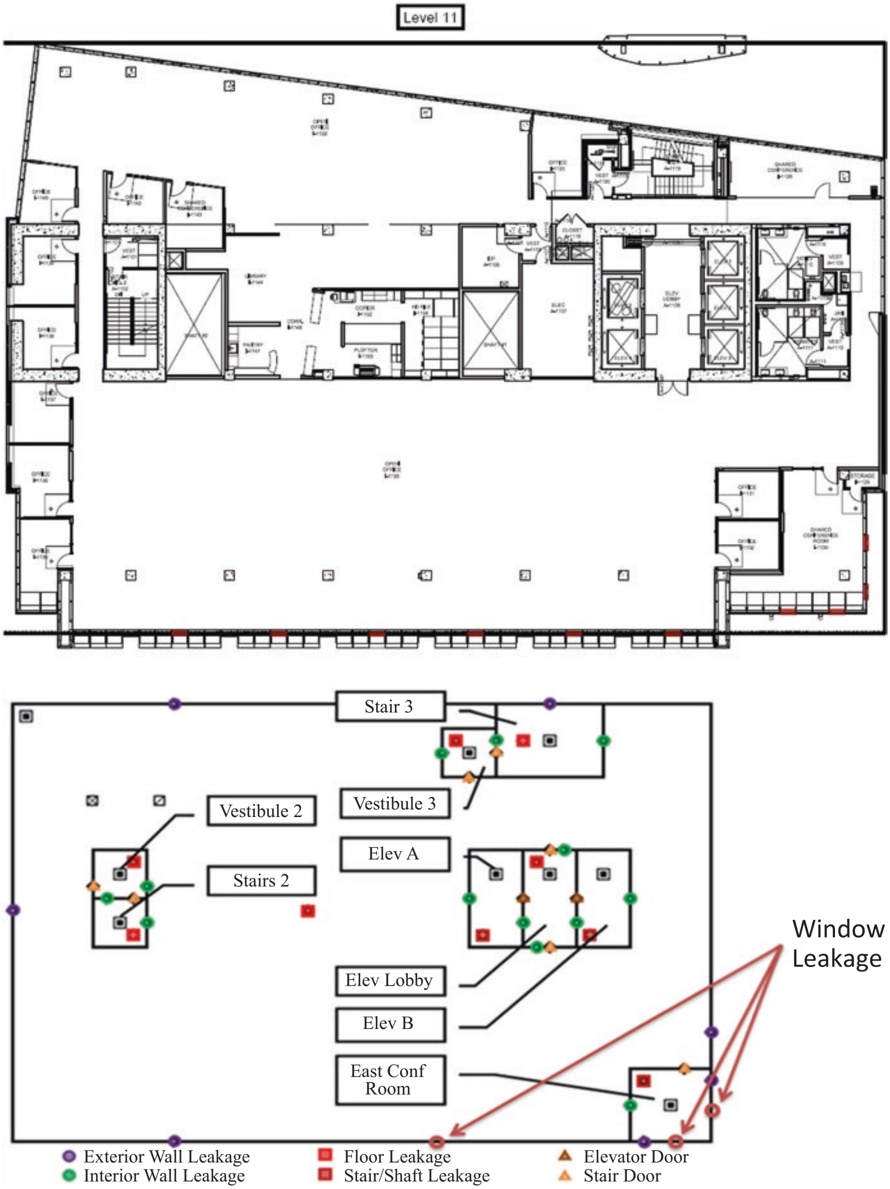

Fig. 16.3 Illustration of CONTAM model

they can address wind and HVAC influences. An example of a CONTAM model is provided in Fig. 16.3.

Table 16.1 illustrates the forces generated by the stack effect for various building heights, leakage areas, and space linkage. Leakage area is a key consideration as this varies with floor layout and expected construction joints or leakages in internal partitions, facades, doors, etc.

Table 16.1 Stack forces

Building height (m [ft])	Elevation of the neutral plane (m [ft])	Shaft to outside (Pa [in w.c.])	Shaft to interior (Pa [in w.c.]) $A_{si}/A_{io} = 1.7$	Shaft to interior (Pa [in w.c.]) $A_{si}/A_{io} = 7$
18.5 (60)	9.25 (30)	16 (0.065)	4 (0.02)	0.3 (0.001)
185 (600)	92.5 (300)	162 (0.65)	42 (0.17)	3 (0.01)
610 (2000)	305 (1000)	533 (2.1)	137 (0.55)	11 (0.044)

Stack effect forces are not large but are significant enough to push smoke through cracks, openings, and penetrations in large enough quantities to put the tenability of remote spaces at risk. Stack effect forces also can result in complicating the pressurization of stairs and elevator shafts.

Wind Effect

Especially in tall buildings, wind plays a major effect on internal uncontrolled air movement and may severely impact the performance of a smoke control system. This is especially true in naturally ventilated buildings with operable window that may be left open during emergency fire condition. Such scenarios should be considered in the design of active or passive smoke control systems. Network models, such as CONTAM, can also evaluate wind influences.

Piston Effect of Elevators

Another concern, found in very tall buildings, is the air movement created by the piston effect of elevators [221, 222]. Piston effect is the air movement caused by the elevator cars ascending or descending within the shafts that can force air through the elevator shaft doors into the floor space. Alternatively, the same effect can create a suction effect and draw smoke into the shaft. This can create a path and pumping system for smoke to move between floors. This effect is more pronounced in taller buildings when higher-speed elevators are employed in single car shafts. In contrast, larger shafts with multiple elevators are expected to have typically less and sometimes negligible piston effect [217].

Building Environmental Control Systems (HVAC)

Building environmental control (HVAC) systems can play a role in smoke spread. Without proper protection, normal operation of such systems can result in smoke transport to other building spaces. An HVAC system can spread smoke via its forced air supply and return ductwork from the fire compartment to other compartments even to remote floors. For this reason, it is common for such systems to be provided with appropriate smoke detection for automatic shutoff. In other cases, such systems may result in the pressurizing of the fire compartment which may push the smoke through gaps and openings, causing smoke spread. The design of smoke control system should consider the impact of the HVAC systems. Even for naturally ventilated building spaces, openings to the exterior can result in either increased stack effects or wind-induced pressures resulting in smoke spread concerns.

Double-skin curtain wall facades are occasionally employed as part of a building's ventilation system. Such facades are often of glass or similar material. The "double skin" creates an unprotected shaft, subject to stack effect, which can allow smoke to spread unmitigated between and across floors. Sprinkler protection may not suffice as a growing fire adjacent to such a shaft has the potential to breach the shaft before sprinkler operation. Once breached, the double skin creates a smoke spread hazard. See Chap. 13 (Building Envelope/Enclosure) for more information.

Fire Safety Goals and Objectives for Smoke Control

With a comprehensive understanding of the potential issues, the design professional, with input from the stakeholders, should be prepared to develop fire safety goals and objectives relevant to the target smoke control performance for the building. In some cases, fire safety codes might prescribe certain goals and objectives. In other cases, the owner, insurer, engineer, or authorities could have special interests and higher goals that are not reflected in the codes. These other interests may drive different performance goals and objectives and, consequently, a stricter design.

Sample Goals and Objectives

Examples of goals and objectives for the smoke control system might include:

- Minimizing the potential for smoke spread to protect occupants who are expected to remain in place for a given time before evacuation
- Minimizing the potential for smoke spread between floors to protect occupants while evacuating
- Minimizing smoke spread between floors for the purposes of protecting contents from smoke damage
- Minimizing the exposure of occupants to hazardous levels of smoke such that they can reach a place of safety that is designed to be free of smoke
- Providing means for fire fighters to access all areas of the building, such as a stairway or elevator system, that is protected from becoming untenable or unusable for fire-fighting operations
- Minimize the spread of hazardous smoke to occupants on remote floors given a fire following earthquake

The goals and objectives are not meant to be an exhaustive list, nor are they necessarily mutually exclusive. One may have both a goal of protecting vertical pathways for the use of the occupants and of protecting the fire fighters while maintaining another goal of minimizing smoke spread to remote areas of the building.

In determining the goals and objectives, consideration should be given to the building occupancy types and population profile. Different occupancy types may present different vulnerabilities and therefore require different types of protection. A very tall office building, where people are expected to be alert, aware of their surroundings, able-bodied, and familiar with the building, may require different considerations than a very tall hotel or hospital, where occupants are expected to be unfamiliar with the building, asleep, incapacitated, or unable to egress on their own.

Once the goal and objectives are clarified, a set of performance criteria can be established. The performance criteria are generally the set of requirements or limits agreed upon by stakeholders that are used during the design and analysis. Optimally, such performance criteria are established before any design or analysis takes place.

Depending on the goal and objectives, the criteria might be quite simple. For example, criteria necessary to meet performance goal #1 may include a set of tenability limits as referenced the literature, maintained for a given amount of time, under either normal or emergency/standby building power on floors remote from the fire. Advanced analyses with computer fire modeling may be necessary to prove that the tenability limits have not been exceeded. While tenability is often used as a metric for smoke control, the occupants on floors other than the fire floor might be expecting a higher level of performance. The literature does not typically address this more restrictive metric, but even prescriptive codes intend to restrict the spread of smoke to adjacent floors at a level far below tenability.

Smoke Control Design Methods

Smoke control design methods for very tall buildings might include passive methods, active methods, or any combination thereof. Passive methods of smoke control do not rely upon the action of a HVAC, an exhaust or supply fan system, or fire sprinkler and alarm system to achieve the intended goals and objectives. Active smoke control systems are those that use mechanically driven air to achieve its goals. Automatic fire sprinkler and fire alarm systems are also often thought as integral active methods, critical aspects of a smoke control system design. The design method or methods chosen needs to address the system's goals and of course be reliable. Smoke control design concepts are described in detail in a number of references, in both handbooks, guides and standards [217, 52, 218] and for very tall buildings, are summarized as follows.

Passive Methods of or Approaches to Smoke Control

Passive features include floors, walls, shafts, and the associated opening protection provided for the barriers, doors, shutters, dampers, and windows.

Passive approaches to smoke control are often the common approach for controlling smoke in apartment, condominium, or hotel type buildings. These types of occupancies offer a high degree of smoke control as they tend to be highly compartmentalized. Walls between residential units are typically fire and/or smoke resistive, lending each floor to a number of compartments with a series of multiple barriers which guard against widespread smoke spread. By reducing smoke spread across a floor, minimizes the likelihood of smoke transmission to remote areas.

For very tall buildings, which rely on such passive smoke control concepts, a potential weakness lies at the edge of slab. Many very tall buildings are designed with curtain wall systems. If passive smoke control is the primary means to control smoke transmission, the intersection of the curtain wall with the perimeter edge of the floor slab can be a weak link. It is an area that requires attention during design, construction, and inspection. The appropriate installation of smoke sealant and fire stopping this junction determines whether the passive approach has been successfully implemented and the floor assemblies are truly smoke resistive. Several products and assemblies have been tested by laboratories; however, since an almost infinite number of combinations of wall systems and slab systems could be designed, if testing data is not available, careful visual inspection and evaluation of this assembly is warranted to ensure proper performance.

The ultimate choice for the method of smoke control (active exhaust, active pressurization, passive etc.) hinges in part on the system's goals and objectives.

Active Methods of or Approaches to Smoke Control

Active smoke control methods include stairway pressurization systems, zoned smoke control provided by HVAC equipment to restrict smoke spread, or exhaust systems to maintain tenability in special case. A common approach for active smoke control systems is to establish the air flow or air pressure differentials between spaces intended to contain the smoke to a given building area, floor, or zone. Zones could be an entire story, multiple stories, or a portion of a story. Sometimes this is referred to a floor-by-floor smoke control system.

With active systems, a given zone in alarm (fire location) is identified by the fire alarm system, which in turns commands the active components of the smoke control system to either exhaust the zone with make-up air, or only exhaust the zone to create a negative pressure zone relative to adjacent zones. Alternatively, the fire alarm system can command the air moving systems to supply the surrounding zones, restricting smoke spread beyond the zone of first alarm. Either option provides a similar benefit – it reducing the possible smoke spread from the zone in alarm.

However, implementation of positive pressure systems, beyond that of stairway pressurization systems, should be approached with caution. If the fire alarm system is not properly programmed and tested, the system might result in pressurizing the fire zone and could inadvertently spread smoke to other zones.

At a minimum, the typical goal for smoke control systems in very tall buildings is to reduce or overcome the stack effect, reduce the potential for smoke spread to remote portions of the building and enhance the ability for occupants to evacuate to safety. Generally, smoke control systems should remain as simple as possible. Zoned smoke control systems, in very tall, mixed use structures, when properly programmed and maintained, are very effective in managing the hazards due to stack effect, but can be complicated to install, program, test and maintain over the lifetime of a building. Any unnecessary design complexities can create challenges during commissioning and impacts the later phases of a building's life.

Factors that Affect Analysis and Design of Smoke Control Systems

Factors that affect analysis and design of smoke control systems in very tall buildings include:

- Wind
- Operable windows
- Stairway pressurization

The following sections address these three factors.

Wind

As buildings increase in height, the effects of wind are more pronounced. [223, 224] Wind can play a role in causing smoke spread, or a role in affecting smoke control features.

As rule, wind pressure on the face of a building increases with the height of the building. [217] However, in some high-density urban corridors with multiple very tall buildings, high winds can present themselves at 10 m (33 ft) above ground just as commonly as at 50 m (164 ft) above ground.

In some cases, wind effects can cause smoke spread and in other cases it can affect the smoke control system. This effect is pronounced for buildings with operable windows and affects buildings where the interior exit stairways are along the building's perimeter wall. A stairway enclosure with an exterior wall along the windward side of a facade may experience significant increased pressures during the highest winds that occur 1% of the year, resulting in over pressurizing the stairway. Such a pressure increase can result in an increase in door opening forces for those occupants attempting to enter the protected stairway. Similarly, an enclosure with an exterior wall along the leeward side of the building may be subject to negative wind pressures, requiring a greater stairway pressurization flow to account for the pressure reduction due to wind. In some urban environments, the wind conditions are difficult to predict.

Operable Windows

Very tall buildings in temperate climates may include operable windows, balconies with manually operable doors or roof decks access with manually operable doors. Such facade openings can create challenges as they can cause wind driven smoke spread or create challenges or for active smoke control systems.

In an active, floor by floor (zoned) smoke control system, where the adjacent floors are positively pressurized with respective to the floor of alarm, open windows only on the leeward side of the building may negate the positive pressurization system.

Wind induced pressures due to open windows can also present additional issues for the stair pressurization systems: similar to the challenges faced by pressurization systems for interior stairs along the perimeter, either over or under pressurization can result if:

1. The facade openings were to be (only) open the windward side of a floor under fire conditions, wind can cause an increase in pressure on the fire floor potentially driving the smoke to other zones and simultaneously nullifying any stair pressurization differentials or,
2. If the facade openings are (only) open on the leeward side, the wind can cause a decrease in pressure on the fire floor relative to other zones, with the result that doors to the exit stairways may be more difficult to open.

A stair pressurization may compound this latter leeward wind challenge (see Chap. 13, Building Envelope/Enclosure).

Note that the probability of these events should be taken into consideration on a project-by-project basis. For example, it would be highly unlikely for example, that a fire occurs, during worst case stack effect (extreme temperatures) with operable windows or doors left open, during worst case wind conditions.

If available, wind tunnel test data should be used to better understand the influences of wind on the building, in the particular environment. Figure 16.4 shows a wind tunnel test for a tall building in Auckland. Figure 16.5 shows wind tunnel test results for a tall building in San Francisco.

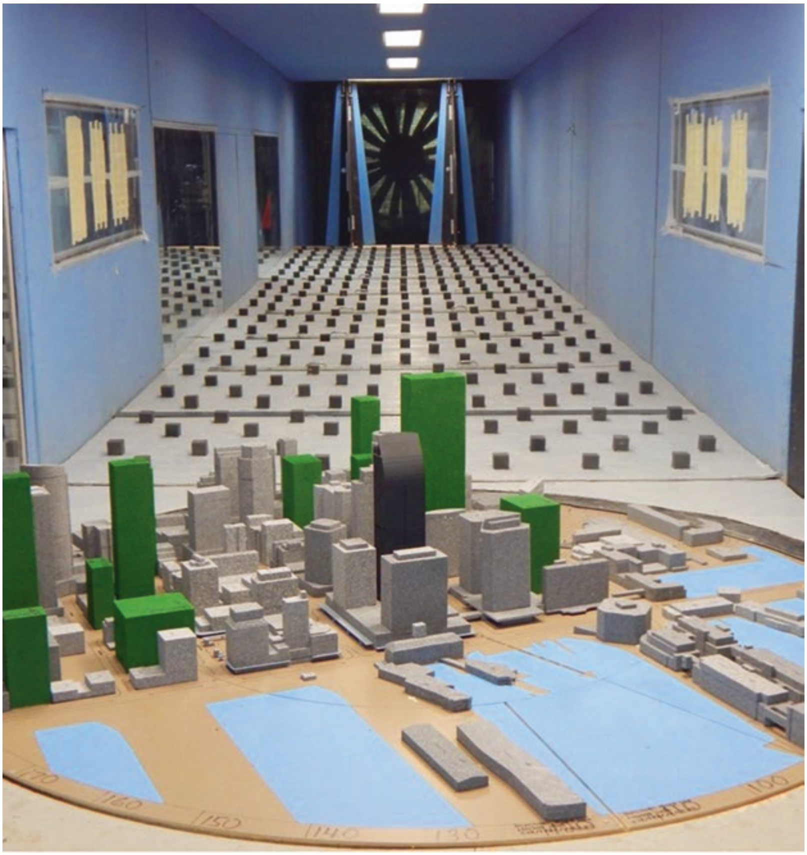

Fig. 16.4 Wind Tunnel Testing of a Tall Building in Auckland. Courtesy of Rowan, William, Davies & Irwin, Inc.

Reliability

The level of reliability of any smoke control system should be established early, during the development of performance goals. A risk analysis, such as described in Chap. 7 (Hazard, Risk and Decision Analysis in Very Tall Building Design) is important to establishing those goals. Expectations of reliability will inform the design and analysis process.

One way to characterize a system's reliability is by categorizing its controllable or uncontrollable factors. Controllable factors include hardware or building design features. Uncontrollable factors include weather, such as wind and climate.

Where multiple fans and dampers are required to modulate, there is a greater potential for failure of the system. As one means to address reliability of system hardware, fire alarm monitoring and automatic system testing may provide the acceptable level of reliability. Where the normal building power supply is inadequate to meet reliability goals, standby or emergency power may be necessary.

