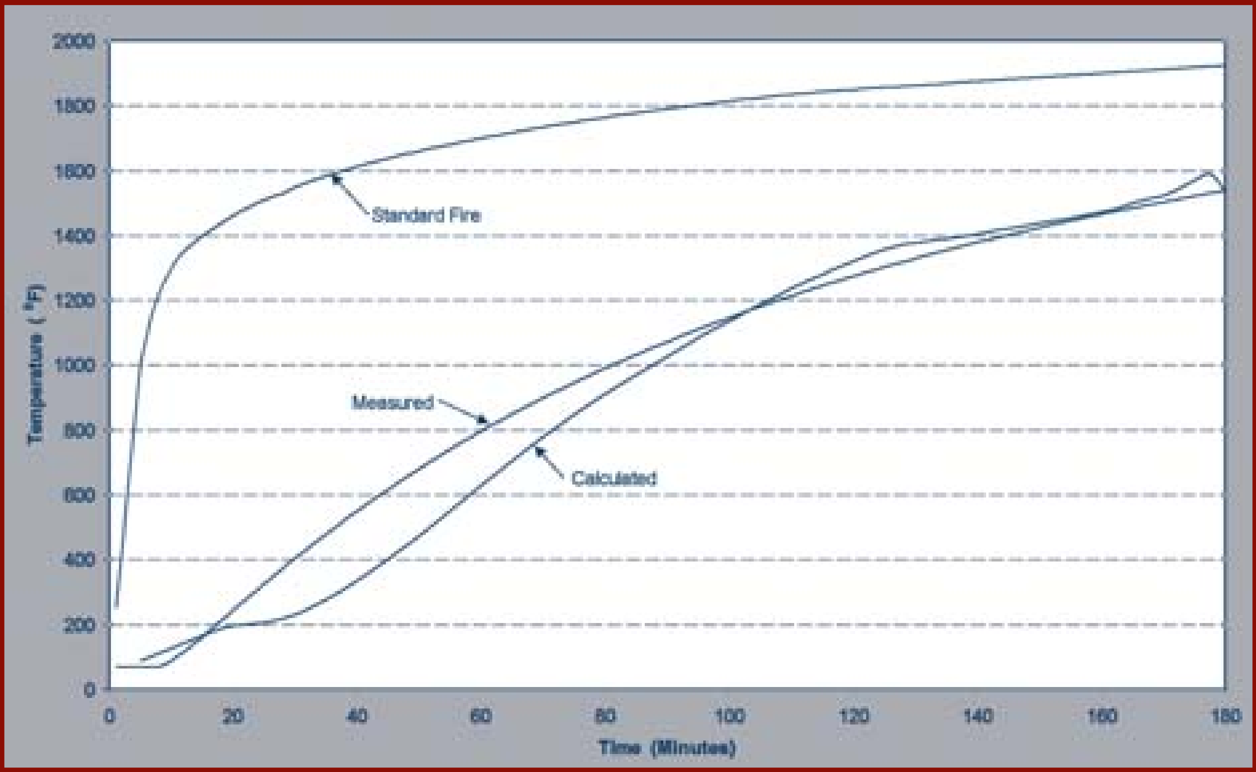
Steel Design Guide 19

# Fire Resistance of Structural Steel Framing



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Steel Design Guide

# Fire Resistance
## of Structural Steel Framing

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# Section I
# INTRODUCTION

## I.1 GENERAL INFORMATION

An important objective of building codes and regulations is to provide a fire-resistive built environment. Thus, building fire safety regulations contain numerous provisions including directives for the minimum number of exits, the maximum travel distances to exits, minimum exit widths, fire compartment requirements, fire detection and suppression mandates, and the protection of structural members in buildings. The focus of this design guide is the fire protection of structural steel framing systems. The guide is arranged such that important information for fire protection design, including that for building codes and test standards, is repeated within the design chapters to allow them to function as self-containing, stand-alone sections.

