Title: **A Review on Fire Safety Engineering: Key Issues for High-Rise Buildings**

Authors: Guo-Qiang Li, State Key Laboratory for Disaster Reduction in Civil Engineering, Tongji University
Chao Zhang, Engineering Laboratory, National Institute of Standards and Technology
Jian Jiang, Engineering Laboratory, National Institute of Standards and Technology

Subject: Fire & Safety

Keywords: Fire Safety
Performance Based Design

Publication Date: 2018

Original Publication: International Journal of High-Rise Buildings Volume 7 Number 4

Paper Type:
1. Book chapter/Part chapter
2. **Journal paper**
3. Conference proceeding
4. Unpublished conference paper
5. Magazine article
6. Unpublished

International Journal of High-Rise Buildings
December 2018, Vol 7, No 4, 265-285
https://doi.org/10.21022/IJHRB.2018.7.4.265

International Journal of
High-Rise Buildings
www.ctbuh-korea.org/ijhrb/index.php

A Review on Fire Safety Engineering: Key Issues for High-Rise Buildings

Guo-Qiang Li[1,2], Chao Zhang[3], and Jian Jiang[3†]

[1]*State Key Laboratory for Disaster Reduction in Civil Engineering, Tongji University, Shanghai 200092, China*
[2]*College of Civil Engineering, Tongji University, Shanghai 200092, China*
[3]*Engineering Laboratory, National Institute of Standards and Technology, MD 20899, USA*

Abstract

This paper presents a state-of-the-art review on the design, research and education aspects of fire safety engineering (FSE) with a particular concern on high-rise buildings. FSE finds its root after Great Fire of Rome in 64 AD, followed by Great London Fire in 1666. The development of modern FSE is continuously driven by industry revolution, insurance community and government regulations. Now FSE has become a unique engineering discipline and is moving towards performance-based design since 1990s. The performance-based fire safety design (PBFSD) involves identification of fire safety goals, design objectives, establishment of performance criteria, and selection of proper solutions for fire safety. The determination of fire scenarios and design fires have now become major contents for PBFSD. To experience a rapid and positive evolution in design and research consistent with other engineering disciplines, it is important for fire safety engineering as a profession to set up a special educational system to deliver the next-generation fire safety engineers. High-rise buildings have their unique fire safety issues such as rapid fire and smoke spread, extended evacuation time, longer fire duration, mixed occupancies, etc., bringing more difficulties in ensuring life safety and protection of property and environment. A list of recommendations is proposed to improve the fire safety of high-rise buildings. In addition, some source information for specific knowledge and information on FSE is provided in Appendix.

Keywords: review, fire safety engineering, high-rise buildings, performance-based design, recommendation

1. Introduction

Fire is one of the most dangerous environmental hazards, and fire safety design is one of the key concerns in the design of civil structures (Kodur et al., 2007). Fire safety design was once exclusively prescriptive based on standard fire tests, which are still commonly used. From the first codified standard fire test ASTM E119 in 1918, standard fire tests have been the backbone of the design process of structures in fire (Maluk and Bisby, 2012), and remain almost unchanged since its initial development for 100 years. The original intent of standard fire tests was to provide a worse-case comparative test methodology for quantifying fire resistance of building materials and systems, rather than to develop a complex test which would be used unchanged for more than one century (Gales et al., 2012). As an alternative, performance-based fire safety design is steadily becoming more common, followed by a growing appeal for conducting real fire tests on real-scale (large-scale) systems (Bundy et al., 2016). The movement towards performance-based design is significantly driven by enormous advances in fire safety science, and knowledge of the thermo-mechanical response of construction materials and systems.

Many people confuse Fire Safety Engineering (FSE) with Fire Protection Engineering (FPE). The confusion may come from the different terminology used by different people in different parts of the world. In general, the two terms FSE and FPE are widely used in Europe and USA, respectively. The former became established in the UK in the early 1980s (Morgan 1999). The Institution of Fire Engineers (IFE51 1999) and International Standards Organization (ISO 16730-1 2015) define FSE as “the application of scientific and engineering principles, rules, and expert judgement, based on an understanding of the phenomena and effects of fire and of the reaction and behaviour of people to fire, to protect people, property and the environment from the destructive effects of fire”. In contrast, the Society of Fire Protection Engineers (SFPE) in the USA defines FPE as “the application of science and engineering principles to protect people and their environment from destructive effects of fire” (SFPE 2005). Wikipedia writes that “Fire Engineering encompasses fire protection engineering which focuses on fire detection, suppression and mitigation and fire safety engineering which focuses on human behavior and maintain-

†Corresponding author: Jian Jiang
Tel: +1-301-975-4566
E-mail: jiangjian_0131@163.com

ing a tenable environment for evacuation from a fire", and it also mentions that "In the United States fire protection engineering is often used to include fire safety engineering." On the contrary, Colin Bailey (2005) insists that fire science and fire protection engineering are the most important subjects in fire safety engineering. To avoid confusion, in this paper, the authors tend to treat "fire engineering", "fire safety engineering", and "fire protection engineering" as synonym. In a word, fire safety engineering is a multi-disciplinary field dealing with all the major disciplines on a building project from architecture, structural engineering, electrical and mechanical engineering, and building management. These include fire dynamics, fire detection systems, fire suppression systems (active and passive fire protection systems), smoke control, evacuation of occupants, structural fire resistance, etc. The increasing need to improve fire safety in buildings has led to the creation of "Structural Fire Engineering" as a new subset of structural engineering (Ali, 2010). It deals with specific aspects of passive fire protection in terms of analyzing the thermal effects of fires on buildings and designing structural members for adequate load bearing resistance.

The last two decades have seen fire-induced collapses of high-rise or tall buildings (>24 m) of different structural forms (Cowlard et al., 2013). Tables A.1 and A.2 in Appendix A summarize the historical fire events in high-rise buildings in the past 50 years. In this period we have seen the collapses of steel framed buildings such as the World Trade Center buildings 1, 2, and 7, USA (NIST, 2005), the partial collapse of the Windsor Tower, Spain (Parker, 2005), and of concrete buildings such as Faculty of Architecture Building at Delft University of Technology, Netherlands (Meacham et al., 2009). Furthermore, we have seen how classic prescriptive solutions failed to manage smoke such as Cook County Building, USA (Madrzykowski et al., 2003), Camberwell fire, UK (Knight et al., 2009), and modern buildings using state-of-the-art fire engineering failed to contain the full propagation of a fire such as CCTV Tower fire, China and Grenfell Tower fire, UK. The collapse of WTC 7 is the first known instance of the total collapse of a tall building primarily due to fires (NIST, 2008). The fire that burned an entire 28-storey residential building in Shanghai in 2010, killing 58 people clearly illustrates the disastrous consequences of fire not being adequately considered or integrated into the design process. The fire spread rapidly via the external facade through the entire building disabling egress. The material allowing for the fast spread was external insulation being installed as part of a government pilot scheme to boost energy efficiency. The external cladding also led to the fast fire spread to the whole building for an apartment building in Busan, Korea (20 mins) and Grenfell Tower, London (15 mins). These failures address the lack of proper design tools required to ensure safety in a rapidly evolving construction industry where issues other than fire safety are the main drivers for innovation.

Previous reviews on fire safety engineering (Hadjisophocleous et al., 1998; Hadjisophocleous and Benichou, 2000; Kobes et al., 2010; Kodur et al., 2012; Davidson et al., 2013; Meacham and Thomas, 2013; Spinardi et al., 2017) apply to all types of buildings, while this paper aims to address some key issues for high-rise buildings. Appendix B of this paper provides various sources of specific knowledge and information that fire engineering professionals may refer to (IFEG, 2005). This paper presented a review on the key issues in fire safety engineering for high-rise buildings. The history of fire safety engineering was first reviewed, followed by a detailed review on design, research and education of fire safety engineering. Finally, the unique fire safety issues and corresponding recommendations of improvement for high-rise buildings were proposed.

2. History of Fire Safety Engineering

The key events in the history of development of fire safety engineering are listed in Table 1. The early examples of fire safety engineering were established as a result of catastrophic historic "big fires". After the Great Fire of Rome in the year AD 64, the Emperor Nero drew up regulations that fireproof materials should be used for external walls in rebuilding the city (Cote 2003). It is perhaps the first recorded example of using passive fire protection methods. London adopted its first building regulation requiring stone and brick houses with fire wall separations after the Great London Fire in 1666, which destroyed over 80 percent of the city. Throughout the Industrial Revolution in UK in the 18th century and in the United States in the early 19th century, urban fires continued but began to decline since non-combustible building materials such as masonry, concrete and steel were increasingly utilized. New industrial processes and material storage practices resulted in greater fire risks, and a number of spectacular building fires occurred during this period. The focus of fire protection engineering thus shifted from addressing community fires to dealing with specific buildings, and public fire departments were formed. During the 19th century, many of the advancements in fire safety engineering were brought about by the insurance industry with the desire to minimize property insurance losses. A number of organizations were formed by the insurance industry in the U.S. that were responsible for fire protection engineering, including Factory Mutual (FM) in 1835, National Fire Protection Association (NFPA) in 1896, Underwriters Laboratories (UL) in 1893.

During the early 1900s, efforts were made both by American and European testing organizations, as well as by other stakeholders involved in the building construction community, to define uniform 'standard' fire resistance tests (Ingberg, 1928). During the first half of the 20th century, building and fire codes and standards became the primary means of applying fire protection engineering for life safety and property protection. Much of these specifications were influenced by other professions, including civil, mechanical, architecture, psychological, electrical engineering. It was only in the latter half of the 20th Century that fire protection engineering emerged as a unique engineering profession, separating from civil, mechanical and chemical engineering (Emmons, 1984). This emergence was primarily due to the development of a body of knowledge specific to fire protection engineering that occurred after 1950. Other factors contributing to the growth of the profession include the start of the Institution of Fire Engineers in 1918 in the UK, and the Society of Fire Protection Engineers in 1950 in the U.S. The publication of the SFPE Handbook of Fire Protection Engineering in 1988 was a major step toward broad distribution of fire protection engineering calculation methods. In 2000, SFPE published the SFPE Engineering Guide to Performance-Based Fire Protection (SFPE 2005) which defined the overall process of performance-based fire protection engineering design.

Technological advancements in the late 20th and early 21st centuries saw the quantitative evaluation of fire safety engineering around the world. Fire safety engineering thus adopted performance-based design in the 1990s. A number of protection aspects began to be considered with greater weight: sprinkler and smoke detector response, smoke development and movement, egress flow in buildings, the particular properties of materials such as fire release and combustibility, fireproof barrier systems like fire doors. These are achieved by continuously improved computational methods for determining a quantitative evaluation of fire protection and computational power of today's computers, which have in turn resulted in the development of more user-friendly fire and structural models for use by the fire safety engineers.