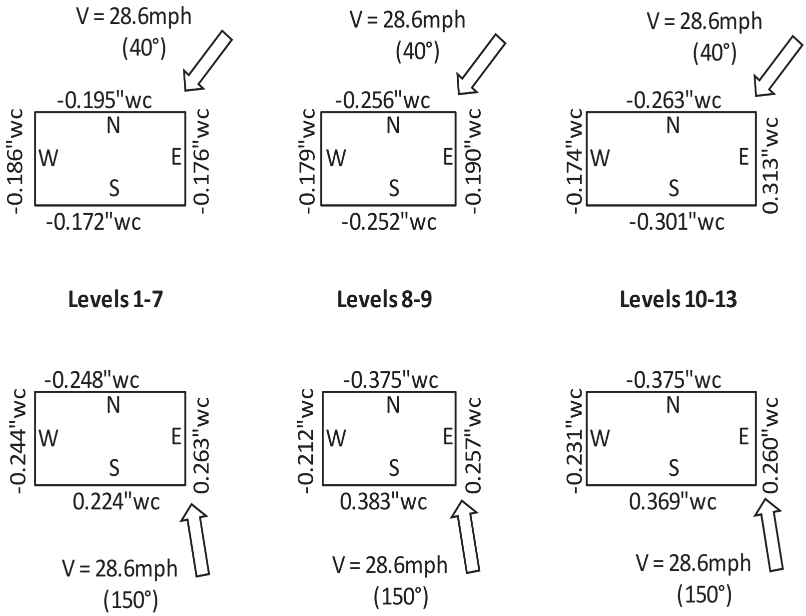

Fig. 16.5 Results of Wind Tunnel Testing of a Very Tall Building in San Francisco, California

The level of reliability may be dependent on the assumptions, or boundary conditions, made during the analysis. As stack effect, which could be considered a "boundary condition," is strongly influenced by temperature differences, what temperature differences are to be assumed? What is the reliability of the system under wind conditions? If a building includes operable windows, is it intended to have a zoned smoke control system that works 100% under extreme wind conditions? Is it likely that the windows would be closed by the occupants during such wind conditions? Should the smoke control system need to function under extreme wind and during extreme stack effect? Is it reasonable to design the event of a fire occurring, with an ineffective sprinkler operation, during such conditions? Such questions should be considered and discussed among the stakeholders during the early stages of design.

Designers need to be cognizant of the potential for systems to interact with each other. For example, an elevator pressurization system may result in increasing the pressure of a fire floor, thereby negating the benefits of the stair pressurization system. Future needs should be anticipated wherever possible. There are immediate needs of the system reliability relative to occupancy characteristics, hazards, population, and uses, but also the needs may change if the occupancy changes. Flexibility of the smoke control system can increase reliability for spaces or buildings that are subject to changes over time, such as office tenants in very tall office buildings. An active floor-to-floor zoned system appropriate for a single tenant per floor open office lease plan may be jeopardized if the leasing arrangements and resulting geometries change years later to accommodate multiple enclosed offices. Similarly, an active zoned system may be jeopardized if the same tenant expands to multiple floors and created open stairways to interconnect the floors. Improvements which occur during the lifetime of a building can create hazardous situations if not carefully monitored and addressed.

For these reasons, it is prudent to consider the least complicated, most flexible, and transparent system whenever possible. See Chap. 9 (System Reliability) for more information about reliability.

Stairway Pressurization

As stairways will generally be used as part of the egress plan for most very tall buildings, it is imperative to maintain tenability within the stairway. Pressurization systems are a common approach to protect stairways in very tall buildings from smoke infiltration.

Stairway Wall Construction

The ability of the stairway walls to resist fire and smoke needs to be preserved over the duration of a fire. During a fire, it is possible for the core to be displaced and/or cracking to occur. Considerations should be given to what type of fire sealant/filler is used for joints, as it may have to be flexible to cope with displacements. When designing stairway pressurization, it is necessary to estimate the leakage that will be present. The Handbook of Smoke Control Engineering [217] provides useful guidance. In addition, some building codes contain impact resistance requirements for shaft enclosure walls to harden the stairways, which in turn could benefit the long-term leakage reliability of the stairway.

Vestibule: Natural Ventilation

Natural vestibule ventilation (venting directly to outside) is generally not used in very tall buildings but can be considered on a case-by-case basis.

Vestibule: Mechanical Ventilation

It is common in some parts of the world to provide a vestibule between the pressurized stairway and the floor as a buffer against smoke spread and to minimize the pressure differential across a single door. The vestibule may either be pressurized or ventilated with a mechanical system. Under the former approach, the vestibule is pressurized (positive to the floor) by either leakage through the stair or direct supply into the vestibule. Under the latter approach, extraction is provided at the top of the vestibule, while inlet is provided at the bottom. The designer must be careful that the pressure differences stay within tolerance to allow effective opening of the doors. As an alternative, the vestibule may be ventilated naturally the exterior, without a mechanical system. These systems are sensitive to internal building pressures generated by stack and wind which increase with building height.

Two examples of mechanical stairway pressurization systems are given in Figs. 16.6 and 16.7. The first offers an approach that is a simple system whereby only the shaft is pressurized to protect from inflow of smoke and hot gasses into the stairway. The second is a diagrammatic representation of a pressurized vestibule inserted between the floor and the stairway, which may or may not include an elevator. The vestibule provides a buffer from the floor, reducing the chance of smoke entering the stairway and can provide a staging area for fire fighters.

Design standards provide guidance on minimum and maximum pressures, calculation methods, types of systems, number of injection points, and venting. Because standards vary considerably, agreement from the authority having jurisdiction should be sought on the use of appropriate standards.

Height Limit

Designers should ascertain early the maximum effective height that stair shaft pressurization systems can be effective. The maximum height depends on several factors, such as minimum and maximum working pressures, leakage areas, and climatic conditions [52, 217, 218, 219].

To provide pressurization levels within the boundaries of the minimum and maximum pressures, stairways may have to be subdivided (known as compartmentation). When doors between stairways are open, the benefits of compartmentation are

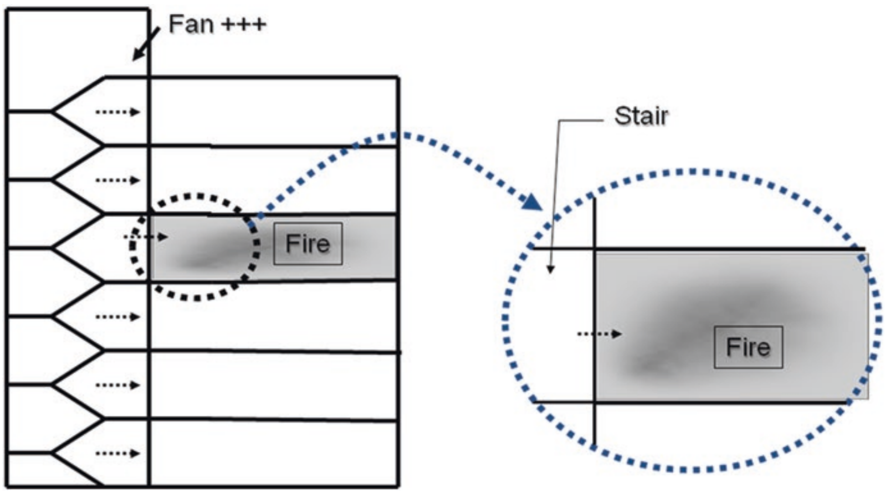

Fig. 16.6 Stairway pressurization system: no vestibule between stairway and floor

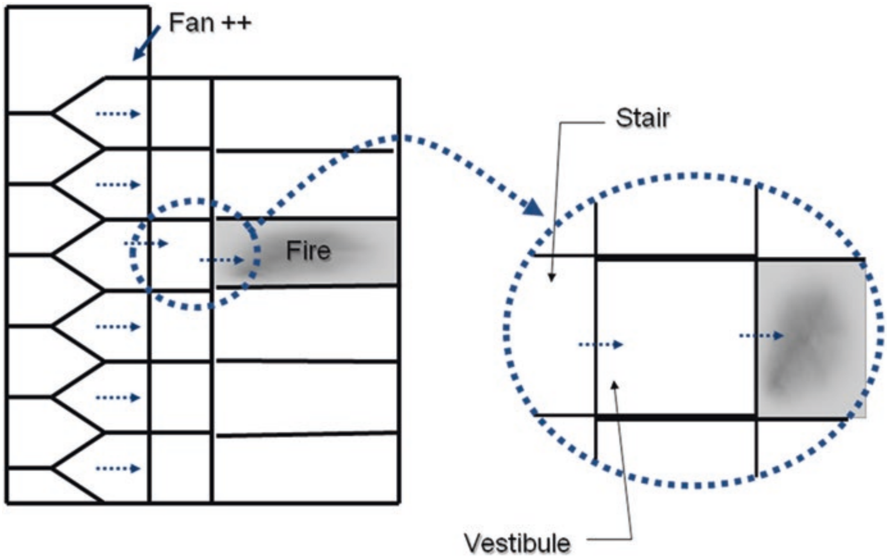

Fig. 16.7 Stairway pressurization system: vestibule between stairway and floor, vestibule is mechanically pressurized

reduced however briefly. Compartmentation does have a disadvantage from an economical and architectural view in that it is likely that it cannot be achieved without increased stairway landing area space, thus losing usable floor space. One option to address these losses is to compartmentalize at intermediate mechanical floors if space is available.

Open Doors

A key design challenge for stair pressurization systems is the assumption whether or how many open doors are used to calculate the fan size. In the United States, one code requires that the design be based on meeting a minimum pressure differential with no interior stair doors open. Other countries may have different standards. From a pure performance standpoint, the designer should evaluate the implications of the evacuation methods, building configuration, and local fire-fighting operations on the quantity, frequency, and length of time doors are open.

Stacked Atria

It is becoming more common in modern very tall buildings to use stacked atria, where the building is vertically divided into multiple open sections (see Fig. 16.6). These atriums are often expected to be evacuated as a single zone; therefore potentially multiple doors can be open simultaneously for significant period of time. As such, the designer may have to consider this when calculating the necessary fan size. The designer should also consider the effects of unusual building configuration on the operability of pressurization systems (Fig. 16.8).

A significant exhaust system may be necessary to address the stacked, village-type atrium hazard, which requires coordination with any stair pressurization system. Stacked atria have implications for the calculation of buoyancy forces, as buoyancy forces are a function of height. Furthermore, sprinkler operation may be delayed in such atria (due to the ceiling heights), allowing for larger fires and greater smoke production rates than in standard ceiling height buildings. This combination of features and factors needs to be considered during the analysis.

Fire-Fighting Operations

The effectiveness of stairway smoke control systems is sensitive to fire-fighting operations, as the operations involve the opening of stairway doors for long periods. Open doors result in a decrease in the stairway pressurization system performance. The placement of standpipe riser outlets in stairway vestibules, when provided, can

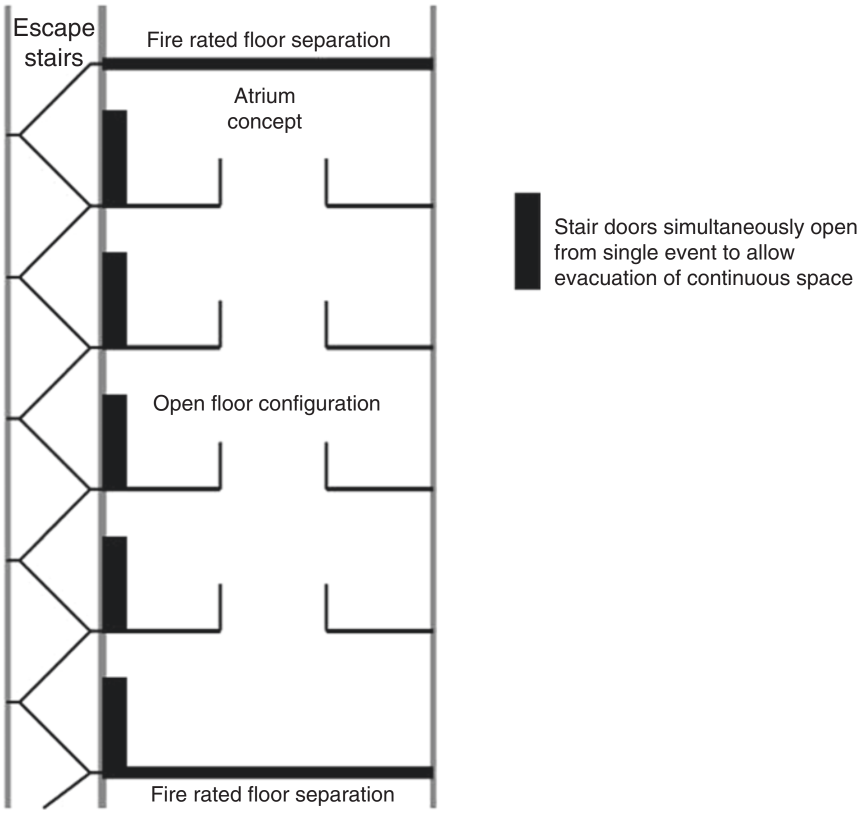

Fig. 16.8 Village-type (atrium) configuration

reduce the frequency and period of door openings. This does not always eliminate the problem, because fire fighters may run hose from the floors below up the stairway onto the fire floor. The designer should be aware of how fire-fighting operations integrate with fire safety and particularly the operation of the smoke control system. See Chap. 14 (Suppression) for more information about standpipe placement.

Duration of Operations

The time a smoke control system operates will be based on the hazard and risk assessment conducted for the building. The designer should be aware that in taller buildings the evacuation time can be considerable; therefore as matter of course, the minimum operation time should be at least equal to the total evacuation time. It is prudent engineering practice to use a safety factor to build a degree of robustness into the design (see Chap. 11, Emergency Egress).

Protection of Elevators

Similar to the need for pressurization or enclosure of stairways, smoke movement through elevator shafts should be considered for very tall buildings. While elevator shafts have historically been addressed with passive smoke containment such as elevator lobbies, an alternate or supplemental approach might involve elevator pressurization. Elevator pressurization systems can prevent floor-to-floor smoke migration, aid in emergency evacuation or relocation of occupants, or allow fire fighters to access upper floors more easily. While the focus of this section is on systems intended to prevent smoke migration, some of the information also applies to pressurization systems intended to aid in elevator evacuation and fire fighter elevators.

Pressurization systems need to be designed to maintain adequate pressurization across the elevator hoistway opening, which means pressurization within minimum and maximum values of pressure differences. The minimum pressure difference needs to be sufficient to prevent smoke from entering the elevator shaft, and the maximum pressure difference should minimize the potential for door jamming and adverse impacts on the elevator equipment. For example, the minimum and maximum pressure differential values specified in the International Building Code [47] are 0.10 and 0.25 inches of water (25 and 60 Pa) relative to the adjacent building areas in alarm.

Sometimes, pressurization can cause elevator doors to get jammed in the closed or open position. Network airflow models can be used to evaluate stack effect and floor-by-floor air movement to determine the air flows and vents necessary to maintain these pressures. There are potential issues with the velocity of air moving past cables and other elevator equipment, which could adversely impact the performance of these systems. Elevators in very tall buildings usually have high operating velocities, and pressurization systems must address the piston effect resulting from these velocities. There is no piston effect once the cabs are parked at the recall floor.

However, if an elevator is designated for fire fighter use, it may run continually throughout a fire incident. For buildings not relying on the continued use of the elevators, the designer can evaluate if the piston effect is of significant consequence for the relatively short time until the cabs are parked. These potential impacts should be accounted for in the design and reviewed as part of the testing of the system.

Elevator pressurization typically requires more supply air than stairway pressurization, resulting in unique design challenges. Except for very loose (leaky) construction, the large amounts of air flowing from the elevator shaft and through the building envelope make it difficult or impossible to maintain adequate pressurization with a system that simply supplies pressurization air to the elevator shaft. This is particularly true on floors where the cabs are recalled with the doors open.

In buildings with elevator and stairway pressurization and zoned, floor-by-floor active smoke control, design analysis of these systems needs to be done with all systems operating as intended. When used for emergency evacuation or fire fighter access, the analysis should also include situations where the zoned system is not operational or is only partially operating. Coordination of pressurization and elevator recall systems is necessary.

When the elevators recall and the doors open, these systems may not maintain pressure differentials across the elevator hoistway doors located below the recall floor. This may require elevator lobbies on these lower floors or a means to supply air below the recall floor.

Extreme Climates

As with any smoke control system which requires HVAC/mechanical intervention, care should be taken in extreme climates. In general, air is necessary to either pressurize stairways, elevator shafts, or provide zoned smoke control systems, generally using 100% outside air. Under extreme climates such as summer in the Middle East, or winter in Scandinavia, 100% outside air, injected into a stairway, for example, in a very tall building, may create environmental conditions inside the stairway that are not tenable for egress of more than a few floors or for sustained fire-fighting operations. Under such situations, it may be necessary to have systems intended to condition the injected air. However, using unconditioned outside air can reduce the stack effect.

Chapter 17
First Responder Considerations

Very tall buildings present significant challenges to first responders, not only due to the height of the structure but also due to the complexity of the structure and the mixed uses found inside these structures. First responders responding to an incident in a very tall building could include fire, police, emergency medical units, and utility companies. Incidents requiring emergency intervention can be divided into two categories: natural and unnatural (i.e., those caused by people). These two categories can be broken down even further as shown in Table 17.1.

These incidents can create hazards to the structure, the occupants, and the first responders. Ownership and building management should develop, implement, and practice emergency response plans to address all the foreseeable incidents that may impact the very tall building. The design team and ownership should review these possible incidents and determine what type of safeguards will be put in place to reduce the risks associated with these types of incidents. Ideally, the first responder will provide input to the design team and ownership regarding what type of resources the first responders can bring to an incident and the actions that they may take to mitigate and bring the incident under control. It is critical for the emergency response plans for very tall buildings to clearly delineate the roles and responsibilities of building management and engineering staff versus those of the first responders. Even more critical is to identify the nature of support expected by first responders from building management and staff during any type of incident.

First responders should have input into and use of the emergency response plans. These plans may include information regarding the use and location of hazardous materials in the building, communication plans, stay/defend-in-place plans, emergency evacuation plans, lockdown plans, and business/operation continuity plans.

Training and drills of these emergency preparedness plans should be developed and conducted in cooperation with the first responders.

Fire Safety for Very Tall Buildings, The Society of Fire Protection Engineers Series, https://doi.org/10.1007/978-3-030-79014-1_17

Table 17.1 Incidents possibly requiring emergency intervention

Natural events	Human events		Technology	
	Unintentional	Intentional (includes all unintentional human and technology events plus the following)	Communication loss	Computer problems
Weather	Fire	All unintentional human and technology events plus the following	Internet	Server crash
Earthquake	Loss of power		Radio	Software failures
Tsunami	Natural gas leak		TV	Virus
Drought	Medical emergency		Social media	Cyber attack
Flooding	Structural failure		Smartphone	
Volcano	Loss of vertical transportation system	Active shooter	Voice communication	
	Loss of building climate control system	Workplace violence		
	Toxic/biological threats	Bomb threat/suspicious package		
	Water leak	Criminal activity		
		Terrorism		

Command and Control

The design team should meet with the local first responders to determine what type of management/command and control system will be used if an incident does occur within the building and how first responders will interface with the building staff. For example, a management system called "incident command system" (ICS) is used in North America by many fire departments, law enforcement, medical services, federal agencies, and even private companies as a tool to organize, control, command, and share information about the incident with the first responder and the public.

Building fire and life safety directors, and where there is no identified director the building engineer familiar with the building systems and controls, should be available to assist the fire department incident commander during an incident.

Communication

The ability to communicate during an incident between first responders, building occupants, owners, and facility employees is critical to understand the impact the incident is having on the building and occupants. Without communication, these groups will not be able to understand if the building's built-in systems are working properly, determine how first responders and occupants should respond, and determine if additional resources or actions are required to control the incident and bring the structure back to a normal state.

Fire alarm systems that are installed within these very tall buildings may have a fire fighter phone system that will allow first responders to communicate from elevators, elevator lobbies, and stairways to the fire control/command room. This system will include a combination of phone station and/or phone jacks. The fire control/command room will have additional phone handset for the first responders' use.

