The Interdisciplinary Nature of Structural Fire Protection

By James A. Milke, Ph.D., P.E.

Meeting fire resistance requirements is often the purview of architects. However, the performance of buildings on 9/11 has raised questions into the design basis and process for structural fire protection. Four buildings collapsed in Lower Manhattan, while other buildings suffered minor structural damage as a result of the fires, impact damage from aircraft or debris, or both. Those buildings that experienced total or partial collapse due solely or partially to fire effects have motivated questions about the required level of fire resistance, techniques to determine fire resistance and requirements for materials used in fire resistant assemblies [FEMA, 2002][NIST, 2005].

Performance Expectations

The performance of the buildings in the World Trade Center complex highlighted the fact that hourly fire resistance ratings do not relate to how long an assembly can continue to perform successfully while being exposed to a fire. The fire resistance ratings are comparative in nature, i.e. a "2-hour" fire resistant assembly performs better in the standard test than a "1-hour" fire resistant assembly. While this is clearly stipulated in the ASTM E119 test standard, this issue seems to be misunderstood or perhaps just forgotten at times [ASTM E119, 2005].

Another key issue resulting from the studies of building performance on 9/11 was the need to define adequate performance. In 1942, the authors of the BMS 92 report from the National Bureau of Standards (NBS, now NIST), provided the following comment to describe the technical basis for fire resistance requirements [NBS, 1942].

> *The Subcommittee believes that the idea of designing some buildings for the full fire severity corresponding to the occupancy… is a logical advance in fire protection engineering.*

The early U.S. building code requirements for fire resistance estimated the fire severity (where fire severity was expressed in terms of the fire duration) following Ingberg's hypothesized relationship between the occupancy of the building (as a surrogate for fuel load) and compartment size. The fire resistance requirements in current U.S. building codes still appear to follow this concept in principle. However, reductions in fire resistance requirements in fully-sprinklered buildings brings into question whether buildings will be able to respond adequately in those rare cases when sprinklers fail to control the fire.

Many recent high-rise building fires, including those at One Meridian Plaza and the First Interstate Bank Building, included virtual complete burn-out of the fuel from some floors without causing any collapse of the structure. In contrast, WTC7 collapsed late in the afternoon on 9-11 due to a fire that had burned for 7 to 8 hours that day, with the sprinkler system disabled. Prior to collapse, the building was completely evacuated. No life loss is known to have occurred in the vicinity as a result of the collapse. Another case from 9-11 includes WTC5 which was also fully evacuated, sprinklers were ineffective due to the loss of water supply and with the fuel load virtually completely consumed. Here, there was a local collapse of approximately four bays for four floor levels which was arrested (see Figure 1). As such, should the collapses of either WTC 5 or WTC 7 be considered "failures"?

Sprinklers were not present in the First Interstate Bank Building. In One Meridian Plaza, the building was being retrofitted with sprinklers. After 19 hours, the fire spread to a floor that had been equipped with sprinklers, were 10 sprinklers operated to control the fire.

Figure 1: Partial Collapse of WTC 5 [FEMA, 2002]

The fire at WTC7 is another indication of the fire resistance ratings not indicating the length of time that a building assembly will continue to perform successfully. The fire resistance ratings for this building were in the range of 2 to 3 hours.

The definition of "failure" depends on the expectations for the building. Performance is not explicitly defined for buildings which are designed to satisfy prescriptive codes. However, buildings designed following a performance-based approach do require a statement of performance expectations.

Prescriptive Design of Fire Resistance

Structural fire protection designs are designed in a large majority of buildings following prescriptive methods. This generally involves referencing a listed design based on results from conducting standard tests. With this approach, structural or fire protection engineers need to review whether the referenced design is applicable for the proposed design, relative to minimum size of steel members, type of concrete, etc. ASCE/SFPE 29 can be referenced in some cases to assess the effect of modifications to listed designs or where steel sizes do not comply with the minimum specified [1999].

Also, an important function for structural engineers is the determination of whether a floor-ceiling or roof-ceiling system is "restrained". Guidance for determining restraint based on the characteristics of the structural frame is included in the appendix of ASTM E119 [2005]. If the stiffness of the frame needs to be calculated (and compared to that of the test furnace), guidance for this calculation is included in AISC Guide 19 [2003].

Performance-Based Design

Performance-based design (PBD) is promoted for many fire protection systems, including structural fire protection. As part of any PBD, the criteria and input for the supporting analysis need to be identified. What pass/fail criteria should be established for structural fire protection? Are traditionally accepted temperature criteria acceptable? Similarly, what load levels and properties should be assumed for the calculations? Do load levels and properties for ambient temperature design have any relevance?

