Fire Events

Building Design for Extreme Events

By Matthew A. Johann, MSc and Brian J. Meacham Ph.D., P.E.

Modern building fire protection can trace its roots back to the protection of urban buildings against conflagration. Through the 20th century, building design for fire protection was focused on protecting against limited or confined fires within single buildings, with unconfined fires considered only in rare instances, such as following earthquakes. However, September 11, 2001 demonstrated the severe hazard associated with more severe fire events, such as unconfined fires within buildings.

The June 2006 issue of STRUCTURE® magazine presented an introduction to building design for extreme events. This article is the first in a series of follow-up articles designed to provide greater detail regarding design theories and techniques for protection of buildings against specific extreme event threats.

Fire as Extreme Events

Fire as an extreme event is not a recent concept, and while it is often discussed in reference to the events of September 11, 2001, there are many more examples. The fires following the 1906 San Francisco and 1995 Kobe earthquakes were extreme fire events, as the fire spread uncontrolled over large areas. The fires in the Meridian Plaza (1991) and Windsor Building (2005) were extreme events, as the fire spread through many floors without being controlled. The fires in the Cocoanut Grove nightclub (1942), the Beverly Hill Supper Club (1977), and The Station nightclub (2003) were extreme events, as the fires developed too quickly to allow safe evacuation of patrons. Fire becomes an extreme event when it grows beyond the expected or the tolerable level of impact (*see sidebar below for more examples*).

Just as extreme fire events are not new, concepts for protection against extreme fire events have been with us for many years. In many ways, current building codes have been designed in response to past extreme fires (*see sidebar*). Code-mandated provisions are sometimes sufficient to protect a building and its occupants from extreme event fires; in other cases, additional mitigation measures may be required. This article discusses the fundamental approach to fire protection design, with a focus on the current approach to structural fire protection design, highlighting how the designer may need to think differently when considering an extreme fire event.