Many first responders use some type of radio communication system. The ability to communicate with other first responders, and other groups such as building engineers and security, may not be possible due to different radio frequencies or interoperability constraints between the radio systems. Radio communications equipment procured by building management for staff use is likely to have several programmable channels. Pre-programming the frequencies of first responders and other responding agencies into the communication system can minimize this problem.

Another issue that most first responders often encounter with radio communication systems within buildings is that the building structural components can affect the ability to transmit radio signals to the other units outside. More frequently today, equipment is being installed into the building to support and amplify this communication. The ability to add additional radio equipment to facilitate first responder radio communication is very expensive after the building is built due to the time factor of installation and finding space for the additional radio equipment. The reliability of the radio communication system must be reviewed to ensure that there is no one point of potential failure. Many codes now require repeaters or distributed antennae systems (DAS) to facilitate fire department communication [48], [225].

The key to any type of communication system that the first responder may use is to ensure that the system is user friendly for the types of incidents that may occur. The reliability and robustness of these systems should be considered as described in Chap. 9 (System Reliability). It would not be unreasonable to consider hardwired fire fighter phones in strategic locations as a backup to the radio repeater systems that facilitate the use of fire department radio systems.

In recent years, some fire departments and building owners have chosen to install sensors or cameras at various locations to help determine conditions or presence of people. The cameras are often installed in stairways and can be used to determine flow or blockages and can also be used after the fact to determine how evacuation evolved. This type of approach needs to be carefully considered by the stakeholders to determine beforehand whether there are concerns for privacy, information overflow, protection and listing of devices, and value of the cost versus benefit.

Building Access

The ability of the first responder to gain access to the site and then into and throughout the building will be critical to provide services. A fire apparatus access road that meets the needs of the first responders needs to be provided. Several access points to the site may be needed depending on the arrangement of the site, and the building itself is likely to require multiple personnel access points. Vehicle access roads would include sufficient width for local apparatus, turning radius, clearance height, and passing lanes and be structurally sufficient to support the loads of the vehicles, including any outrigger supports. The hazard of falling glass should be evaluated with respect to the location of the fire lanes, fire hydrant placement, and entrance/exit points.

The fire apparatus access roads and the location of fire hydrants, building fire system support portals, and water supply components should be designed to meet the needs of the first responders' equipment. Hence, the design team needs to conduct an inventory of current and possible future equipment planned for use by the first responders, and the fire vehicle access roads for the project should be designed as required to accommodate the local fire department planned equipment.

Security devices that may be installed along the fire apparatus access road, such as bollards or gates, can be equipped with devices that allow first responder to have access without the need of on-site security force or special key/knowledge to unlock or lock down the area. Very tall buildings that are iconic in nature may have security features that are intended to restrict access to the building, and first responders will need to have means to access the building when necessary.

First responders will need access to all parts inside the building(s). This can be achieved via a lock box with access keys for the first responders if building security staff is not available 24/7. The use of electric locks, keys, and card access may be used as part of security for a building of this type; however, the first responders must be able to unlock and maintain security as warranted. The design team should coordinate the designed security locking systems with the needs of the fire responders and other fire/life safety systems.

Vertical transportation will be necessary in any incident to transport first responders to the immediate vicinity of the incident. The vertical transportation will typically be via elevator. At least one, and perhaps two, elevator should be designed for use by first responders. These elevators, or groups of elevators, should provide access to all stories of the building. The elevator must be able to function in a harsh environment, which may include water and smoke inside the shaft or on the equipment. Elevators should be provided in adequate size to transport anticipated number of responders and their equipment. They should also be sized to accommodate a stretcher should medical treatment be necessary. The elevators used will vary but can be either the service elevators or elevators used for normal passenger use. Rarely are elevators dedicated for fire fighter use mandated.

Vertical transportation systems design is established early in the overall design of a very tall building; therefore, it is critical that the design team confer with the local first responders to understand the local incident response tactics to accommodate the features necessary within the building. Some fire departments will respond to a floor or two below the floor of incident, while others have come to rely upon the use of fire fighter access elevator lobbies on the floor of incident. Typically, elevators used for fire-fighting support must connect to every floor in the building; transferring elevators during an incident response will hamper and delay incident response.

Before the prevalent use of fire fighter access elevator lobbies, fire fighters would take elevators to one or two stories below the incident and then use exit stairs to move through a protected environment to the incident floor. Many of the very tall buildings today are being designed and constructed with fire fighter access elevator lobbies that are arranged to offer a protected environment into which fire fighter elevators can open and from which fire fighters can directly access an exit stair. Figure 17.1 is one example of such an arrangement.

Elevators designed for use by first responders will need some special features. Some of the safety features that may be used in a fire service elevator include structural integrity of the hoistway enclosures, elevator lobbies sized for the first responders, a means to limit water entering the hoistway shafts, elimination of power shunt trip protection, additional lighting of the hoistway shaft, and standby power for elevator equipment. The reliability and robustness of these systems should be considered as described in Chap. 9 (System Reliability).

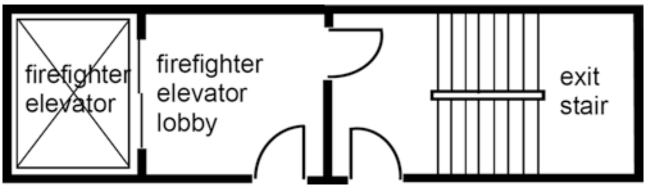

Fig. 17.1 Diagram of a fire fighter elevator lobby

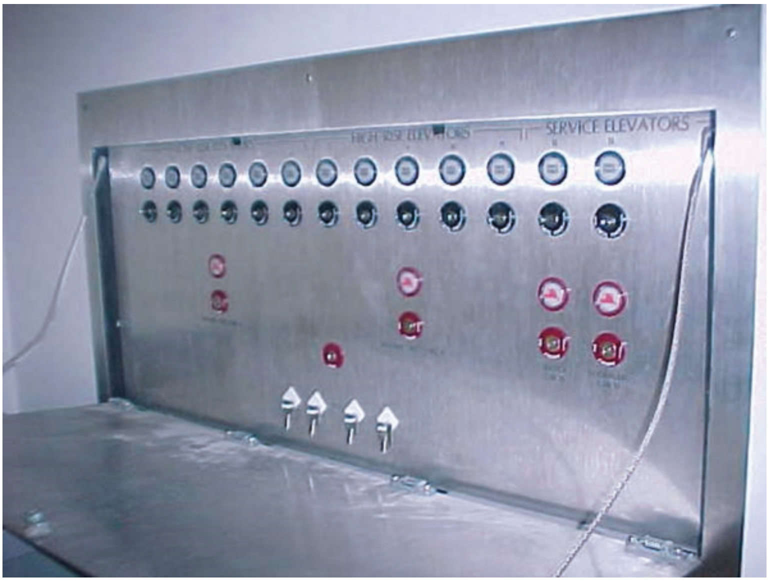

Fig. 17.2 Elevator control panel located inside a fire control room, photo by Joe McElvaney

Initial Response

Once the call for help is received by the first responders, units begin collecting information on the nature of the incident. Alarm and communications systems today can send real-time information directly to first responders, if first responders have sufficient equipment to receive such information. This information will be used to develop an action plan for the incident.

The first responders will depend on the fire/life safety systems working correctly and the staff from the building being available to assist during the incident. This may include controlling the use of elevators, stairways, entrance/exit points, and the fire control room.

The design team should assist the first responders in developing pre-plans or action plans based on some of the common types of incidents (see emergency response planning discussion earlier in this chapter). These plans should consider if there is a failure in a system, what the first responders can expect to happen, and actions that may be needed to overcome failures of the systems.

The location of standpipe outlets and hose stations and the type of threads on these devices will require coordination with the first responders and should be documented on simplified floor plan maps of the building. Additionally, they will need to understand the suppression systems, including design pressures that supply water to the site and fire protection systems.

The fire department should consider how they will replenish self-contained breathing apparatus (SCBA). Building designers should coordinate their design with the approach that will be used by the fire service.

One concept of replenishing SCBA is a refill system that allows first responder the ability to refill SCBA via a piping system of breathing air suitable for the SCBA (see Fig. 17.3). This system may include an air compressor, air cylinders, or other means for supplying air. Refill stations can be located throughout the building in locations that are acceptable to first responders.

Typical locations may include fire fighter elevator lobbies and/or freight elevator lobbies. The design team needs to verify that the system that is implemented will be used by the first responders. Additionally, inspection and testing of the system will increase reliability of the system.

Another feature that first responders have required is installing equipment stations on pre-determined stories to store equipment that can be used by the first responders. The type of equipment and the location of these equipment stations are usually determined by the first responders. The equipment rooms should be designed to meet the needs of the first responders. Understandings and agreements (preferably written) between the building owner and the local fire department to address which party is responsible to supply and maintain the necessary equipment that the first responders will use should be developed early in the design process since these features inevitably will impact architectural planning. The reliability and robustness of these systems should be considered as described in Chap. 9 (System Reliability).

Fig. 17.3 Fire fighter air refilling station located inside a stairway, photo by Joe McElvaney

Coordination with Building Egress

The first responders will need to establish entrance and exit control points that can be used by the first responders and the evacuees. See Chap. 11 (Emergency Egress) for more information on emergency egress.

Fire Control/Command Center

The fire control/command center is the nerve area that will provide information about the incident and how the building systems are operating/responding during the event/emergency. In many jurisdictions, a dedicated room will be used for this area. The fire control/command area is sometimes co-located within a room that is staffed around the clock with personnel that has a working knowledge of all building systems and can control these systems, such as in a security control room (see Fig. 17.4).

Fire control/command centers need to be accessible to the first responders to facilitate a rapid response time. Located within the fire control/command center should be the controls for all building systems, contact information for key building management and operations personnel, current plans of the structure, emergency action plans, egress plans, preplans, and business continuity plans.

Fig. 17.4 Example of a fire/security command center (Photo by Jensen Hughes)

Items located within fire/security command centers may include:

- Fire alarm panel
- Security cameras and video monitors
- Security alarms
- HVAC fan control systems
- Normal/emergency power supply status indicators and remote start
- Smoke management/control panels
- Vertical transportation status panel and remote recall and stop functions
- Access control systems/keys with remote control to unlock doors
- Mass notification/paging system panels
- Fire pump status panels and remote start
- Controls or monitoring of other features unique to the building
- Current set of working plans and diagrams of the building and its systems
- Hazardous materials inventory statement and management plans
- Emergency management plans

Very tall buildings can have large footprints and multiple towers. When buildings contain large footprints, it should be determined in the fire strategy and design of the system whether multiple command center locations should be included. This would provide additional levels of redundancy should the primary command center be blocked or impacted by an event. If this condition occurs, responders and on-site personnel can assemble at an alternate location to monitor and control the life safety systems.

The location of the fire control/command center within a building is critical to the fire department operations within the building. Discussion of the location of the fire control/command center early in the design of the project will ensure that architectural design objectives can be coordinated with the needs of local responders.

Chapter 18
Electrical

Electrical systems for very tall buildings are crucial for normal operation and life safety. Their reliability can be evaluated as described in Chap. 9 (System Reliability). Buildings located in populated areas are more likely to always have normal power available, except for unique circumstances, whereas in less populated areas, buildings may have power only during certain times of the day or for only days at a time. As part of the design of the electrical systems, the reliability of utility power should be investigated.

The reliability of utility power can be evaluated through historical data available from the power company. When this data is not available, it is more difficult to estimate, and allowances should be considered. Furthermore, evaluating the reliability of the utility power needs to consider both total power outages and the quality of power being delivered, as this may impact the equipment as well. In areas where utility power is considered unreliable, enhancements to on-site electrical supply systems should be considered.

At times, using the same equipment for both the augmentation of normal power and emergency power is done, such as generators supplying both normal and secondary power. It may be practical to increase the level of power generation to consider the dual use of such equipment. For example, if on-site generators are used to provide normal and emergency power, these systems may need to be enhanced to increase their reliability during emergency conditions, since they serve a dual purpose.

The quality of on-site-generated power affects the reliability of the power being provided. Often, power coming from generators is sufficient to run critical systems for limited periods of time but may not be designed to run equipment continuously. If on-site power generation is required on a continuous basis, the system needs to be designed as a primary power system rather than standby. One of the things to consider about on-site-generated power is the impact that quality of power will have on equipment that is used during both normal and emergency situations.

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Emergency and Standby Power

Many life safety systems require power to operate. The integrity of the power supply needs to be evaluated for very tall buildings. Many building and electrical codes govern which systems require secondary power and what type of power they need. Loads are subdivided, so those that most directly impact preservation of life and safety are given the highest priority. Typically, these include:

- Emergency power
- Standby power
- Optional standby power

The time required to initiate emergency power after loss of normal power affects the performance of the life safety systems and therefore needs to be determined. During loss of normal power, batteries can be used on some equipment (e.g., exit illumination and fire detection and alarm systems) to maintain operation during switchover. Other systems will have a temporary loss of power until emergency or standby power can be provided (i.e., fire pumps and smoke control systems).

Some systems will tolerate a very short switchover to emergency power, while other systems can have a longer duration of power loss. Generally, emergency power is provided within 10–15 s, whereas standby power is provided within 60 s, based on many of the standards and codes used around the world. Emergency systems for very tall buildings include the following:

- Exit signs and means of egress illumination
- Elevator car lighting
- Fire detection and alarm systems
- Emergency voice alarm and communication systems
- Electrical fire pumps

Standby power is typically required to be available after power is provided to emergency equipment. For very tall buildings, the items that might need standby power include:

- Elevators
- Smoke control systems
- Power and lighting for fire command rooms

Optional standby power systems can also be connected to on-site emergency generators. It is prudent to separate optional equipment from code-required standby systems.

When designing systems for very tall buildings, emergency and standby power is necessary for the continued operation of essential life safety systems. The integrity of the emergency and standby power systems will need to be evaluated as part of the overall building fire strategy. Maintaining power to critical equipment is essential to the preservation of life during emergency events and building evacuation.

Stationary battery systems, such as UPS-type systems, can be a reliable source of power in very tall buildings. They can be used in conjunction with normal and secondary power to supply continuous power to mission-critical systems. They can even be used to stabilize unreliable power being generated at the site, or filter power systems. They can be beneficial in supplying reliable power to certain areas within the building but may be cost prohibitive in supplying power to the entire building. The cost and maintenance of these systems need to be evaluated to determine their benefit in the overall power system. In addition, depending upon the types of batteries being used, additional specialized fire protection measures for the UPS system may be required.

Consideration should be given to the level of protection provided for emergency and standby power circuits and equipment. If a stay- or defend-in-place strategy is implemented, protection of rooms containing emergency and standby power switchgear and transformers must be considered. Providing fire resistance separation for these rooms consistent with the rating of floor assemblies may be appropriate because this will provide a level of protection consistent for the overall compartment. Fire resistance of vertical electric risers consistent with this level of protection is also recommended to protect feeders and circuits supplying systems outside the fire area.

On-site electrical generators are normally used to provide emergency and standby power. Survivability of these systems is a fundamental principle for the design. Separation of the generation system and engines from the normal/utility power service to the building should be considered to avoid common mode failure of sources. The reliability and integrity of the generator system should be evaluated as part of the design process. For very tall buildings, it may be appropriate to provide multiple parallel backup generators so that power is available should one generator be down or taken offline.

The type of fuel that supplies generators should also be considered. Most generators use diesel fuel, but some use natural gas. If natural gas is used, the fuel source needs to be reliable. If diesel fuel is being used, the storage and delivery methods need to be evaluated. If transfer of fuel between the main storage tank and secondary day tank is provided, then the integrity of that fuel transfer system needs to be evaluated, and protection of the fuel transfer systems should be considered.

The location of the generators should also be determined. It might be desirable to disperse generators in different rooms, or locations in the building, to avoid single-point failures in the electrical system. Generators located within the building should be in rooms provided with fire resistance to the level of protection afforded by the surrounding building elements, such as floor assemblies. They should be located where access is reasonably provided and away from other potential hazards. If located outside the building, protection of the generators as well as the fuel supply from vehicular or other damage needs to be provided. Survivability and separation of power sources should be a fundamental design philosophy.

For very tall buildings, the integrity of the emergency and standby power systems is an important part of the overall fire strategy. The life safety systems used to protect building occupants and responding personnel rely on emergency and standby power systems to function under emergency and fire conditions. Separation and segregation for system survival in the event of an incident should be given due consideration as the consequences for common mode failures can be extreme for very tall buildings. This starts with separation of sources and segregation of feeders and distribution infrastructure.

Emergency Lighting and Exit Signage

One of the systems requiring emergency power is means of egress identification and illumination. This includes power to operate exit signs and means of egress illumination. If normal power is interrupted, minimum lighting levels and visible exit signs are needed for safe egress as well as for emergency response personnel. A discussion with local code authorities is necessary to determine just how long these systems should be available, especially if these systems are expected to be available for a complete building evacuation.

Power for emergency lighting, as well as exit signage, can come from on-site generators or from batteries. The time to establish egress illumination should be included in the fire strategy. For a very tall building, this power normally comes from on-site generators, as they are already provided. For buildings without generators, backup power comes from battery packs integral to the sign or light. As noted above, the integrity of the emergency power system is a factor in the operation of emergency lighting and signage under loss of normal power conditions.

Battery power can be used for providing emergency power to lights and exit signs. The battery power can be from centralized (UPS type) systems or batteries integral to the device. Both approaches require periodic testing and maintenance. For a very tall building, the sheer quantity of devices may make an integral battery approach impractical. Centralized battery-based systems reduce maintenance requirements and the number of locations the maintenance must be performed.

It may be beneficial to consider certain key areas of the building to provide battery backup units in addition to generator supplied power. These could include fire command rooms, emergency generator and power rooms, refuge areas on individual stories if refuge areas are part of the egress plan, and other strategic locations.

Elevators

Elevators are typically used by emergency response personnel to access areas in the building during fire or emergency events. They recall to the primary response floor and wait for use by emergency personnel. In some buildings, especially very tall buildings, they are also used for occupant egress because they can reduce time needed for evacuation.

If elevators are being used for occupant evacuation, emergency power supplies and circuits should be provided for the elevator machinery and cars, including any climate control equipment for the machinery rooms. Most likely, these cars and their control equipment would be provided with standby power, but standby power-related critical features should also be considered. This includes power supply circuits for ventilation and cooling equipment as well as other circuits necessary for the operation of these cars.

Protection of the power supplies should also be considered. The level of protection necessary should be consistent with the evacuation scheme and time to evacuate using the elevators. Even if the elevators are not used for evacuation, consideration of power supply protection should be given to emergency operation elevators and their associated equipment.

If elevators are used for occupant evacuation, the egress time should be evaluated to determine if the prescribed fuel supply duration is sufficient to meet this timeframe. If not, the fuel supply should be increased to provide sufficient run time for generators to provide for the time necessary for occupant evacuation using elevators.

Stay- or Defend-in-Place Coordination

Many very tall buildings employ partial evacuation, where only a portion of the building is evacuated and the remainder of the building is not. Power supplies to life safety systems need to include an evaluation of protection and duration to match this concept. Survivability and avoidance of common-mode failure risks due to co-located infrastructure should be a consideration for stay- or defend-in-place strategies due to the consequences of system failures.

The overall fire strategy will need to account for stay- or defend-in-place durations needed, and emergency and standby power systems will need to be designed toward this duration. This may also apply to systems that are not considered required emergency or standby systems, but which are needed to provide comfort for occupants that remain in the building. This can include electrical power for HVAC equipment, pumping systems for domestic and plumbing services, as well as other non-emergency needs.