3. Design

Buildings need to be designed to offer an acceptable level of fire safety and minimize the risks from heat and smoke. Buildings codes can be classified as prescriptive or performance-based in nature (Hadjisophocleous and Benichou, 2000; Marrion, 2005). Prescriptive codes prescribe “how a building is to be constructed”, while performance-based codes states “how a building is to perform”, by specifying desired objectives to be satisfied and allow the designer to use any acceptable approach to achieve these objectives (Buchanan, 2001). Until recently, fire safety design in many countries has been based on prescriptive building codes, with little or no opportunity for designers to take a rational engineering approach to the provision of fire safety. Prescriptive-based fire design codes could sometimes be overly conservative and therefore unnecessarily expensive (Milke et al., 2002). Newer prescriptive codes have alleviated some of the inefficiency, but they still might not provide the most effective designs for very specialized buildings. Therefore, there is a movement towards performance-based fire safety design since 1990s (Woodrow et al., 2013). It allows maximum flexibility while achieving a specified level of safety, by requiring responsibility for setting goals, selecting appropriate levels of protection, and determining the perform-

Table 1. Key events in the history of fire safety engineering (Cote, 2003; Wikipedia)

Year	Key events
64	Great Fire of Rome, as first example of fire protection engineering
1666	Great London Fire, first UK building regulation on fire protection engineering
1835	Formation of Factory Mutual (FM)
1847	First patent for an automatic sprinkler
1893	Formation of Underwriters Laboratories (UL)
1896	Formation of National Fire Protection Association (NFPA)
1898	Formation of American Society for Testing and Materials (ASTM)
1903	First degree program in fire protection engineering
1918	Formation of Institution of Fire Engineers, UK
1918	First standard temperature-time curve ASTM E119
1928	First full-scale fire test conducted by NIST
1950	Formation of Society of Fire Protection Engineers (SFPE)
1964	First computer program in fire protection application (Cote 1990)
1970	First Professional Engineer (P.E.) in fire protection engineering
1973	First Master’s degree in fire safety engineering at University of Edinburgh
1985	Formation of International Association for Fire Safety Science (IAFSS)
1985	Publish of textbook “Introduction to Fire Dynamics” by Dougal Drysdale
1988	SFPE Handbook of Fire Protection Engineering
1990	Formation of new subcommittee SC4 for ISO/TC92 on “Fire Safety Engineering”.
2000	SFPE Engineering Guide to Performance-Based Fire Protection

ance available from the fire protection design options being considered. This requires extensive knowledge of both fire science and fire protection engineering.

Many international and national organizations have contributed to the development of performance-based fire safety design methods, such as International Organization for Standardization (ISO 16730-1, ISO 13387; ISO 23932; ISO 16576), International Code Council (IBC; ICC; IFC), International Council for Research and Innovation in Building and Construction (CIB, 1983), National Fire Protection Association (NFPA 5000; NFPA 1; NFPA 101; NFPA 550; NFPA Primer), Society of Fire Protection Engineers (SFPE), American Society of Civil Engineers (ASCE) (ASCE 7-16; ASCE 29-05), European Committee for Standardization (EN 1991-1-2), National Research Council of Canada (NBC; NFC), Institution of Fire Engineers in UK (IFE 46; IFE 51; IFE 85), Australian Building Codes Board (ABCB; Johnson 1996), Department of Building and Housing in New Zealand (NZBC; Buchanan, 1999), National Institute for Fire and Disaster in Japan (Hadjisophocleous et al., 1998; Lo et al., 2007), China Steel Construction Society in China (Li and Zhang, 2013). China has recently issued a national code for fire safety of steel structures in buildings (NCC, 2017), including steel structures, concrete filled steel tubular columns, composite slabs with profiled decking, composite beams. This code specifies design methods based on load-bearing capacity of structural elements, as well as global stability of structures, depending on the type, importance and load of structures. The load-bearing capacity based design methods for structures in fire as specified in many national codes have been deemed as an important transition step from standard fire tests based design approaches towards performance-based design approaches. The strategies and methodologies for these design methods can also be found in books (Lie, 1972; Pettersson et al., 1976; Partners, 1996; Custer and Meacham 1997; Stollard and Abrahams 1999; Robertson, 1999; Buchanan, 2001; Wang, 2002; Franssen et al., 2009; Li and Wang, 2012; Wang et al., 2013; Hurley and Rosenbaum, 2015).

During the 1960s, high-rise fires, notably at One New York Plaza in 1970 contributed to a growing awareness of the special fire safety challenges of high-rise buildings in the USA. This led to a qualitative approach specified in NFPA 550 (2012) and a quantitative approach described in GSA 5920 (1975), and NBS report (Watts, 1979). Ref-

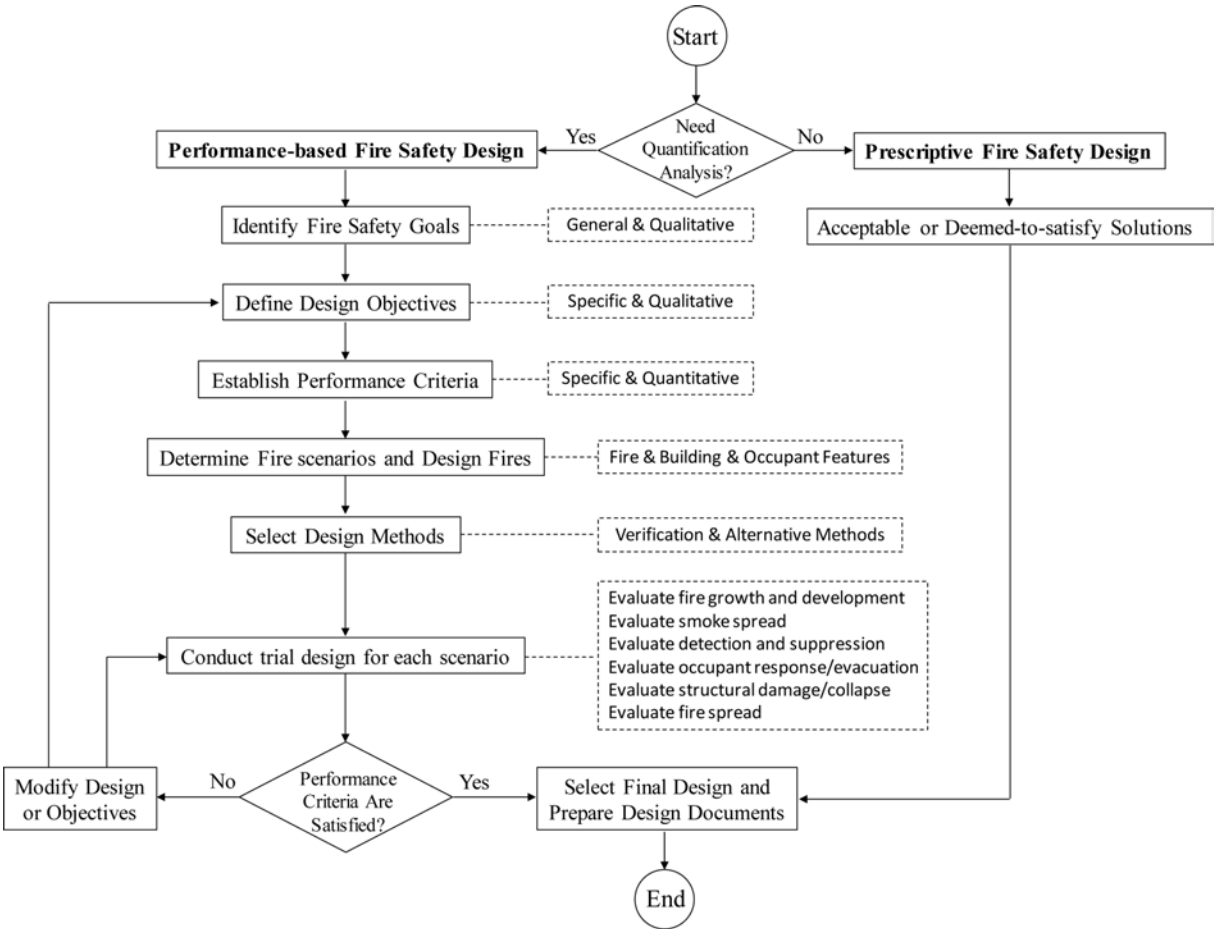

Figure 1. Flow chart illustrating the fire safety design process.

erences in the report provide an excellent history of the early development of performance-based approaches to building fire safety. In Europe, ISO technical committee ISO/TC92 on fire safety set up a new subcommittee SC4 on fire safety engineering in 1990 (Bukowski and Babrauskas, 1994) to address the evaluation and standardization of fire engineering methods. So far, the SC4 has a total of 13 working groups covering comprehensive topics related to fire safety engineering. The first meeting of the SFPE Focus Group on Concepts of a Performance-Based System for the United States in 1996 was to bring together a wide cross-section of the United States' building and fire communities to discuss the transition towards performance-based design methods in the United States (Meacham, 1997). The 2016 edition of ASCE 7 (ASCE 7-16), for the first time, provided Appendix E on the use of performance-based methods to design fire protection (McAllister et al., 2015). Meanwhile, the ASCE/SEI Fire Protection Committee is in the process of developing its first guideline, "Structural Fire Engineering," to present best practices for structural engineers working with fire protection engineers.

A general fire safety design process is illustrated in Fig. 1. The design team has the option to follow the prescriptive code if it is practical and cost-effective. If the building is complex and does not comply with prescriptive code, performance-based fire safety design should be carried out by specifying fire safety goals, design objectives, and performance criteria, determining fire scenarios, and selecting proper design methods to achieve those goals. The features of these five key steps in a performance-based fire safety design are presented in the following subsections.

3.1. Fire Safety Goal

The term "Fire Safety Goal" (NFPA Primer, 1999) represents overall outcome to be achieved with regard to fire. These goals are non-specific and are measured on a qualitative basis. They should be stated in terms of conditions that are intrinsically desirable and do not rely on any assumptions. Thus, goals may be expressed in terms of impact on people, property, or the environment, or in terms of mission continuity as:

- Life safety (for public, building occupants, emergency responders, etc.);
- Property protection (building, contents, historic features, etc.);
- Continuity of operations (maintain ongoing mission, production or operating capability);
- Environmental protection (fire by-products such as smoke and toxic materials, etc.).

3.2. Design Objectives

In undertaking a performance-based fire safety design or analysis, it is important to establish the design objectives prior to establishing criteria for structural fire protection and assessing the fire performance of structural elements. Design objectives are performance requirements for the fire, building, or occupants that must be satisfied in order to achieve a fire safety goal. Objectives are stated in more specific terms than goals, and they will act as a link between the general, qualitative goals and specific, quantitative performance criteria. SFPE (2012) and NFPA Primer (1999) provide some examples of design objectives:

- Prevention of structural damage;
- No life loss in the room of fire origin;
- Separating occupants from fire effects for "a specified period of time";
- Containing the fire to the room of origin;
- Adequate egress times to safe areas;
- Provide fire department access;
- Protect continuity of operations for essential facilities;
- Prevent spread of fire to exposed properties.

3.3. Performance Criteria

The design objectives based on the qualitative goals can be further quantified into performance criteria which are stated in measurable engineering terms (e.g., temperature, radiant heat flux, level of exposure to combustion products). Performance criteria provide threshold values which are used to quantify a proposed performance-based solution. The design output will be compared to performance criteria in order to determine whether the design meets the performance provisions or must be further modified and re-evaluated. Candidate examples of performance criteria are (Hadjisophocleous and Benichou, 2000; Meacham and Thomas, 2013):

- Limiting a structural steel member to less than 540°C;
- Maximum heat release rate of 40 kW/m^2;
- Limiting upper layer temperatures to less than 500°C;
- Limiting radiant flux at the floor to less than 20 kW/m^2;
- Minimum spacing of 8 m between buildings;
- Fire-resistance rating of 1 hour for building stability if more than 3 storeys;
- Minimum evacuation width of 1.40 m if more than 20 persons;
- Maximum length of 20 m for corridor.

3.4. Design Fire Scenarios and Design Fire Curve

The next step of performance-based fire safety design is to establish a list of fire scenarios, which include such aspects as the location of the fire, building characteristics, occupant response, fire loads, fire protection systems (Kirby et al., 1999). The fire locations are determined through a combination of most-likely and worst-case assumptions, and thus each fire scenario has either a high probability of occurrence, serious consequences or both. The number of scenarios depends on the criticality and complexity of the structure, as well as the computational resources available and the anticipated number of design iterations. The main challenge in scenario selection is to find a manageable number of fire scenarios that are sufficiently diverse and representative, and therefore if the design is safe for those scenarios, then it should be safe for all scenarios.