Although structural steel offers the advantage of being noncombustible, the effective yield strength and modulus of elasticity reduce at elevated temperatures. The yield strength of structural steel maintains at least 85 percent of its normal value up to temperatures of approximately 800 °F (427 °C). The strength continues to diminish as temperatures increase and at temperatures in the range of 1,300 °F (704 °C), the yield strength may be only 20 percent of the maximum value[1]. The modulus of elasticity also diminishes at elevated temperatures. Thus, both strength and stiffness decrease with increases in temperature

Measures can be taken to minimize or eliminate adverse effects. An obvious approach is to eliminate the heat source by extinguishing the fire or by generating an alert so that an extinguishing action can be initiated. Extinguishing systems such as sprinklers and smoke and heat detection devices are responses to this approach, and are classified as active fire protection systems.

Another approach to improving the fire safety of a steel structure is to delay the rate of temperature increase to the steel to provide time for evacuation of the environment, to allow combustibles to be exhausted without structural consequence, and/or to increase the time for extinguishing the fire. This approach, which involves insulating the steel or providing a heat sink, is classified as a passive fire protection system. Figure I.1 is a photograph of a steel beam employing such a system using Spray-Applied Fire Resistive Material (SFRM). This design guide concentrates on the passive fire protection of structural steel framing.

The typical approach to satisfying the passive protection system objective is prescriptive. Buildings are classified according to use and occupancy by the building code. For each occupancy classification there are height and area limitations that are dependent upon the level of fire resistance provided. For instance, a building providing for business uses may have a height and floor area requiring building elements to be noncombustible and have a fire resistance rating of 2 hours. Then a tested floor assembly that provides a 2-hour fire resistance rating is identified and, as necessary, adjustments to the specifics of the tested assembly are made to match the actual construction. Thus, the required level of fire resistance is provided based on tests and extrapolation of test results. The process for identifying the appropriate tested assembly and making necessary adjustments is clarified within this design guide.

Improving the fire resistance of steel-framed structures using a passive system is only one of the strategies for providing fire-safe structures. Improvements in fire safety are most effective when used in conjunction with active systems.

An alternative approach to fire-safe construction is performance based. Under this option, calculations are prepared to predict a level of performance of the structure in a fire environment. Extensive research is progressing toward a thorough understanding of the behavior of steel-framed structures when exposed to fire, and an increase in the use of alternative design methods is inevitable.

## I.2 MODEL BUILDING CODES

The standard frequently referenced in this guide is the 2000 version of the International Building Code (IBC)[2]. At the time of this writing, a 2003 version of the IBC has been released. Some of the provisions of

*Fig I.1 Beam protected with SFRM.*

IBC 2000 have been revised in IBC 2003. Since the adoption of a code version by a municipality may follow a code release by several years, it is probable that the IBC 2000 provisions will prevail in many locations for some time. Thus, the decision to use the provisions of IBC 2000 is purposeful, though not intended to preclude application of the principles herein in jurisdictions that have adopted IBC 2003 or another model building code.

The use of IBC provisions is not intended to indicate a preference for the IBC over the National Fire Protection Association (NFPA)[3] building code. Rather, one building code was selected to maintain a consistency in the design guide.

## I.3 RESOURCES

Through the mid 1980's the American Iron and Steel Institute (AISI) served as a prolific and valuable resource for the design of fire protection for steel-framed structures. Design guides and directives were published by AISI addressing general steel construction[4, 5] as well as more focused treatments of beams[6], columns[7] and trusses[8]. In many instances the AISI guidance is still valid, but the AISI publications are currently out of print and more recent information has not been incorporated. This guide has incorporated, verified, expanded, and supplemented this data to provide a single resource for designing fire protection for steel-framed structures.

## REFERENCES


[1] Lie, T.T. (1992), "Structural Fire Protection," *Manual and Reports on Engineering Practice,* ASCE, No. 78.