continued on next page

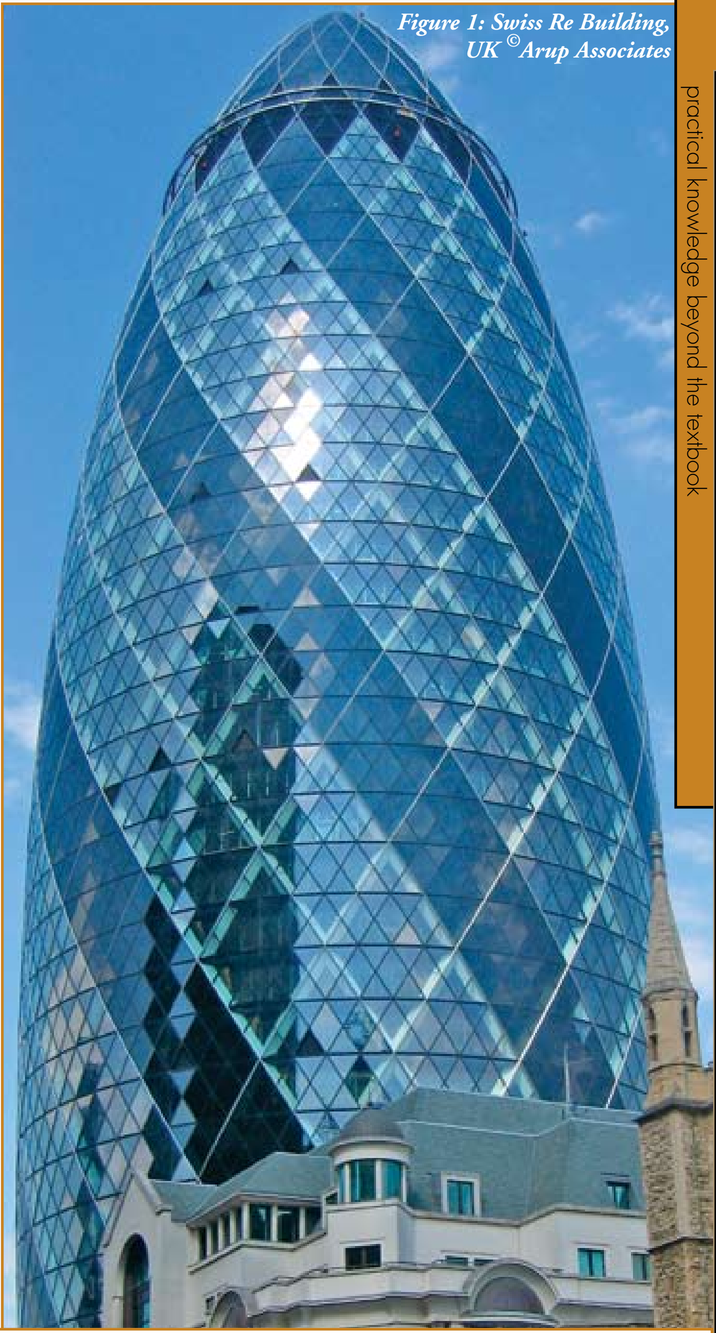

Figure 1: Swiss Re Building, UK ©Arup Associates

Numerous significant fires have helped shape today's building codes and fire protection practices, and provide insight regarding the protection of buildings from extreme fires. An obvious example of this is the attack on the World Trade Center in NY on September 11, 2001, for which numerous studies have been carried out. A sampling of additional past significant fires, and their impacts on the industry, are described below.

- Urban conflagrations in multiple American cities in the late 19th Century and early 20th Century brought about the initial development of building and fire codes, led to the introduction of fire sprinkler systems, and spurred the widespread construction of 'fireproof' buildings.
- The tragic fire at the Beverly Hills Supper Club in Southgate, Kentucky, in 1977 demonstrated the importance of suppression systems and compartmentation in separating occupants from a fire for sufficient time to allow for evacuation. It also inspired code provisions for egress and fire alarm systems in assembly occupancies, and limitations to interior finish combustibility.
- A fire that started in the casino area of the MGM Grand in Las Vegas on November 22, 1980 had a tragic outcome largely because the area where the fire ignited was not equipped with sprinklers. Also, smoke spread throughout the hotel portions of the building through improperly protected vertical openings and via the HVAC system. A sprinkler system in an area adjacent to the casino aided in stopping the fire. This fire led to additional code requirements for sprinklers and alarm systems.
- The Windsor Building was one of the tallest buildings in Madrid, Spain, and was undergoing renovations in 2005. At about 11:00 PM on February 12, 2005, a fire ignited on the 21st floor of the building. The fire spread rapidly to most of the floors above the floor of origin and prevented interior suppression efforts. Large pieces of the facade were dislodged, and in some places they impacted the perimeter bay of the reinforced concrete floor slabs as they fell. The fire eventually also spread downwards from the floor of origin, and caused the collapse of floor slabs in numerous areas. Studies carried out since the fire have looked at the impact of the entirety of multiple floors burning concurrently on the structure.▪