A design fire scenario also includes a design fire (a quantitative description of fire characteristics within the design fire scenario) which is typically defined as a HRR time history, but will also often include fire production rates and effective heat of combustion (Bwalya et al., 2004). A design fire curve can be idealized as four different stages of fire growth: the incipient stage (generally ignored in fire safety engineering design), the growth stage, the fully developed stage, and the decay stage. The detail required for the design fire depends on the issue that is being addressed (Borg et al., 2015). Illustrative characteristics of high challenging scenarios (NFPA Primer; Meacham and Thomas, 2013; NFPA, 101) include:

- High-frequency, low-consequence fire (typical);
- Low-frequency, high-consequence fire (high challenge);
- Fires in critical areas, i.e., areas where local damage will lead to disproportionate collapse;
- Initiating fire close to high occupancy, high fuel load, or critical areas. Examples include storage rooms near large, fully occupied assembly rooms; offices or closets near very large product storage rooms or showrooms; and plenum space fires near computer rooms;
- Fire in a critical egress path, such as a front entrance way or lobby;
- Fire shielded from active systems or other fire fighting activities, e.g., concealed spaces, origin outside building;
- Fire involving materials producing unusually toxic, corrosive, explosive or otherwise harmful combustion products;
- Large, high intensity or fast growing fires, e.g., high initial heat release rate, flash fires, accelerant-fed arson fires, large flammable or combustible liquid spill fires;
- Impairment of various fire protection systems with typical fire scenarios. For example, sprinklers with closed valves, barrier that fail to contain the fire, or detectors that fail to operate.

3.5. Design Methods & Tools

There are various types of tools available to use in the design process, ranging from hand calculation methods to computer models. NFPA Primer (1999) specifies a "verification method" which is a computer model or other tool used to demonstrate that a proposed solution meets the fire safety goals for the applicable fire scenarios. The design methods need to be verified for mathematical accuracy and validated for capability to reproduce the phenomena (Borg and Nja, 2013). The ISO 16730-1 (2015) address the procedures for verification and validation of calculation methods as a key element of quality assurance.

New Zealand Building Code (NZBC, 2005) provides three possible methods: (a) Acceptable solutions (deemed-to-satisfy solution) that are contained in the Compliance Documents (prescriptive methods to meet performance criteria); (b) Verification methods (calculation or test methods) also contained in the Compliance Documents; (c) Alternative solutions (alternative methods, other than those contained in Compliance Documents, to meet performance criteria). Alternative designs can often be used to justify variations from the "acceptable solution" in order to provide cost savings or other benefits.

3.6. Design Needs

There is still a long way for performance-based fire safety design to be used by considering the following design needs (Lataille, 2003; Meacham and Thomas, 2013):

- Treat fire as a "load at an equivalent level to earthquake and wind load;
- Integrate fire protection into the overall design process from the very beginning of the project, i.e., selection of building type and determination of component size;
- Make everyone (architects, structural engineers, fire protection engineers, etc.) involved in the building design process;
- The design load of fire is not clear. The use of standard fire curves is not proper;
- Most performance criteria are "damage criteria which do not really reflect the performance of the building. A higher level of "performance criteria should be provided;
- Uncertainty inherent in the design process need to be analyzed and addressed;
- More concern for life safety of firefighters;
- Risk assessment-based design combined with probabilistic analysis (Bjelland et al., 2015);
- life-cycle fire safety engineering (IFEG, 2005), i.e., maintenance of fire protection measures and change in the use of a building;
- Sustainable fire safety engineering, i.e., energy saving and environmentally friendly.

4. Research

The description of design objectives and performance criteria is always specified in building codes and standards, and is basically similar for different buildings. The big challenge in the fire safety design of a building lies in the determination of fire scenarios and fire behavior of the specified building using a proper method. This section presented a review on the fire behavior of high-rise buildings, including fire modeling, thermal analysis and structural analysis, as shown in Fig. 2. The gas temperature-time history obtained from FDS model is input as boundary conditions in the thermal model where the temperature of structural components is calculated and used in the structural model to determine the structural responses.

Since the Broadgate Phase 8 fire and the subsequent Cardington fire tests (Kirby, 1997) in the 1990s, the global behavior of steel framed structures in fire has received increasing concern. It is confirmed that steel members in real multi-story buildings have significantly greater fire resistance than isolated members in standard fire tests, due

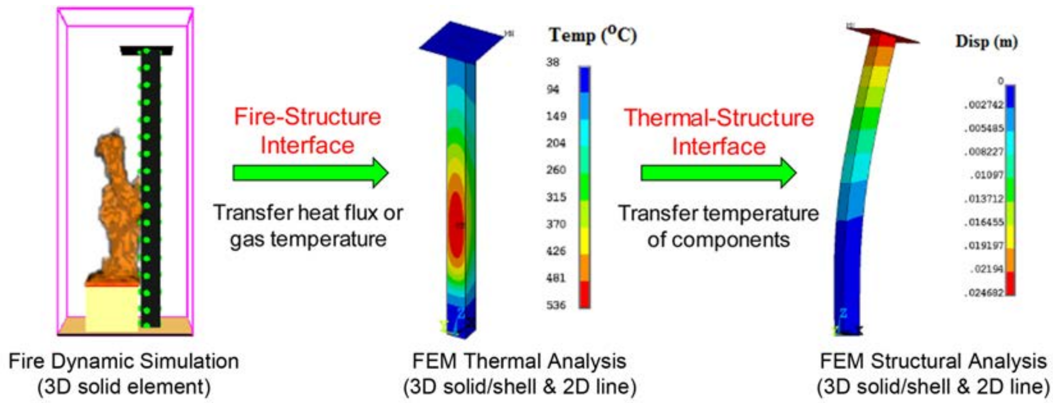

Figure 2. Structural fire analysis at high temperature (Zhang et al., 2016).

to the realistic member dimension, boundary condition, and fire scenario. Especially since the collapse of Word Trade Tower (WTC) under the terrorist attack on September 11, 2001, there have been growing interests in understanding progressive collapse resistance of structures under fire (Usmani et al., 2003; Neal et al., 2012; Jiang et al., 2017). The term "progressive collapse" is defined as "the spread of an initial local failure from element to element, eventually resulting in the collapse of an entire structure or a disproportionately large part of it" (ASCE 7 2005). It implies that large displacements, even failure, of individual structural members are acceptable given the prevention of global structural collapse. An important lesson resulting from the collapse of WTC is that prescriptive fire resistance ratings of individual structural members do not guarantee the adequate performance of a whole building system (Cowlard et al., 2013).

4.1. Fire Modeling

The standard temperature-time curves (ASTM E119, ISO 834, NFPA 251, UL 263), was originally developed for furnace testing, which is not intended to be representative of the heating condition in a real fire. To better represent a realistic fire, natural fire models (e.g., parametric fire model for confined compartment fires, localized fire model for open-flame fires) are developed by taking into account the geometry of the compartment, ventilation condition, fire load density, thermal characteristics of materials. The primary difference between standard and natural fire models is that the latter accounts for the cooling phase and the non-uniform temperature distribution (Fig. 3). It is important to understand and quantify the various stages of the design fire history including ignition, growth rate, peak heat release rate, burning duration and decay. For analysis of structural elements, it is typically important to understand the location of the fire relative to the structural elements, as well as the fire growth rate and duration of the exposure and the impact of the size/geometry of the space on the development of fire induced conditions.

The study of fire dynamics emerged as the foundation for fire protection engineering solutions, involving the study of how materials ignite and burn, how heat is trans-

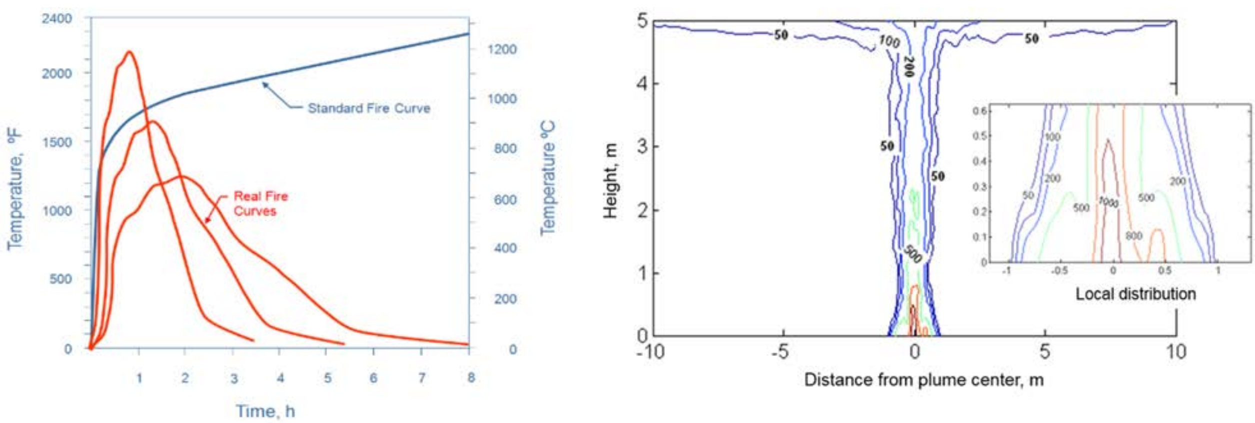

Figure 3. (Left) Standard fire curve vs real fire curves (SFPE, 2012); (right) Non-uniform temperature distribution in a localized fire (Zhang and Li, 2012).

ferred in fires, how smoke moves in buildings and how fire grows from ignition to full-room involvement. The Fire Research Division at the National Institute of Standards and Technology (NIST) develops and maintains a set of computational tools to analyze fire behavior. These tools include the Consolidated Model of Fire and Smoke Transport (CFAST) zone model, the Fire Dynamics Simulator (FDS) computational fluid dynamics model, and Smokeview, which visualizes output from both CFAST and FDS. A project entitled "Fire modeling for performance-based design" has been conducted to extend the capabilities of these models, improve their accuracy and reliability, and to facilitate more accurate two-way coupling between FDS and finite-element structural models.

The influence of fire scenarios on the behavior of structures includes time history of gas temperature in the fire compartment (standard or natural fire), location of fire (internal or external; lower floor or upper floor), number of fire compartments (single or multiple compartments in fire), or spread of fire (travelling fire). A review on these influences is presented as below.

It is found that a frame may collapse in the cooling phase in the high-ventilation fire due to the less rapid temperature rise in the column than the beam because of the large cross-section of the column (Richard Liew et al., 1998; Lien et al., 2009; Agarwal and Varma, 2014) and also the change of temperature distribution which results in moving of neutral axis, shear center, etc. that causes lateral torsional buckling (Zhang et al., 2013). The natural fire for open plan compartments is the critical knowledge gap for performance-based design of structures in fire, and there is a new research direction toward large-compartment fire and travelling fire (Cowlard et al., 2013). Recently, Lou et al. (2018) carried out real fire tests on full-scale steel portal frames. The experimental results showed that the temperature distribution in the frame was significantly non-uniform, and the frames collapsed asymmetrically.

A fire may occur in the interior or exterior of a frame, and also occur on its lower floor or upper floor. Generally, a fire on the ground floor is more severe than that on the upper floor since the ground-floor columns have the largest load ratio. However, it is also necessary to consider the upper-floor fire that columns on the upper floors had a smaller size of cross section and thus faster temperature increase, compared to columns on the lower floor. It was found that the edge bay fire was more prone to induce the collapse of structures than the central bay fire (Jiang et al., 2014). It was also found that the most dangerous situation is the frame subjected to high load ratios exposed to a central bay fire where its progressive collapse may occur as early as 250°C (Jiang et al., 2014). For multi-compartment fires, it was found that the spread of fire in the vertical direction had little effect on the collapse mode of structures, while a horizontally distributed fire scenario was prone to cause a global downward collapse of structures (Jiang et al., 2014). Neal et al. (2012) pointed out that the upper floor fire resulted in a longer survival time compared to the lower floor fire if the beams were not protected.

