# SECTION 19

# Chapter 3

# Fire Resistance of Structural Members and Assemblies

*Revised by*

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**Chapter Contents**



**Key Terms**

beam, ceiling assembly, column, fire barrier, fire endurance, fire resistance, fire test, floor assembly, gypsum, partition, reinforced concrete, roof assembly, structural assembly, structural frame, structural steel, wall, wood

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The selection of building materials and the design of the details of construction always play an important role in overall building fire safety. Two important fire safety considerations regarding the building structure are to minimize the likelihood of collapse of the structural frame during a fire and to ensure that fire barriers remain intact to prevent ignition and fire spread to adjoining spaces. However, there is increasing awareness in the engineering and fire safety professions that structural response in the post-peak phase of a fire as well as the post-fire condition of a structure can be relevant performance objectives.

The following are the three general approaches to structural frame and barrier design for fire resistance:

1. Fire resistance testing based on standardized procedures,
2. Empirical equations or prescriptive requirements to establish a fire resistance rating equivalent to standard fire test exposure and acceptance criteria, and
3. Structural fire engineering based on real fire exposure and structural system performance.

The traditional method of treating the structural aspects of fire protection is through building code requirements for structural members and assemblies based on ratings determined through standardized fire resistance tests or established using calculated fire resistance ratings. Classification of building construction with regard to fire resistance requirements is an approach that has the principal advantage of being relatively easy to incorporate into the design process and to administer from a code enforcement standpoint. It has the major disadvantages of being unable to represent the performance of the structural member or fire barrier under the broad range of fire loads to which it may be exposed and the boundary conditions imposed by the structural system. The fact that code compliance alone may not be sufficient to ensure performance success of barriers or the structural system in some fire scenarios or to achieve project-specific performance objectives required by an owner, such as property protection or business continuity, has motivated the advancement of performance-based design procedures for fire effects on structures in recent years.

This chapter deals primarily with traditional methods to establish fire resistance ratings for structural members and assemblies. It first provides details on fire resistance test procedures followed by illustrative historical fire resistance ratings for building construction and references to current sources for ratings. It then introduces methods of calculating equivalent fire resistance ratings based on standard fire testing exposure and acceptance criteria. The chapter concludes with discussion of the behavior of common building materials at elevated temperatures.

For related topics, see Section 6, Chapter 3, “Concepts and Protocols of Fire Testing”; Section 18, Chapter 1, “Confinement of Fire in Buildings”; Section 19, Chapter 1, “Types of Building Construction”; Section 19, Chapter 2, “Structural Fire Safety Calculation Methods”; and Section 19, Chapter 5, “Analyzing Structural Fire Damage.”

# FIRE RESISTANCE TESTING FOR STRUCTURES

The development and use of fire tests to assess the fire performance of materials and systems within the broader context of fire safety engineering is presented in Section 6, Chapter 3 *Concepts and Protocols of Fire Testing*. This chapter focuses on fire resistance rating of the beams, columns, walls, partitions, floors, roofs and other structural elements used for building construction.

Previous versions of this handbook reference NFPA 251 *Standard Methods of Tests of Fire Resistance of Building Construction and Materials,* which was adopted by NFPA as a tentative standard in 1917 and advanced to official standard status in 1918. NFPA 251 was withdrawn in 2010 and the requirements are found in ASTM E119 *Standard Test Methods for Fire Tests of Building Construction and Materials* and similarly UL 263 *Fire Resistance of Building and Construction Materials*. While distinct standards, the testing procedures in ASTM E119 and UL 263 are nearly identical. NFPA 5000® *Building Construction and Safety Code*®, as well as the International Building Code (IBC), permit the use of either document to establish fire resistance ratings for structural elements. For the purpose of this handbook, ASTM E119 will be referenced.

## Fire Resistance Test Procedures

As described in Section 6, Chapter 3, fire resistance tests expose a test specimen to a prescribed time-temperature curve. When required, the fire exposure is followed by application of a pressurized fire hose water stream. Test procedures with and without superimposed mechanical force on the test specimen are available. The superimposed force is equal to the maximum-load condition allowed under nationally recognized structural design criteria unless limited design criteria are desired and a corresponding reduced load is applied. Specimens representing floor and roof assemblies are always subjected to a superimposed force. Walls, partitions, columns, beams and other structural elements can be tested with or without superimposed force depending on the fire resistance rating sought. For some structural elements and assemblies, separate test procedures are provided for arrangements involving restrained or unrestrained mechanical boundary conditions.

Conditions of acceptance in ASTM E119 are specific to the assembly or structural element tested and the chosen test procedure (load or no load, restrained or unrestrained). Evaluation criteria include the following:

1. Failure to support load (loadbearing members and assemblies),
2. Passage of hot gas or flame sufficient to ignite cotton waste (walls, partitions, floors, and roofs),
3. Specified limits on single point temperatures and/or average temperature increase from the initial temperature, and
4. Failure under hose streams (walls and partitions).

## Fire Resistance Ratings

Fire resistance ratings, previously known as fire endurance classifications, represent the time duration a structural member or assembly withstood a fire test conducted in accordance with test procedures permitted by the applicable building code. Although the actual duration is recorded to the nearest integral minute when the first failure criterion is reached, fire resistance ratings are given in standard intervals. Typical fire resistance ratings for construction elements are 15 minutes, 20 minutes, 30 minutes, 45 minutes, 1 hour, 1½ hours, 2 hours, 3 hours, and 4 hours. Therefore, a 1 hour fire rating indicates that the assembly withstood the standard fire resistance test for 1 hour or longer.

Several organizations and laboratories in the United States test assemblies of building construction materials for fire resistance. Some of these organizations publish results in so-called *Directories* or *Approval Guides.* These guides and directories have illustrations of building assemblies that have met the test criteria for specific fire resistance hourly ratings. The vast number of published fire resistance ratings make it almost impossible to tabulate in a single form all the data on the various assemblies that have been tested. Later in this chapter, historical test results for representative assemblies are included to illustrate the basic requirements for test specimens and how the results of tests are recorded.

Over decades of use, fire resistance tests have generated substantial data on the performance of common structural members and assemblies. In many cases, this allows for calculation of an equivalent fire resistance rating to that which the construction would achieve in a standard fire resistance test. These calculation methods are outlined later in the chapter. Additionally, building codes may include tables of construction assemblies that will be accepted as meeting code requirements in terms of fire resistance rating without calculation when they fulfill prescribed specifications. Such tables are usually based upon fire test data, but some include ratings determined by experience, judgment, and extrapolation of test data.

Finally, are the many useful data sheets and summaries published by trade associations of the building materials manufacturers. These sources are not cited because they are numerous and because the information published either pertains to the products of a specific manufacturer or consists of tabulated ratings for a single type of construction material.

## Limitations of Fire Resistance Tests

The standard fire resistance test provides a relative measure of specific aspects of the thermal endurance of comparable assemblies under uniform fire exposure conditions. It does not represent the complex thermal and mechanical conditions in a real structure nor does it consider suitability for use after fire exposure. Moreover, it does not measure the degree of control or limitation of the passage of smoke or products of combustion through the test specimen or how the specimen contributes to the fire hazard by generation of smoke, toxic gases, or other products of combustion.

A frequently encountered misconception in fire protection is the belief that a fire resistance rating indicates the time that the assembly will survive an actual fire. The fire resistance rating is the amount of time the member or assembly withstood the standard fire resistance test. It is not the time duration the assembly will perform without failure under actual fire conditions. For example, a 2 hour assembly meets specified conditions of acceptance for at least 2 hours when subjected to the standard fire resistance test exposure. Under field conditions, the same assembly may fail in a considerably shorter or longer time duration.

Although standard fire resistance test procedures require that materials in the specimen and the workmanship be representative of those in actual buildings, considerable variation in field practice can occur.

For example, the properties and proportions of aggregates and binders have an important influence on the results of fire resistance tests. Gypsum plaster with lightweight aggregates, mixed with 2 $ft^3$ to 3 $ft^3$ (0.057 $m^3$ to 0.085 $m^3$) to each 100 lb (45 kg) of gypsum, provides a fire resistance rating 10 percent to 70 percent greater than equal thicknesses of sanded gypsum plaster. The use of such aggregate in specific constructions should be adopted only after consulting the publication of ratings based on tests in which these aggregates have been used. Vermiculite aggregate plaster, if too wet when applied, may be subject to shrinkage cracks. Such cracks, can affect fire resistance. Finishing lime produced from dolomite contains magnesium oxide. Material designated as “normal” finishing hydrate may not be sufficiently hydrated, and sometimes subsequent gradual hydration results in destructive expansion. Plasters containing such lime are subject to rapid destruction in the event of fire. This difficulty is avoided with lime hydrated under high temperature and pressure and known as “special” or “autoclaved” lime. So-called stabilized gypsum plaster containing a small percentage of the normal hydrated lime may similarly be subject to deterioration with age and may not provide the fire resistance to be expected from such constructions. Approving “or equal” clauses in construction specifications should be thoroughly evaluated to avoid substitutions of materials that have not been listed with the assembly.

The moisture content in members and assemblies in structures in the field may differ from that in test specimens. This is particularly true for concrete members where the drying time to reach a moisture content representative of that in the field could be prohibitive for laboratory tests. ASTM E119 allows for the testing of concrete specimens with higher moisture content when it can be shown that the in-situ construction will fail to meet stipulated conditions after a 12 month conditioning period. Nevertheless, moisture content can significantly influence the thermal and mechanical (spalling) response of concrete.

In addition to the material variation noted, construction differences may be even more significant. For example, a standard fire resistance test does not provide information on performance of assemblies constructed with components or lengths other than those tested. Because thermal expansion increases with increased length and area of heat exposure, standard fire resistance tests may not capture significant detrimental aspects of deformation compatibility at member boundaries or between materials with different coefficients of thermal expansion in an assembly for large construction elements in the field.

Possibly the most significant aspect of fire resistance testing in the United States in the context of construction differences between test specimens and actual structures is the distinction between restrained or unrestrained conditions. Requirements to evaluate structural members based on restrained and unrestrained conditions were introduced into standardized fire testing in 1970. The member or assembly end restraint conditions during a fire test significantly influence the test results and, consequently, fire resistance ratings. ASTM E119 defines a restrained condition as one in which expansion and rotation at the ends and supports of a load carrying test specimen resulting from the effects of the fire are resisted by forces external to the test specimen. An unrestrained condition is defined as one not classified as “restrained.”

One justification for incorporating two differing means of end restraint is to simulate simple (statically determinant) and continuous (statically indeterminant) conditions. Figure 19.3.1 illustrates simple and continuous spans. All else being equal, continuous span construction is typically stronger than simple span construction. However, the amount of increased strength in an indeterminant structure can vary depending on the type of construction materials used, the location of structural members within the structure, the degree of indeterminancy, the loading conditions, and the details of construction; e.g., the structural connections.