Another consideration for emergency and standby power supplies is the load and duration needed for emergency response personnel operations. The required systems are generally those needed by response personnel to work in the building under an emergency event. However, for very tall buildings, additional time and loads may be required to serve response personnel needs. This could include increased run time for emergency elevators, smoke control systems, smoke removal systems, breathing apparatus systems, etc.

The optional standby loads will impact the sizing and selection of the generators. If not considered during the design of the power supply systems, the generators may not be adequate to sustain personnel in the building in stay- or defend-in-place strategies, both occupants not being evacuated and emergency response personnel working within the building.

Chapter 19
Buildings Under Construction

Serious fires can occur in very tall buildings during construction. Buildings under construction present fire protection risks that are often overlooked, including incomplete or missing internal and exterior fire barriers; limited water supplies; extraordinary combustibles in and/or adjacent to the building; limited ingress and egress routes; extraordinary ignition sources from the temporary arrangement of utilities and the construction operations; and extraordinary security conditions. These risks are magnified in very tall buildings, suggesting that a risk analysis is recommended for each project. The risk analysis may drive the need to plan for and implement earlier activation of the fire protection systems as the building is constructed.

Awareness of emergency conditions is critical to the successful evacuation of persons from a very tall building. However, some parts of the designed building's egress systems, as well as other passive and most of the active systems, are likely not operational at points during construction of a building. Construction phasing plans need to be coordinated with the fire protection systems because of the number of workers that can be present within the building as it nears completion.

NFPA 241, Standard for Safeguarding Construction, Alteration, and Demolition Operations provides guidance on preventing or minimizing fire damage to buildings, including those during construction, alteration, or demolition [125]. This standard also provides guidance for the increased risk associated with the construction of mass timber buildings.

Fire Hazards

There are several fire hazards present within a building under construction. Those hazards will vary with the construction techniques employed. Since construction techniques can be almost as varied as the designs of a new building, a detailed assessment of those potential hazards should be conducted for each project.

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Those hazards can be roughly grouped into three categories:

1. Conditions increasing the potential for fire development, including unusual ignition sources, increased fuel loads, and temporary fuel loads that may not normally be encountered in the typical very tall building such as combustible forms and form lumber and flammable solvent vapors.
2. Incomplete or missing permanent fire protection barriers and systems
3. Conditions that can hamper fire-fighting operations

The ignition hazards in a very tall building under construction differ little from those observed in other buildings under construction. As such, the ignition hazards are not considered herein. What is different is the fact that there is a great potential for many more occurrences of ignition hazards to exist; they will be spread over a much larger area and for a longer duration.

In a very tall building, fire fighters are typically required to be inside the building to attack the fire. Fire fighters may need to travel great vertical distances within the building to bring fire protection equipment and water to the fire. The water supply and vertical transportation systems may not be developed sufficiently to assist in those fire-fighting operations. These are some of the additional challenges fire fighters may face in very tall buildings.

Given the large amount of stored construction and packaging materials as a normal circumstance of construction, one ignition hazard that occurs on construction sites is careless discarding of smoking materials. Smoking is prevalent on construction sites, creating an environment with a higher likelihood for ignition and growth of a fire in a building that may have incomplete fire barriers and fire suppression and fire detection systems. Regular disposal of excess combustible construction and packaging materials becomes critical in the construction planning considerations. Open flames present a greater risk in the construction of tall mass timber buildings. Torch-applied roofing should not be used in the construction, alteration, or repair of tall mass timber buildings.

Fires in very tall buildings can also present significant fire exposure to adjacent properties. The nature of distance to and importance of the exposed properties should be considered when developing the fire safety program for the construction phase of very tall buildings. To limit the exterior fire exposure to adjacent structures during the construction process, an analysis that considers fire exposure to adjacent structures should be performed. The analysis should include the maximum number of combustible stories that can be constructed before installing passive protection and/or sprinklers in service, the width and height of each exposing story, and the separation distance to other structures.

Challenges in Buildings Under Construction

Construction of very tall buildings can take several years to complete. There can be many workers in these buildings and, in some instances, workers who have been domiciled within the building. With fire alarm signaling systems not yet completed, informing the construction workers within the building of emergency events is difficult. Occupant awareness of a potential fire situation is likely by word of mouth or through direct-connect phones.

Planning and implementation of worker safety programs are usually left up to the general contractor. However, in very tall buildings, the design team may also be involved in planning for and designing for fire protection systems to come online during construction, if for no other reason than to support fire-fighting operations that are significantly impacted during the construction of a very tall building. Providing protected means of egress is a significant consideration during construction, especially since other fire protection systems are not likely to be active throughout the building. Maintaining at least one fire-rated means of egress starting two or three stories below the main line of construction provides a degree of protection to the workers.

Several conditions will hamper fire-fighting operations when a fire occurs in very tall buildings under construction, and some of them can be particularly challenging. Site access is usually restricted to keep the public from being hurt and to provide security on the construction site. Construction sites are especially susceptible to accidental fires caused by unauthorized people attempting to find shelter out of the weather and to intentional fires set by arsonists. However, restricting site access also limits the ability of the fire department to maneuver apparatus necessary to carry equipment or pump water into the building. Proximity of fire fighter access to the building's vertical transportation system is important.

The availability of vertical transportation becomes even more important in very tall buildings because fire fighters rely upon elevators or exterior hoists for transportation of personnel and equipment to just below the fire floor. The operating procedures of the hoists are different from elevators. Fire fighters should become familiar with the operation the hoists if used on the project. Overhead crane operations should also be taken into consideration when planning fire department access. It is important to consider fire fighters' operational needs as the general contractor plans the projects' vertical transportation during construction.

One of the biggest challenges in fighting fires in very tall buildings is having a sufficient water supply. Most fire department vehicles can supply standpipes and provide adequate pressure up to about 130 m (420 ft) of building height. Taller buildings must rely upon internal pumping systems to provide water for fire fighting at higher elevations. Some fire departments in developed countries with experience with very tall buildings have special apparatus designed specifically for very tall buildings, capable of pumping to heights higher than 130 m (420 ft). That apparatus is likely to have multi-stage pumps that can achieve pressures of 4100–4800 kPa (600–700 psi). These pumpers can achieve a 700 kPa (100 psi) residual pressure at the top of a 365 m (1,200 ft) building for fire-fighting purposes. More commonly, no such apparatus is available. When such systems are employed, the pressure ratings of piping and equipment should be designed to accommodate these higher pressures.

Providing standpipes with automatic water supplies is even more complicated while the building is under construction because some of the planned standpipe piping, fire pumps, and water storage tanks will not yet be installed. Temporary pumps and standpipes should be employed early in the construction of a very tall building. Dry standpipe systems having pressurized air for supervisory purposes are also used. A properly protected power supply should be in place if pumps are used. Standpipes should be extended upward as the floors are constructed, with hose outlets available not more than one floor below the highest floor under construction. The capabilities of the local fire department should be reviewed prior to planning for protecting the building during the construction period.

Phased Occupancy

For purposes of this Guide, phased occupancy is defined as permanently occupying part of the building prior to completing the construction of the building structure or its exterior envelope. Generally, vertical construction continues when phased occupancy is used. There are higher risks associated with this type of occupancy.

More and more owners of very tall buildings are realizing the economic need to phase occupancy to begin generating revenue to meet financial obligations. Phased occupancy has become common in some jurisdictions that have developed their own policies on conditions to allow phased occupancy for a project. Some cities have specified minimum physical fire separations of the occupied portions of the building from those having construction operations. For instance, buildings with three or more stories are required to have 3 h fire-resistive construction.

Phased occupancy presents higher risks for both the building occupants and the fire fighters. A detailed hazard and risk analysis of the proposed phased occupancy is encouraged to address the unusual conditions that will be specific to a given project. If there is to be phased occupancy, it should be planned early in the design phase.

One or more cranes may be used to service the building, and overhead operations are likely to continue daily. Building occupants and fire fighters need safe access for ingress and egress. Therefore, overhead protection of ingress and egress paths is necessary. Although construction operations may occur on opposite sides of the building from normal occupant access routes, overhead protection should be considered because the need to conduct overhead operations over the access routes may not be fully foreseen.

Protection from overhead operations is also needed for building service equipment, especially those that the fire department needs to use in fighting a fire in the building. This will include fire department connections, and the paths leading thereto, and the path leading to the fire command center door. Consideration should also be given to provide protection from overhead at points and paths where the water supply pipes, power supplies, and communications lines enter the building. Depending on the overall height of the building and the depth of cover over these utilities, buried utilities could be damaged from construction materials inadvertently falling from the crane that can penetrate the ground.

The fire and life safety systems in the permanently occupied portions of the building, and between those occupied portions and the level of exit discharge, should be essentially complete and functional. Consideration should also be given to the occupancies and the risks created by them on levels *below* the level of exit discharge. Fire protection systems, including sprinkler, standpipe, fire pumps, fire detection and notification, smoke control, stairway pressurization, emergency power, and elevator emergency operation systems within the area to be occupied, should be fully functional and connected with intended integrated systems as part of the permitted phased occupancy. Therefore, the design of the fire protection systems should provide for zoning of those systems to allow coordination with those parts of the building that will be initially permanently occupied. Those systems should be fully tested and commissioned as if there were to be no further construction. It is also advisable to perform spot checks of previously approved systems that are subject to possible compromise or deterioration during the remainder of the construction. For example, the programming of a fire detection and alarm panel can be altered after an acceptance test has been conducted in the previously approved portion of the building.

Beyond the areas to be occupied, standpipes should be available within the construction areas. Careful planning will be necessary in phasing the extension of the construction area standpipe system from permanent systems serving the occupied part of the building, especially in climates where standpipes within construction areas may be subject to freezing temperatures. Manual fire stations can be connected to the building fire alarm system, even if only temporarily so, within the construction area.

A less formal variation of phased occupancy may occur during the construction of very tall buildings where the workforce may reside within the building when not working. Transportation vertically in the building is severely limited and can be a significant barrier to efficiently moving construction workers up and down the building. This practice is not likely to be known during the design phase but should be addressed once identified. Providing properly protected means of egress and means of communicating with the building workers is important, even if only temporary.

Partial Occupancy

For purposes of this guide, partial occupancy means the incomplete occupancy of a structure where the only significant ongoing construction is that of tenant buildouts. This situation will occur most often in the construction of a new very tall building. It is likely that there will be some shell space not yet sold or leased and, therefore, unoccupied.

There are no significant differences in the occurrences of shell space in very tall buildings over those that may occur in other buildings. The key difference is the potential impact of a fire in one of these spaces can be greatly magnified if proper protection features are not fully in place. Therefore, the use of and access to these areas need to be controlled.

Electrically supervised sprinkler protection should be provided for empty shell spaces because they may be used as storage areas. Any fire detection required should also be provided and functional. Risk assessments may suggest these spaces should be isolated from remaining areas on the floor by fire-resistant assemblies in an attempt to contain the fire. Finally, smoke removal systems that may be required within the building should also be considered for these spaces depending upon the building's overall fire safety strategy.

Tenant Changes

Tenancy in very tall buildings is a dynamic condition over the life of the building. As a result, there can be a constant evolution of changes to the design, fit-out, and use of stories or parts of stories within the building. Each tenant change that includes renovation of the space will impact several life and fire safety features designed for the building and should be evaluated in consideration of the building's overall strategy.

In the design phase, it is important to consider how the progression of tenant changes will affect the overall safety of the building. For instance, changes in occupancy can affect fire protection system capabilities, egress capacities, and differences in fuel loading that may impact the design fires used as the basis for a performance-based fire protection design or the hazard classification basis for the design of a sprinkler system. If a building undergoes frequent changes over its life cycle, it may be cost-effective to include flexibility in the systems' original design to accommodate those changes. Planning for such changes may be able to reduce system outages and the need for – or duration of – fire watches during the renovations.

Fire protection system impairments and increased fire hazards such as rubbish/waste fuel loads, presence of flammable/combustible liquids, hot works, etc. could increase the risk to building occupants. Depending upon the scope of the tenant renovation, it may be prudent to conduct a risk analysis to identify unusual risks to building occupants so that specific provisions to address those risks can be developed.

Change of Use/Occupancy

Changes in occupancy can present a major impact on the operations in an existing very tall building. The means to deal with the issue is the same as for any building, varying only in degree.

For instance, sprinkler system design densities appropriate for a previous tenant may not be sufficient when a transition occurs. Design assumptions, especially those in a performance-based design, may be invalidated when fire loads or occupant loads are changed in a building. Specific types of detection and suppression may no longer be applicable when tenant changes occur. As such, tenant changes should be reviewed within the context of the building fire/life safety program.

Major Repairs

Certain major repairs to existing very tall buildings require careful consideration of the associated hazards and implementation of proper safeguards. For example, roof repairs involving open flames and the temporary storage of combustible insulation materials present a high risk of fire in the challenging geometry of a very tall building.

A fire safety program specific for the building and the anticipated hazards should be developed. The program should include the following components: housekeeping, control of ignition sources, control of combustibles within the area of operations, fire protection systems, fire extinguishers, communication ability with the local fire warden and the fire department, site security, and a fire watch.

Chapter 20
Building Life Cycle Management

Building Operations

Operations in very tall buildings need to consider any special provisions that may be associated with the facility. It is important that change control be implemented for very tall buildings where unique design features (which are likely to be predicated on a performance-based design approach) have been implemented to allow for design flexibility that may not be anticipated.

For example, unique assembly events may incorporate the use of either flame effects or pyrotechnics. Flame effects can be used in conjunction with performers or simply to add effect to a room. Several iconic, very tall buildings throughout the world have incorporated commercial pyrotechnic launch capabilities into the building facade and on the rooftop. Both represent ignition sources and dangerous fuel loads that would not normally be encountered in very tall buildings. Flame effects can be coupled with ornate interior finishes. Commercial pyrotechnics are Class C explosives which are not usually permitted to be stored or used within occupied buildings, let alone very tall buildings. Since these features are often incorporated during a tenant improvement process (often long after the vertical transportation systems construction has begun), there is likely little consideration to the path these materials will take through a very tall building to reach the ultimate destination or the significant increase in risk to the safety of the building occupants. As either of these two examples can significantly increase risks to building occupants, a detailed risk assessment should be conducted to determine when, or if, pyrotechnics or exposed flames will be used within a very tall building.

More and more elevators are part of an evacuation program for very tall buildings, and an elevator taken out of service in a very tall building may need to be addressed in a manner similar to the closing of a stair or blocking of an exit door in a normal building. Provisions may need to be implemented to limit occupant loads or instruct building occupants to potential exiting configuration changes, particularly in a situation where many building stories could be impacted.

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The integrity of horizontal exits and other fire-resistant separations also needs to be maintained. The simple act of routing telephone cable across these barriers may impact their integrity, yet this occurs commonly in tenant build-out construction. Without proper knowledge and demarcation of these barriers, contractors or even building occupants themselves may violate the integrity of these barriers without knowledge.

If the unique life safety provisions incorporated into the building's design are not documented for future building users, the very existence of these provisions may be lost. As renovations occur and design professionals previously associated with the building are no longer involved, documentation should be made available to future designers.

Building personnel should be charged with a method to document potential building changes that could impact any of the various unique design provisions. These provisions are probably best communicated through a single document which summarizes fire/life safety provisions. Fire Protection Basis of Design Reports should include the pertinent fire protection/life safety features incorporated into the building design. These can include, but are not limited to, the following:

- Any alternate methods of construction or performance-based design provisions used in the building design, including documentation of all computerized fire and egress modeling performed
- Passive fire-resistant provisions, including structural fire resistance, fire-resistive separations, and interior finish requirements
- Egress system provisions, including the use of horizontal exits, phased evacuation zones, egress and exit travel distance calculations, and unique exiting configurations
- Fire suppression system provisions, including sprinkler design densities, unusual fuel loads, special suppression systems, and fire pump arrangements
- Fire alarm system provisions, including zoning, special detection provisions, and emergency communication system configurations
- Smoke management system provisions, including design approaches, pertinent design calculations, and integration with fire suppression and detection systems
- Emergency and standby power provisions
- Hazardous materials

Fire Wardens and Incident Management

Properly trained fire wardens are critical components of evacuation strategies in very tall buildings. Since very tall buildings may not lend themselves to standard evacuation methods, fire wardens can provide critical information to building occupants during emergency scenarios (see Chap. 11, Emergency Egress) and to first responder personnel.

Emergency operation plans should be established for very tall buildings. Building personnel of all types have roles during emergency operations, and these roles must be outlined and periodically practiced prior to an emergency occurrence. These personnel include, but are not limited to, the following:

- Building engineers
- Building security
- Fire wardens
- Facility first responders

Emergency operations plans should include all necessary actions required to interface with first responders. This can include shutdown of building utilities, coordination with fire wardens for evacuation, and coordination with building security for access to normally inaccessible portions of the building. Specific roles and responsibilities should be outlined, documented, and imparted through regular training activities.

Tenants within the building should also be familiar with the emergency operations plans as they assist their staff during emergency operations. Tenant fire wardens working in conjunction with the building fire wardens can help facilitate emergency operation plans.

When implementing the assistance of fire wardens in building evacuations, it is important to consider the "human element." Fire wardens can be sick, affected by the event itself, or absent from a building during a fire event. Periodic training on the facility fire/life safety provisions and applicable evacuation methods (see Chap. 11, Emergency Egress) needs to be implemented and regularly rehearsed. Additional staff should be trained in the event primary fire wardens are unable to assist during the event. Methods of communication need to be devised to allow for the implementation of such a program in the early stages of a fire evacuation.

Facility personnel, such as building engineers and fire safety directors, can be a valuable resource to first responders due to their inherent knowledge of facility fire/life safety systems and operational protocols. Procedures should be set in place and coordinated with the local fire department to have their capabilities available for incident command in the event of an emergency.

Chapter 21
Commissioning

Proper commissioning of building systems, and especially fire protection systems, is critical in very tall buildings. In general terms, commissioning is intended to verify that:

- The owner's requirements have been met.
- The building and its systems have been constructed as designed.
- All systems and features are functioning as intended.
- The owner has been provided with the required documentation regarding the operation, inspection, testing, and maintenance of the building.
- Building personnel have been properly trained to operate and maintain the building.

Due to the complexity of the systems associated with very tall buildings as outlined throughout this document, the importance of proper commissioning cannot be overstated.

Commissioning Starts with the Design

Proper commissioning needs to be considered throughout the design process, including the conceptual design phase. One of the reasons commissioning is performed is to determine that the owner's requirements have been met. During the planning phase, the owner's requirements need to be clearly defined. In developing the owner's requirements, consideration should also be given to how the commissioning will take place. What is the role of the design team during building commissioning? Will the installing contractors be responsible for performing the tests? How are the integrated systems to be tested and by whom?

Locally adopted codes and standards may dictate commissioning requirements. For instance, in the United States, if the building is constructed in a municipality adopting codes and standards published by NFPA, then the commissioning process

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is outlined in detail within NFPA 3 [226], *Standard for Commissioning of Fire Protection and Life Safety Systems*. NFPA 3 requires that there be a fire commissioning agent having specific qualifications be a part of the commissioning team [226]. ASHRAE Guideline 5 [227] describes commissioning of smoke control systems.