Both the standard and parametric fire curves assume a uniform temperature distribution in the compartment considering the occurrence of flash-over. A flash-over is the near-simultaneous ignition of most of the directly exposed combustible material in an enclosed area. The assumption of flash-over is valid for a relatively small compartment (i.e., small compartment fire), up to 500 m^2 of floor area without openings in the roof and for a maximum compartment height of 4 m (EN 1991-1-2 2005). Flash-over is unlikely to occur in large or open compartments, and thus a localized fire should be taken into account where a non-uniform temperature is assumed (Zhang et al., 2015). Ali et al. (2004) found that a frame under a small compartment fire will collapse inward due to the catenary action of the heated beams which drive the columns inward. When the fire localized to the column, the column will buckle outward pushed by the expanding beam at a relatively low temperature.

Observations from realistic fires such as those in WTC tower and Windsor Tower have revealed that the fire in large open areas travels across the floors rather than burning simultaneously for the duration. Indeed, combustible materials in large compartments are consumed at a rate governed by the ventilation condition, leading to a non-uniform temperature in the compartment. A review of research on travelling fire can be found in the reference (Behnam and Rezvani, 2015, Rackauskaite et al., 2015). The spread of fire can produce larger beam deflection than does simultaneous heating of multiple compartments, and there was possibility that a frame collapsed during the cooling phase (Bailey et al., 1997). Behnam and Rezvani (2015) pointed out that the frame was more vulnerable to travelling fire compared to standard fire. However, the collapse mechanism of structures under travelling fire is still not clear, and thus further work should be done.

4.2. Thermal Analysis

The objective of the thermal analysis is to determine the temperature in the structure during and after the fire scenario. Eurocode EN 1993-1-2 provides calculation methods of unprotected and protected steel members, and EN 1994-1-2 provides a tabulated temperature distribution in a solid concrete slab of 100 mm thickness. One challenge is to determine the temperature of protected steel members by intumescent coatings where this insulation material can swell when heated, leading to a varying thickness and corresponding varying thermal conductivity. A number of research studies have attempted to develop methods to calculate the thermal conductivity of intumescent coatings (Zhang et al., 2012; Cirpici et al., 2016). These methods are sophisticated and require a number of additional material properties that cannot be provided by furnace fire tests alone. In practice, the effective thermal conductivity or equivalent thermal resistance is usually adopted (ISO

834-11 2014; EN1993-1-2 2005). The inverse equation for calculating the temperature of fire protected steelwork is used to determine the effective thermal conductivity of intumescent coatings based on the fire and steel temperatures from fire resistance tests. However, even with this simplification, it is still inconvenient to use the temperature-dependent variable thermal conductivity of intumescent coatings to determine the required fire protection thickness. To address this issue, the concept of effective constant thermal conductivity was proposed by Li et al. (2012). This value is defined as the temperature-averaged effective thermal conductivity over the temperature range of 400~600ºC in steel. The feasibility of this method for intumescent coatings without topcoat in accurately predicting the temperature increase of steel structures in many fire conditions has been verified (Li et al., 2016, 2017). The effect of topcoat on the performance of intumescent coatings was experimentally investigated by Xu et al. (2018).

4.3. Structural Analysis

The third step is to perform a structural analysis with the temperatures obtained from the thermal analysis. The increase in temperature has two effects on the structure: it reduces the strength and stiffness of the materials, and it develops thermal stresses in the restrained members. A nonlinear analysis must be used to predict the large deformations that occur during fires, taking into account all of the possible failure modes of the critical components. The analysis must also be able to detect global instabilities. Since the structural analysis uses the results from the thermal analysis, the challenge is to model each step with appropriate amount of detail and to facilitate the flow of information between the thermal and structural domains (Ellingwood, 2007).

Many finite element simulations of structural behavior at elevated temperatures have been published and agree well with experiments, such as the Cardington tests. These include specialist programs such as ADAPTIC, SAFIR, VULCAN and commercial packages such as ABAQUS, ANSYS, LS-DYNA (Jiang et al., 2018) and DIANA (Johann et al., 2006). ADAPTIC developed by Izzudin (1991) at Imperial College to study the non-linear dynamic behavior of framed structures at ambient temperatures was extended to include fire and explosion effects on steel framed structures (Izzudin, 1996) and then to reinforced concrete floor slabs (Song, 1998). The program SAFIR developed by Franssen (2003) at University of Liege, Belgium is widely used by researchers and practitioners all over the world to model structures in fire. The program VULCAN was developed by successive researchers since 1985 at the University of Sheffield, UK (Saab, 1990; Najjar, 1994; Bailey, 1995). Although specialist programs are cost-effective to purchase and easy to use they lack generality and versatility, but more tellingly continuous development, quality, robustness and long-term sustainability of such research group based software must remain in perpetual doubt because of a relatively small number of users and developers. The commercial packages have a large library of finite elements and excellent GUIs to enable efficient and detailed modeling of structural responses to fire and also allow user subroutines for modeling special features of behavior. Despite obvious advantages commercial packages require substantial recurring investment for purchase and maintenance that often make them unaffordable for researchers and deter new entrants to the field. Furthermore, the development of commercial codes is not in the hands of the user and users have little control over the direction the development takes. This is usually dictated by the needs of the largest commercial subscribers and rarely address the needs of discounted subscription paying researchers. The research team led by A.F. Usmani at the University of Edinburgh (now Hong Kong Polytechnic University) add a “structures in fire” modelling capability (SIFBuilder) in OpenSees (Jiang and Usmani, 2013; Jiang et al., 2015a), an open source object oriented software framework developed at UC Berekeley (McKenna, 1997). This capability involves a heat transfer model, a structural model and an interface between them to map the temperature data automatically from the heat transfer analysis to the structural analysis, without losing the spatial and temporal resolution of the temperatures when applied to the structural elements. OpenSees offers the potential of a common community owned research code with large and growing modelling capability in many areas of structural engineering enabling researchers to collaborate freely across geographical boundaries with a much greater potential longevity of research and development efforts. Further work is planned to link OpenSees to the open source CFD model OpenFOAM (capable of modelling compartment fires), leading to a fully automated software framework for modelling fire, heat transfer and structural response.

There is no fire-thermal-structural model that is available for all fire applications. The selection of a computer model depends on a number of factors including understanding the limitations and assumptions used in the model, validation of the model, documentation accompanying the model and ease of use (Hadjisophocleous and Benichou, 2000). Further, when using a fire model, it is wise to determine the sensitivity of the output to changes in the input to determine if changes in the data or the model assumptions and applicability will lead to a different decision (Rackauskaite et al., 2017). The sensitivity analysis will determine the most dominant and significant variables. Furthermore, fire safety engineering models can provide a good estimate of the effects of fire.

There are many research references on global stability of buildings in fire. Usmani et al. (2003) investigated the stability of WTC tower exposed to fire alone. The results showed that the collapse of the tower was mainly due to the thermal expansion effect rather than the material effect of loss of strength and stiffness since the temperature of columns was found within 400°C when the collapse occurred. The collapse was triggered by the buckling of external columns due to the loss of its lateral support provided by the composite truss floor systems. The loss of stiffness in floors was due to the material softening and buckling induced by restrained thermal expansion. The details of this collapse mechanism were further studied by Usmani (2005) and Flint et al. (2007), and it was found that the main reason for the collapse was the low membrane capacity in compression of the truss floor. Based on the stiffness of floors, Lange et al. (2012) proposed two collapse mechanisms: a weak floor failure mechanism and a strong floor failure mechanism (Fig. 4). The former was initiated by the buckling of the adjacent floor below the fire-exposed floor which experienced large membrane compressions. If the floor was strong enough, the external column would collapse due to the formation of plastic hinges in it on the fire-exposed floors. Li et al. (2017) conducted standard fire tests on four full-scale composite slabs, and the effect of secondary steel beams was investigated.

Some attempts have been made by using bracing systems to enhance redundancy of structures at ambient temperatures and provide alternative load redistribution path after a local failure. The hat bracing is effective to uniformly redistribute loads to adjacent columns, and thus delay or prevent the collapse of structures (Flint et al., 2007). However, it failed to resist the lateral drift of columns which may lead to a global downward collapse (Sun et al., 2012). A vertical bracing system can act as a barrier to prevent the spread of local failure to the rest of structures (Jiang et al., 2015b). It is thus recommended to use a combined bracing system in practical design. Jiang et al. (2015b) recommended an interior arrangement of vertical bracings which effectively prevented the spread of local damage to the rest of structures.

The application of fire protections will delay the temperature rise in the steel members and enhance their fire resistance. Neal et al. (2012) considered a combination of fire protection of beams and columns. They concluded that fire protection had an important effect on the collapse resistance. The unprotected beam always failed before the column because it experienced a faster temperature increase due to its three-side fire exposure. If the beam was protected, the collapse mode and time were affected significantly by the fire location and the fire type. Fang et al. (2013) proposed that the application of fire protection is not always an effective way to increase the collapse resistance for a localized fire with limited fire affected area. Fire protection may even lead to an undesirable reduction in overall resistance due to the elimination of thermal expansion which can enhance the rotation capacity and ductility of joints. The collapse mechanism of an 8-storey braced steel frame with concrete slabs was studied by Jiang and Li (2017b). It was found that the fire protection of steel members had a significant influence on the resistance of structures against fire-induced collapse. A protected frame did not collapse immediately after the local failure but experienced a relatively long withstanding period of at least 60 min (Jiang and Li, 2017b). This indicated that the overall fire resistance of the frame against global collapse was somewhat 1-hour longer than that of individual members.

4.4. Research Needs

The following research priorities are identified (Franssen, 2005; Bailey, 2006; Croce et al., 2008; Kodur et al., 2012; Kotsovinos et al., 2013; Bisby et al., 2013):

- A hierarchy of meaningful benchmark fire experiments and simulations;
- Tractable combustion models that capture the essence of materials and finished products, and with simple multistep reaction mechanisms for prediction of CO and soot;
- Data sets and experimental facilities for unraveling the relationships within and interactions among fire dynamics, structural dynamics, and human behavior;
- Efficient interfaces among fire, structural, human behavior;
- Improvement of our ability to predict the impact of active fire protection systems on fire growth and the distribution of combustion products;
- Estimation of uncertainty and the means to incorporate it into hazard analyses and risk assessment;
- The relationship between aspects of the building design and the safety of building occupants;
- The impact of material and geometry changes on fire growth and products of combustion;
- The prediction of the response of a structure to full building burnout;
- Testing real behavior of large-scale structures in real fire;
- Multi-hazard analysis, post-earthquake fire and post-blast fire;
- Determination of more realistic fire scenarios, such as localized fire and travelling fire
- Risk assessment

5. Education

Performance-based fire safety design is outside the scope of the structural engineer's work in the majority of building projects. Structural engineers generally do not have the knowledge and experience necessary to analyze structural performance at elevated temperatures (Mowrer and Emberley, 2018). Moreover, they lack the knowledge and experience to deal with uncertain fire conditions because the structural engineering curriculum in universities and colleges do not usually include courses in heat transfer and fire dynamics (Zhang and Usmani, 2015). In fact, fire protection engineers are seldom members of building design teams, and their participation is limited to exceptional circumstances or unique structures. Instead, architects typically participate to identify and select structural assemblies that comply with the types of construction and fire-resistance ratings according to the building's occupancy, height, and area.

To experience a rapid and positive evolution in design and research consistent with other engineering disciplines, it is essential for fire safety engineering as a profession starting within the educational systems, charged with delivering the next generation of fire safety engineers. Through education, training, and experience, a fire safety engineer is familiar with the dynamics and characteristics of fire and its products of combustion, understand how fires originate, spread through structures, and can be detected, controlled, and suppressed, as well as being capable of predicting the behaviors of various materials, structures, and processes to protect life, property and the environment (Lataille, 2003).