Guidance for specification of restrained fire resistance ratings in the context of steel beam floor and roof assemblies is provided by Gewain[1] and more recently in an AISC technical resource document.[2] However, experts have challenged the restrained versus unrestrained paradigm as being paradoxical and having potentially harmful impact to the industry.[3] Unlike in the United States, fire resistance ratings used in other parts of the world (e.g., in Europe[4]) do not make this distinction.

**FIGURE 19.3.1** Schematic Illustrating Simple and Continuous Spans

The standard fire resistance test does not incorporate information regarding the effect on fire resistance of conventional openings in the assembly, such as electrical receptacle outlets, pipe chases, and so on. Poke-through construction for electrical services or piping often is not patched properly. Transfer grilles, windows, and other penetrations are often incorporated into barriers without considering their impact on fire resistance.

The standard fire resistance test does not address the contribution of combustible construction to fire intensity. This can result in lower fuel consumption in order to maintain the ASTM E119 time-temperature regime in a furnace. This topic has received scrutiny in recent years with the increase in testing of combustible specimens such as cross laminated timber construction.[5,6] Recent studies concluded that fire resistance tests of combustible construction represents a less onerous test in terms of energy absorbed or fuel made available than one of a noncombustible construction, implying that the existing fire resistance framework may not be appropriate for timber structures, but that further study is required.[7]

The fact that structural member and assembly performance in standard fire resistance tests and during real structure fires may be vastly different for reasons including those mentioned above is not intended to demonstrate that fire resistance ratings do not have value. Over the years standard fire resistance testing has resulted in improved fire performance of buildings. However, one must understand the limitations of the procedure so that unrealistic reliance is not placed on the construction.

## ILLUSTRATIVE FIRE RESISTANCE RATINGS FOR STRUCTURAL MEMBERS AND ASSEMBLIES

To illustrate the effect of materials and geometry on the fire resistance rating of structural members and assemblies, several examples are provided. The data in these examples has been aggregated by editors of this handbook over several decades. In some cases, these data have found their way into current design guidelines and others are purely of historical interest. Users of this handbook should consult code-approved fire resistance directories and guides for design specifications for members and assemblies that have been physically tested or the tabulated prescriptive fire resistance ratings for common members and assemblies provided in the applicable building code.

### Reinforced-Concrete Members

Historically, reinforced-concrete construction has generally exhibited good performance with regard to its ability to withstand structural collapse in fires. Because concrete has a low thermal conductivity and a low thermal capacity, it provides an effective cover for reinforcing steel. For example, Figure 19.3.2 shows the temperature gradient in a 6 in. (152 mm) slab after a 2 hour fire exposure.[8] Although undoubtedly the moisture in the concrete greatly influences the values, the significant feature is that the temperatures vary considerably throughout the thickness, even after a considerable time.

**FIGURE 19.3.2** Thermal Gradient in a 6 in. Slab After 2 Hour Fire Exposure. For SI units: 1 in. = 25.4 mm; °C = 5⁄9 (°F – 32).

The low thermal conductivity and high thermal mass of concrete are reasons that reinforced-concrete systems often perform well during fire exposure. Consider, for example the continuous monolithic reinforced-concrete construction shown in Figure 19.3.3. With reference to the temperature gradient of Figure 19.3.2, it will take significant time before the tension steel (positive reinforcement) at midspan is affected. Even after the tension steel at midspan reaches its yield value, the steel reinforcement in the negative moment region near the top of the beam or slab over the supports has not been significantly affected because of the insulating effect of the concrete. It is noted that yield capacity of steel decreases at high temperatures, which in turn can reduced the capacity of reinforced-concrete construction. It is thus important that the concrete cover between the fire exposed side of the member and the steel reinforcement remain intact and not undergo excessive spalling.

**FIGURE 19.3.3** Monolithic Reinforced-Concrete Beam and Slab

Continuous (restrained) slab construction can have capacity far greater than statically determinant (simple unrestrained) construction because with proper detailing considerable stress redistribution can take place before collapse will occur. Although the members may be damaged by the fire, structural stability against collapse can remain for a considerable period of time if sufficient reinforcement with appropriate detailing is present.

The level of stress in a reinforced-concrete member exposed to the elevated temperatures of a fire can have a significant influence on its fire resistance. This is illustrated with the example of a column. A series of tests was conducted on 15 in. × 15 in. (381 mm × 381 mm) columns with four number-nine reinforcing bars.[8] Each column was loaded at a different percentage of the design load. Table 19.3.1 illustrates the effects of stress level on the fire resistance of reinforced-concrete columns. It can be seen that the magnitude of stress during a fire causes significant reductions in capacity. This is attributed primarily to the reduction in the mechanical properties of steel and concrete at elevated temperatures.

**TABLE 19.3.1** Influence of Stress on Fire Resistance of Concrete Columns

| *Applied Load (% Design Load)* | *Fire Resistance (min)* |
|---|---|
| 150 | 68 |
| 100 | 124 |
| 75 | 198 |
| 50 | 248 |
| 30 | 358 |

The details of construction and the concrete mixture affect the fire resistance of concrete structures. Some examples of historical fire resistance ratings for reinforced concrete beams are given in Table 19.3.2 and for prestressed concrete girders, beams, joists, and slabs in Table 19.3.3. Because the cold-drawn, high-strength steel tendons used in prestressed concrete are more adversely affected by high temperatures than normal reinforcement steel, these tendons require a thicker protective cover than is required in conventional reinforced concrete. An example of the fire resistance of reinforced concrete columns is shown in Table 19.3.4.

The designations Grade 1 and Grade 2 concrete are no longer used in the United States. These designations are believed to correspond to what is charactered in current building codes as carbonate aggregate concrete (Grade 1) and siliceous aggregate concrete (Grade 2). Additionally, advancements in cement and concrete technology have enabled the production of higher strength concretes. Modern concrete typically includes fine mineral binders, such as fly ash or silica fume, and high-range water-reducing admixtures to produce concrete with higher strength and lower water–cement ratio. Without modifications such as air entrainment, these cement replacement minerals and admixtures generally result in denser concrete that may respond differently under fire exposure than older concrete. Therefore, while the trends indicated in Table 19.3.2 to Table 19.3.4 are illustrative, the reader should consult the applicable building code when assessing a particular structure. ACI 216.1 *Code Requirements for Determining Fire Resistance of Concrete and Masonry Construction Assemblies* contains requirements for the design of concrete for fire exposure including materials and dimensioning for assemblies deemed to have specified fire resistance ratings.

**TABLE 19.3.2** Reinforced-Concrete Beams and Girders of Medium Size

| *Concrete Grade*[a] | *Protective Cover of Reinforcement (in.)* | *Fire Resistance Rating*[b] *(hr)* |
|---|---|---|
| 1 | ¾ | 1 |
| | 1 | 2 |
| | 1¼ | 3 |
| | 1½ | 4 |
| 2 | ¾ | ½–1[c] |
| | 1 | 1–2[c] |
| | 1½ | 2–3[c] |
| | 2 | 2–4[c] |

[a]For lightweight concrete having an oven-dried density of 110 pcf or less, the cover shown for concrete Grade 1 may be reduced 25 percent.

[b]May be increased if some bars are better protected by being away from corners or in an upper layer or if beam is large. Should be decreased if beam is small.

[c]Variable depending on spalling characteristics of aggregate. The use of mesh to hold cover in place will give ratings about as high as for concrete of Grade 1.

For SI units: 1 in. = 25.4 mm.

**TABLE 19.3.3** Prestressed Concrete Girders, Beams, Joists, and Slabs (Grade 1 Concrete)

| *Type of Unit* | *Condition of Restraint* | *Cross-Sectional Area (in.*$^2$*)*[b] | Cover for Fire Rating Shown (in.)[a] | | | |
|---|---|---|---|---|---|---|
| | | | *1 hr* | *2 hr* | *3 hr* | *4 hr* |
| Girders, beams, and joists | Unrestrained | 40 to 150 | 2 | 2.5 | — | — |
| | | 150 to 300 | 1.5 | 2.5 | 3.5[c] | — |
| | | Over 300 | 1.5 | 2.25 | 3[c] | 4[c] |
| | Axially restrained | 40 to 150 | 1.5 | 2 | — | — |
| | | 150 to 300 | 1 | 1.5 | 2 | — |
| | | Over 300 | 1 | 1.5 | 1.5 | 2 |
| Slabs, solid or covered, with flat undersurface | Unrestrained | | 1 | 1.5 | 2 | 2.5 |
| | Biaxial restraint | | 0.75 | 1.25 | 1.5 | 2 |

Note: Data in this table are based on 67 standard ASTM fire tests.

[a]Cover for an individual steel tendon is measured to the nearest exposed surface. For several tendons in the same member having different concrete covers, the minimum cover may be reduced slightly. The covers shown may be reduced 25 percent for lightweight concrete having an over-dried density of 110 pcf or less. For Grade 2 concrete, the cover may need to be increased.

[b]In computing the cross-sectional area of joists, the area of the flange must be added to the area of the stem, but the total width of the flange so used must not exceed three times the width of the stem.

[c]Provide against spalling of the cover by means of a light, 2-in., U-shaped mesh, covered about 1 in.

For SI units: 1 in. = 25.4 mm; 1 in.$^2$ = 645 mm$^2$.