[2] International Code Council, Inc. (ICC) (2000), *International Building Code, 2000,* Falls Church, VA.

[3] National Fire Protection Association (NFPA) (2003), *NFPA 5000: Building Construction and Safety Code,* 2003 Edition, Quincy, MA.

[4] American Iron and Steel Institute (AISI) (1974), *Fire-Resistant Steel-Frame Construction*, Second Edition, Washington, D.C.

[5] American Iron and Steel Institute (AISI) (1979), *Fire-Safe Structural Steel, A Design Guide,* Washington, D.C.

[6] American Iron and Steel Institute (AISI) (1984), *Designing Fire Protection for Steel Beams*, Washington, D.C.

[7] American Iron and Steel Institute (AISI) (1980), *Designing Fire Protection for Steel Columns*, Third Edition, Washington, D.C.

[8] American Iron and Steel Institute (AISI) (1981), *Designing Fire Protection for Steel Trusses*, Second Edition, Washington, D.C.

# Section II BUILDING CODE REQUIREMENTS

## II.1 GENERAL INFORMATION

Model building codes are the resource for building guidelines adopted by a jurisdiction. Either by direct adoption or by reference, these codes provide a standardized set of rules and regulations for the built environment. The intent of these regulations is to provide minimum standards to ensure public safety, health and welfare insofar as they are affected by building construction. Although there is a general trend to provide regulations in terms of performance rather than providing a rigid set of specifications, the prescriptive nature of the current building regulations remains in use and will likely always be an accepted alternative.

## II.2 BUILDING CODES

The predominant building and safety organizations in the United States are:

- Building Officials and Code Administrators (BOCA)
- Southern Building Code Congress International (SBCCI)
- International Conference of Building Officials (ICBO)
- International Code Council (ICC)
- National Fire Protection Association (NFPA)

In 1994, BOCA, SBCCI, and ICBO came together to create ICC. The purpose of this organization is to consolidate the different model code services and produce a single set of coordinated building codes that can be used uniformly throughout the construction industry. In 2000, ICC published a comprehensive set of 11 construction codes, including the International Building Code (IBC)[1]. As of January 2003, BOCA, SBCCI, and ICBO no longer function as individual entities, and have been completely integrated into the ICC organization[2].

There is still no complete consensus within the industry for a single national building code. In 2003, the NFPA developed and published its own set of building regulations, based on the American National Standards Institute (ANSI)-accredited process, with its building code NFPA 5000[3].

## II.3 IBC FIRE RESISTANT DESIGN

The IBC allows both prescriptive and performance-based fire-resistant designs, although its current emphasis is clearly on the former. Section 719 of the code explicitly lists several detailed, prescriptive fire-resistant designs. However, the IBC also allows the designer to choose from other alternative methods for design as long as they meet the fire exposure and criteria specified in the American Society for Testing and Materials (ASTM) fire test standard ASTM E119[4].

*703.3 Alternative methods for determining fire resistance.*

1. *Fire resistance designs documented in approved sources.*
2. *Prescriptive designs of fire resistance rated building elements as prescribed in Section 719.*
3. *Calculations in accordance with Section 720.*
4. *Engineering analysis based on a comparison of building element designs having fire resistance ratings as determined by the test procedures set forth in ASTM E119.*
5. *Alternative protection methods as allowed by Section 104.11.*

Notwithstanding the ability to use a performance-based design approach, this design guide's treatment of the building codes will generally be based on the application of the prescriptive provisions of the IBC.

## II.4 REQUIRED FIRE RESISTANCE RATINGS

Fire-safe construction is a major focus of the building codes, which mandate certain levels of fire protection. The required fire protection for a building is determined by a combination of the following:

1. Intended use and occupancy
2. Building area
3. Building height
4. Fire department accessibility
5. Distance from other buildings
6. Sprinklers and smoke alarm systems
7. Construction materials

Once these factors have been resolved, the fire resistance rating requirements for a particular building can be determined. The ratings are given as a specified amount of time the building's structural elements are required to withstand exposure to a standard fire.