To illustrate the complexity of commissioning, when looking at just one fire protection feature of a very tall building, consider a zoned smoke control system. The smoke control system is most likely initiated by automatic smoke detection or sprinkler water flow. Activation of the smoke control systems typically requires interface with controls for the building HVAC system. Dedicated fans and dampers specifically designed for the smoke control system likely need to be activated. The building evacuation methodology may result in operation of elevators for egress purposes or the opening of doors used for egress purposes. The basis for the design of the smoke control system may assume environmental factors (temperature, wind, etc.) that are not the same as may be present the day the system is commissioned. How many members of the design team and how many installing contractors are involved in the above general description of one of the many systems that may be present in a very tall building? If the responsibilities for commissioning, along with the procedures to be used, are not considered early in the project, problems will likely arise as the owner tries to get the building opened and the authority having jurisdiction attempts to approve the building for occupancy.

It is common for contractors to assume some responsibility for testing the systems, features, and components that they install. However, proper commissioning of the overall system, such as the smoke control system, requires coordination and cooperation between multiple designers and contractors. There are also scheduling considerations to make sure the necessary members of the team are present when such integrated systems are commissioned. Without proper planning, the owner can anticipate additional costs and scheduling delays as the project proceeds toward completion.

The owner needs to determine if the commissioning will be performed by the system designers or if a separate commissioning team will be employed. Codes may require special inspectors for some of these systems. Using a separate commissioning team permits the system designers to focus on the design of the systems and offers a necessary check-and-balance to ensure the fire protection systems in the building are functioning as intended.

During the design phase, the commissioning agent needs to identify what features of the building or system need to be evaluated and how they are to be evaluated. In many instances, the procedures and documentation for verifying compliance with individual components and systems are covered by a code or reference standard. However, the reference standards are often limited in scope to the respective system addressed by the standard and lack proper guidance on how to perform proper commissioning of an integrated system. Therefore, the commissioning agent should also consider how each system in the building is integrated with others and determine what aspects of the integration must also be tested or evaluated. Lastly, the design team needs to develop the commissioning process that provides the necessary information for the ongoing periodic inspection, testing, and maintenance of the building.

The assumptions made during the performance-based design, or as part of an equivalency, need to be properly documented by the design team so they can be evaluated during useful life of the building. These assumptions and the resulting inspection, testing, and maintenance requirements need to be properly documented as part of the operations and maintenance manual for the building.

The information necessary for proper commissioning, as well as the information needed by the owner for the life of the building, will often be included in a “basis of design” document. This should be included in the documentation provided to the owner at the completion of the project.

Commissioning and the Construction Phase

Although it is often misunderstood that the commissioning happens at the end of the construction phase, there are aspects of commissioning that need to occur throughout the construction process. Certain aspects of both active and passive fire protection features can only be confirmed during the construction phase, without resulting in additional costs, destructive testing/investigation, or project delays.

Access to evaluate through-penetration fire-stop systems, the construction of a fire-resistant assembly, and to confirm the type of sprinkler pipe that is installed may not be available after construction is complete.

The design documents, particularly the commissioning documents, should clearly identify what aspects of the commissioning process need to occur at various phases of construction. Some party, typically the general contractor in cooperation with the commissioning agent, should monitor the progress of construction and determine that all commissioning activities occur according to the schedule. In addition, all changes made to the original design documents or to the construction schedule need to be evaluated to determine if they affect the commissioning plan.

A commissioning plan should be developed by the lead commissioning agent, with support and input from others on the commissioning team as necessary, to outline what needs to be tested, by whom, and what events are expected to take place once a life safety device is activated. Often very tall buildings have complex life safety systems and are integrated with different systems. The commissioning plan is the record of what needs to be tested during the various phases of construction.

Another aspect of commissioning during the construction phase is the development of the documentation for the owner, specifically record (“as-built”) drawings. If an owner is to be provided with accurate record drawings, contractors need to constantly update the drawings with the information, changes, and modifications that occur. Failing to do so and waiting until construction is complete typically result in poorly prepared and inaccurate drawings and subsequent delays in the commissioning of the building and systems therein.

In very tall buildings, this activity can be compounded by the fact that construction and occupancy of the building may take place in phases. The commissioning plan needs to take this into account, not only to provide proper protection of the occupants who may be in the areas of the building in which construction has been completed but also to allow for the ongoing commissioning of building features and systems as the construction progresses in other areas of the building. This is particularly critical when commissioning systems whose operation relies upon software programming. Often during commissioning of systems, software programs must be modified, and it is important to verify that the software change had not adversely impacted the previously approved and functioning systems in the occupied portions of the building.

Commissioning Prior to Occupancy

While commissioning starts in the planning phase and continues throughout design and construction, a major part of commissioning will occur just prior to occupancy. This includes testing and evaluation of the installed systems and building features. Documentation should be submitted that will allow the owner to properly occupy, inspect, test, and maintain the building systems and features throughout the life of the building.

In buildings using risk assessments and performance-based design approaches, the documentation associated with those methodologies must be part of the material provided to the owner. The bounding conditions and assumptions must be understood and documented so that they continue to be met throughout the life of the building.

Chapter 22
Existing Building Considerations

Very tall buildings constructed before many of the technological advancements over the past 30–40 years present unique challenges. While other chapters of this guide provide considerations that are generally applicable to new construction, there are thousands of existing very tall buildings in major cities throughout the world that are subject to consideration for fire safety improvements.

The fire safety of very tall existing buildings is an issue in most major cities of the world. These buildings are of various construction types, uses, heights, and ages. The buildings can reasonably be expected to have various conditions of disrepair and various levels of fire safety. There are numerous examples of fires involving buildings built before the use of fire safety strategies that are commonly used in new construction today: fire resistive construction, compartmentation, automatic sprinklers, fire detection and notification, and adequate and reliable means of egress.

In response to these fires, some cities have adopted local laws applicable to existing buildings with requirements to provide a reasonable minimum level of safety for building occupants. Many of the local codes adopted to address this issue include one or more of the following features: a minimum number of protected exits, emergency lighting, vertical opening protection, automatic sprinkler systems, fire detection and occupant notification systems, and automatic elevator recall. Other cities have gone further to provide a higher level of protection for building occupants and to facilitate fire department operations, including features such as emergency power systems, smoke control, automatic emergency control of elevators, and two-way communication systems. Of course, while these additional features can significantly improve building life safety, additional safety features will result in higher costs. It was only within the last 20 years that hundreds of very tall buildings in one major city, constructed in the 1950s and 1960s, were mandated to be retrofitted with occupant notification systems and other minimum fire protection features.

The modification of an existing very tall building to improve its fire safety often presents great challenges. The cost of installing fire safety features and systems following original construction will be greater than if completed during the building's original construction phase. There can also be significant costs associated with the

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abatement or encapsulation of hazardous materials (e.g., asbestos) in the building's structure. In the case of a sprinkler system installation in an existing building, the cost associated with asbestos abatement can be considerably more than the cost of the sprinkler system itself. Other related retrofit costs may include the effects upon and restoration of the building's architectural finishes and costs for the fire alarm system upgrades or complete system replacement to monitor the sprinkler system (e.g., sprinkler waterflow, valve supervision, fire pump power, etc.) and notify occupants and/or responsible personnel. Retrofit installations may also influence building operations in commercial buildings and may influence the tenants' ability to use commercial or residential buildings during the construction period, involving loss or rebates of rent.

A building having historic features or finishes often requires great care in design and construction of retroactive fire safety improvements to preserve the building's historic character. These can also have an appreciable impact on the costs of completing the fire safety improvement project.

Providing a reasonable minimum level of fire safety in an existing very tall building involves employing fundamental principles of fire protection outlined below. In the absence of any other guidance from applicable local codes or laws, a reasonable level of life safety can be achieved if these four objectives are met:

- A means to detect the presence of a fire
- A means to notify the occupants and emergency forces of the fire
- Protected pathways for occupants to exit the building or reach an area of rescue assistance
- A means to control the spread of the fire

Many of the very tall buildings constructed prior to the 1970s when fire safety in very tall buildings became a focus are likely to not employ one or more of these principles. Some designs relied primarily on existing structural protection or compartmentation. Surveys should be conducted of an existing building to identify the fire protection features of the building so that they can be integrated into a comprehensive strategy for the renovation.

Existing very tall buildings may have unprotected or inadequately protected vertical openings between floors. To control the spread of fire and smoke within the building, consideration should be given to protecting these openings. These include open stairwells, unprotected elevator and hoistway shafts, as well as unprotected utility shafts. While a means to detect a fire in its early stage and notification to the building occupants is important, the methods to control the spread of fire should be examined carefully when considering upgrades to fire and life safety features in very tall buildings.

In existing buildings where no major renovation work is planned, something as simple as providing a door closer on an apartment unit door and educating residents about the importance of that door closer in a fire can have a significant impact on the outcome of a fire. While it would be ideal to be able to mandate the retrofit of fire sprinklers (which can achieve three of the four objectives) throughout all very tall buildings, funding those projects is often difficult for the owners of these buildings.

Another more formalized resource in cities where there is no directive on achieving fire safety in existing buildings is documented in NFPA 550, *Guide to the Fire Safety Concepts Tree* (see Chapter 7) [28]. Other tools include performance-based design approaches which are included in Chap. 3 (Components of Performance-Based Design).

Nevertheless, several cities have enacted retroactive laws mandating specific fire safety improvements in the aftermath of a major fire in a very tall building, including sprinkler systems, rated dwelling unit doors, and detection and notification systems, among others. Other cities have adopted ordinances that allow a building owner to demonstrate that a minimum level of safety is provided – or can be provided – by means of a scoring system based on the principles included in NFPA 550 [28]. Examples of scoring systems can be found in NFPA 101A, *Guide on Alternative Approaches to Life Safety* [228]. Similar systems can also be found in the International Existing Building Code [229]. NFPA 101® *Life Safety Code*® [116] allows the use of an "engineered life safety system" as an alternative to automatic sprinklers in existing business and residential buildings. In that case, however, a specific system is not defined but, rather, is left to the fire engineer to develop a custom solution for each building and requires the approval of the local authorities.

Scoring systems, sometimes known as fire safety evaluation systems (FSES), have been employed for many years to demonstrate a reasonable level of fire safety in health-care occupancies and, also, using similar approaches, in business and residential buildings. Locally developed scoring systems were used in New York City, Chicago, and, more recently, Honolulu. In these cases, if the minimum score cannot be obtained by other measures, automatic sprinkler protection is required. Effectively, the points systems allow a combination of fire safety features in existing buildings to serve as an alternative to automatic sprinkler protection. It should be recognized that, while these features may constitute an alternative to automatic sprinkler protection, they do not constitute an equivalency to automatic sprinkler protection. The resulting level of safety should be reviewed by the fire engineer.

The use of any of these tools to evaluate and develop fire safety plans for an existing very tall building where no formal direction (codes or laws) exists results in what most would consider to be a performance-based approach to achieving fire safety. As in any performance-based solution, it is important that a fire protection engineer experienced in all facets of building fire safety lead the team developing the overall fire safety solution for the existing building.

Renovations and Additions

Because of their overall size, very tall buildings are often undergoing renovations, especially those that are multi-tenant, commercial buildings. Renovations are typically limited to the demolition and reconstruction that are related to the specific tenant changes, but sometimes a larger-scale, building-wide renovation may occur.

These are opportune times to consider improving the overall fire and life safety provided throughout the building, since there is construction already taking place.

Tenancy in very tall buildings is a dynamic condition over the life of the building. As a result, there can be a constant evolution of changes to the design, fit-out, and use of stories or parts of stories within the building. Each tenant change that includes renovation of the space will impact several life and fire safety features designed for the building and should be evaluated in consideration of the building's overall strategy.

In the design phase, it is important to consider how the progression of tenant changes will affect the overall safety of the building. For instance, changes in occupancy can affect fire protection system capabilities (e.g., automatic sprinklers, smoke control, etc.), egress capacities (i.e., doors, stairways, corridors, etc.), and differences in fuel loading that may impact the design fires used as the basis for a performance-based fire protection design or the hazard classification basis for design of a sprinkler system. It can be extremely difficult and costly to add or widen egress stairways in a building where a tenant floor changes from an office space to a meeting level. Similarly, it can be difficult and costly to increase the size of fire pumps in an existing building due to changes of hazard in a portion of the building. If a building is expected to undergo such changes over its life cycle, it may be cost-effective to include flexibility in the systems' original design to accommodate those changes. Planning for such changes may be able to reduce system outages and the need for – or duration of – fire watches during the renovations.

Fire protection system impairments and increased fire hazards (i.e., rubbish/waste fuel loads, presence of flammable/combustible liquids, hot work, etc.) could increase the risk to building occupants. Depending upon the scope of the tenant renovation, it may be prudent to conduct a risk analysis to identify unusual risks to building occupants so that specific provisions to address those risks can be developed.

Adaptive Reuse and Change of Occupancy

Some very tall buildings constructed for a specific purpose have become obsolete over time and can become vacant for several reasons. To make use of the stock of vacant buildings that may exist in any given city, extensive renovations of very tall buildings that include a change of occupancy, or use, can occur. Adapting an existing building for a new and possibly very different use is likely to result in a need to conform with many requirements applicable to new design and construction. Regardless of applicable codes or local laws, thoroughly understanding the fire and life safety system present in the existing very tall building is an important first step to being able to assess the impact of the proposed change of use.

For instance, sprinkler system design densities appropriate for a previous tenant may not be sufficient when a transition occurs, which can impact the size of the fire pump and/or water supply. Specific types of detection and suppression may no longer be applicable when tenant changes also include a change of occupancy. As such, tenant changes should be reviewed within the context of the building's fire/life safety program, or a new risk analysis should be considered.

Design assumptions, especially those in a performance-based design, may be invalidated when fire loads or occupant loads are changed in a building, which are likely to occur with change of occupancy. In such cases, the entire performance-based design should be revisited, including conducting the computer models used to support the analysis.

Adaptive reuse and/or change of occupancy is likely to change the basis of design upon which the fire protection program of the very tall building was initially conceived, and therefore re-evaluation of the overall building program commensurate with the scale of the reuse or occupancy change is necessary.

Chapter 23
Inspection, Testing, and Maintenance

The performance of a very tall building as a system will depend on the reliability and performance of the system's components. In this regard, a program of routine system inspections, testing, and maintenance (ITM) will be directly correlated to its reliability.

Chapter 7 (Hazard, Risk and Decision Analysis in Very Tall Building Design) addresses how fire protection system reliability becomes part of the overall reduction in risk to an acceptable threshold. ITM programs can discover problems in a system that could result in a failure. By correcting such problems, system failure rates will decrease, thereby increasing the overall reliability of a fire protection system.

In addition to active fire protection systems, other components of fire safety design should be inspected and maintained to achieve the goals and objectives of the fire protection engineer. These components include fire resistive construction, egress and exiting systems, changes in occupancy or fuel load, and additional electrical loads. The occupants of very tall buildings would be vulnerable to hazards from fire, earthquake, or other man-made and natural disasters if critical life safety components are not maintained and kept in service.

For a system to be deemed reliable, it must function as originally designed. This is based on the design goals and objectives of the stakeholders but, for very tall buildings, would generally be based on the following objectives: (1) provide life safety, (2) conserve property/limit property damage, and (3) provide continuity of the critical mission functions of a facility. The reliability of a system is the combination of the reliability of multiple components including system design, installation, equipment, and operational maintenance. Reliability is a function of statistical probability and can be calculated following the Lusser Product Law, which is calculated through the product of individual component's reliability [75], [230], [231]. This becomes a very important design parameter to consider in performance-based fire safety design, where a particular reliability is assumed in the fire risk assessment.

Life cycle costs should be considered when determining the appropriate measures to be implemented into an ITM program. Life cycle costs are generally

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incurred through the inspection, testing, and maintenance (ITM) process for fire protection systems, particularly in large structures like very tall buildings. These life cycle costs are typically offset by the increased reliability of fire protection systems. This is especially critical in very tall buildings where interdependence on these systems is necessary for life safety.

Consideration should be given to performing a life cycle cost analysis to determine total costs associated with building operation during the life of the building [232]. The rate of return for these savings can be calculated to determine the total cost savings provided through an ITM program [233].

Integrated Systems

The overall life safety system for a very tall building will likely be comprised of several systems that work together to achieve life safety performance. These systems are integrated to work as a whole so that the building's life safety design is met. Integrated systems for a very tall building will include, as a minimum, fire alarm and detection systems, emergency voice alarm systems, automatic sprinkler and standpipe systems, smoke control systems, emergency and standby power systems, elevator fire fighter controls, building management systems (BMS), as well as security systems. While each system can and will be separate from the others, how they function together is what makes up the integrated system. Additional information related to integrating fire protection systems can be found in Chap. 8 (Integration of Building Design and Systems).

Many local fire codes mandate periodic inspection of individual systems that make up the integrated system. NFPA standards, such as NFPA 25 [234], outline the individual component testing required for various systems and provide timelines as to when these systems or portions of the system are required to be inspected and tested. In general, fire alarm and sprinkler systems are tested annually with other portions, such as pressure-reducing valves every five years. It is important to maintain the periodic inspection and testing of the individual components so that these systems operate as required. It is also as important to test the overall integrated system to make sure the interface between the individual systems is functioning.

NFPA 4, *The Standard for Integrated Fire Protection and Life Safety System Testing* [235], is a relatively new standard that addressed testing of these complex systems. Not only does it address the initial testing but also addresses periodic testing after the building is occupied so that the systems continue to perform as intended. The key element of this testing is to verify and document that the operation and function of all interconnected fire protection and life safety systems perform as designed.

Integrated system testing includes the test team, a test plan, and the test documentation. In very tall buildings, one needs to consider the complexity of the combined systems and the performance intended to be achieved. Once the life safety system plan is developed for the building, the test team can develop the test plan. The test plan is then the document used for the life of the building to confirm the overall operation of the integrated systems. This does not eliminate the testing required for the individual systems but adds the layer of making sure the interaction between systems takes place as designed. As the building changes over its life cycle, the test plan will need to be updated to reflect changes in the life safety system operation.

The test plan should consider a variety of things, including the interface between the various sub-systems. It should also consider the continuity of building occupancy and operation as inspection and testing take place. Because very tall buildings will likely have many occupants, business continuity should be considered should portions of the systems be taken offline for testing or malfunction and require repair. Spare parts could be maintained on site to alleviate any business continuity impacts as well as emergency response times in maintenance agreements.

Operations and Maintenance Manual

An operations and maintenance (O&M) manual is a tool for the building owner, the construction installers, and the facility staff to operate and maintain the systems present in a very tall building. The O&M is specific to each individual system and would benefit from having a test plan consistent with the integrated test plan for how that specific system interfaces with the building's overall life safety system. While an O&M manual is necessary for buildings designed with a performance-based approach to properly document the design basis, it will also become invaluable through the life cycle of the building.

It will serve as the basis for the ITM program in very tall buildings, as well as prescribing boundary conditions and restrictions related to occupancy, fire protection system design, and fuel loading. While traditional construction procedures often leave much of the O&M manual production to the system installers, it is important in very tall building design for the fire protection engineer to be involved in the process of documenting the parameters related to fire protection systems. The engineer's insight into the design basis and boundary limitations may not be readily apparent to the installing contractors, which could inadvertently leave important facets and operation and maintenance requirements missing from this document.