**TABLE 19.3.4** Fire Resistance of Reinforced-Concrete Columns*

| Column | | | | Concrete | | | Reinforcement | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Section | | Load | Aggregates | | Mix | Vertical | | | Lateral | | Concrete Cover | Fire Resistance | |
| *No.* | *(in.)* | *Area(in.²)* | *in 1000 lb* | *Fine* | *Coarse* | *Cement Fine Coarse* | *Number* | *Bar Size No.* | *(in.²)* | *Diam. (in.)* | *Spacing (in.)* | *Thickness* | *hr* | *min* |
| 70 | 16 × 16 | 256 | 101 | Fox River sand | Chicago limestone | 1:2:4 | 4 | 9 | 4.00 | ¼ | 12 | 2¼ | 8<br>(13+ | 40<br>—) |
| 71 | 16 × 16 | 256 | 101 | Long Island sand | New York trap rock | 1:2:4 | 4 | 9 | 4.00 | ¼ | 12 | 2¼ | 7 | 22 |
| 72 | 17 dia | 227 | 107.5 | Fox River sand | Chicago limestone | 1:2:4 | 6 | 9 | 6.00 | ¼ | 12 | 2½ | 8<br>(12+ | 04<br>—) |
| 73 | 17 dia | 227 | 107.5 | Long Island sand | New York trap rock | 1:2:4 | 6 | 9 | 6.00 | ¼ | 12 | 2½ | 7 | 57 |
| 74 | 17 dia | 227 | 129 | Fox River sand | Chicago limestone | 1:2:4 | 6 | 6 | 2.64 | ¼ | 1½ | 2¼ | 8<br>(13+ | 06<br>—) |
| 75 | 17 dia | 227 | 129 | Long Island sand | New York trap rock | 1:2:4 | 6 | 6 | 2.64 | ¼ | 1½ | 2¼ | 8 | 02 |
| 25 | 16 × 16 | 256 | 92 | Pittsburgh sand | Pittsburgh gravel | 1:2:4 | 4 | 8 | 3.16 | ¼ | 12 | 1½ | 4<br>(6 | —<br>30) |
| 44 | 16 × 16 | 256 | 92 | Long Island sand | Pure quartz gravel | 1:2:4 | 4 | 8 | 3.16 | ¼ | 12 | 1½ | 4<br>(6 | —<br>—) |
| 51 | 16 × 16 | 256 | 92 | Pittsburgh sand | Blast furnace slag | 1:2:4 | 4 | 8 | 3.16 | ¼ | 12 | 1½ | 4<br>(8 | —<br>—) |
| 56 | 16 × 16 | 256 | 92 | Pittsburgh sand | New Jersey trap rock | 1:2:4 | 4 | 8 | 3.16 | ½ | 12 | 1½ | 4<br>(7 | —<br>—) |
| 7 | 18 dia | 254 | 99.75 | Pittsburgh sand | Pittsburgh gravel | 1:2:4 | 8 | 6 | 3.52 | ¼ | 12 | 1½ | 5<br>(6 | —<br>—) |
| 2 | 18 dia | 254 | 141 | Pittsburgh sand | Pittsburgh gravel | 1:2:4 | 8 | 6 | 3.52 | 3/16 | 2 | 1½ | 4 | — |
| 48 | 18 dia | 254 | 141 | Pittsburgh sand | Blast furnace slag | 1:2:4 | 8 | 6 | 3.52 | 3/16 | 2 | 1½ | 4<br>(10+ | —<br>—) |
| 85 | 18 dia | 254 | 141 | Elgin, IL, sand | Elgin, IL, sand | 1:2:4 | 8 | 6 | 3.52 | 3/16 | 2 | 1½ | 4<br>(12+ | —<br>—) |
| 12 | 18 dia | 254 | 81 | Pittsburgh sand | Pittsburgh gravel | 1:2:4 | None | — | — | — | — | — | 4 | — |
| 33 | 12 dia | 113 | 51 | Pittsburgh sand | Pittsburgh gravel | 1:2:4 | 4 | 5 | 1.24 | ¼ | 2¹/₈ | 1½ | Avg. 3 | of 2<br>— |

*Column Nos. 70 to 75 tested at UL. Test No. 70 of the group was stopped at 8 hours 40 minutes; others at failure or at 8 hours, and all loaded to failure at end of fire exposure (NBS Tech. Paper 184). All other columns tested at NBS Laboratory at Pittsburgh, PA. The fire endurance test of Col. No. 7 stopped at 5 hours, all others of series stopped at 4 hours. Figures in parentheses are estimates of fire resistance if tests had continued to failure (NBS Tech. Paper 272).

For SI units: 1 in. = 25.4 mm; 1 in.$^2$ = 645 mm$^2$; 1 lb = 0.45 kg.

## Structural Steel Members

The popularity of steel-frame building construction is in large part due to its high strength, ease of fabrication, and ensured uniformity of quality. Exposed structural steel, however, is vulnerable to fire damage. To possess fire resistance, structural steel must be protected with other materials from the high temperatures encountered in fires with other materials. Protection for steel beams, girders, and columns, with encasements of hollow clay tile, brick, and concrete masonry blocks, has generally been superseded by spray-applied fire resistive materials (SFRM) and intumescent coatings.

Table 19.3.5 gives historical examples of minimum thicknesses of concrete encasement for steel beams. Tables 19.3.6 and 19.3.7 illustrate the influence of various methods of encasement on the fire resistance of columns. Figures 19.3.4 and 19.3.5 illustrate methods of encasement for steel columns. AISC 360 *Specification for Structural Steel Buildings* contains current requirements for the fire protection of structural steel including descriptions of generic steel assemblies deemed to have specified fire resistance ratings.

**TABLE 19.3.5** Concrete Protection for Steel Beams (All reentrant portions filled)

| Fire Resistance Rating | | Thickness of Concrete Protection (in.) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Grade 1 Size of Member (Flange Width) | | | | Grade 2 Size of Member (Flange Width) | | | |
| *hr* | *min* | *2 to 3¾ in.* | *4 to 5¾ in.* | *6 to 7¾ in* | *8 in. and over* | *2 to 3¾ in.* | *4 to 5¾ in.* | *6 to 7¾ in.* | *8 in. and over* |
| 4 | — | 4 | 3¼ | 2½ | 2 | 4¾ | 3¾ | 3 | 2½ |
| 3 | — | 3½ | 2½ | 2 | 1½ | 4 | 3 | 2½ | 2 |
| 2 | — | 2½ | 2 | 1½ | 1 | 3 | 2½ | 1¾ | 1¼ |
| 1 | 30 | 2 | 1½ | 1 | 1 | 2½ | 1¾ | 1¼ | 1 |
| 1 | — | 1½ | 1 | 1 | 1 | 1¾ | 1¼ | 1 | 1 |

Note: Protective concrete having thickness one-fourth of flange width or less must have steel wire reinforcement spaced nor more than four times the thickness of the concrete covering the flange. Grade 1 = carbonate aggregate concrete. Grade 2 = siliceous aggregate concrete.

For SI units: 1 in. = 25.4 mm.

**TABLE 19.3.6** Fire Resistance of Steel Columns with Lath and Plaster Protective Coverings

| Metal Column | | | | Protective Covering | | | | | | | | Fire Resistance Rating | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Type of Covering | | | | | | | | | |
| | | | | | Plaster | | | | | | | | | |
| *Type of Section* | *Size (in.)* | *Weight per Lin Ft (lb)* | *Area of Metal (in.²)* | *Design* | *Type* | *Aggregate* | *Mix, Volumes* | *Thickness $T^b$ (in.)* | *Furring $T^b$ (in.)* | *Bond of Covering* | *Total Area of Materials (in.²)* | *hr* | *min* | *Notes* |
| H | 6 | 44 | 13 | — | Portland cement and lime | Sand | 1:1/10:2½ | 7/8 | 1 | Metal lath | 40 | — | 45 | Metal lath furred out |
| H | 6 | 31 | 9 | — | Two thicknesses of above | Sand | 1:1/10:2½ | 7/8 + 7/8 | 1 & 1 | Metal lath | 80 | 1 | 30 | Metal lath furred out |
| H | 10 | 49 | 14.5 | A | Gypsum-cement mixture | Lightweight[a] | Mill mix | 1¾ | 3/8 | Wire fabric | 125 | 3 | 25 | |
| H | 10 | 49 | 14.5 | A | Gypsum | Lightweight[a] | Mill mix | 1 7/8 | 5/8 | Metal lath | 125 | 4 | — | ½-in. channel behind lath |
| H | 10 | 49 | 14.5 | A | Gypsum | Lightweight[a] | 1½:2<br>1½:3 | 1¾ | 3/8 | Metal lath | 125 | 4 | — | Self-furring lath |
| H | 10 | 49 | 14.5 | A | Gypsum | Lightweight[a] | 1½:2<br>1½:3 | 1 3/8 | 3/8 | Metal lath furred out | 102 | 3 | — | Self-furring lath |
| H | 10 | 49 | 14.5 | A | Gypsum | Lightweight[a] | 1½:2<br>1½:3 | 1 | 3/8 | Metal lath | 78 | 2 | — | Self- furring lath |
| H | 10 | 49 | 14.5 | B | Gypsum | Lightweight[a] | ½:3½<br>½:4 | 2 1/8 | ½ | 18-gauge wire and wire fabric | 145 | 4 | — | Gypsum |
| H | 10 | 49 | 14.5 | C | Gypsum | Lightweight[a] | 1½:2<br>1½:3 | 1½ | 1 | 18-gauge wire and wire fabric | 140 | 4 to 15<br>4 to 40 | | Gypsum lath |
| H | 10 | 49 | 14.5 | B | Gypsum | Lightweight[a] | 1½:2½ | 1½ | ½ | 18-gauge wire and wire fabric | 110 | 3 | 40 | Gypsum lath |
| H | 10 | 49 | 14.5 | D | Gypsum | Lightweight[a] | 1:2½ | ½ | 3/8 | 18-gauge wire ties | 53 | 1 | 20 | Perforated gypsum lath |
| H | 10 | 49 | 14.5 | D | Gypsum | Lightweight[a] | 1:2½ | 5/8 | 3/8 | 18-gauge wire ties | 60 | 1 | 30 | Perforated gypsum lath |
| H | 10 | 49 | 14.5 | D | Gypsum | Lightweight[a] | 1½:2 1½:3 | 1 | 3/8 | 18-gauge wire ties | 80 | 2 | 15 | Perforated gypsum lath |
| H | 10 | 49 | 14.5 | D | Gypsum | Lightweight[a] | 1½:2 1½:3 | 1½ | 3/8 | 18-gauge wire ties | 104 | 2 | 30 | Perforated gypsum lath |
| O | 7 | 51 | 15.5 | — | Portland cement and lime | Sand | 1:1/10:2½ | 1¼ | 7/8 | 7/8-in. rib lath | 70 | 2 | 45 | Metal lath on cast column |

[a]Lightweight aggregate can be either perlite or vermiculite.

[b]Dimensions as shown in Figure 19.3.4.

For SI units: 1 in. = 25.4 mm; 1 in.$^2$ = 645 mm$^2$; 1 ft = 0.305 m; 1 lb = 0.454 kg.