5.1. History of Education for Fire Safety Engineering

The early fire safety engineering education is motivated by the need for loss-control engineers from insurance companies to create training programs in which graduate engineers could be educated as fire protection engineers (Milke and Kuligowski, 2003). A formal degree program in fire protection engineering was first established in 1903, when several prominent fire insurance companies (FM) and UL joined forces to establish the first FPE program in the U.S. at Armour Institute of Technology in Chicago (now Illinois Institute of Technology). In 1956, the fire protection engineering program at the University of Maryland was established, and in 1979, the first master of science program in fire protection engineering was begun at Worcester Polytechnic Institute (WPI). In the late 1970s, the state of California established an examination for a P.E. registration in FPE. In 1981, the National Council of Examiners for Engineering and Surveying (NCEES) made the FPE exam available on a national basis. Today, 46 states in the U.S. license fire protection engineers. Fire protection engineering is one of fifteen engineering disciplines that offer a P.E. examination through the NCEES (Lataille, 2003). The Master's degree program in fire safety engineering was begun at the University of Edinburgh in 1973, followed by University of Ulster, UK in 1991, University of Canterbury, New Zealand in 1994, Victoria University of Technology, Australia in 1994, and University of British Columbia, Canada in 1995 (Magnusson et al., 1995).

The International Working Group on Fire Safety Engineering Curricula was formed at the 2nd international Symposium on Higher Fire Technical Education, held in Edinburgh in 1989 (Magnusson et al., 1995). One important task for the working group was to develop a new general curriculum for fire safety engineering, helping to identify the discipline of fire safety engineering and to distinguish fire safety engineering from other engineering disciplines. Five modules were identified to represent the core of a fire safety engineering program: fire fundamentals, enclosure fire dynamics, active fire protection, passive fire protection, human behavior and fire. In 2011, the BRE Centre for Fire Safety Engineering at the University of Edinburgh held a one-week seminar on FSE education, aimed at reflecting on both the content and methodology required in a comprehensive university training program (Woodrow et al., 2013; Maluk et al., 2017). Over the years, a number of FPE degree programs have been established around the world, including programs in Canada, New Zealand, Sweden, Australia, Scotland, Hong Kong and Northern Ireland.

5.2. Education needs

The growing need for fire safety engineering (FSE) design around the world has led to a set of short courses and higher education degrees, many of which lack strong foundations in fundamental knowledge and are somewhat deficient in developing skills and appropriate attitudes (Woodrow et al., 2013). The following needs are proposed to improve the quality of current education systems:

- More University education on fire protection engineering and structural fire engineering at the graduate and undergraduate levels;
- More attention on design-based education, in additional to technology-based education;
- Feedback of engineering lessons into educational program;
- More education in performance-based design and fire science;
- More fundamental knowledge than prescriptive application;
- More education on risk assessment.

6. Fire Safety for High-Rise Buildings

The fire safety strategy for a tall building is essentially a function of time. It contains two principle components: evacuation strategy and building performance. Building performance can be further divided into structural performance and fire spread mitigation (e.g., compartmentation). The evacuation strategy is concerned with defining the time required to safely evacuate all occupants. Building performance concerns the time that the structure can withstand the effects of the fire and the compartmentation remains in place and functional. Times associated to evacuation are typically of the order of minutes while structural/compartmentation times are more typically of the order of hours. It is thus usually inherent that the structure and compartmentation will remain intact for a period that comfortably allows for the implementation of the egress strategy. That is why the two components can usually be dealt with separately. However, this is not the case for tall buildings. The ever exaggerated heights together with the limited number of vertical escape routes results in coupling of these two components. Evacuation times are extended to an order of magnitude comparable with that of the potential failure times of the building. Evacuation and structural/compartmentation failure are therefore at risk of overlapping as was the case of the WTC towers. This problem will become worse as buildings become taller and more complex. In 2012, a National Basic Research Program (973 program) of China entitled "Research on key fundamental aspects of high-rise building fire protection" has been setup by Ministry of Science and Technology of China (Sun et al., 2013) to address the fire safety issues in high-rise buildings.

6.1. Unique Features of Fire Safety for High-Rise Buildings

Fire safety of high-rise buildings has attracted extensive attention due to serious fire accidents. The above-mentioned design and research approaches are not specified for high-rise buildings. Although fire hazards in high-rise buildings are essentially the same as in low-rise buildings of similar uses (e.g., business, residential, mixed-use), the consequences of a fire have a potential to be more severe given the large numbers of occupants, the inherent limitations in egress and access, and the physical aspects of the structure which can affect the hazard (e.g., chimney effect). Compared to typical room fires, the fire behaviors in high-rise buildings have the following unique features (SFPE, 2000, 2012; Ma and Guo, 2012; Sun and Luo, 2014):

6.1.1. Rapid Fire and Smoke Spread

Because of the "chimney effect" of the high-rise building, fire and smoke can spread to the upper or lower floors very rapidly through internal staircases, elevator shafts and pipes in a very short time if the fire and smoke control measures are not adequate. Furthermore, if a indoor fire leads to the rupture of the glass curtain wall and come out of the window, the fire will not be easily controlled at all. More recently, the external combustible cladding systems significantly contribute to a fast vertical fire spread.

6.1.2. Limited Exterior Rescue and Firefighting Capability

Factors like the height of the building beyond available resources of fire department ladders, and inadequate firefighting equipment certainly increase the difficulties of the firefighting in a high-rise building. The rapid fire spread through cladding also increases the difficulties for firefighters to do exterior firefighting and rescue. The interior firefighting also results in additional physical demands upon the firefighters and extended time to reach the fire floor.

6.1.3. Extended Evacuation Time

The time necessary for full building evacuation increases with building height and amount of occupants. Generally speaking, there will be more occupants in a high-rise residential building than those of a multi-storey building. Crowd evacuation in high-rise buildings in case of fire becomes a major safety issue. In the case of very tall buildings, full building evacuation via stairways might be impractical. A "defend-in-place" strategy has been employed in many building designs. The lack of common sense of fire safety and ability of escaping safely from the building in case of fire increases the safe evacuation time.

6.1.4. Longer Duration of Fire

Fire lasts longer in a high-rise building because of large amount of floor areas and fire loads. Therefore, high-rise building fire often lasts longer and sometimes it may spread to the adjacent buildings.

6.1.5. Limited Water Supply

Supplemental pumps are required in a high-rise building to boost the pressure of public water supplies to the upper floor of a building. If they are out of service, the fire compartment can supply water to the sprinkler systems in the building which has limited capability.

6.1.6. Greater Challenge of Mixed Occupancies

Many tall buildings contain mixed occupancies, involving various combinations of occupancies such as retail, residential, automobile parking, business, restaurant, transportation facilities, health care, educational, 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 tall buildings.

6.2. Recommendations for Fire Safety of High-Rise Buildings

In 1970, a fire occurred above the 30th floor of the office building at One New York Plaza in New York City. The difficulty encountered by the fire department in combating this fire highlighted growing concerns within the fire protection engineering community for fire safety in modern high-rise office buildings. As a result of this fire, the General Services Administration (GSA) convened an international conference to develop solutions to the fire problem in high-rise buildings. It was concluded that fire protection for high-rise buildings was not keeping pace with high-rise building design. The National Institute of Standards and Technology (NIST) was funded to investigate the mechanism of the collapse of the World Trade Tower in 2001, and the influence of fire on the structure is one focus. A list of 30 recommendations was released in 2005 in the final report on WTC (NIST, 2005) for improving the safety of buildings, particularly for tall buildings. It calls on designers, builders, owners, and code-writing organizations to make significant changes in the way tall buildings are designed, constructed, and operated (Gurley, 2007). These recommendations can be grouped into eight categories: increased structural integrity, enhanced fire endurance of structures, new methods for fire resistant design of structures, enhanced active fire protection, improved building evacuation, improved emergency response, improved procedures and practices, and education and training.

There are some specifications in IBC (2012) for high-rise buildings. It allows fire-resistance-rating reductions in high-rise buildings having sprinkler devices for each floor. For example, for buildings not greater than 128 m (420 ft), the fire-resistance rating of primary structural frame can be reduced from 3 hour to 2 hour (except the columns supporting floors), and the required fire-resistance rating of the fire barriers enclosing vertical shafts is permitted to be reduced to 1 hour where automatic sprinklers are installed in the shafts at the top and at alternate floor levels. A minimum bond strength of 21 KPa (430 psf) and 48 KPa (430 psf) of sprayed fire-resistant materials (SFRM) is specified for high-rise buildings up to 128 m and greater than 128 m, respectively. IBC requires that high-rise buildings should be equipped throughout with an automatic sprinkler system, smoke detection system, fire alarm system. A standpipe system and a secondary water supply system (i.e. required fire pumps) should be supplied by connections to no fewer than two water mains located in different streets.

The following recommendations are summarized based on the NIST report, and other references are provided to improve the fire safety of high-rise buildings (Ma and Guo, 2012):

General:

- Develop performance-based standards and codes as an alternative to current prescriptive design methods;
- Need national education and training effort of fire safety knowledge for fire protection engineers, structural engineers, architects, code officials, as well as occupants;
- The fire safety objective for high-rise buildings is to prevent fire spread and to maintain structural integrity until the available fuel load has burned out, rather than until a limited period to allow for occupant egress;
- Multiple levels of pumps and water storage tanks are provided.

Evacuation:

- Design stairwell that are large enough to accommodate not only occupants on their way out but also rescue workers on their way in;
- Develop next generation evacuation technologies including protected/hardened elevator, exterior escape devices, stairwell descent devices;
- Implement reliable, real-time, and off-site transmission of information (e.g., bi-communication system, wireless fire communication network);
- The "defend in place strategy or phased evacuation is recommended in high-rise buildings, rather than full evacuation. The occupants are encouraged to remain in their original location or move to a safe location;
- Smoke spread is controlled by designing ventilation systems to pressurize adjacent spaces in high-rise buildings, rather than to exhaust smoke directly from the fire zone as in large open buildings;
- Enhance redundancy of life safety systems of power, alarm and fire suppression systems to maintain a high level of life safety even in the event of partial system failure;
- Increased number of exit stairways, use of safe areas or refuge floors, use of elevator;
- Increased access for fire fighters, dedicated elevator for fire fighters;
- Use of elevators for evacuation;
- Horizontal stair transfer.

Fire protection:

- Consistency in the fire protection provided to all of the structural elements (i.e., beam and bracing members have the same fire resistance rating as columns);
- Enhance in-service performance and ductility of fire protection materials;
- Improve performance and redundancy of active fire protection systems according to increasing building height and opening spaces;
- Need to control the flammability of high-rise facades, as lessons from the recent façade fires at the Grenfell tower in London and the Torch tower in Dubai;
- Set appropriate compartmentation limit to retard fire spread in buildings with large, open floor plans.

Structure fire resistance:

- Progressive collapse should be prevented in buildings by providing alternative paths for carrying loads, and structural fire resistance should be evaluated to withstand full burnout of fires;
- Determine appropriate construction classification and fire rating requirements by explicitly considering timely access by emergency responders, full evacuation of occupants or the time required for burnout without partial collapse;
- Test components, assemblies, and systems under realistic fire and load conditions, rather than standard fire curve, and extrapolate the results of tested assemblies to prototypical building systems;
- Test and evaluate the performance of high-performance materials (high-strength steel and concrete, pre-stressed concrete, etc);
- Correct selection of define fire scenarios and design fire (cooling phase, localized fire, travelling fire).