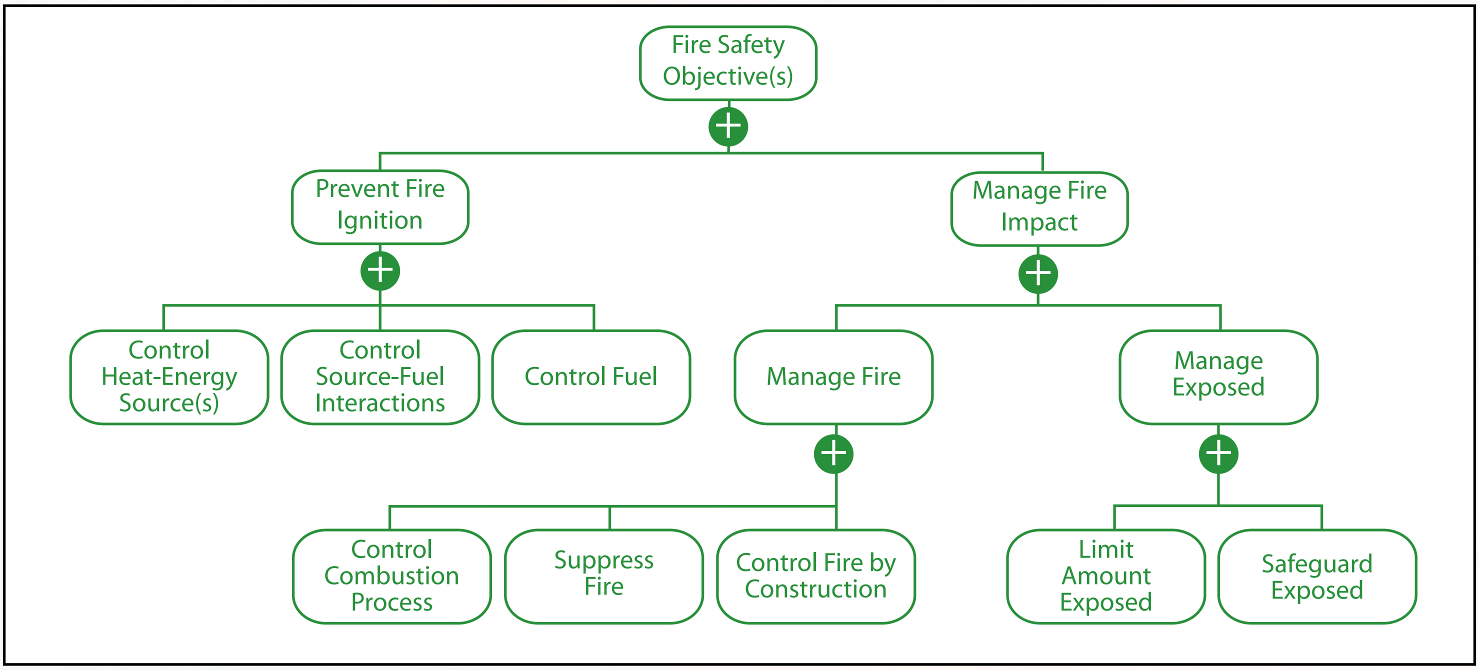

Figure 2: Main Branch of the Fire Safety Concepts Tree

Design Approach: The Fire Safety Concepts Tree

There are two fundamental approaches to fire protection design: prevent ignition or manage the fire impact. This has been memorialized in the Fire Safety Concepts Tree, published by the National Fire Protection Association (NFPA). *Figure 2* shows the main branch of the Tree.

Application of the Fire Safety Concepts Tree helps provide strategies for protecting a building and its occupants from a fire, regardless of its severity.

Preventing Ignition

Prevention of ignition can be achieved in numerous ways. These include the separation of fuels from ignition sources, proper housekeeping policies, employee training programs, and equipment maintenance. In most cases, the building designer has little control over the implementation of these strategies. However, depending on the types of events that are deemed credible by a risk-based analysis, consideration can be given as to what ignition sources may be present or introduced and the impact these may have on the building. Appropriate selection and placement of contents to limit ignition during or following an extreme event can help isolate potential ignition sources from combustible materials.

Extreme events introduce the possibility that the ignition source and part of the fuel load is not yet located within the building. This can be extremely challenging to design for, for a variety of reasons.

Managing Fire Impact

Numerous means are available to manage the impact of a fire. The challenge that is faced by the designer is the appropriate selection and implementation of protection measures for a given building. These measures include, but are not limited to:

- Selection and placement of contents
- Selection of interior finish and construction materials
- Limiting or controlling fuel loads
- Controlling geometry and ventilation details of compartments
- Providing means to detect a fire and notify occupants
- Designing appropriate and effective egress systems
- Suppressing a fire
- Exhausting smoke and heat
- Providing inherent fire resistance in the structure
- Protecting a structure where needed
- Providing features to aid emergency responders in their operations

Extreme events place significant additional demands on the systems designed to limit the impact of a fire in a building. Also, they can damage these systems before they have any chance to do their jobs. Scenarios can include arson, blasts, and impacts by vehicles, planes, missiles, among others. Arson-related fires and impacts by vehicles holding liquid fuels may introduce accelerants that serve as substantial sources of fire spread. These can simultaneously ignite large amounts of fuel and thus can produce large fires that greatly challenge the building's design. Depending on the types of extreme events deemed credible for a given building, the potential impact on enhancing fire development and spread and on compromising the building's protection systems should be assessed.

Structural Fire Protection

In order to allow occupants to safely evacuate and emergency responders to extinguish a fire, a structure must remain intact and upright for a minimum duration. Prevention of disproportionate and local structural collapse limits adverse impacts on adjacent portions of a structure or other structures in the area. Structural protection can also help to achieve fire and life-safety goals and objectives by meeting established performance criteria. Such performance criteria may include:

- Limit structural element damage
- Prevent local collapse
- Prevent or limit deformation (bending, expansion, etc.) of structural elements
- Prevent progressive collapse
- Prevent disproportionate collapse

Building codes typically require that structural elements withstand fire exposures for specified durations. Elements are assigned fire ratings based upon their theoretical ability to withstand fire exposures. The ratings required for different elements within a building depend on the size of the building and its occupancy type. Fire ratings are based upon member and assembly performance in standardized tests, which assess a structural element's response to a standard time-temperature heat exposure curve in a furnace.