**TABLE 19.3.7** Fire Resistance of Steel Columns Encased with Concrete, Masonry, or Sprayed Fibers

| Steel Column | | | Protective Covering | | | | | | | Fire Resistance Rating | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Type of Section* | *Size (in.)* | *Weight per Lin Ft (lb)* | *Design* | *Type of Covering* | *Thickness Outside Steel TI (in.)* | *Reentrant Portion Filled* | *Plaster Thickness (in.)* | *Section Area of Solid Material (in.²)* | *Bond of Covering* | *hr* | *min* | *Notes* |
| H | 8[e] | 34 | | None | 0 | No | 0 | 8 | — | — | 10 | Bare column |
| H | 6[e] | 20 | E | Siliceous gravel concrete, 1:2½:3½ mix | 2 | Yes | 0 | 100 | 8 gauge wire spiral 8 in. pitch | 3 | 30 | NBS test |
| Plate and angle | 6[e] | 34 | E | Trap rock or cinder concrete, 1:6 mix[a] | 2 | Yes | 0 | 130 | 6 gauge wire spiral | 3 | 45 | UL test |
| H | 8[e] | 34 | E | Limestone concrete, 1:6 mix[a] | 2 | Yes | 0 | 144 | 6 gauge wire spiral | 6 | 30 | UL test |
| H | 8[e] | 34 | E | Limestone concrete, 1:6 mix[a] | 4 | Yes | 0 | 256 | 6 gauge wire spiral | 7 | 30 | UL test |
| H | 8[e] | 34 | E | Trap rock, granite, cinders, 1:6 mix[a] | 4 | Yes | 0 | 256 | 6 gauge wire spiral | 7 | — | UL test |
| Plate and angle | 6[e] | 34 | E | Gypsum concrete[b] | 2 | Yes | ½ | 114 | 4 in. mesh fabric | 6 | 30 | NBS test gypsum plaster |
| Plate and angle | 6[e] | 34 | E | Gypsum block | 2 | No | ½ | 107 | 1 by 1/8 in. O clamps Block bond | 4 | — | NBS test gypsum plaster |
| Plate and angle | 6e | 34 | E | Cinder block | 3¾ | Yes | ¾ | 240 | Brick bond | 7 | — | NBS test gypsum plaster |
| H | 8[e] | 34 | E | Common brick | 4¼ | Yes | 0 | 270 | Wire ties | 7 | — | UL test |
| H | 8[e] | 34 | E | Semi-fire clay hollow tile | 2 | No | 0 | 96 | Wire ties | 1 | 30 | UL test |
| H | 8[e] | 34 | E | Semi-fire clay hollow tile | 4 | No | 0 | 158 | No special adhesive | 1 | 30 | UL test |
| H | 10[e] | 49 | F | Sprayed mineral fiber[c] | 2¼ | Yes | — | 164 | Special adhesive | 5 | — | |
| H | 10[e] | 49 | F | Sprayed mineral fiber[c] | 3 3/8 | Yes | — | 238 | Special adhesive | 5 | — | |
| H | 8[e] | 28 | F | Sprayed mineral fiber[c] | 2 | Yes | — | 44 | No special adhesive | 5 | — | |
| I | 8[e] | 28 | F | Sprayed asbestos fiber[c] | 2 | Yes | — | 38 | No special adhesive | 3 | — | |
| | 8[e] | 35 | E | Sprayed asbestos fiber[c] | 1 | Yes | — | 90 | No special adhesive | 2 | — | |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 8[e] | 35 | E | Sprayed asbestos fiber[c] | 1¾ | Yes | — | 98 | No special adhesive | 4 | — | |
| | 8[e] | 35 | E | Sprayed asbestos fiber[c] | 1 7/8 | Yes | — | 120 | No special adhesive | 4 | — | |
| I | 8[e] | 28 | F | Sprayed asbestos fiber[c] | 1½ | Yes | — | 28 | — | 2 | — | UL test |
| O | 7.6[f] | 24 | | None (bare steel pipes filled with concrete)[d] | 0 | Yes | 0 | 46 | | — | 35 | UL test |

[a]Concrete mix—1 part cement to 6 parts total aggregate including sand and coarse aggregate.

[b]Gypsum concrete—7 parts gypsum stucco to 1 part wood shavings, by weight.

[c]Mineral fibers, with bonding agent as required, sprayed on to all surfaces of column shaft to thicknesses indicated. (Thickness different on account of characteristics of fiber and binder.)

[d]Concrete-filled columns require vent holes to prevent explosion in the event of fire.

[e]Approximate depth, flange width per Table 19.3.5.

[f]Inside diameter.

For SI units: 1 in. = 25.4 mm; 1 in.$^2$ = 645 mm$^2$; 1 ft = 0.305 m; 1 lb = 0.454 kg.

**FIGURE 19.3.4** Examples of Steel Column Protection Using Lath and Plaster Assemblies. For SI units: 1 in. = 25.4 mm; 1 lb = 0.454 kg.

**FIGURE 19.3.5** Examples of Steel Column Protection Using Concrete, Masonry, or Sprayed Fibers

## Floor and Roof Assemblies

The fire resistance of floor and roof assemblies is important from a structural standpoint and for the prevention of vertical fire spread. Fire resistance ratings from the standard fire test are typically determined from unpenetrated assemblies. The anticipated fire resistance may be greatly reduced in building construction when holes and poke-throughs are not protected adequately or when details do not conform to the tested assembly.

The method of attaching ceilings can be a major factor in determining the fire resistance of floors. For example, the nailing of gypsum lath, metal lath, or gypsum wallboards to the soffits of wood joists is often critical in plaster construction. The longer, thinner nails, particularly those with cement coatings, conduct less heat to char the wood surrounding them than do the common types of wire nails. Similarly, the integrity of suspended ceilings must be maintained to reduce the likelihood of premature failure on some assemblies. Details such as attention to expansion of the supporting framework are essential to preventing premature ceiling failures

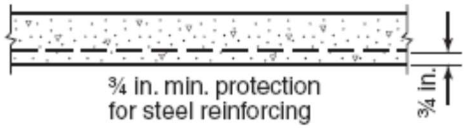
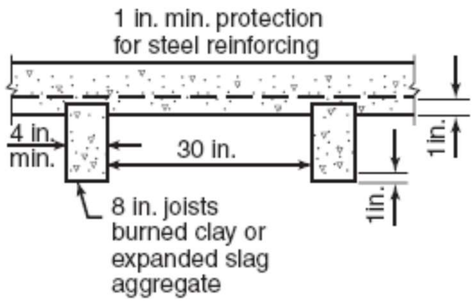
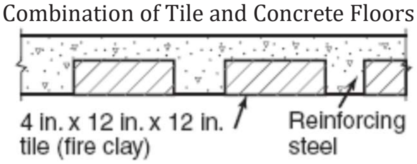
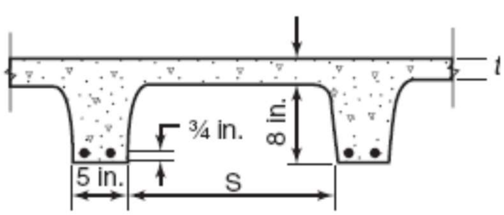
Suspended ceilings with openings for air diffusers and light troughs should be designed so that such openings are not points of vulnerability to fire. Continuous construction above recesses for lighting fixtures and properly designed self-closing dampers for air ducts provide protection.

Roof assemblies are tested and rated in a manner similar to the floor assemblies. However, roof assemblies often have a specified thickness of insulation in place at the test. If additional thicknesses of insulation are desired, the fire resistance rating may be reduced.

Table 19.3.8 shows historical examples of the fire resistance for several types of concrete floor constructions. Table 19.3.9 shows historical test results for structural steel joist floor and roof constructions.

Fire-resistance ratings for floor and roof assemblies using proprietary materials are typically supplied by product manufacturers and can be found in code-approved fire resistance directories and guides. Materials and dimensioning for generic floor and roof assemblies deemed to have specified fire resistance rating can be found in ACI 216.1 *Code Requirements for Determining Fire Resistance of Concrete and Masonry Construction Assemblies*, AISC 360 *Specification for Structural Steel Building, and* AWC *Design for Code Acceptance (DCA) No. 3 Fire Rated Wood Floor and Wall Assemblies*.[9]

**TABLE 19.3.8** Reinforced Concrete Floor Constructions

| | Fire Resistance Rating | |
|---|---|---|
| *Materials* | *hr* | *min* |
| Reinforced Concrete (free or partly restrained, 1500–2500 psi) | | |
|  | | |
| 3 in. thick | — | 45 |
| 4 in. thick | 1 | 15 |
| 6 in. thick, 1 in. minimum protection for steel | 2 | — |
| Reinforced Concrete on Precast Joists | | |
|  | | |
| Reinforced concrete, 1:3½:4, 3 in. thick, no ceiling | 45 | — |
| Reinforced concrete, 1:3½:4, 3 in. thick, ceiling of gypsum wallboard ½ in. thick, nailed to wood, strips wired to joists | 1 | — |
| Combination of Tile and Concrete Floors | | |
|  | | |
| Concrete 2 in. or 1½ in. thick, and fire clay tile 6 in. or 4 in. thick, no ceiling finish | 1 | — |
| Concrete 1½ in. thick, and tile 4 in. thick with gypsum-sand plaster ceiling finish, 1:3 mix, 5/8 in. thick | 1 | 30 |
| Concrete 2 in. thick, and fire clay tile 6 in. thick with gypsum plaster ceiling finish, 1:3 mix, 5/8 in. thick | 2 | — |
| Concrete 2½ in. thick, limestone aggregate 4 in. thick, expanded slag concrete tile | 3 | — |
| Reinforced Concrete Ribbed Slab | | |
|  | | |
| Concrete, ribbed slab, limestone aggregate, $t$ = 1½ in., $S$ = 20 in. | — | 20 |
| Concrete, ribbed slab, limestone aggregate, $t$ = 2½ in., $S$ = 20 in. | — | 45 |
| Same with metal lath and 7/8 in. gypsum-sand plaster ceiling, 1:2, 1:3 mix | 2 | 30 |
| Concrete, ribbed slab, limestone aggregate, $t$ = 3 in., $S$ = 30 in. | 1 | — |

For SI units: 1 in. = 25.4 mm; 1 psi = 6.89 kPa.

**TABLE 19.3.9** Steel Joist Floor or Roof Constructions

| Joists | | | | | | | Fire Resistance Rating | |
|---|---|---|---|---|---|---|---|---|
| *Type* | *Depth (in.)* | *Floor Slab* | *Thickness (in.)* | *Furring* | *Ceiling Kind* | *Thickness (in.)* | *(hr)* | *(min)* |
| I or S[a] | 8 | T & G wood flooring on 2 in. by 2 in. wood strips | 25/32 | 3.4 lb metal lath | Gypsum—sand plaster | ¾ | — | 45[b] |
| I or S[a] | 8 | T & G wood flooring on 2 in. by 2 in. wood strips | 1 5/8 | 3.4 lb metal lath | Gypsum—sand plaster | ¾ | 1[b] | — |
| I or S[a] | 8 | Reinforced concrete, precast concrete, or gypsum planks | 2 | 3.4 lb metal lath | Gypsum—sand or portland cement-sand plaster | ¾ | 1 | — |
| S | 8 | Reinforced concrete or precast gypsum tile | 2¼ | 3.4 lb metal lath | Gypsum—sand plaster, 1:2; 1:3 mix | ¾ | 2 | — |
| S | 10 | Reinforced concrete or reinforced gypsum tile or planks | 2 | 3.4 lb metal lath | Neath gypsum, or gypsum-vermiculite plaster, 1:2; 1:3 | 1¾ | 2 | 30 |
| S | 10 | Reinforced concrete | 2½ | 3.4 lb metal lath | Gypsum—sand plaster | 7/8 | 2 | 30 |
| | | Reinforced concrete | 2½ | 3.4 lb metal lath | Gypsum-perlite of gypsum-vermiculite plaster, 1½:2; 1½:3 | ¾ | 3 | — |
| S | 8 | Reinforced concrete perlite or vermiculite aggregate | 2½ | 3.4 lb metal lath | Gypsum-perlite or gypsum-vermiculite plaster, 1½:2; 1½:3 | ¾ | 3 | — |
| S | 10 | Reinforced concrete, 1:2:4 gravel aggregate | 2½ | 3 lb metal lath | Gypsum-vermiculite or gypsum-perlite plaster, 1½:2; 1½:3 | 1 | 4 | — |
| S | 10 | Reinforced concrete, 1:2:4 gravel aggregate | 2 | Gypsum lath[c] | Gypsum-perlite or gypsum-vermiculite plaster, 1½:2½ | 5/8 | 1 | — |
| S | 10 | Reinforced concrete, 1:2:4 gravel aggregate | 2 | Gypsum and wires[c,d] | Gypsum-perlite or gypsum-vermiculite plaster, 1½:2½ | ½ | 2 | — |
| S | 10 | Reinforced concrete, 1:2:4 gravel aggregate | 2 | Gypsum[c,e] | Gypsum-vermiculite or perlite plaster, 1½:2; 1½:3 | 1 | 4 | — |
| S | 10 | Reinforced concrete, 1:2:3.4 gravel | 2½ | Gypsum and wires[c,d] | Sprayed-on mineral fiber | ¾ | 3 | — |
| S | 10 | Reinforced concrete, 1:2.5:3.5 gravel | 2 | Special Z section[f] | Special acoustical tiles (see UL list) | 5/8 | 2 | — |
| S | 12 | Reinforced concrete, gravel aggregate | 2 | Nailing channels 16 in. o.c. 2¾ in. × 7/8 in. | Type X[g] wallboard | 5/8 | 1 | 30 |
| S | 12 | Reinforced concrete, 1:3:3 2/3 gravel aggregate Reinforced concrete, 1:2:4 | 2 | 26 gauge 14 in. o.c. channels | Type X[g] wallboard applied with No. 6 by 1 in wallboard screws | 5/8 | 1 | 30 |
| S | 10 | gravel aggregate | 2 | 25 gauge nailing channels 16 in. o.c. | Gypsum board applied with 1¼ in. long barbed nails 3/8 in. diam. head | 5/8 | 1 | — |