Because most tall building designs will employ at least some approaches in performance-based design, it is useful to have an O&M manual available to the owner/tenant, building maintenance engineers, AHJs, and other stakeholders. Templates are available for writing O&M manuals for fire protection systems, as well as the integrated system test plans. NFPA 3, The Recommended Practice for Commissioning of Fire Protection and Life Safety Systems [226], and NFPA 4 [235] provide useful sample documentation that can be used for the testing and documentation of an ITM program. It is also important for the O&M manual to cover changes that would affect the design basis parameters. It is difficult to maintain the design criteria for very tall buildings unless the O&M manual is available and kept current.

Codes and Standards

Requirements for inspection, testing, and maintenance that will provide overall fire safety in very tall building design begins with an examination of building codes and standards, as well as insurance considerations applicable to maintaining fire protection system reliability. The use of a code or standard is often determined by the requirements of the sovereign nation or entity where the building is to be constructed. However, in some developing nations, there may not be standards regulated by law, but there will most likely be a requirement from the building owner or insurer to comply with certain codes and standards.

The fire protection engineer for very tall building design should also be familiar with performance-based test and inspection methods that will help to achieve the design goals and objectives.

In many performance-based design approaches, fire protection systems are pushed more to their operational limits. As a result, reliability becomes even more critical function for the fire protection engineer to consider. In very tall building design, the engineer may determine that ITM schedules in excess of what would be required by the applicable local codes and standards may be necessary to better address the overall building system reliability.

Impairments to fire protection systems will likely occur during the life cycle of the building. So, it is important to consider a program for impairments – both for those planned impairments during building alterations and modernizations and the unplanned or emergency impairments that are likely to occur. The operations and maintenance manual (O&M manual) should include impairment procedures to verify system performance and reliability during building construction changes and emergency situations.

The qualifications for ITM program personnel/contractors are important to consider in implementing a proper maintenance program. While codes and standards typically indicate the need for such persons to be qualified, individual system standards do not typically specify the training programs, education, certification, or licensure to qualify a person to perform inspection, testing, and maintenance. However, NFPA 4 [235] outlines who should be on the testing team, their responsibilities, and qualifications. The testing team should include an integrated testing agent. The agent is responsible for who is on the testing team, developing the test plan and preparing the testing documentation.

AHJ Inspections

The Authority Having Jurisdiction (AHJ) may play a role in ITM programs. A regular inspection program has been documented to reduce property damage and casualties in buildings where regular inspections were performed [236]. Thus, very tall buildings will benefit from regular AHJ inspections to verify ITM programs are being competently conducted in a thorough manner, abate noted hazards to fire and life safety, and maintain fire and life safety system reliability. In the absence of a local AHJ having the ability to participate in such a verification, fire protections engineers experienced in very tall building fire safety design could provide invaluable oversight and input to building management on the effectiveness of the ITM program.

The AHJ can take many roles but is generally part of a municipality or insurance interest. AHJ inspections typically take on the role of fire prevention inspections, property maintenance inspections, or risk evaluations in the case of insurance interests. The user of this document is advised to refer to the local codes and standards in effect for the jurisdiction in question. These various codes and standards are typically used in conjunction with other local building codes to address risks from inadequate maintenance.

The aspects of performance-based design implemented into very tall building designs must be maintained, so it becomes critical for the engineer to consider maintenance inspections throughout the life of the building. In the development of the operations and maintenance (O&M) manual, the fire protection engineer must consider the role of municipal or other insurance inspections, as well as the frequency, qualifications, fee structure, and even methods for employing third parties independent of the AHJ for inspection purposes. The O&M manual will also prove to be invaluable insight to the AHJ in understanding the boundary limitations of the very tall building design so that appropriate requirements will be applied.

Documentation

As noted above, it is important to retain copies of all test records and test plans. For very tall buildings, this is especially important as there are larger and likely more complex systems than found in other types of buildings. Proper documentation increases the potential for maintaining the life safety system performance as initially designed as the building ages. NFPA 4 [235] recommends that the initial testing records, as well as the last two periodic integrated test documents, be retained. The owner or operator may want to consider keeping additional periodic test records for very tall buildings.

Chapter 24
Aerial Vehicle Platforms

Throughout the history of very tall buildings, a place to land a helicopter on the building has often been planned and provided as part of the project. In some cities, helicopter landing areas were required by local laws or ordinances, but in most cases, they have been voluntarily provided to serve a functional purpose.

They have traditionally been referred to as heliports or helipads. Heliport implies longer-term use (such as storage, repair, and maintenance), whereas helipad implies a temporary drop-off/pick-up type of use. Looking toward the (near) future, it is reasonable to think that these landing zones will be used for UAVs (unmanned aerial vehicles) deployed for package delivery as well as human transport. Regardless, considering the risks associated with landing an aerial vehicle on top of any building, a detailed fire hazards risk assessment must inform the decision-making (see Chap. 7, Hazard, Risk and Decision Analysis in Very Tall Building Design). This chapter will use the term aerial vehicle platforms (AVPs).

Aviation authorities local to the site of any very tall building planned to have a AVP should have detailed guidelines on the structural loading requirements, flight path considerations, requisite illumination, identification lighting, and even fire protection system requirements that will inform the design and arrangement of any such AVP [237]. This chapter will review historical uses of AVPs as well outline some aspects of the very tall building that should be considered for planning and design purposes.

Egress and Fire-Fighting Considerations

Back when very tall buildings were not typically protected throughout with fire sprinklers, helicopters were successfully used to rescue occupants from the roof and to place first responders above the floor of event/emergency. Some past examples include the 1980 MGM fire in Las Vegas, NV, in the United States; the 1972 and 1974 fires in Sao Paulo, Brazil; and the 1986 DuPont Plaza hotel fire in Condado,

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Puerto Rico. Reports from those who were rescued from the rooftops suggested that most of these people were located above the fire incident within the building, and they reported smoke conditions getting worse as they descended within egress stairs; thus they would turn back and go up.

During an evacuation, people usually travel in a downward direction – there is a natural instinct in a fire, or any emergency, to get to the ground level and then out of the building as opposed to traveling upward and away from perceived hazards. This combined with the fact that other occupants within the stairway will be traveling downward results in very few occupants opting to escape upward. That said, there have been instances where occupants have made their way to the roof of building. This has usually been because there has been a failure in or absence of some other fire safety system which has made upward travel their only option.

Even if evacuees decide to escape to the roof, the number of people that can be evacuated by helicopter in a single trip is usually relatively small. For large groups of evacuees, without careful and rigorous crowd management being implemented, the issue of establishing the priority of evacuees has the potential to escalate into a dangerous situation, and therefore such a rescue operation must be carefully planned and executed.

Because of the unreliability of using helicopters for evacuation purposes, the standard internal facilities of stairways will be required irrespective of the provision of the helipad, i.e., no credit in the egress provision should be sought based on having a helipad because of the limitations of using it for fire egress. At best, the provision of a helipad only represents an enhancement to the existing provisions.

Some very tall buildings are provided with AVPs as part of the building's functional use, such as hospitals or a high-end residential/hotel development. In fact, several of the most recently constructed very tall buildings have been equipped with AVPs as an amenity for the building residents. In such instances, the use of these AVPs may seem a good additional safety feature; however, whether to provide AVPs for fire fighter access requires careful consideration. The design team will need to coordinate with the first responders to determine if helicopters will be used as part of the fire-fighting process and, if so, the type of aircraft that may be used to determine proper design considerations.

The use of helicopters in fire emergencies is a controversial issue that seems to divide many fire safety professionals and first responders around the world. Advocates of helicopter use by first responders point to several instances whereby their use has been effective. Opponents are concerned for the safety of first responders trying to utilize AVPs on top of a burning building. The landing of a helicopter on the roof of a burning building is an extremely dangerous operation. Lack of visibility due to smoke or high winds could make it difficult for the helicopter to land.

The benefit of using helicopters for first response is the ability to deliver personnel and equipment to the upper portions of a building, avoiding delays caused by climbing stairwells or impairments with elevators. For very tall buildings, this approach could reduce response time. Lack of visibility due to smoke and high winds could cause the helicopter to crash which would exacerbate an already dangerous situation.

Protection from Fires

From a life safety perspective, plans for rooftop AVPs must include fire-fighting facilities and providing proper means of egress. Unfortunately, such plans must anticipate the worst-case scenario of a crash on the rooftop. A reliable method of communicating the existence of an emergency on the AVP to facilitate notification of the local fire department should be considered.

Fighting aircraft fires often involves providing fixed fire suppression systems using a foam-based suppressing agent to address the flammable aviation fuels. Aviation fire-fighting tactics often include the use of high expansion foams, but such foams (air inflated foamy suds) are likely to be adversely affected by the strong swirling winds likely to be encountered and therefore rendered ineffective. Both fixed and manually deployed fire-fighting systems must consider the extreme conditions (i.e., temperatures and winds) that are likely to exist at the top of the building.

A common foam used in fire fighting, called aqueous film forming foam (AFFF), is more of a liquid foam film that would not be as susceptible to the swirling winds and is likely to be a better choice of suppressant. Providing equipment necessary for fire fighters to easily deploy an AFFF type foam through standpipe hose lines from two opposite vantage points on the rooftop will be invaluable in laying down an effective blanket of foam while minimizing the unpredictable effects of the winds. Advancing knowledge and technologies may suggest alternative fire suppressants to that of AFFF to address the known health hazards and potentially improve suppression capabilities. Designers are strongly advised to work with the local fire department to determine what kind of fire-fighting facilities should be provided.

The AVP should be pitched to provide drainage in case of a fuel spill resulting from a crash. This is to protect the primary egress path, passenger holding area, and fire protection activation systems. The drainage flow should not affect alternate egress points, stairways, ramps, hatches, and other openings not designed for runoff from drainage. A secondary means to contain fuel runoff from the drainage system may be considered, which, if properly designed with flame arresters, will assist in removing the fuel from fire loads in a crash scenario.

Buildings with AVPs should be provided with two means of egress stairs from the rooftop to the building's egress system. Access to a second means of egress is critical on the day the winds blow smoke from a fire across and obscure the entrance to the other exit stair entrance. Building stair entrances should also be located within easy direct line of sight of the AVP access points. To help mitigate the effects of the swirling winds that are likely on the roof of a very tall building, the two building exit stairs should be located on opposite sides of the rooftop, as far apart as is feasible. Clearly visible exit signage and pathway marking should be provided.

The design team should consider the fire rating of the roof assembly beneath an AVP landing zone. Ideally, the roof assembly separating the landing one from the building interior will be at least 2 h fire-resistive-rated assembly. Further, the combustibility of the roof-covering materials used when an AVP landing zone is present should be those that meet the least combustible flammability fire test criteria of the local building code requirements.

Chapter 25
ESS in Very Tall Buildings

Energy storage systems (ESS), as its name implies, are used to store energy for later use. They could be used for peak shaving, resiliency, feeding back into the grid, and various other reasons.

In buildings, the most frequent technology used is electrochemical. This chapter will focus only on this technology. At the time of preparation of this edition of this Guide, the codes and standards for ESS were not fully developed, so the hazards are identified in general terms. Judgments can be made as to how to best protect ESS indoors in a building.

This chapter provides information specific to ESS in general. Care should be taken on the use of ESS in very tall buildings as the location and application could have an impact on the life safety of building occupants. Due to the potential hazards associated with ESS, their locations within very tall buildings should be carefully examined. Placement high up within the building may impact the ability to fight a fire on the ESS or deal with the hazards associated with them. The fire protection features to reduce the potential impact to life and property in very tall buildings include increased fire-resistance ratings, explosion protection, containment, and increased sprinkler protection. ESS in very tall buildings should undergo more stringent inspection and maintenance procedures to identify potential hazards before they impact the building.

Electrochemical Technologies

There are various types of electrochemical technologies. The most common in use today are:

- Lithium-ion: The most dominant rechargeable battery chemistry. This has high energy density with the use of flammable organic electrolytes that creates fire safety challenges.

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- Lead-acid Flooded and valve-regulated lead-acid (VRLA). Flooded cells require room ventilation where hydrogen and oxygen can escape as gas during normal operation. Flooded lead acid batteries require maintenance as water is lost from the electrolyte due to gassing during normal use. VRLA batteries are sealed and pressurized to contain the gases generated during normal cycling. Hydrogen and oxygen are recombined to form water so none of the water escapes as gas. The electrodes are lead or lead oxide and the electrolyte is an aqueous sulfuric acid solution.
- Redox flow battery [238]: Energy is stored in two tanks that are separated from the cell stack. The cell stack converts chemical energy to electrical energy or vice versa. Vanadium flow batteries use vanadium of different valence states in separate tanks. The cell stack has sulfate and chloride solution that is used as an electrolyte.

Thermal Runaway

Electrochemical batteries can undergo thermal runaway, but the likelihood and severity of thermal runaway are varied across technologies. For example, thermal runaway cannot be reversed or stopped with lithium-ion chemistries but can be stopped in other battery technologies.

There could be many causes for lithium-ion cell failure [239]. When the initiating failure causes self-heating of the cell, it leads to a self-sustaining exothermic reaction within the cell. The rapid self-heating that occurs within the cell from the exothermic reaction is called thermal runaway and leads to release of its stored chemical and electrical energy. The more energy a cell has stored, the more energetic the thermal runaway; that is why the state of charge is important. When a lithium-ion cell goes into thermal runaway, the following may occur:

- Internal temperature increases in the cell.
- Internal pressure in the cell increases.
- The cell pressure rise causes venting of flammable gases and vapors from electrolytes and electrolyte decomposition products.

Cell thermal runaway may propagate from one cell to adjacent cells. For example, the heat released from one cell in thermal runaway may cause sufficient thermal exposure of a nearby cell to cause that cell to go into thermal runaway.

Thermal runaway in a VRLA battery [240] occurs when the temperature inside the battery is high enough that it is unable to be dissipated from the casing, causing a temperature increase exterior to the battery. This in turn increases the temperature within the battery, ultimately leading to case meltdown and exposure of the battery internals. Accidental overcharging may cause thermal runaway, but this is usually reversed if charging is stopped.

Hazards

The major hazard associated with lithium-ion batteries is the explosion hazard. This was demonstrated in the Arizona Peoria ESS incident where an explosion severely injured two fire fighters and injured more than six fire fighters. The consequences of the explosion hazard are exacerbated if the ESS is installed in an occupied very tall building. An appropriate explosion mitigation system should be incorporated.

Lead-acid batteries also have an explosion hazard. Hydrogen and oxygen are released as in the case of overcharging. The accumulation of hydrogen and oxygen in the containers housing the lead acid batteries or the room could lead to a hydrogen explosion. Precautions such as hydrogen monitoring and deflagration venting may be considered. Early detection and isolating the fault such as overcharging may help in preventing the hazard from escalating to a point where it becomes a major incident.

Flow batteries also have an explosion hazard, but not to the extent of lithium-ion batteries. Under a fault condition, they could produce hydrogen gas and chlorine gas in some chemistries. While the system is engineered to take care of these gases, a failure of a system may cause these gases to accumulate, causing a hydrogen explosion or a release of toxic chlorine gas.

The fire hazard can be severe in lithium-ion batteries. Designers are encouraged to review the applicable codes/standards, to know what is relevant, NFPA 855, Standard for the Installation of Stationary Energy Storage Systems [241], Model Building Codes, Product Standards such as UL 1973 [242] and UL 9540 [243], and Test Standard UL 9540A [244] "Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage." They should also review the series of tests conducted by FM Global [245] and other reputable laboratories to understand the hazard and how well they can be addressed. Lead-acid technology has been around for many decades and is well known. Lead-acid battery fires are more easily controlled with water compared to lithium-ion batteries. The risk of reignition is not present. The evolution of hydrogen under fault conditions should be kept in mind while dealing with these fires. Flow batteries also have a less benign fire compared to lithium-ion; however, the evolution of hydrogen and chlorine in some chemistries is a factor to deal with during a fire.

A product standard for batteries used in energy storage systems applications such as photovoltaic, wind turbine storage, uninterruptable power supplies (UPS) and other like applications is available and can provide more reliable energy storage systems in very tall buildings [242]. It evaluates the batteries' ability to withstand simulated abuse conditions and covers both batteries and modules.

The above shows that the chemistry, capacity, and environment in which ESS is installed will affect the design of a safe installation. The FM Global test series with just two different lithium-ion chemistries have demonstrated differences in fire performance, where fire with the LFP chemistry could be limited to the rack of origin but could not with the LNO/LMO chemistry. The number of sprinklers that operated also varied drastically.

Codes require safe equipment separation distances, but they must be justified by a test that proves adjoining units will not get involved in the initial fire if the spacing is less than the minimum specified by code [243], [244]. Sprinklers are effective to the extent that they can delay or prevent the spread of the fire to adjacent ESS racks. Adequate separation further helps. For a prolonged fire duration, high water demand and water damage to the surroundings is likely. With the limited data publicly available, it has been demonstrated that sprinklers alone may not be sufficient to mitigate an ESS fire. Flame height and protection of the ceiling is important. In most standard rooms, the flames from an ESS fire would impinge on the ceiling leading it to be exposed to flame temperatures for an extended period. Structural stability should also be considered.

First responders will need to address severe ESS fires while making sure they are not exposed to potential explosions and toxic hazards. The design professional should consider developing an emergency response procedure in conjunction with the fire department and other first responders prior to installation. Additionally, commissioning and de-commissioning procedures (especially de-commissioning post-fire events) should be developed and approved by the AHJ and first responders.

Safe egress of all occupants must also be considered, as they could be exposed to an explosion, very high temperatures, and toxic gases. These hazards can be difficult to address at grade level and more difficult if the ESS is in a very tall building. All available information including the information in this section should be used in selecting a battery chemistry and technology and the appropriate protection features in the building.

References

1. SFPE Engineering Guide to Performance-Based Fire Protection, 2nd edition, Quincy, MA, MA: NFPA, 2007.
2. SFPE, Engineering Guide: Fire Safety for Very Tall Buildings, 1st edition, Washington, DC: ICC, 2013.
3. National Fire Protection Association, "Fire Protection Handbook, 13th edition," NFPA, Quincy, MA, 1969.
4. W. R. Powers, "Report of Fire at One New York Plaza," New York Board of Fire Underwriters, New York, 1970.
5. R. Best and D. P. Detmers, "Investigation Report on the MGM Grand Hotel Fire," National Fire Protection Association, Quincy, MA, 1982.
6. T. J. Klem, "Fire Investigation Report, First Interstate Bank Building Fire, Los Angeles, California," National Fire Protection Association, Quincy, MA, 1988.
7. T. J. Klem, "Fire Investigation Report, One Meridian Plaza, Philadelphia, Pennsylvania," National Fire Protection Association, Quincy, MA, 1991.
8. M. S. Isner and T. J. Klem, "Fire Investigation Report, World Trade Center Explosion and Fire, February 26, 1993," National Fire Protection Association, Quincy, MA, (undated).
9. "Final Report on the Collapse of the World Trade Center Towers," National Institute of Standards and Technology, Gaithersburg, MD, 2005.
10. "Final Report on the Collapse of World Trade Center Building 7," National Institute of Standards and Technology, Gaithersburg, MD, 2008.
11. D. Madrzykowski and W. D. Walton, "Cook County Administration Building Fire, 69 West Washington, Chicago, Illinois, October 17, 2003: Heat Release Rate Experiments and FDS Simulations," National Institute of Standards and Technology, Gaithersburg, MD, 2004.
12. J. Moncada, "Fire Unchecked," *NFPA Fire Journal,* March/April 2005.
13. I. Wilkinson, "Madrid skyscraper destroyed in blaze," *The Telegraph,* 14 February 2005.
14. B. Blanchard, "Fire Claims Building at CCTV Beijing Headquarters," Reuters, 9 February 2009. [Online].
15. W. Clem, "Flammable foam lined Shanghai tower before fire," *South China Morning Post,* 19 November 2010.
16. G. Genco, "Lacrosse Building Fire, 673 La Trobe Street, Docklands on 25 November 2014 (DM ref# 8989066)," City of Melbourne, Melbourne, Australia, 2015.
17. D. Millward and J. Winch, "Dubai hotel fire: Inferno at 63-storey Address Downtown hotel near New Year's Eve fireworks display," *The Telegraph,* 2 January 2016.
18. H. Alexande, "Dubai Marina Torch Tower fire: 'We had to run down 72 flights of stairs'," *The Telegraph,* 21 February 2015.