Few buildings mimic the standardized test furnace, and even fewer fires follow the standard fire curve used in these tests. Thus, structural assemblies, including their individual members and any fireproofing materials, may not respond as predicted by small-scale tests in a real building fire. Real buildings include complex geometries, unusual connections, or varied fire exposures (due to fuel loads, fire locations, barriers, and so forth), and all of these factors can lead to varied structural performance. Also, small-scale tests ignore interactions with other structural elements within a building, and thus load paths and load redistribution are neglected.

Detailed analyses of proposed structural systems can provide a more accurate assessment of a structure's ability to maintain its integrity during a fire by specifically considering in-place conditions and design fires that may differ from those in standardized tests, particularly in terms of growth rate and duration.

Design Fires

An in-depth structural analysis is only as valid as the parameters that are input. For structural fire engineering, the design fire is perhaps the most critical input. Just as a standardized test may not represent an actual fire in a building and can thus lead to misleading fire performance results, an improperly chosen design fire can imply that a structure will perform in a way that it will in fact not. It is critical that the range of possible fire growth rates, peak heat-release rates, and durations is assessed, as well as the potential locations of the structural elements in relation to different fires. Building geometry and compartmentation must be considered, since they can affect such details as peak compartment temperatures and heat exposure to structural elements (i.e. direct flame impingement vs. radiant exposure).

Additionally, the fire may be affected by suppression systems, smoke management systems, ventilation systems, etc, and thus these also have an indirect effect on the performance of a structure. These systems should also be considered when assessing the performance of the structural elements, and the type and degree of structural fire protection needed.

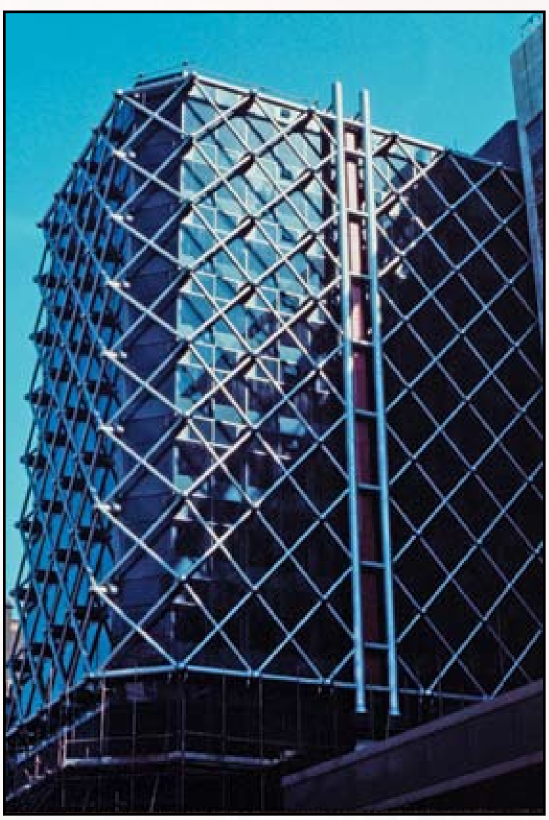

Figure 3: Bush Lane House, UK, with Water-Cooled Hollow Steel Structural Members © Arup Associates

Increasing Fire Resistance

Assemblies that do not have sufficient inherent fire resistance can be protected in order to limit the transfer of heat to structural elements. Fire proofing is available in multiple forms:

- Direct application (spray on),
- Filling (i.e., concrete, water, etc.)
- Membrane protection (i.e., gypsum board, etc.)
- Intumescent paints
- Water spray
- Radiation blocking

Structural elements can also be specifically designed to withstand fires of varying severity, for example, by increasing their size, providing redundancy, and locating them away from fuel loads.

Underwriters Laboratories (UL) produces directories of various fireproofing methods and their associated fire ratings. Recent advancements have also been made using fire-resistant steel that may have advantages in certain instances.

Other Design Considerations

Fire-induced changes to structural elements can sometimes impact other building systems, such as sprinkler piping and smoke management ductwork, and these should be considered during the design process. The response of a structure to elevated temperatures in a fire may include transfer of loads between elements, composite action of floor slabs/frames, and greater than normal loads or moments on connections. Left unchecked, such conditions can lead to progressive collapse and/or disproportionate collapse, and thus should be considered in the design.

Structural Fire Engineering for Extreme Event Fires

While the considerations discussed above apply to the case of extreme events, there is one major difference when designing for extreme event fires: the design fire. While typical structural fire engineering generally looks at individual fuel packages, or combinations of fuel packages that are located near each other, an extreme event may include, for example, full burnout of a large compartment, or even an entire floor of an office building, or the loss of suppression systems. This can mean that structural members are exposed to intense heating, or that large structural assemblies are exposed to high temperatures across their entire span. Also, extreme event fires are often after effects of other extreme events, such as blasts or impacts, that themselves can negatively affect a structure. Given these possibilities, a robust design is necessary.