[a]I-beam or open-web type joists.
[b]Combustible construction.
[c]All gypsum lath 3/8 in. perforated type.
[d]Gypsum lath and No. 20 gauge wires attached to nailing channels. Wires attached diagonally to reinforce and support lath and plaster.
[e]1 in. hexagonal mesh wire fabric to reinforce plaster and hold up lath and plaster.
[f]Special No. 25 gauge galvanized steel Z runners 12 in. o.c.
[g]Type X wallboard is gypsum board with a specially formulated core that provides greater fire resistance than regular gypsum board of the same thickness.
[h]Unsanded wood-fiber plaster.
For SI units: 1 in. = 25.4 mm; 1 lb = 0.454 kg.

## Walls and Partitions

Loadbearing and non-loadbearing walls and partitions, along with floor and roof assemblies, help define the functional layout of rooms and spaces in a building. In normal functional use of a building, these components provide privacy, security, protection from the elements, and noise control. They can also provide fire protection by delaying or preventing heat and products of combustion from spreading throughout the building.

The effectiveness of a barrier in preventing fire spread depends on several factors. One is fire severity, which is influenced by the fuel in the space, as well as the size and location of openings, the size of the room, and the thermal properties of the wall and ceiling construction. The fire severity represents the thermal load applied to the barrier surface. The performance of the barrier is affected by the materials of construction, as well as factors such as the applied structural loads or constraint, the details at connections, and the dimensions. Of great importance is the effect of openings and penetrations in the barrier. The most common cause of fire spread from one room to an adjacent room is through unprotected openings in barriers. Information on protection of openings can be found in NFPA 80, *Standard for Fire Doors and Other Opening Protectives.* Often code requirements and expensive constructions are rendered ineffective because of lack of attention to the details of opening protection.

Building codes through construction classifications identify the fire resistance requirements of walls and partitions. In addition, special locations, such as around vertical shafts, are required to provide specific fire resistances. Both combustible and noncombustible barriers can obtain fire resistance ratings in the standard fire test. The limitations expressed earlier in this chapter with regard to the interpretation of the fire resistance time durations apply here.

For a more detailed discussion of fire barrier systems, see Section 18, Chapter 1, "Confinement of Fires in Buildings," NFPA 221 *Standard for High Challenge Fire Walls, Fire Walls, and Fire Barrier Walls,* and NFPA 5000® *Building Construction and Safety Code*®.

Walls and partitions are commonly constructed of masonry, wood, or metal studs faced with fire-resistant materials. Table 19.3.10 gives historical examples of the fire resistance of loadbearing brick or clay tile walls. Figure 19.3.6 shows examples of the fire resistance of burned clay brick walls with and without plaster. Tables 19.3.11 and 19.3.12 provide historical examples of fire resistance ratings for wood stud walls and Figure 19.3.7 illustrates the fire resistance of stud walls faced with common construction materials. Table 19.3.13 and Figure 19.3.8 illustrate of the fire resistance of solid, non-loadbearing partition materials.

Fire-resistance ratings for wall and partition assemblies using proprietary materials are typically supplied by product manufacturers and can be found in code-approved fire resistance directories and guides. Materials and dimensioning for generic wall and partition assemblies deemed to have specified fire resistance ratings can be found in ACI 216.1 *Code Requirements for Determining Fire Resistance of Concrete and Masonry Construction Assemblies*, AISC 360 *Specification for Structural Steel Building, and* AWC *Design for Code Acceptance (DCA) No. 3 Fire Rated Wood Floor and Wall Assemblies*.[9]

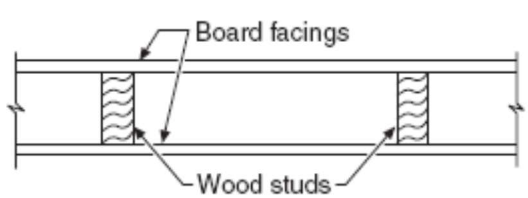
**TABLE 19.3.10** Load-Bearing Brick and Clay Tile Walls

| | | | Hollow Units | | Fire Resistance Ratings (hr) | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Combustible Members Framed 4 in. into Wall | | No Combustible Members Framed into Wall | |
| *Material* | *Wall Thickness (in.)* | *Solid Content of Walls (percent)* | *Number of Cells in Wall Thickness* | *Thickness of Shells of Unit (in.)* | *No Plaster* | *Plaster on Two Sides* | *No Plaster* | *Plaster on Two Sides* |
| Brick, clay, or shale | 12 | 90 to 100 | — | — | 8 | 9 | 10 | 12 |
| | 10[a] | 72 | {2 in. cavity | — | 2 | 2½ | 5 | 7 |
| Loadbearing hollow tile (not partition tile) | 8 | 90 to 100 | — | — | 2 | 2½ | 5 | 7 |
| | 4[b] | 90 to 100 | — | — | — | — | 1 | 1½ |
| | 12 | 45 | 3 | 0.7 | 2½ | 3½ | 3 | 6 |
| | 12[c] | 48 | 4 | 5/8 | 2½ | 4 | 5 | 7½ |
| | 10[a] | 36 | {2 + 2 in. cavity | — | — | 1¼ | — | 4 |
| | 8 | 48 | 3 or 4 | — | 1 | 1¾ | 2½ | 3½ |
| | 8 | 40 | 2 | — | ¾ | 1½ | 2 | 3 |
| | 6[b] | 40 | 2 | 5/8 | — | — | ¾ | 1½ |

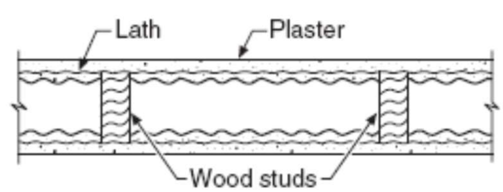
[a]Cavity wall with metal ties across cavity.
[b]Non-loadbearing wall restrained in all edges.
[c]Two units, 8 in. by 12 in. by 12 in. 6-cell and 3¾ in. by 12 in. by 12 in. 3-cell tiles, in wall thickness.
For SI units: 1 in. = 25.4 mm.

**TABLE 19.3.11** Wood Stud Walls and Partitions (Combustible) (Loadbearing and non-loadbearing: 2 in. by 4 in. studs spaced 16 in. on center, firestopped)

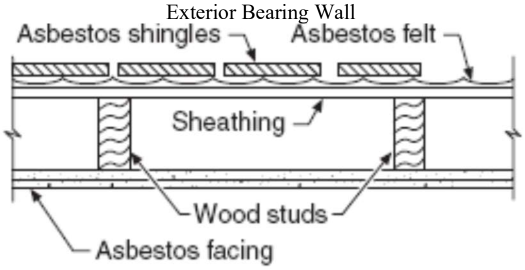
**Plasterless Types of Construction**




**Plaster and Lath Construction**




| | Fire Resistance Rating | | | | | Fire Resistance Rating | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Partition Hollow | | Partition Filled with Mineral Wool* | | | Partition Hollow | | Partition Filled with Mineral Wool* | |
| *Material* | *hr* | *min* | *hr* | *min* | *Material* | *hr* | *min* | *hr* | *min* |
| The following are applied to both sides of studs: | | | | | The following are applied to both sides of studs: | | | | |
| Sheathing boards (tongue-and-groove) ¾ in. thick | — | 20 | — | 35 | Gypsum-sand plaster, 1:2, 1:3, ½ in. thick on wood lath | — | 30 | 1 | — |
| Gypsum wallboard, 3/8 in. thick | — | 25 | — | — | Lime-sand plaster, 1:5, 1:7.5, ½ in. thick on wood lath | — | 30 | — | 45 |
| Gypsum wallboard, ½ in. thick (non-load-bearing only for mineral wool filled) | — | 40 | 1 | — | Gypsum-sand plaster, 1:2, 1:2, ½ in. thick on 3/8 in. perforated gypsum lath | 1 | — | — | — |
| Gypsum wallboard, 3/8 in. thick, in two layers each face | 1 | — | — | — | Gypsum-sand plaster, 1:2, 1:2, ¾ in. thick on metal lath | 1 | — | 1 | 30 |
| Gypsum wallboard, ½ in. thick, in two layers each face | 1 | 30 | — | — | Gypsum lath, ½ in. thick, | 1 | — | — | — |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | Type X, and 1/8 in. gypsum-sand plaster, each face | | | | |
| Gypsum wallboard, ½ in. thick, Type X, one layer each face | — | 45 | — | — | Gypsum wallboard, ½ in. thick, Type X, and 1/16 in. gypsum plaster, each face | 1 | — | — | — |
| Gypsum wallboard, 5/8 in. thick, Type X, one layer each face | 1 | — | — | — | Portland cement-lime-sand plaster, 1:1/30: 2, 1:1/30:3 and asbestos-fiber plaster, 7/8 in. thick on metal lath | 1 | — | — | — |
| Gypsum wallboard, 5/8 in. thick, Type X, on fire retardant wood fibreboard, ½ in. thick | 1 | — | — | — | Gypsum-vermiculite, or perlite plaster, 100 lb gypsum to 2½ $ft^3$ aggregate, ½ in. thick on 3/8 in. perforated gypsum lath | 1 | — | — | — |
| Fir plywood, ¼ in. thick | — | 10 | — | — | Gypsum perlite plaster, 1:2, ¾ in. thick on metal lath | 1 | — | — | — |
| Fir plywood, 3/8 in. thick | — | 15 | — | — | | | | | |
| Fir plywood, ½ in. thick | — | 20 | — | — | | | | | |
| Fir plywood, 5/8 in. thick | — | 25 | — | — | | | | | |
| Cement-asbestos board, 3/16 in. thick | — | 10 | — | 40 | | | | | |
| Cement-asbestos board, 3/16 in. thick, on gypsum wallboard, 3/8 in. thick | 1 | — | — | — | | | | | |
| Cement-asbestos board, 3/16 in. thick, on gypsum wallboard, ½ in. thick | 1 | 25 | — | — | | | | | |
| Exterior Bearing Wall   | | | | | Outside: Cement-asbestos shingles, 5/32 in. thick, on layer of asbestos felt on wood sheathing, ¾ in. thick, on wood studs; inside: Cement-asbestos facing, 1/8 in. thick on fiberboard, 7/16 in. thick | — | 30 | — | — |
| | | | | | Outside: Gypsum sheathing, ½ in. thick; inside 1:2 gypsum-sand plaster, ½ in. thick on 3/8 in. perforated gypsum lath | 1 | 30 | — | — |