For a specific occupancy, the larger the building, the higher the probability is that it will experience a fire in its lifetime. Building codes often require a longer period of fire endurance for larger buildings than for smaller buildings of similar occupancy. Some occupancies are naturally at greater fire risk for inhabitants than others. For instance, occupants of a nursing home with non-ambulatory patients could be at a greater risk during fires than occupants of a similar office building. A greater period of fire resistance is required for the occupancies that present a greater life safety risk to occupants. The degree of protection can also vary with the type of building material, either combustible or noncombustible, and whether the building poses risk to neighboring buildings. Thus, the building code attempts to mandate the required level of fire protection considering numerous parameters.

Buildings are generally constructed to serve a specific function and several occupancy classifications may be required to satisfy functional needs. For instance, an education facility can have both classrooms (i.e. educational occupancy) and an auditorium (i.e. assembly). The building code addresses these mixed occupancy conditions by allowing the building to be constructed to meet the requirements of the more restrictive type of construction of either occupancy. Alternately, the uses may be separated by fire barrier walls and/or horizontal fire-rated assemblies. The size and height of the building evolves from creating space needed to allow the function to be performed within its enclosure. Early in the planning process, the occupancy, height, and area are established. These parameters are used to determine the level of fire resistance. The IBC occupancy classifications are listed in Table II.1.

The structural system is generally established in the early stages of project development. Often, the selection of the structural system is influenced by the height and area restrictions to the building code limited construction type. The construction types are defined in IBC Chapter 6. A tabulation of construction types with an abbreviated description is indicated in Table II.2.

Structural steel framing is noncombustible, and can be used in construction classified as Type I, Type II, Type III, or Type V. Type I and Type II construction allows only noncombustible materials to be used in construction. Type I permits greater building heights and areas to be used than Type II does, thus requiring a greater duration of fire resistance. Type III construction allows both combustible and noncombustible interior building elements with noncombustible exterior walls. Type V construction allows combustible materials in all building elements. For a specific occupancy classification, the allowable height and area for Type II construction always equals or exceeds the height and area allowable for Type III or Type V construction. The exterior wall fire resistance rating for Type III construction is more severe than that required for Type II construction. Therefore, since steel framing systems satisfy the noncombustible framing requirements, they are most efficiently used in Type II and Type I construction.

The height above the ground plane and area per floor limitations for the various types of construction are indicated in IBC Table 503. In addition to the area per floor limitation, the IBC also limits the maximum area of the building to be the area per floor as prescribed in IBC Table 503 multiplied by the number of stories of the building up to a maximum of three stories. The height and area limitations included in the IBC Table 503 can be increased if specific additional life safety provisions are included in the facility. Descriptions of these modifications are listed below.

**II.4.1 Area Modifications.** An increase in fire department accessibility (frontage) and/or incorporating an approved automatic sprinkler protection can modify the allowed building area. Requirements for using these area modifications are described in Section 506 of the IBC, and are illustrated in Example II.1 in this chapter.

**II.4.2 Fire Wall Separations.** A fire wall can often be used to divide the building into segments. Through the use of fire walls, height and area limitations can be applicable to the segment rather than the entire floor area. The segment area may permit the use of a construction type having less stringent fire resistance rating requirements than those for the entire building. In some cases the need for structural fire protection can be completely eliminated, as the non-combustible steel without protection will provide an acceptable level of fire safety. To qualify as a fire wall, specific requirements must be met, such as the stability condition defined in IBC paragraph 705.2:

> *Fire walls shall have sufficient structural stability under fire conditions to allow collapse of construction on either side without collapse of the wall for the duration of time indicated by the required fire resistance rating.*

Further construction requirements for fire walls are included in IBC Section 705.