7. Conclusions

This paper presented a detailed review on the history of design, research and education of fire safety engineering. It was found that the development of fire safety engineering was significantly driven by big city fires at the early stage, industry revolution and insurance industry later, and government regulation and international/national organizations. The key motivation is to ensure life safety, and protect property and environment. There has been great achievement on the movement from prescriptive approaches to performance-based approaches. However, it is still needed to improve the performance-based fire safety design approach on selection of design fire scenarios and design fires, uncertainty analysis and risk assessment, proposal of realistic "performance criteria". For the increasing interests in the research on global behavior of buildings in real fire, there is still a lack of benchmark real fire experiments on large-scale systems, especially for high-rise buildings, and more concerns are needed on interaction between fire, structure performance, and human behavior. The education in fire safety engineering should pay more attention on fundamental knowledge on fire science and performance-based fire safety techniques.

Compared to low-rise buildings, high-rise buildings have unique fire safety issues such as rapid fire and smoke spread, extended evacuation time, longer duration of fire, mixed occupancies, limited water supply, difficult exterior fire extinguishing, etc. It is recommended to take specific measures to improve fire safety of high-rise buildings, including "defend in place" or phased evacuation strategy, improving in-service performance and redundancy of active and passive fire protection systems, enhancing collapse resistance for full burnout of fires, developing next generation evacuation technologies (protected/hardened elevator, exterior escape devices, stairwell descent devices), implementing reliable, real-time, and off-site transmission of information.

Acknowledgements

The work presented in this paper was supported by the National Natural Science Foundation of China with grant 51408418, and Research project of State Key Laboratory for Disaster Reduction in Civil Engineering with grant SLDRCE14-A-05.

References

ABCB. Fire Safety Engineering Guidelines, Australian Building Codes Board, Canberra, Australia, 2001

ABCB. Building Code of Australia, Australian Building Codes Board, Canberra, Australia, 2005

Agarwal, A., and Varma, A. H. (2014). "Fire induced progressive collapse of steel building structures: The role of interior gravity columns." Engineering Structures, 58, 129-140.

Ali, H. M., Senseny, P. E., and Alpert, R. L. (2004). "Lateral displacement and collapse of single-storey steel frames in uncontrolled fires." Engineering Structures, 26, 593-607.

Ali, F. A. (2010) Structural fire engineering, Encyclopedia of Life Support Systems (EOLSS).

ASCE 7-16. American Society of Civil Engineers Standard 7 Minimum Design Loads for Buildings and Other Structures, American Society of Civil Engineers, 2016.

ASCE/SEI/SFPE 29. Standard Calculation Methods for Structural Fire Protection. American Society of Civil Engineers and Society of Fire Protection Engineers, 2005.

ASTM E119. Standard test methods for fire tests of building construction and materials. West Conshohocken (PA), ASTM International, 2010.

Bailey, C. G. (1995). "Simulation of the structural behavior of steel-framed buildings in fire", PhD thesis, Department of Civil and Structural Engineering, University of Sheffield, UK.

Bailey, C. G., Burgess, I. W., and Plank, R. J. (1997). "Analysis of the effects of cooling and fire spread on steel-concrete-framed buildings." Research Report. Sheffield (UK): University of Sheffield.

Bailey, C. (2005). One Stop Shop in Structural Fire Engineering, University of Manchester, http://www.mace.manchester.ac.uk/project/research/structures/strucfire/

Bailey, C.G. (2006). "Advances in fir engineering design of steel structures." Proceedings of the Institute of Civil Engineers, 159, 21-35.

Barber, D. (2016) "Hurley and Rosenbaum: Performance-Based Fire Safety Design. CRC Press and SFPE, Boca Raton, 2015." Fire Technology, 52, 2159-2161.

Behnam, B. and Rezvani, F. H. (2015). "Structural evaluation of tall steel moment-resisting structures in simulated horizontally travelling postearthquake fire." Journal of Performance of Constructed Facilities, DOI:10.1061/(ASCE)CF.1943-5509.0000696.

Bisby L., Gales, J., and Maluk C. (2013). "A contemporary review of large-scale non-standard structural fire testing." Fire Science Reviews, 2, 1-27.

Bjelland, H., Nja, O., Heskestad, A. W. and Braut, G. S. (2015). "The concepts of safety level and safety margin: Framework for fire safety design of novel buildings." Fire Technology, 51, 409-441.

Borg, A. and Nja, O. (2013). "Concept of validation in performance-based fire safety engineering." Safety Science, 52, 57-64.

Borg, A., Nja, O., and Torero, J. L. (2015). "A framework for selecting design fires in performance based fire safety engineering." Fire Technology, 51, 995-1017.

Buchanan, A. H. (1999). "Implementation of performance-based fire codes." Fire Safety Journal, 32, 377-383.

Buchanan, A. H. (2001) Structural Design for Fire Safety. John Wiley & Sons.

Bukowski, R. W. and Babrauskas, V. (1994). "Developing rational, performance-based fire safety requirements in model building codes." Fire and Materials, 18, 173-191.

Bundy, M., Hamins, A., Gross, J. et al. (2016). "Structural fire experimental capabilities at the NIST National Fire Research Laboratory." Fire Technology, 52, 959-966.

Bwalya, A., Sultan, M. and Benichou, N. (2004). "A literature review of design fires for fire safety engineering." Proceedings of CIB World Building Congress, Toronto, Ontario, 1-13.

CIB. A Conceptual Approach Towards a Probability Based Design Guide on Structural Fire Safety. Workshop Report: CIB W14 Workshop "structural Fire Safety", 1983.

Cirpici, B. K., Wang, Y. C., and Rogers, B. (2016). "Assessment of the thermal conductivity of intumescent coatings in fire." Fire Safety Journal, 81, 74-84.

Cote, A. E. (1990). "The computer and fire protection engineering-25 years of progress." Fire Technology, 195-201.

Cote, A., (2003). "History of Fire Protection Engineering." National Fire Protection Association, Quincy, MA.

Cowlard, A., Bittern, A., Abecassis-Empis, C. and Torero, J. (2013). "Fire safety design for tall buildings." Procedia Engineering, 62, 169-181.

Croce, P. A., Grosshandler, W. L., Bukowski, R. W., and Gritzo L. A. (2008). "The International FORUM of Fire Research Directors: A position paper on performance-based design for fire code applications." Fire Safety Journal, 43, 234-236.

Custer, R. L. P. and Meacham, B. R. (1997). "Introduction to performance-based fire safety." National Fire Protection Association, Quincy, MA.

Davidson, M. T., Harik, I., and Davis, D. B. (2013). "Fire impact and passive fire protection of infrastructure: State of the art." Journal of Performance of Constructed Facilities, 27(2), 135-143.

Drysdale, D. (1985). An Introduction to Fire Dynamics, John Wiley & Sons, Cichester, UK.

Ellingwood, B. R. (2007). "Structural design for fire conditions: New developments." Structural Congress, ASCE.

Emmons, H. W. (1984). "The further history of fire science." Combustion Science and Technology, 40, 167-174.

EN 1991-1-2. Actions on structures, Part 1-2: general actions – actions on structures exposed to fire. European Committee for Standardization (CEN), Brussels, 2002.

EN 1993-1-2. Design of steel structures, Part 1.2: General Rules-Structural Fire Design. European Committee for Standardization (CEN), Brussels, 2005.

EN 1994-1-2. Design of composite steel and concrete structures, Part 1.2: General Rules-Structural Fire Design. European Committee for Standardization (CEN), Brussels, 2005.

Fang, C., Izzuddin, B. A., Elghazouli, A. Y., and Nethercot, D. A. (2013). "Robustness of multi-storey car parks under localised fire-Towards practical design recommendations." Journal of Constructional Steel Research, 90, 193-208.

Flint, G., Usmani, A.S., Lamont, S., Lane, B., and Torero, J. (2007). "Structural response of tall buildings to multiple floor fires." Journal of Structural Engineering, 133(12), 1719-1732.

Franssen, J. M. (2003). "SAFIR: a thermal/structural program modelling structures under fire." Proceedings of the North American Steel Construction Conference, April, A.I.S.C. Inc., Baltimore.

Franssen, J. M. (2005). "Structures in fire: yesterday, today and tomorrow." Proceedings of the 8th International Symposium on Fire Safety Science, 21-35.

Franssen, J. M., Venkatesh, K., and Zaharia, R. (2009). "Designing steel structures for fire safety". CRC Press.

Gales, J., Maluk, C. and Bisby, L. (2012). "Structural fire testing: where are we, how did we get here, and where are we going." Proceedings of 15th International Conference on Experimental Mechanics, Portugal.

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.

Gurley, C. (2007). "Structural design for fire in tall buildings." Practice Periodical on Structural Design and Construction, 13(2), 93-97.

Hadjisophocleous, G. V. Benichou, N., and Tamin, A. S. (1998). "Literature review of performance-based fire codes and design environment." Journal of Fire Protection Engineering, 9(1), 12-40.

Hadjisophocleous, G. V. and Benichou, N. (2000). "Development of performance-based codes, performance criteria and fire safety engineering methods." International Journal on Engineering Performance-based Fire Codes, 2(4), 127-142.

Hurley, M. J. (2015). Rosenbaum E. R. Performance-Based Fire Safety Design. CRC Press, Boca Raton.

IBC. International Building Code, International Code Council (ICC), 2012.

ICC. International Code Council Performance Code for Buildings and Facilities, International Code Council, Falls, Church, VA, 2015.

IFC. International Fire Code, International Code Council (ICC), 2018.

IFE 51. Fire Safety Engineering — A Basic Guide for Fire Authority Enforcement Fire Service Manual Volume 3, Institution of Fire Engineers (IFE), 1999.

IFE 46. Fire Safety - Basic Principles of Building Construction, Fire Service Manual Volume 3, Institution of Fire Engineers (IFE), 1999.

IFE 85. Fire Safety - Fire Protection of Buildings, Fire Service Manual Volume 3, Institution of Fire Engineers (IFE), 1999.

IFEG. International Fire Engineering Guidelines. The National Research Council of Canada (NRC), the International Codes Council (ICC) United States of America, the Department of Building and Housing, New Zealand (DBH) and the Australian Building Codes Board (ABCB), 2005.

Ingberg, S. (1928). "Tests of the Severity of Building Fires." NFPA Quarterly, 22, 43-61.

ISO 16730-1. Fire Safety Engineering – Procedures and requirements for verification and validation of calculation methods-Part 1: General. The International Organization for Standardization (ISO), Geneva, Switzerland, 2015.

ISO/TR 13387. Fire Safety Engineering. The International Organization for Standardization (ISO), Geneva, Switzerland, 1999.

ISO 23932. Fire safety engineering-General principles, The International Organization for Standardization (ISO), Geneva, Switzerland, 2009.

ISO/TR 16576 Fire safety engineering-Examples of fire safety objectives, functional requirements and safety criteria, The International Organization for Standardization (ISO), Geneva, Switzerland, 2017.

ISO 834. Fire-resistance tests–Elements of building construction, The International Organization for Standardization (ISO), Geneva, Switzerland, 2014.

ISO/CD 834-11: 2014, MOD. Fire Resistance Tests— Elements of Building Construction, Specific requirements for the assessment of fire protection to structural steel elements, The International Organization for Standardization (ISO), Geneva, Switzerland, 2014.

Izzudin, B. A. (1991). “Nonlinear dynamic analysis of framed structures”, PhD thesis, Department of Civil Engineering, Imperial College, London.

Izzudin, B. A. (1996). “Quartic formulation for elastic beam-columns subject to thermal effects.” ASCE Journal of Engineering Mechanics, 122(9), 861-871.

Jiang, J. and Usmani A. (2013). “Modelling of steel frame structures in fire using OpenSees.” Computers & Structures, 118, 90-99.

Jiang, J., Li, G. Q., and Usmani, A. S. (2014). “Progressive collapse mechanisms of steel frames exposed to fire.” Advances in Structural Engineering, 17(3), 381-398.