*Mineral wool fill requires some degree of anchorage so as to be held in place after partition facing has been burned away.
For SI units: 1 in. = 25.4 mm; 1 lb = 0.454 kg; 1 $ft^3$ = 0.0283 $m^3$.

**TABLE 19.3.12** Various Finishes over Wood Framing, One Side (Combustible) with Exposure on Finish Side

| *Material* | *Fire Resistance Rating[a] (min)* |
|---|---|
| Fiberboard, ½ in. thick | 5 |
| Fiberboard, flameproofed, ½ in. thick | 10 |
| Fiberboard, ½ in. thick, with ½ in.-1:2, 1:2 gypsum-sand plaster | 15 |
| Gypsum wallboard, 3/8 in. thick | 10 |
| Gypsum wallboard, ½ in. thick | 15 |
| Gypsum wallboard, 5/8 in. thick | 20 |
| Gypsum wallboard, laminated, two 3/8 in. | 28 |
| Gypsum wallboard, laminated, one 3/8 in. plus one ½ in. thick | 37 |
| Gypsum wallboard, laminated, two ½ in. thick | 47 |
| Gypsum wallboard, laminated, two 5/8 in. thick | 60 |

| | |
|---|---|
| Gypsum lath, plain or indented, 3/8 in. thick, with ½ in.-1:2, 1:2 gypsum-sand plaster | 20 |
| Gypsum lath, perforated, 3/8 in. thick, with ½ in.-1:2, 1:2 gypsum-sand plaster | 30 |
| Gypsum-sand plaster, 1:2, 1:3, ½ in. thick, on wood lath | 15 |
| Lime-sand plaster, 1:5, 1:7.5, ½ in. thick, on wood lath | 15 |
| Gypsum-sand plaster, 1:2, 1:2, ¾ in. thick, on metal lath (no paper backing) | 15 |
| Neat gypsum plaster, ¾ in. thick on metal lath (no paper backing)[b] | 30 |
| Neat gypsum plaster, 1 in. thick, on metal lath (no paper backing)[b] | 35 |
| Lime-sand plaster, 1:5, 1:7.5, ¾ in. thick, on metal lath (no paper backing) | 10 |
| Portland cement plaster, ¾ in. thick, on metal lath (no paper backing) | 10 |
| Gypsum-sand plaster, 1:2, 1:3, ¾ in. thick, on paper-backed metal lath | 20 |

[a]From National Bureau of Standards BMS-92.
[b]Unsanded wood-fiber plaster.
For SI units: 1 in. = 25.4 mm.

**TABLE 19.3.13** Solid Partitions: Non-loadbearing

| | Fire Resistance Rating | |
|---|---|---|
| *Materials* | *hr* | *min* |
| Sheathing planks (tongue-and-groove), in 2 layers, each ¾ in. thick (1 in. nominal) and with joints staggered | — | 15[a] |
| Same, with layer of 30 lb asbestos felt between planks | — | 25[a] |
| Planking, pine (tongue-and-groove), 2 in. thick (nominal), wet vertically | — | 12[a] |
| Wallboard, 3/8 in. gypsum, full height facings on two thicknesses ½-in. coreboard, full height, cemented with staggered vertical joints to form 1¾ in. thick partition, external joints finish taped | 1 | — |
| Wallboard, 5/8 in. gypsum, Type X[c], full height facings, cemented and nailed or screwed to ribs made of two thicknesses of ½ in. gypsum board 3½ or 6½ in. wide and 1 in. by 5/8 in. wood runners top and bottom, external joints finish taped | 1 | — |
| Wallboard, ½ in. gypsum, full height, nailed and cemented to 1 in. thick coreboard factory laminated from two ½ in. thick by 24 in. wide coreboards with staggered edges, external joints staggered, butted and finish taped with joint finisher | 2 | — |
| Gypsum tile, 3 in. thick, cored | 2 | — |
| Gypsum tile, 4 in. thick, cored | 2 | — |

| | | |
|---|---|---|
| Gypsum tile, 3 in. solid, no cores | 3 | — |
| Gypsum tile, 3 in. cored, ½ in. of 1:3 gypsum-sand plaster on each side | 3 | — |
| Gypsum tile, 4 in. cored, ½ in. of 1:3 gypsum-sand plaster on each side | 4 | — |
| Gypsum-vermiculite or perlite plaster, 1½:2, 1½:3 by vol., ¾ in. thick on each side of 1½ in. gypsum lath, vertical full height, tied to floor and ceiling runners, no studs | 1 | 30 |
| Gypsum-sand plaster, 1:2, 1:3 by wt, ¾ in. thick on each side of ½ in. gypsum lath vertical full height, tied to floor and ceiling runners, no studs | 1 | — |
| Partition tile, burned clay, 4 in. thick, 1 cell in thickness | — | 10[b] |
| Cinder block, 4 in. thick, solid | 1[b] | — |
| Cinder block, 6 in. thick, 1 cell in thickness | 1 | 15[b] |
| Calcareous gravel concrete tile, 4 in. thick, 65 percent solid | — | 45[c] |
| Calcareous gravel concrete tile, 8 in. thick, 55 percent solid | 2 | 30 |

[a]Combustible.

[b]When plastered on both sides with ½ in. 1:3 gypsum-sand plaster, the tile partition described has 45 minute fire resistance and the cinder block and 4 in. concrete tile assemblies described have 2 hour fire resistance.

[c]Type X wallboard designates gypsum wallboard with a specially formulated core that provides greater fire resistance than regular gypsum wallboard of the same thickness.

For SI units: 1 in. = 25.4 mm; 1 lb = 0.454 kg.

**FIGURE 19.3.6** Fire Resistance of Burned Clay Brick Walls: (A) Unplastered; (B) Plastered Both Sides

**FIGURE 19.3.7** Fire Resistance of Wood or Metal Stud Partitions Faced with Gypsum Wallboards or Gypsum Plaster on Metal Lath: (A) Type X gypsum wallboards or wood fiber gypsum plaster; (B) 1:1 gypsum-sand plaster; (C) 1:2 gypsum-sand plaster; and (D) 1:2 and 1:3 gypsum-sand plaster

**FIGURE 19.3.8** Fire Resistance of Solid Partitions of Metal Lath and Plaster: (A) wood fiber gypsum; (B) 1:½ gypsum-sand; (C) 1:1 gypsum-sand; (D) 1:1½ gypsum-sand; (E) 1:2 gypsum-sand; (F) 1:2 and 1:3 gypsum-sand; (G) 1:2 and 1:3 Portland cement + 0.2 lime to cement

# CALCULATING EQUIVALENT FIRE RESISTANCE RATINGS

After over a century of use, fire resistance tests have generated a substantial amount of data about the behavior of structural members and assemblies during standard fire testing. These data have allowed calculation methods to be developed for many common elements of construction. In 1999, the American Society of Civil Engineers (ASCE) and the Society of Fire Protection Engineers (SFPE) published a jointly developed standard for the calculation of fire resistance of structural elements and assemblies. ASCE/SFPE 29 *Standard Calculation Methods for Structural Fire Protection,* provides methods of calculating fire resistance ratings that are equivalent to the results obtained from standard laboratory fire resistance tests. These calculation methods are applicable to structural steel, plain concrete, reinforced concrete, wood, concrete masonry, and clay masonry within specified limits of applicability.

ASCE/SFPE 29 consolidates in one place technical content found in material-specific standards such as ACI 216.1 *Code Requirements for Determining Fire Resistance of Concrete and Masonry Construction Assemblies*, AISC 360 *Specification for Structural Steel Building, and ANSI/*AWC *National Design Specification® (NDS) for Wood Construction*, and their supporting technical references. Over the years, these documents have been, and continue to be, revised, appended and harmonized.

The 2021 version of NFPA 5000® *Building Construction and Safety Code*® permits the use of ASCE/SFPE 29 to establish the fire resistance rating of structural elements and assemblies. It further permits the use of ACI 216.1 to establish the fire resistance rating of concrete or masonry elements or assemblies. The 2018 International Building Code (IBC) permits the use of ACI 216.1 for concrete, concrete masonry, and clay masonry, ASCE/SFPE 29 for steel, and *ANSI/*AWC NDS for wood to calculate equivalent fire resistance ratings.

## Equivalent Fire Resistance of Plain and Reinforced Concrete

ACI 216.1 *Code Requirements for Determining Fire Resistance of Concrete and Masonry Construction Assemblies* and similarly ASCE/SFPE 29 *Standard Calculation Methods for Structural Fire Protection* provide calculation procedures to determine the fire resistance of concrete walls, floors, roofs, and columns. They additionally include provisions for concrete cover to reinforcement in beams. Both ACI 216.1 and ASCE/SFPE 29 stipulate that the provisions contained therein apply to concrete members and assemblies designed in accordance with ACI 318 *Building Code Requirements for Structural Concrete and Commentary*. ASCE/SFPE 29 further limits its scope to concrete with specified compressive strength not to exceed 10,000 psi (69 MPa).

Loadbearing and non-loadbearing concrete walls, floor slabs and roof slabs are required to meet the minimum equivalent thickness requirements to provide fire resistance ratings of 1 hour to 4 hours specified in Table 19.3.14. For solid walls with flat surfaces, the equivalent thickness is equal to the actual thickness of the member. For hollow-core slabs or walls, or slabs, walls or other barrier elements with surfaces that are not flat, the reader is directed to ACI 216.1 (or ASCE/SFPE 29) to determine how equivalent thickness is to be calculated.