Building design for extreme events is centered around three key principles: redundancy, reliability, and tenability. The most important of these tools in structural design for extreme fire events is redundancy, because it can help provide reliability and tenability for other systems.

Redundancy is not a new concept in the fire protection community. For example, building codes generally require a minimum of two remote exits from a space with a certain number of occupants, even if one will suffice to allow those occupants to leave the space in a timely manner. Two separate exits help ensure that an exit will be available, even if one is blocked by fire. Structural redundancy (for normal, non-fire conditions) is frequently employed to mitigate the potentially disastrous consequences of a structural failure.

For an extreme fire event, redundancy can mean the combination of various protective measures. Fire detection and suppression systems, in addition to some level of structural fire resistance, can pro-

Figure 4: Fire Test of Roof Trusses for the HACTL Super Terminal 1, Chek Lap Kok Airport Hong Kong © Arup Associates

vide a recognized level of protection through a combination of early detection, rapid suppression, and, as a last resort, inherent protection against failure. Redundancy within or amongst these systems is currently not always required by codes and design practices, and where provided, may not be well understood or quantified. Proper implementation of this type of redundancy, both within individual systems and across systems that work together, should be based upon analysis that considers the failure of part or all of each system and looks at the subsequent change in overall performance.

Inherent structural fire resistance, in normal (i.e. non-extreme) fire conditions, is generally the last line of defense in a fire. Early detection and rapid suppression are preferred means of control and help minimize threats to occupants and property. However, if left uncontrolled, even a small fire can grow to an extreme event under the right conditions.

Even so, current codes allow a single sprinkler riser (or a combined sprinkler riser/standpipe) to supply a sprinkler system. This lack of redundancy can prove fatal to the sprinkler system if the single supply riser is compromised by the initiating event. As a result, the role of defense would fall to the structure and any fire barriers; thus, it is important to keep these intact for as long as possible. Consideration of sprinkler system redundancy during the design process could reduce the demand on the rated construction. A risk-informed approach can help determine appropriate systems and redundancies for a given building.

Summary

Extreme events can introduce unique and severe fire protection challenges into a building. Tools and approaches are available to deal with these challenges, but the onerous task faced by the designer is identifying the threats that must be designed for and combining the available tools in such a way as to appropriately protect the building and its occupants. As usual in building design, cost must be balanced with functionality and performance. A risk-based approach, centered on the assessment of threats, the development of appropriate design objectives, and the verification of achieved performance, can make this task less onerous and more successful.▪

*Matthew A. Johann, MSc, is a fire specialist with Arup in their Westborough, MA office. He is also a Certified Fire and Explosion Investigator. Matt can be reached via email at **matt.johann@arup.com**.*

*Brian J. Meacham, Ph.D., P.E., is a Principal with Arup in their Westborough, MA office. He is the Business Leader of Arup's global Risk Consultancy. Brian can be reached via email at **brian.meacham@arup.com**.*

For more details on extreme fire events and in-depth descriptions of the approaches described here, see Chapter 11 of the book *Extreme Event Mitigation in Buildings – Analysis and Design*, from which this article is derived.

References

1. Marrion, C. and Custer, R. (2006). "Design to Manage Fire and Its Impact," Chapter 11 in Meacham, B.J. and Johann, M.J., eds. *Extreme Event Mitigation in Buildings: Analysis and Design*. Quincy, MA: National Fire Protection Association, 2006.
2. NFPA 550: *Fire Safety Concepts Tree*, 2002 Edition. Quincy, MA: National Fire Protection Association, 2002.
3. Marrion, C., et al. *Fire Safety Protection of Structural Steel in High-Rise Buildings Materials*. Reston, VA: Civil Engineering and Research Foundation, 2004.
4. NFPA 5000: *Building Construction and Safety Code*, 2006 Edition. Quincy, MA: National Fire Protection Association, 2006.
5. Buchanan, A. H. *Structural Design for Fire Safety*. New York, NY: John Wiley & Sons, 2001.
6. *Fire Resistance Directory (Vol. 1)*. Underwriters Laboratories, Inc., 2003.
7. ThyssenKrup Steel (TKS). *Fire Resistant Structural Steel (FR 30)*. Duisberg, Germany: ThyssenKrup Steel, 2001.