Design for Fire Resistance

The 2005 specification contains a new appendix that provides guidelines governing structural design for fire conditions.

By Bruce R. Ellingwood

Structural engineers seldom have been responsible for fire protection of structural systems. This responsibility has typically rested with the project architect and, occasionally, a fire protection engineer. The 2005 AISC *Specification for Structural Steel Buildings* contains a new appendix—Appendix 4, Structural Design for Fire Conditions—that provides guidelines governing structural design for fire conditions. So why was this appendix added to the *Specification*?

Code requirements in the United States for fire protection traditionally have been based on component qualification testing and prescriptive design requirements and methods. The 2003 *International Building Code*, Sections 703 and 720, and the *National Fire Protection Association (NFPA) 5000: Building Construction and Safety Code*, Section 8.2.2, both are keyed to an hourly fire rating based on the ASTM E119 standard fire test, which has its antecedents in the early 20th century.

The ASTM E119 criteria are useful for product classification, for making comparisons of performance of structural components and other building products under standardized conditions, and for demonstrating code compliance. On the other hand, such prescriptive requirements and hourly ratings are not indicative of actual structural performance during a fire in modern steel building construction. They stipulate an unrealistic fire (one in which the fuel supply is inexhaustible during the rating period). They do not distinguish differences in compartment ventilation or composition and do not account for realistic structural loads, thermal effects, or conditions of structural restraint. Perhaps most importantly, they focus on fires that are localized in compartments and do not address the impact of the fire on the structural system as a whole. As a result, current fire protection practices may lead to inefficient or uneconomical solutions—modern structural systems generally perform better during severe fires than might otherwise have been anticipated from a standard fire test.

Recent advances in fire science and modern structural analysis have made it possible to consider realistic fire scenarios and fire effects on a building's structural system as a whole as part of the building design process. The worldwide move toward performance-based fire engineering (PBFE) is aimed at developing alternatives to traditional prescriptive fire protection methods. PBFE requires a systematic approach to identifying building performance objectives and quantitative structural analysis tools to verify that these objectives have been achieved. In the United States, performance-based engineering solutions for fire protection are permitted under the "alternate means and methods" provisions of building codes, but the lack of technical methods and data has inhibited PBFE for all but special buildings and other structures.

Appendix 4 provides a basis for PBFE but also contains a prescriptive alternative to permit the design objectives to be verified by the traditional rating and qualification testing process. The specification committee recognized that many structural engineers may be unwilling to assume responsibility for fire engineering as part of their professional design services. The enabling language for Appendix 4 is found in Section B3.10 of the *Specification*, where it is stated that:

1. Compliance with the fire protection requirements in the applicable building code shall be deemed to satisfy the requirements of Appendix 4, and
2. The provisions are not intended to create a contractual requirement for the engineer of record responsible for structural design. The responsibility for designing for fire conditions is a contractual matter that must be addressed on each project.

General Provisions

The general provisions contain a glossary of terms that may be unfamiliar to structural engineers, followed by statements of the performance objective, the two design approaches permitted—design by engineering analysis and design by fire testing—and load combinations and required strength.

The performance objective underlying Appendix 4 is that of life safety. Three limit states are envisioned for structural components that may also serve as fire barriers:

- heat transmission leading to unacceptable rise of temperature on the unexposed surface;
- breach of barrier due to cracking or loss of integrity; and
- loss of load-bearing capacity.

For structural components that do not have a separating function, only the load-bearing capacity limit state applies. Other performance objectives for a specific building project may be determined by the stakeholders within the general context above.

Appendix 4 permits two methods of design—design by engineering analysis or design by qualification testing. Compliance with the performance objectives can be demonstrated by either method. Design by qualification testing is the prescriptive method specified in most building codes.

For those who opt for design by engineering analysis, load combinations are required to determine the required strength under fire conditions. The load combination presented in the appendix as equation A-4-1,

$$(0.9 \text{ or } 1.2)D + T + 0.5L + 0.2S \qquad \text{(A-4-1)}$$

in which T equals structural action associated with the fully developed fire, reflects the fact that the occurrence of a severe fire is a low-probability event. This load combination also appears as equation C2.5-3 in Commentary C2.5 of ASCE Standard 7-05 on minimum design loads. This load combination represents a departure from ASTM E119, which requires that the full live load be imposed when qualifying a component for fire resistance.

Design by Engineering Analysis

Design by engineering analysis involves four steps:

1. Identifying a design-basis fire, expressed as a relation between compartment temperature and time, through an analysis of fuel and compartment characteristics and effects of any active fire protection systems present for the occupancy of interest;
2. Determining the temperatures in structural members, components, and systems through a heat transfer analysis;
3. Calculating the response of the structural system, taking into account the effect of elevated temperatures on strength and stiffness; and
4. Checking the structural response against the design strength, as specified in Section B3.3, and taking into account changes in material properties at the temperatures developed by the design-basis fire.

Two methods of structural analysis are permitted. The advanced method is required when the overall structural system response to fire, or residual strength following a fire, must be considered. Generally, this method would require a coupled thermal-structural analysis. The simple method can be used to evaluate the performance of individual members—tension members, compression members, flexural members, and composite floor members—when the member can be assumed to be subjected to uniform heat flux and to exhibit a uniform temperature distribution.

Design by Qualification Testing

The committee anticipated that in the majority of cases, structural engineering for fire conditions would continue the traditional practice of providing protection to achieve ratings for specific structural members and components and for specific building occupancies as stipulated in the governing building code. In recognition of this fact, a simple alternative was provided that allows the engineer to demonstrate compliance with ASTM Standard E119 using the procedures specified for steel construction in ASCE/SFPE Standard 29-99, AISC's *Steel Design Guide 19—Fire Resistance of Structural Steel Framing*, and similar documents. A clear distinction is drawn between restrained and unrestrained construction, where an improper selection of category can lead to uneconomical fire solutions for steel structures.

Commentary to Appendix 4

A detailed commentary to Appendix 4 explains the basis for the provisions in the *Specification*. Extensive literature on the performance of building structural systems exposed to severe fires has become available over the past two decades. The commentary includes a bibliography as a point of departure for further study.

Appendix 4 in the 2005 AISC specification is oriented toward performance-based fire engineering, as the committee believed that it was essential for the steel community to develop its own voluntary consensus standard on an issue so important to the health of the industry. On the other hand, the committee recognized that a large segment of the structural engineering profession is unfamiliar with structural design for fire conditions, views PBFE as in a state of flux, and is hesitant to undertake the additional responsibility (and liability) for providing structural engineering services for fire resistance. Accordingly, Appendix 4 also permits the use of traditional methods based on qualification testing to demonstrate compliance with performance objectives. The committee believes that while traditional fire protection methods have served the public well from a public safety standpoint, structural engineers should be provided the opportunity to add value to the building process through their professional services. ★

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