Jiang, J., Li, G. Q., Usmani, A. S. (2014). “Influence of Fire Scenarios on Progressive Collapse Mechanisms of Steel Framed Structures.” Steel Construction-Design and Research, 7, 169-172.

Jiang J., Jiang L. M., Kotsovinos P., Zhang J., et al. (2015a). “OpenSees software architecture for the analysis of structures in fire.” Journal of Computing in Civil Engineering, 29(1), 04014030 https://doi.org/10.1061/(ASCE)CP.1943-5487.0000305

Jiang, J., Li, G. Q., and Usmani, A. S. (2015b). “Effect of bracing systems on the fire-induced progressive collapse of steel structures.” Fire Technology, 51, 1249-1273.

Jiang, J. and Li, G. Q. (2017a). “Progressive collapse analysis of 3D steel frames with concrete slabs exposed to localized fire.” Engineering Structures, 149: 21-34.

Jiang, J. and Li, G. Q. (2017b). “Disproportional Collapse of 3D Steel-framed Structures Exposed to Various Compartment Fires.” Journal of Constructional Steel Research, 138, 594-607.

Jiang, J. and Li, G. Q. (2018). “Parameters Affecting Tensile Membrane Action of Reinforced Concrete Floors subjected to Elevated Temperatures.” Fire Safety Journal, 96, 59-73.

Johnson, P. (1996). “The process of fire safety design-Development of fire engineering guidelines in Australia.” Fire Technology, 298-307.

Johann, M. A., Albano, L. D., Fitgerald, R. W., and Meacham, B. J. (2006). “Performance-based structural fire safety.” Journal of Performance of Constructed Facilities, 20(1), 45-53.

Kirby, B.R. (1997). “British steel technical European fire test program design, construction and results. Fire, static and dynamic tests of building structures.” London.

Kirby, B.R., Wainman, D.E., Tomlinson, L.N. et al. (1999). “Natural fires in large scale compartments.” International Journal on Engineering Performance-based Fire Codes, 1(2), 43-58.

Knight, K. (2009). Report to the Secretary of State by the Chief Fire and Rescue Adviser on the Emerging Issues Arising from the Fatal Fire at Lakanal House, Camberwell on 3 July 2009, Communities and Local Government.

Kobes, M., Helsloot, I., Vries, B., Post, J.G. (2010). “Building safety and human behavior in fire: A literature review.” Fire Safety Journal, 45, 1-11.

Kodur, V.K., Garlock, M.E., and Iwankiw, N. (2007). “National Workshop on Structures in Fire: State-of-the-Art, Research and Training Needs.” Report CEE-RR – 2007/03, National Institute of Standards and Technology (NIST).

Kodur, V. K., Garlock, M. E., and Iwankiw, N. (2012). “Structures in fire: state-of-the-art, research and training needs.” Fire Technology, 48, 825-839.

Kotsovinos P., Jiang Y.Q., and Usmani, A. (2013). “Effect of vertically travelling fires on the collapse of tall buildings.” International Journal of High-rise Buildings, 2(1), 49-62.

Lange, D., Roben, C., and Usmani, A.S. (2012). “Tall Building Collapse Mechanisms Initiated by Fire: Mechanisms and Design Methodology.” Engineering Structures, 36, 90-103.

Lataille, J.I. (2003) Fire protection engineering in building design, 1st Ed., Elsevier Science, Burlington, MA, USA.

Li, G.Q. and Wang, P.J. (2012). Advanced Analysis and Design for Fire Safety of Steel Structures, John Wiley & Sons, LTD.

Li, G.Q., Lou, G.B., Zhang, C., et al. (2012). “Assess the fire resistance of intumescent coatings by equivalent constant thermal resistance.” Fire Technology, 48, 529-546.

Li, G.Q., and Zhang, C. (2013). “The Chinese performance-based code for fire-resistance of steel structures.” International Journal of High-Rise Buildings, 2(2), 123-130.

Li, G.Q., Han, J., Lou, G.B., et al. (2016). “Predicting intumescent coating protected steel temperature in fire using constant thermal conductivity.” Thin Wall Structures, 98, 177-184.

Li, G.Q., Han, J., and Wang, Y.C. (2017). “Constant effective thermal conductivity of intumescent coatings: analysis of experimental results.” Journal of Fire Science, 35(2), 132-155.

Li, G.Q., Zhang N.S. and Jiang, J. (2017). “Experimental investigation on thermal and mechanical behaviour of composite floors exposed to fire.” Fire Safety Journal, 89, 63-76.

Lie, T.T. (1972). Fire and Buildings (Architectural Science), Elsevier Science Ltd.

Lien, K.H., Chiou, Y.J., Wang, R.Z., and Hsiao, P.A. (2009). “Nonlinear behavior of steel structures considering the cooling phase of a fire.” Journal of Constructional Steel Research, 65, 1776-1786.

Lo, S.M., Gao, L.J., and Yuen, K.K. (2007). “The development of performance-based fire safety engineering design in Hong Kong and Japan.” International Journal on Engineering Performance-based Fire Codes, 9(3), 133-139.

Lou, G.B., Wang, C.H., Jiang, J., et al. (2018a). “Experimental and Numerical Study on Thermal-Structural Behaviour of Steel Portal Frames in Real Fires.” Fire Safety Journal, 98, 48-62.

Lou, G.B., Wang, C.H., Jiang, J., et al. (2018b). “Fire Tests on Full-scale Steel Portal Frames against Progressive Collapse.” Journal of Constructional Steel Research, 145, 137-152.

Ma, Q.L. and Guo, W. (2012). “Discussion on the fire safety design of a high-rise building.” Procedia Engineering, 45, 685-689.

Madrzykowski, D. et al., (2003) Cook County Administration Building Fire, 69 West Wachington, Chicago, Illinois: Heat Releasse Rate Experiments and FDS Simulations, NIST SP-1021.

Magnusson, S.E., Drysdale, D.D., Fitzgerald, R.W., et al. (1995). “A proposal for a model curriculum in fire safety

engineering." Fire Safety Journal, 25, 1-88.
Maluk, C. and Bisby, L. (2012). "120 years of structural fire testing: moving away from the status quo." Proceedings of 2nd Fire Engineering Conference, Valencia, Spain.
Maluk, C., Woodrow, M., and Torero, J.L. (2017). "The potential of integrating fire safety in modern building design." Fire Safety Journal, 88, 104-112.
Marrion, C. (2005). "Design of structures for fire loading and understanding fire/life safety system interdependencies." Structures Congress.
McAllister, T.P., LaMalva, K.J., and Garlock, M.E. (2015). "ASCE/SEI 7 Appendix E proposal: Performance-based design procedures for fire effects on structures." Structures Congress, 807-818.
McKenna, F.T., (1997). Object-Oriented Finite Element Programming: Frameworks for Analysis, Algorithms and Parallel Computing, PhD thesis, University of California, Berkeley.
Meacham, B.J. (1997). "Concepts of a performance-based building regulatory system for the United States." Proceedings of the 5th International symposium on fire safety science, Melbourne, Australia.
Meacham, B. et al. (2009). "Collection of Data on Fire and Collapse, Faculty of Architecture Building, Delft University of Technology." National Science Foundation, CMMI, Research and Innovation Conference.
Meacham, B.J. and Thomas, J.R. (2013). "20 Years of Performance-Based Fire Protection Design: Challenges Faced and a Look Ahead." Journal of Fire Protection Engineering, 23(4) DOI: 10.1177/1042391513484911.
Milke, J., Kodur, V. and Marrion, C. (2002). "Overview of fire protection in buildings." Appendix A of FEMA 403, World Trade Center Building Performance Study: data collection, preliminary observations, and recommendations, Federal Emergency Management Agency (FEMA), New York.
Milke, J. and Kuligowski, E. (2003). "Fire Protection Engineering Education Programs." History of Fire Protection Engineering, National Fire Protection Association, Quincy, MA.
Morgan, H.P. (1999). "Moves towards performance-based standards in the UK and in the European committee for standardization (CEN)." International Journal on Engineering Performance-based Fire Codes, 1(3), 98-103.
Mowrer, F.W. and Emberley, R.L. (2018). "An overview of fire protection for structural engineers: Part 1 Fire safety objectives." Structure Magazine, 22-25.
Mowrer, F.W. and Emberley, R.L. (2018). "An overview of fire protection for structural engineers: Part 2 Fire safety systems and features." Structure Magazine, 9-11.
Mowrer, F.W. and Emberley, R.L. (2018). "An overview of fire protection for structural engineers: Part 3 Structural fire engineering." Structure Magazine, 16-19.
Najjar, S.R. (1994). "Three-dimensional analysis of steel frames and subframes in fire." PhD thesis, Department of Civil and Structural Engineering, University of Sheffield, UK.
NBC. National Building Code of Canada, Canadian Commission on Building and Fire Codes, 2005.
NCC. Code for Fire Safety of Steel Structures in Buildings (GB51249-2017), National Code of China, 2017.
NFC. National Fire Code of Canada, Canadian Commission on Building and Fire Codes, 2005.
NFPA 5000. Building Construction and Safety Code. National Fire Protection Association (NFPA), Quincy, MA, 2015.
NFPA 1. National Fire Protection Association (NFPA) 1, Uniform Fire Code. National Fire Protection Association (NFPA), Quincy, MA, 2018.
NFPA 101, Life Safety Code, National Fire Protection Association (NFPA), Quincy, MA, 2006.
NFPA 550, Guide to the Fire Safety Concepts Tree, National Fire Protection Association (NFPA), Quincy, MA, 2012.
NFPA Primer. Performance-Based Primer Codes & Standards Preparation, National Fire Protection Association (NFPA), Quincy, MA, 1999.
Neal, M.C., Garlock, M.E.M., Quiel, S.E., and Marjanishvili, S. (2012). "Effects of fire on a tall steel building designed to resist disproportionate collapse." Structures Congress 2012, ASCE, 246-256.
NIST. Final report on the collapse of the World Trade Center Towers, NIST NCSTAR 1, National Institute of Standards and Technology (NIST), Gaithersburg, MD, 2005.
NIST. Final report on the collapse of the World Trade Center Building 7, NIST NCSTAR 1A, National Institute of Standards and Technology (NIST), Gaithersburg, MD, 2008.
NZBC. New Zealand Building code. Department of Building and Housing, New Zealand, 2005.
NZBC. New Zealand Building Code Handbook, Department of Building and Housing, 3rd Ed, New Zealand, 2014.
Parker, D. (2005). "Madrid Tower Designer Blames Missing Fire Protection for Collapse." New Civil Engineer.
Partners, B.A. (1996). Design principles of fire safety. H.M. Stationery Office, London, 1996.
Pettersson, O., Magnusson, S.E., and Thor, J. (1976). "Fire engineering design of steel structures." Bulletin of Division of Structural Mechanics and Concrete Construction, Bulletin 52. Lund Institute of Technology.
Rackauskaite, E., Hamel, C., Law, A., and Rein, G. (2015). "Improved formulation of travelling fires and application to concrete and steel structures." Structures, 3, 250-260.
Rackauskaite, E., Kotsovinos, P. and Rein, G. (2017). "Model parameter sensitivity and benchmarking of the explicit dynamic solver of LS-DYNA for structural analysis in case of fire." Fire Safety Journal, 90, 123-138.
Richard Liew, J.Y., Tang, L.K., Holmaas, T., and Choo, Y.S. (1998). "Advanced analysis for the assessment of steel frames in fire." Journal of Constructional Steel Research, 47, 19-45.
Robertson J.C. (1999). Introduction to fire prevention. Prentice Hall Health, 1999.
Saab, H. A. (1990). "Non-linear finite element analysis o steel frames in fire conditions", PhD thesis, Department of Civil and Structural Engineering, University of Sheffield, UK.
SFPE. SFPE engineering guide to performance-based fire protection analysis and design of buildings, Society of Fire Protection Engineers (SFPE) and National Fire Protection Association (NFPA), 2nd Ed. Quincy, MA, 2005.
SFPE. Guidelines for Designing Fire Safety in Very Tall Build-

ings, Public Review Draft, Society of Fire Protection Engineers (SFPE), 2012.