**TABLE 19.3.14** Fire-Resistance of Single-Layer Concrete Walls, Floors and Roofs

| Aggregate type | Minimum Equivalent Thickness for Fire Resistance Rating, in. | | | | |
|---|---|---|---|---|---|
| | 1 hour | 1-1/2 hours | 2 hours | 3 hours | 4 hours |
| Siliceous | 3.5 | 4.3 | 5.0 | 6.2 | 7.0 |
| Carbonate | 3.2 | 4.0 | 4.6 | 5.7 | 6.6 |
| Semi-Lightweight | 2.7 | 3.3 | 3.8 | 4.6 | 5.4 |
| Lightweight | 2.5 | 3.1 | 3.6 | 4.4 | 5.1 |

For SI units: 1 in. = 25.4 mm.

In some cases, ACI 216.1 distinguishes between normalweight concrete made with siliceous or carbonate aggregates, semi-lightweight concrete, and lightweight concrete for calculation of fire resistance ratings as follows (definitions in ASCE/SFPE 29 are similar):

**Siliceous-aggregate concrete** – concrete made with normal-density aggregates having constituents composed mainly of silica and or silicates (such as quartz or granite),
**Carbonate-aggregate concrete** – concrete made with coarse aggregate consisting mainly of calcium carbonate or a combination of calcium and magnesium carbonate (for example, limestone or dolomite),
**Semi-lightweight concrete** – concrete made with a combination of lightweight aggregates (expanded clay, shale, slag, slate or sintered fly ash) and normalweight aggregates, having an equilibrium density of 105 lb/ft$^3$ to 120 lb/ft$^3$ (1682 kg/m$^3$ to 1922 kg/m$^3$) in accordance with ASTM C567, and
**Lightweight-aggregate concrete** – concrete made with aggregates conforming to ASTM C330 or C331.

ACI 216.1 stipulates that the minimum cover protection for steel reinforcement shall be based on the "structural end-point" criteria of ASTM E119 that states that the specimen shall sustain the applied load during the standard fire resistance test without collapse. Minimum concrete cover requirements differ based on the member or assembly type (floor and roof slabs, beams) and the mechanical restraint conditions (restrained or unrestrained), as well as for nonprestressed and prestressed concrete. The reader is directed to ACI 216.1 (or ASCE/SFPE 29) to determine minimum concrete cover requirements to achieve calculated equivalent fire resistance ratings for concrete.

For columns having a design compressive strength of 12,000 psi (82.7 MPa) or less, to provide fire resistance ratings of 1 hour to 4 hours ACI 216.1 requires the least dimension of the column to be as specified in Table 19.3.15 and Table 19.3.16. For columns having a design compressive strength greater than 12,000 psi (82.7 MPa), to provide fire resistance rating of 1 hour to 4 hours the column must have a least dimension of 24 in. (609 mm). These values are independent of concrete type. Additional detailing and cover requirements are specified. ACI 216.1 additionally provides fire resistance rating calculations for structural steel columns protected by concrete and for hollow structural steel sections filled with concrete.

**TABLE 19.3.15** Minimum Concrete Column Size

| Aggregate type | Minimum Column Dimension for Fire Resistance Rating, in. | | | | |
|---|---|---|---|---|---|
| | 1 hour | 1-1/2 hours | 2 hours | 3 hours | 4 hours |
| Siliceous | 8 | 9 | 10 | 11 | 12 |
| Carbonate | 8 | 9 | 10 | 12 | 14 |
| Semi-Lightweight | 8 | 8-1/2 | 9 | 10-1/2 | 12 |

For SI units: 1 in. = 25.4 mm.

**TABLE 19.3.16** Minimum Concrete Column Size with Fire Exposure Conditions on Two Parallel Sides

| Aggregate type | Minimum Column Dimension for Fire Resistance Rating, in.* | | | | |
|---|---|---|---|---|---|
| | 1 hour | 1-1/2 hours | 2 hours | 3 hours | 4 hours |
| Siliceous | 8 | 8 | 8 | 8 | 10 |
| Carbonate | 8 | 8 | 8 | 8 | 10 |
| Semi-Lightweight | 8 | 8 | 8 | 8 | 10 |

* Minimum dimensions are acceptable for rectangular columns with a fire exposure condition on three or four sides, provided that one set of the two parallel sides of the column is at least 36 in. (914 mm) long.
For SI units: 1 in. = 25.4 mm.

## Equivalent Fire Resistance of Structural Steel

ASCE/SFPE 29 *Standard Calculation Methods for Structural Fire Protection* provides calculation procedures to determine equivalent fire resistance ratings for insulated steel columns, beams, girders, and trusses. The 2022 version of AISC 360 *Specification for Structural Steel Building* will similarly contain procedures for calculation of equivalent fire resistance ratings, in addition to providing tabulated fire resistance ratings for common generic steel assemblies and criteria for the design and evaluation of structural steel components, systems, and frames for fire conditions.

The fire resistance of structural steel members and assemblies can be improved using thermally insulating materials such as gypsum wallboard, sprayed fire-resistive materials, intumescent coatings, as well as encasement with concrete or masonry. Equation 1 (1m for SI units) calculates the fire resistance of steel wide-flange columns protected by sprayed or intumescent fire-resistant coatings.

$$R = \left[C_1\left(\frac{W}{D}\right) + C_2\right]h \tag{1}$$

$$R = \left[C_3\left(\frac{W}{D}\right) + C_4\right]h \tag{1m}$$

where,

*R* = Fire resistance, min
*W* = Nominal weight of the steel shape, lb/ft (kg/m)
*D* = Heated perimeter of the steel column, in. (mm)
*h* = Thickness of sprayed fire-resistant material, in. (mm)
$C_1$, $C_2$, $C_3$, $C_4$ = Constants that are empirically derived for the insulating material

The material-dependent constants should be determined for specific fire-protection materials based on standard fire resistance tests conducted in accordance with ASTM E119. Empirical constants for common coatings can be found in the AISC *Steel Design Guide 19*.[10] It should be noted that the version of the above formula used in Design Guide 19 (as well as in ASCE/SFPE 29) calculates the fire resistance in hours instead of minutes, so the values of the coefficients must be converted accordingly. The usage of these equations and the associated material-dependent constants should be limited to the range of their underlying fire test basis.

The fire resistance of columns with weight-to-heated perimeter ratios (*W/D*) less than or equal to 3.65 lb/ft/in. (0.22 kg/m/mm) and protected with Type X gypsum wallboard can be determined using Equation 2 (2m for SI units) for a maximum fire resistance rating of 4 hours.

$$R = 130\left[\frac{h(W'/D)}{2}\right]^{0.75} \tag{2}$$

$$R = 96\left[\frac{h(W'/D)}{2}\right]^{0.75} \tag{2m}$$

where,

W' = Total weight of steel shape and gypsum wallboard protection, lb/ft (kg/m)
*D* = Inside heated perimeter of the gypsum wallboard, in. (mm)
*h* = Total nominal thickness of Type X gypsum wallboard, in. (mm)

The total weight of the column plus wallboard can calculated using Equation 3 (3m for SI units).

$$W' = W + \frac{50(hD)}{144} \tag{3}$$

$$W' = W + 0.0008hD \tag{3m}$$

For columns with weight-to-heated-perimeter ratios, (*W/D*) greater than 3.65 lb/ft/in. (0.22 kg/m/mm), the thickness of Type X gypsum wallboard required to achieve the specified fire-resistance ratings is the same as the thickness determined for *W/D* = 3.65 lb/ft/in. (0.22 kg/m/mm). For additional detailing requirements for columns see ASCE/SFPE 29 or AISC 360.

ASCE/SFPE 29 (and similarly AISC 360) provides equations to establish an equivalent fire resistance rating for structural steel beams and girders that differ in size from those specified in approved fire resistance rated assemblies. Beams with a larger *W/D* ratio can always be substituted for the structural member listed with a specific fire-resistive covering without changing the thickness of the covering. Larger or smaller shapes than those approved in a fire resistance rated assembly may be substituted for the approved shape as long as the coating thickness is adjusted as a function of the *W/D* ratio according to Equation 4 (4m for SI units).

$$h_2 = \left(\frac{W_1/D_1+0.6}{W_2/D_2+0.6}\right)h_1 \quad (4)$$

$$h_2 = \left(\frac{W_1/D_1+0.036}{W_2/D_2+0.036}\right)h_1 \quad (4m)$$

where,

- $W$ = Nominal weight of the steel beam or girder, lb/ft (kg/m)
- $D$ = Heated perimeter of the steel beam or girder, in. (mm)
- $h$ = Thickness of sprayed fire-resistant material, in. (mm)

Subscript 1 refers to the beam and fire-resistant material thickness in the approved assembly. Subscript 2 refers to the substitute beam or girder and the required thickness of fire-resistant material.

The following are limitations of this formula:

1. $W_2/D_2$ values must be 0.37 (0.22 in SI units) or greater,
2. $h_2$ must be 3⁄8 in. (9.5 mm) or greater,
3. The unrestrained beam rating and restrained beam rating must both be at least 1 hour, and
4. For restrained beams, the beam must be a “compact” section per AISC *Steel Construction Manual*.[11]

The thickness of protection for steel truss members can be determined the same way as for columns. The weight-to-heated-perimeter ratio (*W/D*) of truss members exposed to fire on all sides can be determined on the same basis as columns. The weight-to-heated-perimeter ratio (*W/D*) of truss members that directly support floor or roof construction can be determined on the same basis as beams and girders.

## Equivalent Fire Resistance of Masonry

ACI 216.1 *Code Requirements for Determining Fire Resistance of Concrete and Masonry Construction Assemblies* and similarly ASCE/SFPE 29 *Standard Calculation Methods for Structural Fire Protection* provide calculation procedures to determine the fire resistance of concrete masonry and clay masonry assemblies.

The fire resistance rating for masonry begins by determined by calculating an equivalent thickness for the assembly and then using lookup tables that provide equivalent fire resistance ratings up to 4 hours. The lookup tables are differentiated by the type of masonry used and the structural application. Guidelines for masonry wall assemblies and reinforced masonry columns and lintels, as well as structural steel columns protected by masonry, are provided.