There are no consensus adopted answers to these questions for all structures. In order to address these questions, the definition of "fire resistance" included in ASTM E176 [2005] is useful to appreciate the two possible aspects of a fire resistant assembly:

- Wall and floor assemblies serve as barriers to prevent the spread of fire, contributing to a strategy of compartmentation. In such cases, the barrier needs to be a sufficient insulator so as to limit temperature rise on the surface of the unexposed side of the barrier. In addition, the barrier needs to resist the passage of flame, i.e. maintain its integrity to resist the development of holes or cracks in the barrier that are large enough to permit flame to project through the barrier.
- Load-bearing assemblies need to maintain their structural integrity, supporting the weight of the structure and its contents. Thus, the load-carrying ability of the structural element needs to be preserved, despite changes in mechanical properties that occur as a result of an increase in temperature of the structural element and the imposition of thermal strain.

Compartmentation is a strategy utilizing physical barriers to restrict fire spread from one building space to another, thereby dividing the building into numerous compartments. The origin of the strategy is often attributed to measures taken following the Great Fire of London in 1666.

With these statements, PBD should include three analyses:

- Description of the fire exposure, based on an analysis of fuel load and ventilation, is provided to define the boundary conditions for the heat transfer analysis.
- A heat transfer analysis is conducted to determine the temperature distribution in the structural assembly as a result of the fire exposure. This temperature distribution is needed to determine thermal strains and evaluate mechanical properties (which are temperature-dependent).
- A structural analysis of a fire-exposed structural assembly accounts for load levels, thermal strains, and material property changes to determine the load-carrying capability of the structural assembly or deflections.

The first two parts of the analysis is best done by fire protection engineers, given their familiarity with fire behavior and heat transfer. Structural engineers have the expertise to conduct the structural analysis.

Questions on parameters for this analysis revolve around load levels and whether to account for the performance of automatic sprinkler systems. AISC [2005] suggests that the factored loads for the structural analysis should be:

$L_f = D + cL + T + .2S$

Where L_f is the load for fire calculations, D is the dead load and L is the live load, T incorporates the forces and deformations that result from temperature effects and support conditions, S is the snow load. AISC [2005] suggests that the constant, c, should be 0.5, Buchanan [2001] presents a similar equation and suggests a value of 0.6 for c. The suggested values of the constant are appreciably less than that used for ambient temperature design. Half of the live load is approximately the average of the live load experienced over time. The average, rather than the maximum, expected live load is appropriate for structural fire protection given the low probability of a coincident maximum transient live load and a serious fire. Ellingwood and Corotis [1991] estimate that a load equal to the sum, D + 0.5L, is only exceeded 10% of the time. Given that a fire is already a rare event, the likelihood of a serious fire occurring at the same time as an abnormal live load is considered very small.

Whether the benefits of sprinkler operation should be considered is an issue of significant debate. Current building code requirements permit the required fire resistance ratings to be reduced in fully-sprinkler protected buildings. However, as a result of 9/11 where the sprinklers were disabled due to disrupted water supplies in and around the World Trade Center complex, the appropriateness of the reduction in sprinklered buildings is being debated. The AISC specification suggests that active fire protection systems may be considered and references the European approach of reducing the fuel load by 60% in its commentary [AISC, 2005][ECCS, 2001].

Summary

Structural fire protection is inherently inter-disciplinary, especially where PBD is applied, given the trio of analyses that need to be performed. Both structural and fire protection engineers have important roles to play in the provision of a level of fire resistance which meets the expectations of the stakeholders in the design, including the building owner, fire department, and public.▪

James A. Milke, Ph.D., P.E. is an Associate Professor and Associate Chair of the Department of Fire Protection Engineering at the University of Maryland.

References

AISC, 2005, "Specification for Steel Structural Buildings," Chicago, IL, American Institute of Steel Construction.

AISC, 2003, J.L. Ruddy, J.P. Marlo, S.A. Ioannides, and F. Alfawakhiri, "Fire Resistance of Structural Steel Framing," Steel Design Guide 19, Chicago, IL, American Institute of Steel Construction.

ASCE/SFPE 1999, Standard Calculation Methods for Structural Fire Protection, ASCE/SFPE 29, Reston, VA, American Society of Civil Engineers.

ASTM E119, "Standard Test Methods for Fire Tests of Building Construction and Materials," West Conshohocken, PA, American Society of Testing and Materials.

ASTM E176, 2005, "Standard Terminology of Fire Standards," West Conshohocken, PA, American Society of Testing and Materials.

Buchanan, A., 2001, "Structural Design for Fire Safety," John Wiley, New York.

ECCS, 2001, Model Code of Fire Engineering, European Convention for Constructional Steelwork, Brussels.

Ellingwood, B.R. and Corotis, R.B., 1991, "Load Combinations for Buildings Exposed to Fires," Engineering J., 28, 1, 37-44.

FEMA, 2002, World Trade Center Building Performance Study, FEMA Report 403, Washington, DC, Federal Emergency Management Agency, May.

NBS, 1942, Fire-Resistance Classifications of Building Constructions, Report BMS 92, Building Materials and Structures, Washington, DC., National Bureau of Standards.

NIST, 2005, Final Report of the National Construction Safety Team on the Collapses of the World Trade Center Towers, NCSTAR 1, Gaithersburg, MD., National Institute of Standards and Technology.