SFPE. SFPE Handbook of Fire Protection Engineering, 3nd edition, SFPE and NFPA, Quincy, MA, 2002.

Song, L. (1998). "Integrated analysis of steel buildings under fire and explosion", PhD thesis, Department of Civil Engineering, Imperial College, London.

Spinardi, G., Bisby, L., and Torero, J. (2017). "A review of sociological issues in fire safety regulation." Fire Technology, 53, 1011-1037.

Stollard, P. and Abrahams, J. (1999). Fire from first principles: A design guide to building fire safety, 3rd Ed. E & FN Spon, London, 1999.

Sun, R.R., Huang, Z.H., and Burgess, I. (2012). "The collapse behaviour of braced steel frames exposed to fire." Journal of Constructional Steel Research, 72, 130-142.

Sun, J.H., Hu, L.H., and Zhang, Y. (2013). "A review on research of fire dynamics in high-rise buildings." Theoretical & Applied Mechanics Letters, 3, 042001.

Sun, X.Q. and Luo, M.C. (2014). "Fire risk assessment for super high-rise buildings." Procedia Engineering, 71, 492-501.

UL 263. Standard for Fire Tests of Building Construction and Materials, Underwriters Laboratory (UL), 2003.

Usmani, A.S., Chung, Y.C., and Torero, J.L. (2003). "How did the WTC towers collapse: a new theory." Fire Safety Journal, 38, 501-533.

Usmani, A.S. (2005). "Stability of the World Trade Center twin towers structural frame in multiple floor fires." Journal of Engineering Mechanics, 131(6), 654-657.

Wang, Y.C. (2002). Steel and Composite Structures - Behaviour and Design for Fire Safety. Spon Press, London.

Wang, Y.C., Burgess, I., Wald, F. and Gillie, M. (2013). Performance-based Fire Engineering of Structures. CRC Press.

Wikipedia. https://en.wikipedia.org/wiki/Fire_protection_engineering

Watts, J. (1979) "A theoretical rationalization of goal-oriented systems approach to building fire safety." NBS-GCR-79-163, Washington, DC: National Bureau of Standards.

Woodrow, M., Bisby, L., and Torero, J.L. (2013). "A nascent educational framework for fire safety engineering." Fire Safety Journal, 58, 180-194.

Xu, Q., Li, G.Q., Jiang, J., and Wang, Y.C. (2018). "Experimental study of the influence of topcoat on insulation performance of intumescent coatings for steel structures." Fire Safety Journal, 101, 25-38.

Zhang, C., Silva, J.G., Weinschenk, C., Kamikawa, D., Hasemi, Y. (2016). "Simulation methodology for coupled fire-structure analysis: modeling localized fire tests on a steel column." Fire Technology, 52, 239-262.

Zhang, C. and Li, G.Q. (2012). "Fire dynamic simulation on thermal actions in localized fires in large enclosure." Advanced Steel Construction, 8, 124-136.

Zhang, C., Gross, J.L., and McAllister, T.P. (2013). "Lateral torsional buckling of steel W-beams subjected to localized fires", Journal of Constructional Steel Research, 88, 330-338.

Zhang, C., Gross, J.L., McAllister, T.P., and Li, G.Q. (2015). "Behavior of unrestrained and restrained bare steel columns subjected to localized fire", Journal of Structural Engineering-ASCE., 141(10), DOI:10.1061/(ASCE)ST.1943-541X.0001225

Zhang, C., and Usmani, A. (2015). "Heat transfer principles in thermal calculation of structures in fire". Fire Safety Journal, 78, 85-95.

Zhang, Y., Wang, Y.C., Bailey, C.G., Taylor, A.P. (2012). "Global modelling of fire protection performance of intumescent coating under different cone calorimeter heating conditions." Fire Safety Journal, 50, 51-62.

Appendix A

Table A1. List of key fire events in high-rise buildings (Cowlard et al., 2013)

Year	Building	Structural type	Total story/ Height	Fire source Location (floor)	Fire duration (h)	Damage	Fatalities
1946	Winecoff Hotel, Atlanta, USA	Commercial, steel framed	15F	3	-	-	119
1970	One New York Plaza, New York	Office	50F/ 195m	33	6	-	2
1975	WTC 1, New York	Office, steel framed-tube	110F/ 412m	11	3	Six floors in fire but no collapse	-
1980	MGM Grand Hotel, Las Vegas	Commercial	26F	3	-	Most fatalities were due to smoke inhalation	85
1987	Schomburg Plaza, New York	Apartment	35F	27	-	-	7
1988	First Interstate Bank Building, USA	Commercial, steel framed	62F/ 262m	12	4	5 floors in fire	1
1991	One Meridian Plaza, USA	Office, steel framed	38F/ 150m	22	19	8 floors in fire	3
2001	WTC 1, New York	Office, steel framed-tube system	110F/ 417m	94-98	1.5	Globally collapsed after 102 mins	
2001	WTC 2, New York	Office, steel framed-tube system	110F/ 415m	78-84	1	Globally collapsed after 56 mins	>3000
2001	WTC7, New York	Office, steel framed-tube system	47F/ 190m	7-17	7	10 floors in fire, globally collapsed after 7 hours	
2003	Cook County Administration Building, Chicago, USA	Office, reinforced concrete	35F	12	1	Fatal smoke inhalation as the fire source was adjacent to stairwell	6
2004	Caracas Tower, Venezuela	Office	56F/ 220m	34	17	26 floors in fire and two floors collapsed	-
2005	Windsor Tower, Spain	Commercial, reinforced concrete core with perimeter steel frames	32F/ 106m	21	18	All floors above the fire source were on fire in one hour. Partially collapsed (above the 17^{th} floor) after 5 hours.	-
2008	Faculty of Architecture Building, Delft Univ. of Technology, Netherlands	Office, reinforced concrete	13F	6	8	A major portion of the building collapsed after 8 hours	-
2009	Lakanal house fire in Camberwell, London	Apartment, reinforced concrete	14F/ 42m	9	1	Fire spread fast across exterior cladding, but no collapse	6
2009	CCTV Tower, Beijing, China	Commercial, reinforced concrete	34F/ 159m	Top	6	The whole building was in fire, but no collapse	1
2010	Apartment block, shanghai, China	Apartment, reinforced concrete	28F/ 85m	10	19	The whole building was in fire	58
2010	Apartment building, Busan, Korea	Residential, reinforced concrete	38F	4	2.5	Fire spread across 33 floors in 20 minutes	-
2013	Grozny-City Towers, Russia	Commercial, reinforced concrete	40F/ 150m	4	8	Fire enveloped the building in 2 hours, but no collapse	-
2015	Torch Tower, Dubai	Commercial	63/ 300m	20	-	No collapse	-
2017	Grenfell Tower, London	Residential, reinforced concrete	24F/ 69m	4	60	The whole building was in fire in 15 mins	72
2018	Trump Tower, Azerbaijan	Commercial	33F	Top	-	20 floors were in fire	-
2018	Edificio Wilton Paes de Almeida, Brazil	Residential, steel framed	24F/85m	5	1.5	Globally collapsed	7

Table A2. List of key fire events in high-rise buildings

						
First Interstate Bank Building, USA, 1988	One Meridian Plaza, USA, 1991	WTC 7, USA, 2001	Caracas Tower, Venezuela, 2004	Windsor Tower, Spain, 2005	Faculty of Architecture Building at Delft Univ. of Technology, Netherlands, 2008	
						
CCTV Tower, China, 2009		Apartment building, China, 2010	Grozny-City Towers, Russia, 2013	Torch Tower, Dubai, 2015	Grenfell Tower, London, 2017	Edificio Wilton Paes de Almeida, Brazil, 2018

Appendix B

The following list of journals, conferences, universities, organizations, may provide a useful resource for fire engineering professionals.

Journals:
- Case Studies in Fire Safety (Elsevier)
- Combustion and Flame (Elsevier)
- Combustion Science and Technology (Taylor & Francis)
- Combustion Theory and Modelling (Taylor & Francis)
- Fire and Materials (John Wiley & Sons)
- Fire Research (PAGEPress)
- Fire Safety Journal (Elsevier)
- Fire Science Reviews (Springer)
- Fire Technology (Springer)
- Fire Protection Engineering Magazine (SFPE)
- International Journal for Fire Science and Technology
- International Journal on Performance Based Fire Codes
- Journal of Applied Fire Science (SJR)
- Journal of Fire Sciences (SAGE)
- Journal of Structural Fire Engineering (Emerald Insight)
- NFPA Journal (NFPA)
- Proceedings of the Combustion Institute (Elsevier)

Conferences:
- Asia-Oceania Symposium on Fire Science and Technology (AOSFST)
- European Symposium on Fire Safety Science (ESFSS)
- International Conference on Applications of Structural Fire Engineering (ASFE)
- International Conference and Exhibition on Fire Science and Engineering (Interflam)
- International Conferences on Fire Research and Engineering (ICFRE)
- International Conferences on Performance Based Design and Fire Safety Design Methods (SFPE)
- International Conference on Protection of Structures against Hazards (PSH)
- International Conference on Structures in Fire (SiF)
- International Conference on Structural Safety under Fire and Blast (CONFAB)
- International Symposium on Fire Safety Science (IAFSS)
- International Symposium on Combustion
- International Symposium on Human Behaviour in Fires
- International Tall Building Fire Safety Conference
- Performance, Protection & Strengthening of Structures under Extreme Loads (PROTECT)
- SFPE Europe Fire Safety Engineering Conference & Expo

Universities & Institutes:
- University of Maryland, USA
- Oklahoma State University, USA
- University of New Haven, USA
- Michigan State University, USA
- Worcester Polytechnic Institute, USA
- National Institute of Science and Technology (NIST), USA
- Carleton University, Canada
- University of New Brunswick, Canada
- National Research Council (NRC), Canada
- University of Edinburgh, UK

- University of Greenwich, UK
- University of Leeds, UK
- University of Ulster, UK
- University of Manchester, UK
- University of Sheffield, UK
- Building Research Establishment (BRE), UK
- University of Liege, Belgium
- Queensland University of Technology, Australia
- University of Technology, Australia
- University of Western Sydney, Australia
- Victoria University of Technology, Australia
- University of Canterbury, New Zealand
- Building Research Association of New Zealand (BRANZ), New Zealand
- Lund University, Sweden
- University of Science and Technology of China, China
- Tongji University, China
- China Academy of Building Research, China
- Nanyang Technological University, Singapore
- Science University of Tokyo, Japan

Organizations:

- ABCB, Australian Building Codes Board, Australia
- ANSI, American National Standards Institute, USA
- ASCE, American Society of Civil Engineers, USA
- ASTM, American Society for Testing and Material, USA
- CEN. European Committee for Standardization, Europe
- China Fire Protection Association, China
- CIB, International Council for Building Research Studies and Documentation, Netherlands
- CTICM, France
- Fire Department of Ministry of Public Security, China
- FEMA, Federal Emergency Management Agency, USA
- FPAA, The Fire Protection Association of Australia, Australia
- IAFSS, International Association for Fire Safety Science, UK
- ICC, International Code Council, USA
- IFE, Institution of Fire Engineers, Engineering Council Division, UK
- ISO, The International Standards Organization, Switzerland
- IOSH, Institution of Occupational Safety and Health, USA
- National Institute for Fire and Disaster, Japan
- NFPA, National Fire Protection Association, USA
- NRCC, National Research Council of Canada, Canada
- SFPE, Society of Fire Protection Engineers, US