Fire Safety for Very Tall Buildings, The Society of Fire Protection Engineers Series, https://doi.org/10.1007/978-3-030-79014-1

19. B. Henderson and C. Graham, “Dubai skyscraper fire: Torch Tower residents wake to screams as flames engulf 79-storey building,” *The Telegraph,* 4 August 2017.
20. D. Kirkpatrick, D. Hakim and J. Glanz, “Why Grenfell Tower Burned: Regulators Put Cost Before Safety,” *The New York Times,* 24 June 2017.
21. FEMA 403, “World Trade Center Building Performance Study: Data Collection, Preliminary Observations, and Recommendations,” Federal Emergency Management Agency, Washington, DC, 2002.
22. NFPA 1123, Code for Fireworks Display, Quincy, MA: NFPA, 2018.
23. L. Peng, Z. Ni and X. Huang, “Review on the fire safety of exterior wall claddings in high-rise,” in *The 9th Asia-Oceania Symposium on Fire Science and Technology*, Tianjin, China, 2013.
24. “Grenfell Tower Inquiry,” [Online]. Available: https://www.grenfelltowerinquiry.org.uk/. [Accessed 21 January 2021].
25. The Rt Hon Sir Martin Moore-Bick, “Grenfell Tower Inquiry Phase 1 Report, Part I, Background matters, Paragraph 3.9,” London, 2019.
26. The Rt Hon Sir Martin Moore-Bick, “Grenfell Tower Inquiry Phase 1 Report, Part I, Background Matters, Paragraph 3.13,” London, 2019.
27. The Rt Hon Sir Martin Moore-Bick, “Gregnfell Tower Inquiry: Phase 1 Report Part I, Background matters, Paragraph 6.1,” London, 2019.
28. NFPA 550, Guide to the Fire Safety Concepts Tree, Quincy, MA: NFPA, 2017.
29. GSA 5920.9, Building fire safety criteria: Appendix D, Interim guide for goal-oriented systems approach to building fire safety, Washington, DC: General Services Administration, 1975.
30. J. M. Watts, “A Theoretical Rationalization of a Goal-Oriented Systems Approach to Building Fire Safety,” National Bureau of Standards, Washington, DC, 1979.
31. B. J. Meacham, “The Evolution of Performance-Based Codes and Fire Safety Design Methods,” National Institute of Standards and Technology, Gaithersburg, MD, 1998.
32. B. J. Meacham, “International Experience in the Development and Use of Performance-Based Fire Safety Design Methods: Evolution, Current Situation, and Thoughts for the Future,” in *Proceedings of the International Association for Fire Safety Science, 6th Internation Symposium*, 1999.
33. BS 7974, Application of Fire Safety Engineering Principles to the Design of Buildings, London: BSI, 2001.
34. International Fire Engineering Guidelines, Canberra: Austrailian Building Codes Board, 2005.
35. ISO 23932-1, Fire Safety Engineering -- Part 1: General, Geneva: International Organization for Standardization, 2018.
36. B. J. Meacham, “An International Perspective on the State of Perfomance-Based Design for Fire,” *Fire Protection Engineering,* no. Q3, 2018.
37. “Eurocode 1: Actions on structures (abbreviated (EN 1991), Part 1-2: Actions on structures exposed to fire,” European Commission, Brussels, Belgium, 2002.
38. SFPE, Engineering Guide for Substantiating a Fire Model for a Given Application, Gaithersburg, MD, SFPE, 2011.
39. SFPE, Guideines for Peer Review in the Fire Protection Design Process, Gaithersburg, MD: SFPE, 2020.
40. SFPE, “Recommended Minimum Technical Core Competancies for the Practice of Fire Protection Engineering,” SFPE, Gaithersburg, MD, 2018.
41. ABCB, “National Construction Code,” Canberra, Australia, 2020.
42. NRC Canada, “National Building Code of Canada 2015,” Ottawa, 2015.
43. The Building Center of Japan, “1The Building Standard Law of Japan,” Tokyo, 2019.
44. Singapore Civil Defense Force, “Code of Practice for Fire Precautions in Buildings,” Singapore, 2018.
45. Dubai Civil Defense, “United Arab Emirates, Fire and Life Safety Code of Practice”.
46. BSI, “BS 9999, Fire safety in the design, management and use of buildings,” London, 2017.
47. ICC®, International Building Code®, Washington, DC, 2021.
48. ICC®, International Fire Code®, Washington, DC, 2021.

49. "NFPA 5000®, Building Construction and Safety Code®," Quincy, MA, 2021.
50. S. M. V. Gwynne and E. R. Rosenbaum, "Employing the Hydraulic Model in Assessing Emergency Movement," in *SFPE Handbook of Fire Protection Engineering 5th Edition*, Chapter 59 Gaithersburg, MD: Society of Fire Protection Engineers, 2016, Chapter 59.
51. SFPE, Engineering Guide to Human Behavior in Fire, 2nd edition, Gaithersburg, MD: SFPE, 2018.
52. J. H. Klote, "Smoke Control," in *SFPE Handbook of Fire Protection Engineering, Chapter 50*, Gaithersburg, MD: SFPE, 2016.
53. SFPE Engineering Guide to Fire Risk Assessment, 2nd edition (To be published in 2021), Gaithersburg, MD: SFPE, 2021.
54. "Busan High-Rise Fire Sends Urgent Warning," The Chosunilbo, 4 October 2010. [Online].
55. E. Kurtenbach, "Shanghai Fire Toll at 58; Beijing Reviews Projects," Associated Press, 19 November 2010. [Online].
56. SFPE, Engineering Guide to Predicting Room of Origin Fire Hazards, Gaithersburg, MD, 2007.
57. S. Lamont and S. Ingolfsson, "High Rise Buildings with Combustible Exterior Wall Assemblies: Fire Risk Assessement Tool," National Fire Protection Association, Quincy, MA, 2018.
58. A. Sekizawa, M. Ebihara and H. Notake, "Development of Seismic-induced Fire Risk Assessment Method for a Building," in *Fire Safety Science – Proceedings of the Seventh International Symposium, International Association for Fire Safety Science*, 2003.
59. S. Chen and G. Lee, "Hazard Mitigation for Earthquake and Subsequent Fire," 2004. [Online]. [Accessed 20 August 2007].
60. "1994 Northridge Earthquake: Performance of Structures, Lifelines and Fire Protection Systems, NISTIR 5396," National Institute of Standards and Technology, Gaithersburg, 1994.
61. R. P. Fleming, "Analysis of Fire Sprinkler System Performance in the Northridge Earthquake, NIST-GCR-98-736," National Institute of Standards and Technology, Gaithersburg, 1998.
62. United States Department of Homeland Security,, "SAFETY Act for Liability Protections," 2020. [Online]. Available: https://www.dhs.gov/sites/default/files/publications/5299_safety_act_factsheet_2020.pdf.
63. Standard Practice for System Safety, MIL-STD 882D, Washington, DC: Department of Defense, 2000.
64. ISO 31000, Risk management – Principles and Guidelines, Geneva: Interantional Organization for Standardization, 2009.
65. T. F. Barry, "Risk-Informed Industrial Fire Protection Engineering, Chapter 83," in *SFPE Handbook of Fire Protection Engineering*, Gaithersburg, MD, SFPE, 2016.
66. B. J. Meacham, "Understanding Risk: Quantification, Perception and Characterization," *Journal of Fire Protection Engineering,* vol. 14, no. 3, pp. 199-228, 2004.
67. B. J. Meacham, D. Charters, P. Johnson and M. Salisbury, "Building Fire Risk Analysis," in *SFPE Handbook of Fire Protection Engineering*, Gaithersburg, MD, Society of Fire Protection Engineers, 2016.
68. H. A. Donegan, "Decision Analysis," in *SFPE Handbook of Fire Protection Engineering*, Gaithersburg, Society of Fire Protection Engineers, 2016.
69. R. Clemen and T. Reilly, Making Hard Decisions, Pacific Grove: Cengage Learning, 2001.
70. G. Ramachandran, The Economics of Fire Protection, London: Taylor & Francis, 1998.
71. J. M. Watts, "Engineering Economics," in *SFPE Handbook of Fire Protection Engineering*, Gaithersburg, MD, Society of Fire Protection Engineers, 2016.
72. NFPA 557, Standard for Determination of Fire Loads for Use in Structural Fire Protection Design, Quincy, MA: NFPA, 2020.
73. B. J. Meacham and M. Johann, Extreme Event Mitigation in Buildings: Analysis and Design, Quincy, MA: National Fire Protection Association, 2004.
74. A. Alvarez and B. J. Meacham, "Toward an Integrated Performance-Based Design Approach for Life Safety Across Different Building Use Groups," in *Conference Proceedings - 12th International Interflam*, Nottingham, 2010.

75. F. Joglar, "Reliability, Availability and Maintainability," in *SFPE Handbook of Fire Protection Engineering*, Gaithersburg, MD, Society of Fire Protection Engineers, 2016.
76. J. Pauls, Informed Emergency Responses Through Improved Situation Awareness; Discussion Panel; NRCC 51388, National Research Council of Canada, 2009.
77. R. P. Schifiliti, R. L. P. Custer and B. J. Meacham, "Design of Detection Systems," in *SFPE Handbook of Fire Protection Engineering*, Gaitherburg, MD, Society of fire Protection Engineers, 2016.
78. E. D. Kuligowski and B. L. Hoskins, "Elevator Messaging Strategies," Fire Protection Research Foundation, Quincy, 2011.
79. E. D. Kuligowski, "Developing Emergency Communication Strategies for Buildings," National Institute of Standards and Technology, Gaithersburg, 2012.
80. E. D. Kuligowski, "Human Behavior in Fire," in *SFPE Handbook of Fire Protection Engineering, fifth edition*, Gaitthersburg, MD, Society of Fire Protection Engineers, 2016.
81. J. Fruin, Pedestrian Planning and Design, Revised Edition, Mobile: Elevator World, Inc., 1987.
82. E. D. Kuligowski, "A Review of Building Evacuation Models," National Institute of Standards and Technology, Gaithersburg, 2005.
83. J. Lord, B. J. Meacham, A. Moore, R. Fahy and G. Proulx, "Guide for Evaluating the Predictive Capabilities of Computer Egress Models," National Institute of Standards and Technology, Gaithersburg, 2005.
84. J. L. Bryan, "Behavioral Response to Fire and Smoke," in *SFPE Handbook of Fire Protection Engineering*, Quincy, National Fire Protection Association, 2008.
85. CIBSE, "Guide E, Fire Engineering, Chapter 4, Means of Escape and Human Factors," Chartered Institution of Building Services Engineers, 2003.
86. Nordic Committee on Building Regulations, NKB Fire Safety Committee, "Performance Requirements for Fire Safety and Technical Guide for Verification by Calculation," 1995.
87. G. Proulx and R. F. Fahy, "The Time Delay to Start Evacuation: Review of Five Case Studies," in *Fire Safety Science – Proceedings of the Fifth International Symposium*, London, 1997.
88. E. Cable, "An Analysis of Delay in Staff Response to Fire Alarm Signals in Health Care Occupancies," Worchester Polytechnic Institute, Worchester, 1993.
89. R. F. Fahy, "Chapter 2 – Section 4 Calculation Methods for Egress Prediction," in *Human Behavior in Fire Emergencies*, Quincy, National Fire Protection Association, 2003.
90. O. Bukvic, G. Carlsson, G. Gefenaite, S. B. S. M. Schmidt and E. Ronchi, "A review on the role of functional limitations on evacuation performance using the International Classification of Functioning, Disability and Health. Fire Technology," *Fire Technology,* 2020.
91. K. Boyce, "Safe evacuation for all-Fact or Fantasy? Past experiences, current understanding and future challenges.," *Fire Safety Journal,* vol. 91, pp. 28-40, 2017.
92. E. D. Kuligowski, "NIST Special Publication 1032 – Review of 28 Egress Models," in *Workshop on Building Occupant Movement During Fire Emergencies*, 2005.
93. E. D. Kuligowski, R. D. Peacock and B. L. Hoskins, "A Review of Building Evacuation Models, 2nd Edition (Rep. No. NIST TN 1680)," NIST, Gaithersburg, MD, 2010.
94. E. D. Kuligowski, "Computer Evacuation Models for Buildings," in *SFPE Handbook of Fire Protection Engineering, 5th edition*, Gaithersburg, MD, 2016.
95. E. Ronchi and D. Nilsson, "Assessment of Total Evacuation Systems of Tall Buildings," Fire Protection Research Foundation, Quincy, MA, 2013.
96. T. Engineering, "Pathfinder, Agent Based Evacuation Simulation".
97. M. Almeimai and B. J. Meacham, "The Effects of Cultural and Social Differences between the West and Saudi Arabia on Emergency Evacuation: Preliminary Findings," in *Proceedings, 5th International Symposium on Human Behavior in Fire*, London, 2012.
98. E. R. Galea, M. Sauter, S. Deere and L. Filippidis, "Investigating the Impact of Culture on Evacuation Behavior- A Turkish Data-Set," in *Proceedings of the International Association for Fire Safety Science, 10th International Symposium*, London, 2011.
99. R. Ono and K. Tatebe, "A Study on School Children's Attitude Towards Firesafety and Evacuation Behaviour in Brazil and the Comparison with Data from Japanese Children," in *Proceedings, 3rd International Symposium on Human Behavior in Fire*, London, 2011.

100. E. R. Galea, “Investigating the Impact of Culture on Evacuation Behaviour,” in *Conference Proceedings - 12th Internationl Interflam*, Nottingham, 2010.
101. K. Andrée and B. Eriksson, “Cultural differences in an evacuation scenario- A study comparing Australian and Swedish responses,” Lund University, Lund, 2008.
102. C. Zhao, S. Lo, M. Liu and S. Zhang, “A Post-fire Survey on the Pre-evacuation Human Behavior,” Fire Technology, 2008.
103. S. M. V. Gwynne, K. E. Boyce, E. D. Kuligowski, D. Nilsson, A. Robbins, R. Lovreglio, A. Roy-Poirier and J. R. Thomas, “Enhancing Egress Drills: Preparation and Assessment of Evacuee Performance,” *Fire and Materials,* 2017.
104. J. S. Tubbs and B. J. Meacham, “Egress Design Solutions, A Guide to Evacuation and Crowd Management Planning,” John Wiley and Sons, Inc., Hoboken, 2007.
105. K. Hsuing, “A Research of the Elevator Performance for Taipai 101 Financial Center,” in *6th International Conference on Performance-Based Codes and Fire Safety Design Methods*, Tokyo, Japan, 2006.
106. G. Proulx, “Evaluation of the Effectiveness of Different Photoluminescent Stairwell Installations for the Evacuation of Office Building Occupants,” National Research Council of Canada, Ottawa, 2007.
107. A. J. M. Aikman, “Elevator Operation During Fire Emergencies in High Buildings,” in *Elevators and Fire*, Baltimore, Council of American Building Officials and National Fire Protection Association, 1991, pp. 16-21.
108. J. H. Klote, “Elevators as a Means of Fie Escape,” *American Society of Heating Refrigerating and Air Conditioning Engineers Transactions,* vol. 89, no. 2, pp. 1-16, 1982.
109. A. Gatfield, “Principles of Fire Safety for Disabled People in Buildings: The Use of Lifts for Evacuation,” in *Annual Meeting of the National Fire Protection Association*, Washington, 1989.
110. A. J. Gatfield, “Designing for Safety,” in *Elevators and Fire*, Baltimore, Council of American Building Officials and National Fire Protection Association, 1991, pp. 95-107.
111. J. H. Klote, S. Deal, E. A. Donoghue, B. M. Levin and N. E. Groner, “Fire Evacuation by Elevators,” *Elevator World,* vol. 41, no. 6, pp. 66-70, 72-75, June 1993.
112. R. W. Bukowski, S. R. Burgess and P. A. Reneke, NIST Special Publication 983 – Collected Publications Related to the Use of Elevators During Fires, Gaithersburg: National Institute of Standards and Technology, 2002.
113. B. M. Levin and N. E. Groner, Human Factors Considerations for the Potential Use of Elevators for Fire Evacuation of FAA Air Traffic Control Towers, Gaithersburg: National Institute of Standards and Technology, 1994.
114. J. R. Quiter, “Application of Performance Based Concepts at the Stratosphere Tower, Las Vegas, Nevada,” National Fire Protection Research Foundation, San Francisco, 1996.
115. J. Maddox, “A Study in Occupant Evacuation Elevators,” *Fire Protection Engineering,* vol. Quarter 4, 2017.
116. NFPA 101®, Life Safety Code®, Quincy, MA: NFPA, 2021.
117. R. Bukowski, “Elevator Controls,” *NFPA Journal,* vol. 100, no. 2, pp. 42-57, 2006.
118. K. Clawson and O. D.J., “Title:Considerations and Challenges for Refuge Areas in Tall Buildings,” in *CTBUH 2011 Seoul Conference*, Seoul, 2011.
119. Bureau of Indian Standards, “National Building Code of India (NBC 2016),” 2016.
120. C. Cheng, “Wind-induced Natural Ventilation of the Refuge Floor of a High-rise Building in Hong Kong,” Queensland University of Technology, Brisbane, 2006.
121. C. Chow and W. Chow, “Fire Safety Aspects of Refuge Floors in Supertall Buildings with Computational Fluid Dynamics,” *Journal of Civil Engineering and Management,* vol. 15, no. 3, pp. 225-236, 2009.
122. W. Kwok, D. Chen, K. Yuen, S. Lo and J. Lu, “A Pilot Study of the External Smoke Spread in High-Rise Buildings,” *Journal of Building Surveying,* vol. 2, no. 1, pp. 4-9, 2000.
123. B. M. Levin and N. E. Groner, “Human Behavior Aspects of Staging Areas for Fire Safety in GSA Buildings.,” National Institute of Standards and Technology, Gaithersburg, 1992.

124. UL 263 Fire Tests of Building Construction and Materials, Thirteenth Edition, Northbrook: Underwriters Laboratories Inc, 2003.
125. “NFPA 241, Standard for Safeguarding Construction, Alteration, and Demolition Operations,” NFPA, Quincy, MA, 2019.
126. CAN/ULC S101, Standard Methods of Fire Endurance Tests of Building Construction and Materials, Fifth Edition, Ottawa: Underwriters Laboratories Canada, 2014.
127. “Method for determination of the fire resistance of elements of construction,” in BS476 Fire Tests, London, British Standards Institution, 1987, p. Part 20.
128. ISO 834-11: Fire resistance tests — Elements of building construction, International Organization for Standarization, 2014.
129. “Part 4: Fire-resistance test of elements of construction,” in Australian Standard, Methods for fire tests on building materials, components and structures, Sydney, Standards Australia, 2005.
130. NFPA 251 Standard Methods of Tests of Fire Endurance of Building Construction and Materials, Quincy, MA: NFPA, 2006.
131. British Standards Institution , “BS EN 1363-1:2020: Fire resistance tests. General requirements,” BSI, London, February 2020.
132. British Standards Institution , “BS EN 1364-2:2018: Fire resistance tests for non-loadbearing elements. Ceilings,” BSI, London, February 2018.
133. British Standards Institution , “BS EN 1365-2:2014: Fire resistance tests for loadbearing elements. Floors and roofs,” BSI, London, February 2014.
134. British Standards Institute, “BS EN 1366-11:2018: Fire resistance tests for service installations,” BSI, London, February 2018.
135. UL, “UL Product iQ™,” [Online]. Available: https://www.ul.com/resources/apps/product-iq. [Accessed 17 11 2020].
136. ASCE/SFPE/SEI 29, Standard Calculations Methods for Structural Fire Protection, Reston: American Society of Civil Engineers, 2005.
137. J. A. Milke, “Analytical Methods for Determining Fire Resistance of Steel Members,” in *SFPE Handbook of Fire Protection Engineering*, Gaithersburg, MD, Society of Fire Protection Engineering, 2016.
138. J. A. Milke, V. Kodur and C. Marrioon, “Appendix A: Overview of Fire Protection in Buildings,” in *FEMA 403 - World Trade Center Building Performance Study*, Federal Emergency Management Agency, 2002, pp. A1-A28.
139. BS 5950, Structural Use of Steelwork in Building, London: British Standards Institution, 2003.
140. BS 8110, Structural Use of Concrete, London: British Standards Institution, 1985.
141. AS 4100, Steel Structures, Sydney: Standards Australia, 1998/2016.
142. Standards New Zealand, “AS/NZS 2327:2017: Composite structures - Composite steel-concrete construction in buildings,” Standards New Zealand, Wellington, 2017.
143. NZS 3404, Steel Structures, Wellington: Standards New Zealand, 2009.
144. A. S. Usami, Behavior of Steel Framed Structures Under Fire Conditions, Edinburgh: University of Edinburgh, 2000.
145. SFPE, S.01, Engineering Standard on Calculating Fire Exposures to Structures, Gaithersburg, MD: SFPE, 2010.
146. SFPE, S.02, Engineering Standard on Calculation Methods to Predict the Thermal Performance of Structural and Fire Resistive Assemblies, Gaithersburg, MD: SFPE, 2015.
147. ASCE, SEI/ASCE 7 - Minimum Design Loads and Associated Criteria for Buildings and Other Structures, Reston, VA: American Society of Civil Engineers, 2016.
148. J. M. Franssen and N. Iwankiw, “Structural Fire Engineering of Building Assemblies and Frames,” in *SFPE Handbook of Fire Protection Engineering*, Gaithersburg, MD, Society of Fire Protection Engineers, 2016.
149. European Commission, “Eurocode 2: Design of concrete structures,” European Commission, Brussels, 1992.
150. European Commission, “Eurocode 4: Design of composite steel and concrete structures,” European Commission, Brussels, 1994.

151. D. Parkinson, V. Kodur and P. D. Sullivan, Performance-Based Design of Structural Steel for Fire Conditions: A Calculation Methodology, Reston: American Society of Civil Engineers, 2008.
152. A. Buchanan and A. Abu, Structural Design for Fire Safety 2nd ed, West Sussex: John Wiley & Sons, 2017.
153. ISO, ISO/TR 3956:1975 Principles of structural fire-engineering design with special regard to the connection between real fire exposure and the heating conditions of the standard fire-resistance test, International Organization for Standardization, 1975.
154. ASCE Manuals and Report on Engineering Practice No. 138, Structural Fire Engineering, American Society of Civil Engineering, Reston, VA, 2018.
155. ASCE Manuals and Report on Engineering Practice No. 78, Structural Fire Engineering, American Society of Civil Engineers, Reston, VA, 1992.
156. Joint ACI/TMS Comm, ACI 216.1-14 Code Requirements for Determining Fire Resistance of Concrete and Masonry Construction Assemblies, American Concrete Institute, Farmington Hills, WI, 2019.
157. ASCE, Performance-Based Structural Fire Design: Exemplar Designs of Four Regionally Diverse Buildings using ASCE 7-16, Appendix E, Reston, VA, 2020.
158. AISC, "AISC 360-16. Specification for Structural Steel Buildings," Specification for Structural Steel Buildings, Chicago, IL, 2016.
159. J. Gross, N. Iwankiw and M. Johann, "Structural Fire Engineering: Overview and Application Examples of Appendix 4 of AISC Specification," *Engineering Journal, American Institute of Steel Construction,* vol. 50, pp. 273-290, 2013.
160. D. Moore, C. Bailey, T. Lennon and Y. Wang, Designers' Guide to EN 1991-1-2, EN 1992-1-2, EN 1993-1-2 and EN 1994-1-2, London: ICE Publishing, 2007.
161. S. P. Hunt, J. Cutonilli and M. J. Hurley, "Evaluation of Enclosure Temperature Empirical Models," Society of Fire protection Engineers, Bethesda, 2010.
162. O. Pettersson, S. Magnusson and J. Thor, "Fire Engineering Design of Steel Structures," Swedish Institute of Steel Construction, 1976.
163. V. Babrauskas and R. B. Williamson, "Post-Flashover Compartment Fires—Application of a Theoretical Model," *Fire and Materials,* vol. 3, no. 1, 1976.
164. J. F. Cadorin and J. M. Franssen, "A Tool to Design Steel Elements Submitted to Compartment Fires - Ozone V2 - Part 1: Pre and Post-Flashover Compartment Fire Mode," *Fire Safety Journal,* vol. 38, no. 5, pp. 395-427, 2003.
165. S. E. Magnusson and S. Thelandersson, "Temperature-time curves of complete process of fire development," Lund Institute of Technology, Stockholm, 1970.
166. "ASTM E119-19: Standard Test Methods for Fire Tests of Building Construction and Materials," ASTM, West Conshohocken, PA, 2019.
167. V. Babrauskas, "Post-Flashover Compartment Fires—Application of a Theoretical Model," *Fire Safety Journal,* vol. 4, pp. 63-73, 1981.
168. "Part 1.2 General Actions – Actions on Structures Exposed to Fire," in Eurocode 1: Actions on Structures, London, British Standard Institute, 2002.
169. T. T. Lie, "Characteristic Temperature Curves for Various Fire Severities," *Fire Technology,* vol. 10, no. 4, pp. 15-326, 1974.
170. Z. Ma and P. Mäkeläinen, "Parametric Temperature-Time Curves of Medium Compartment Fires for Structural Design," *Fire Safety Journal,* vol. 34, no. 4, pp. 361-375, 2000.
171. Fire Safe Structural Steel - A Design Guide, Washington, DC: American Iron and Steel Institute, 1979.
172. B. Y. Lattimer, "Heat Transfer from Fires to Surfaces," in *SFPE Handbook of Fire Protection Engineering*, Gaithersburg, MD, Society of Fire Protection Engineers, 2016.
173. R. D. Peacock, W. W. Jone, G. P. Forney and P. A. Reneke, CFAST – Consolidated Model of Fire Growth and Smoke Transport (Version 6) User's Guide, Gaithersburg: Nation Institute of Standards and Technology, 2005.

174. C. A. Wade, "'B-Risk User Guide and Technical Manual' BRANZ Study Report SR282," BRANZ Ltd, Porirua City, 2013.
175. K. B. McGrattan, R. McDermott, S. Hostikka and J. Floyd, Fire Dynamics Simulator (Version 5) User's Guide, Gaithersburg: National Institute of Standards and Technology, 2010.
176. J. Ewer, E. R. Galea, M. K. Patel, S. Taylor, B. Knight and M. Petridis, "SMARTFIRE: An Intelligent CFD Based Fire Model," *Journal of Fire Protection Engineering,* vol. 10, no. 1, pp. 13-27, 1999.
177. X. Dai, S. Welch and A. Usm, "A critical review of "travelling fire" scenarios for performance-based structural engineering," *Fire Safety Journal,* pp. 568-578, 2017.
178. SFPE Handbook of Fire Protection Engineering, 5th edition, Gaithersburg, MD: SFPE, 2016.
179. H. Mostafaei, P. Leroux and P. S. Lafrance, "Hybrid Fire Testing for Performance Evaluation of Structures in Fire - Part 2: Application," NRC Canada, Ottawa, 2011.
180. R. Gerard, D. Barber and A. Wolski, Fire safety challenges of tall wood buildings – Part 1, Quincy: Fire Protection Research Foundation and Arup North America, 2013.
181. D. Brandon and B. Ostman, Fire safety challenges of tall wood buildings – Part 2, Quincy: Fire Protection Research Foundation and Arup North America, 2016.
182. J. Su and P. Lafrance, "Fire safety challenges of tall wood buildings – Phase 2: Task 2 & 3 – Development and Implementation of Cross Laminated Timber (CLT) Compartment Fire Tests," Fire Protection Research Foundation, Quincy, MA, 2018.
183. "Fire safety challenges of tall wood buildings – Phase 2: Task 4 – Engineering Methods," Fire Protection Research Foundation, Quincy, MA, 2018.
184. "Fire safety challenges of tall wood buildings – Phase 2: Task 5 – Experimental Study of Delamination of Cross Laminated Timber (CLT) in Fire," Fire Protection Research Foundation, Quincy, MA, 2018.
185. E. Rackauskaite, P. Kotsovinos and D. Barber, "Letter to the Editor: Design Fires for Open-Plan Buildings with Exposed Mass-Timber Ceiling," *ire Technology,* 2020.
186. J. Su, P. Leroux, P. Lafrance, R. Berzins, K. Gratton, E. Gibbs and M. Weinfurter, "Fire Testing of Rooms with Exposed Wood Surfaces in Encapsulated Mass Timber Construction," NRC Canada, Ottawa, 2018.
187. S. Zelinka, L. E. Hasburgh, K. J. Bourne, D. Tucholski and J. P. Ouellette, "Compartment Fire Testing of a Two-story Mass Timber Building, Gen. Tech. Rep. FPL-GTR-247," U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI, 2018.
188. C. Fleischmann, "Analytical Methods for Determining Fire Resistance of Concrete Members," in *SFPE Handbook of Fire Protection Engineering*, Gaithersburg, MD, Society of Fire Protection Engineers, 2016.
189. ASTM E 605/E605M-19, Standard Test Methods for Thickness and Density of Sprayed Fire-Resistive Material Applied to Structural Members, West Conshohocken, PA: ASTM, 2019.
190. ASTM E 736/E736M—19, Test Method for Cohesion/Adhesion of Sprayed Fire-Resistive Materials Applied to Structural Members, West Conshohocken, PA: ASTM, 2019.
191. ASTM E 759/E759M—92 (2020), Test Method for Effect of Deflection of Sprayed Fire-Resistive Material Applied to Structural Members. (NOTE: Laboratory test for SFRM applied to the underside of roof decks and structural members), West Conshohocken, PA: ASTM, 2020.
192. ASTM E 760/E760M-92 (2020), Test Method for Effect of Impact on Bonding of Sprayed Fire-Resistive Material Applied to Structural Members. (NOTE: Laboratory test for SFRM applied to the underside of roof decks and structural members), West Conshohocken, PA: ASTM, 2020.
193. ASTM E 761/E761M-92 (2020), Test Method for Compressive Strength of Sprayed Fire-Resistive Material Applied to Structural Members. NOTE: Laboratory procedure., West Conshohocken, PA: ASTM, 2020.
194. ASTM E 859/E859M—93 (2020), Test Method for Air Erosion of Sprayed Fire-Resistive Materials Applied to Structural Members. NOTE: Laboratory procedure, West Conshohocken, PA: ASTM, 2020.

195. NFPA 285, Standard Fire Test Method for Evaluation of Fire Propagation Characteristics of Exterior Wall Assemblies Containing Combustible Components, Quincy, MA: NFPA, 2019.
196. N. White and M. Delichatsios, "Fire Hazards of Exterior Wall Assemblies Containing Combustible Components, the Fire Protection Research Foundation Final Report (EP142293),," Fire Protection Research Foundation, Quincy, MA, 2014.
197. D. O'Connor, "The building envelope: Fire spread, construction features and loss examples," in *SFPE Handbook of Fire Protection Engineering, Fifth Edition, Vol II, chapter 86*, Gaithersburg, MD, Society of Fire Protection Engineers, 2016, pp. 3242-3282.
198. I. Oleszkiewicz, "Vertical Separation of Windows Using Spandrel Walls and Horizontal Projections," *Fire Technology,* vol. 25, no. 4, pp. 334-340, 1991.
199. J. Foley, "Modern Building Materials Are Factors in Atlantic City Fires. http://www.fireengineering.com/articles/2010/05/modern-building-materials-are-factors-in-atlantic-city-fires.html," *Fire Engineering,,* 2010.
200. J. Beitel, T. Fay and A. Parker, "Report Concerning the Exterior Wall Claddings Involved in the Monte Carlo Hotel Fire. Project No. 1JJB05264.006, 2008.," Hghes Associates, Baltimore, MD, 2018.
201. ASTM, ASTM E2307-20, Standard Test Method for Determining Fire Resistance of Perimeter Fire Barriers Using Intermediate-Scale, Multi-story Test Apparatus, West Conshohocken, PA: ASTM, 2020.
202. British Standards Institute, EN 1364-4, Fire resistance tests for non-loadbearing elements. Curtain walling, London, 2004.
203. FM Global, ANSI/FM 4411, American National Standard for Cavity Wall Systems, Norwood, MA: FM Global, 2020.
204. FM Global, ANSI/FM 4880, American National Standard for Evaluating the Fire Performance of Insulating Panel Assemblys and Interior Finish Materials, Norwood, MA: FM Global, 2017.
205. ISO, ISO 13785-2. Reaction-to-fire tests for façades –Part 2: Large-scale test. ISO, Geneva, 2002.
206. Standards Australia, AS 5113. Fire propagation testing and classification of external walls of buildings, Sydney, 2016.
207. British Standards Institution, BS 8414 Fire P\erformance of Bexternal Cladding Systems, London, 2015.
208. SP, FIRE 105. Issue 5. Large scale testing of facade systems, Boras Sweden, 1994.
209. French Ministry of Internal Affairs, LEPIR II Test. Large-scale Fire Performance testing of construction systems for façade, 2013, Paris.
210. ASTM, "ASTM E108, Standard Test Methods for Fire Tests of Roof Coverings," West Conshohocken, PA, 2020.
211. FM Global, "FM Approval Standard 4470, Single-Ply, Polymer-Modified Bitumen Sheet, Built-Up Roof (BUR) and Liquid Applied Roof Assemblies, for Use in Class 1 and Noncombustible Roof Deck Construction," Norwood, MA, 2010.
212. UL, "UL 1256, Standard for Fire Test of Roof Deck Constructions," Northbrook, IL, 2002.
213. ISO, ISO/IEC 17065, Conformity assessment - Requirements for bodies certifying products, processes and services, Geneva, Switzerland, 2012.
214. M. Ahrens, U.S. Experience with Sprinklers, Quincy: National Fire Protection Association, 2017.
215. E. Budnick, "Automatic Sprinkler System Reliability," *Fire Protection Engoneering,* vol. 9, no. 7, 2001.
216. NFPA, "NFPA 72® National Fire Alarm and Signaling Code®," NFPA, Quincy, MA, 2019.
217. J. H. Klote, J. A. Milke, P. G. Turnbull, A. Kashef and M. J. Ferreira, "Handbook of Smoke," ASHRAE, Atlanta, GA, 2012.
218. J. A. Milke and J. H. Klote, "Smoke Movement in Buildings, Fire Protection Handbook," National Fire Protection Association, QUincy, MA, 2008.
219. M. Owen, "ASHRAE Handbook," ASHRAE, Atlanta, GA, 2012.

220. D. Walton and S. Dols, "CONTAM User Guide and Program Documentation," NIST, Gaithersburg, MD, 2010.
221. J. H. Klote and G. Tamura, "Elevator Piston Effect and the Smoke Problem, NBSIR 88-3751," National Bureau of Standards, Gaithersburg, MD, 1986.
222. J. H. Klote, "An Analysis of the Influence of Piston Effect on Elevator Smoke Control," National Bureau of Standards, Gaithersburg, MD, 1988.
223. A. Cernak, "Wind Tunnel Studies of Buildings and Stuctures," ASCE, Reston, VA, 1999.
224. J. Barlow, W. Rae and A. Pope, "A Low Speed Wind Tunnel Testing," Wiley-Interscience, London, 1999.
225. NFPA 1, Fire Code, Quincy, MA: National Fire Protection Association, 2021.
226. "NFPA 3, Standard for Commissioning of Fire Protection and Life Safety Systems," NFPA, Quincy, MA, 2018.
227. "ASHRAE Guidline 5, Guideline to Commissioning Smoke Management Systems," ASHRAE, Atalanta, GA, 1994.
228. NFPA 101A Guide on Alternative Approaches to Life Safety, Quincy, MA: Natinal Fire Protection Association, 2019.
229. ICC®, International Existing Building Code®, Wasington, DC, 2018.
230. J. Cholin, "Inspection, Testing and Maintenance of Fire Alarm Systems," in *Fire Protection Handbook*, Quincy, MA, National Fire Protection Association, 2008.
231. D. Yung, Principles of Fire Risk Assessment in Buildings, West Sussex, UK: John Wiley & Sons, 2008.
232. S. Fuller and S. Pererson, "Life Cycle Costing Manual, NIST Handbook 135,," National Institute of Standards and Technology, Gaithersburg, MD, 1995.
233. J. Watts and R. Chapman, "Engineering Economics," in *SFPE Handbook of Fire Protection Engineering*, Gaithersburg, MD, Society of Fire Protection Engineers, 2016.
234. "NFPA 25, Standard for the Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems," NFPA, Quincy, MA, 2020.
235. "NFPA 4, Standard for Integrated Fire Protection and Life Safety System Testing," NFPA, Quincy, MA, 2018.
236. Measuring Code Compliance Effectiveness for Fire -Related Portions of the Code, Quincy, MA: Fire Protection Research Foundation, 2008.
237. US Dept of Transportation, Federal Aviation Administration, "AC No. 150/5390-2C: Heliport Design," Washington, DC, 2012.
238. United States Department of Energy, "Vanadium Redox Flow Batteries," Washington, DC.
239. R. T. Long and A. Blum, "Lithium Ion Batteries Hazard and Use Assessment," Fire Protection Research Foundation, Quincy, MA, 2016.
240. M. H. C. Hirschbold, "Verifying the Health of Backup or Emergency Power Supply Batteries," Schneider Electric.
241. NFPA 855, Standard for the Installation of Stationary Energy Storage Systems, Quincy, MA: NFPA, 2020.
242. "UL-1973:2018 Batteries for use in Stationary, Vehicle Auxiliary Power and Light Rail Applications," UL, Northbrook, IL, 2018.
243. "UL 9540 Standard for Energy Storage Systems June 28 2019 (Draft)," UL, Northbrook, IL, 2019.
244. UL 9540A, Standard for Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems, Northbrook, IL, 2019.
245. B. Ditch and D. Zeng, "Development of Sprinkler Protection Guidance for Lithium Ion-Based Energy Storage Systems," FM Global, Norwood, MA, 2019, Revised Oct 2020.