The equivalent thickness of masonry assembles, $T_{ea}$, can be calculated using Equation 5.

$$T_{ea} = T_e + T_{ef} \quad (5)$$

$$T_e = V_n/LH \quad (6)$$

where,

- $T_{ea}$ = Equivalent thickness of the masonry assembly, in. (mm)
- $T_e$ = Equivalent thickness of the masonry unit, in. (mm)
- $T_{ef}$ = Equivalent thickness of finishes, in. (mm)
- $V_n$ = Net volume of the masonry unit, in$^3$. (mm$^3$)
- $L$ = Specified length of masonry unit, in. (mm)
- $H$ = Specified height of masonry unit, in. (mm)

For concrete masonry construction, $V_n$, $L$, and $H$ are to be determined in accordance with ASTM C140. For clay masonry construction, the manufacturer specified values of $V_n$, $L$, and $H$ are used. The equivalent thickness, $T_e$, for hollow, ungrouted or partially grouted masonry units can be calculated using Equation 6. For solid or solid grouted masonry units, the equivalent thickness, $T_e$, is the specified thickness of the unit. The equivalent thickness, $T_e$, of hollow masonry units completely filled with loose material can be taken to be the specified thickness of the unit when the fill materials are sand, pea gravel, crushed stone, or slag conforming to ASTM C33; pumice, scoria, expanded shale, expanded clay, expanded slate, expanded slag, expanded fly ash, or cinders conforming to ASTM C331; perlite conforming to ASTM C549; or vermiculite conforming to ASTM C516. For clay masonry assemblies, ACI 216.1 requires that the equivalent thickness of finishes, $T_{ef}$, be taken as zero.

Lookup tables and installation requirements to account for the effect of finishes (e.g., plaster or gypsum wall board) on the fire resistance rating are provided in ACI 216.1 and similarly in ASCE/SFPE 29. For finishes applied to the non-fire-exposed side of the assembly, the actual thickness of the finish is multiplied by a factor that is a function of the wall construction type and finish material to establish an adjusted thickness of the finish. The adjusted finish thickness is then added to the equivalent thickness of the masonry assembly, $T_{ea}$. The finish modification factors are based on the "heat transmission" end-point criteria of ASTM E119 limiting the temperature rise of the unexposed side to an average of 250°F (139°C) for all measurement points or a maximum of 325°F (181°C) for any one point. Note that ASCE/SFPE 29 does not permit increase in fire resistance for hollow clay masonry where a finish is added to the non-fire-exposed side of the assembly. However, it does allow the equivalent thickness of finishes for other masonry types, $T_{ef}$, to be used in the calculation of the equivalent thickness of the masonry assembly, $T_{ea}$. For finishes applied to the fire-exposed side of the assembly, a time assigned to the finish in a lookup table is added to the calculated fire resistance rating of the assembly.

The fire resistance lookup tables in ACI 216.1 are valid for single-wythe assemblies but equations to extend the method to multi-wythe assemblies are provided. Additional requirements on the design, construction, and material requirements of masonry, including units, mortar, grout, control and expansion joint materials, and reinforcement can be found in ACI 216.1.

## Equivalent Fire Resistance of Wood

*Chapter 16 of ANSI/*AWC *National Design Specification® (NDS) for Wood Construction* establishes fire design procedures for exposed wood members and wood connections. The procedures for fire-exposed wood members calculate the capacity of the exposed wood using basic engineering mechanics and reduced properties computed assuming an effective char depth as a function of time.

For structures that require fire resistance rated assemblies or members, fire resistive membranes, such as gypsum wallboard, and other protective measures are typically used in conjunction with wood elements to achieve the required rating. In addition to the prescriptive requirements to achieve specific fire resistance ratings for generic wood assemblies provided in building codes and ratings available in fire resistance directories and guides, calculation procedures in lieu of laboratory testing are available. In North America, equivalent fire resistance ratings for wood frame assemblies are determined as the sum of the time assigned to the membrane on the fire-exposed side, the time assigned to the framing members, and the time assigned for additional contribution by other protective measures such as insulation. The membrane on the unexposed side of the assembly is not considered in determining fire resistance ratings. Details regarding this approach and tables of typical assigned times for the three components (membrane, framing, other protection) can be found in AWC *Design for Code Acceptance (DCA) No. 4 Component Additive Method (CAM) for Calculating and Demonstrating Assembly Fire Resistance*[12], AWC *Technical Report 10: Calculating the Fire Resistance of Exposed and Protected Wood Members*[13]*,* and ASCE/SFPE 29. The reader must refer to the applicable building code when determining permitted methods and values for calculating fire resistance ratings.

# STRUCTURAL MATERIALS AT ELEVATED TEMPERATURES

The ability of structural members and assemblies to perform successfully during and after a fire can depend significantly on both the thermal and mechanical properties of the constituent materials. Relevant thermal properties include thermal conductivity, specific heat, thermal expansion, emissivity, and mass loss. Relevant mechanical properties include tensile and compressive strength, modulus, and creep. In general, these properties vary as a function of temperature. Material properties are implicitly evaluated during standard fire resistance tests through how they contribute to the success of a member or assembly to achieve a fire resistance rating; however, it is sometimes necessary to characterize material properties individually. This is particularly true in the context of structural fire engineering where computational methods that use these properties are often applied.

This chapter provides a brief introduction into the behavior of common structural materials at elevated temperature. General information about the properties of building materials in fire can be found in the SFPE *Handbook of Fire Protection Engineering*.[14] Relations for variation of temperature dependent thermal and mechanical properties of construction materials can be found in the ASCE *Manuals and Reports on Engineering Practice No. 138 - Structural Fire Engineering*[15], the *Eurocode 2*[16], and the material specific references mentioned earlier in this chapter.

## Plain and Reinforced Concrete

The word concrete describes a diverse range of materials that are a mixture of portland cement (finely pulverized sintered mixture of clay and limestone or similar materials) or any other cementitious material, aggregates, and water. Reinforced concrete additionally includes steel or other materials embedded in the concrete to help carry tensile and shear forces. Concrete is used both as a loadbearing structural material and a protective covering for other materials to improve fire resistance. Concrete is noncombustible and considered to have good performance as a fire-resistive building material. However, its behavior at elevated temperatures can be complex and should be considered within the context of the application for which it is used. Significant influencing parameters on behavior from a structural viewpoint include the concrete strength, type of aggregate, use of steel or polymer fibers, moisture content, level of mechanical stress during the fire exposure, and the rate of heating. Kodur provides detailed discussion about tests methods and needs for characterizing concrete properties at elevated temperature.[17]

One significant factor in determining the change in strength and the thermal characteristics of concrete at elevated temperature is the type of aggregate. In the context of fire resistance, building codes in the United States differentiate normalweight concretes with siliceous aggregate (composed mainly of silica and or silicates, such as quartz or granite) or carbonate aggregate (composed mainly of calcium carbonate and magnesium carbonate, such as limestone or dolomite), and lightweight aggregate (e.g., expanded clay, shale, slag, slate or sintered fly ash). Aggregate properties can vary widely from region to region.

Figures 19.3.8 and 19.3.9 illustrate the effect of various aggregates on the fire resistance of reinforced-concrete slabs.[8] In this example, the lightweight aggregates, such as expanded shale and expanded slag, have considerably more fire resistance than do normal-weight concretes made from carbonate and siliceous aggregates.

**FIGURE 19.3.8** Effect of Various Types of Aggregate on the Fire Resistance of 4-¾ in. (121 mm) Slabs

**FIGURE 19.3.9** Relationship of Slab Thickness and Type of Aggregate to Fire Resistance

The moisture content of concrete has a significant influence on its thermal performance. A considerable quantity of the heat energy of a fire is expended in vaporizing the absorbed and capillary moisture in concrete. In the case of horizontal members, the water vapor is driven primarily upward and maintains a temperature at the top of the member of 212°F (100°C) until the water has been driven off. This increases the fire resistance, as it keeps the temperature on the unexposed side below that defined as the failure temperature in a standard fire resistance test. However, the voids caused by the evaporation of water contribute to shrinkage and a decrease in concrete strength. Moreover, depending on the moisture transport characteristics of the concrete, which are influenced by factors including the concrete density, pore structure, mechanical stress level, presence of polymer fibers, and the heating rate, as the water is driven out of the concrete spalling can occur. Spalling is the breaking of pieces or layers of concrete from the surface of the member, often in an explosive manner. The consequences of spalling may be limited if the damage area is small, but extensive spalling can lead to exposed reinforcement and loss of stability or integrity of the concrete member or assembly.

The mechanical properties of concrete are significantly reduced at elevated temperatures. Figure 19.3.10 shows the effect on the compressive strength and modulus of elasticity by increasing the temperature.[8] After heating to temperatures above about 752°F (400°C) the calcium hydroxide in portland cement will begin to dehydrate resulting in a significant reduction in the physical strength of the material. At higher temperatures aggregates begin to decompose.

**FIGURE 19.3.10** Effect of Temperature on Modulus of Elasticity and Compressive Strength.

## Structural Steel

Whether it acts as the reinforcement for concrete or the structural framework for buildings, steel is an essential load-carrying material in modern construction. From a designer's viewpoint, steel possesses many qualities, such as high strength and ductility, that make it a desirable structural material. However, the mechanical properties of steel are adversely affected by fire.

Steel is noncombustible and thus, like other noncombustible construction materials, does not contribute fuel to a fire. In the past, this property has sometimes provided a false sense of security with regard to its durability in a fire because it overshadowed the fact that steel loses strength and stiffness when subjected to temperatures attained in a fire. The relative seriousness of the problem depends on several factors, such as the function of the steel element, its level of stress, the support conditions, its surface area and thickness, and the temperature within the steel itself. This temperature can be quite different from the gas temperature in the compartment.

From a structural viewpoint, the yield stress of steel is a significant parameter in establishing load-carrying capacity. The tensile stress strain diagram for A36 steel at various temperatures is shown in Figure 19.3.11.[18] It can be seen that both the yield strength and the modulus of elasticity decrease with increasing temperatures. Figure 19.3.12 shows the ratios of modulus of elasticity and yield stress for A36 steel at various temperatures.[19] As can be seen, both values decrease with an increase in temperature.

**FIGURE 19.3.11** Stress-Strain Curves for an ASTM A36 Steel

**FIGURE 19.3.12** Ratio of Modulus and Yield Strength with Temperature—A36 Steel

This reduction in strength, combined with the reduction in the modulus of elasticity, causes compression members to be particularly sensitive to high temperatures. Figure 19.3.13 shows the influence of temperature on the critical stress of compression members of A36 steel.[19]

**FIGURE 19.3.13** Critical Stress as a Function of the Slenderness Ratio for Various Temperatures—A36 Steel

It should be recognized that the temperature considered for stress limitations is the temperature within the steel and not the compartment gas temperature. Because steel has a high thermal conductivity, it can transfer heat away from a localized heat source relatively quickly. This property, in conjunction with its thermal capacity, enables steel to act as a heat sink. When the steel has an opportunity to transfer heat to cooler regions, it can take a relatively long time for a member to reach its critical value. On the other hand, an extensive fire that distributes heat simultaneously over a greater area reduces this time considerably.

Related to this thermal activity is the effect of mass and surface area of structural steel members. Heavy, thick sections have a far greater resistance to the effects of building fires than do lighter ones. Unprotected lightweight sections, such as those found in trusses and open-web joists, can collapse after short durations of direct fire exposure.

Another property of steel that affects its performance at elevated temperatures is its coefficient of thermal expansion. For structural and reinforcing steels AISC 360 *Specification for Structural Steel Building* stipulates a coefficient of thermal expansion of $7.8 \times 10^{-6}$/°F ($14 \times 10^{-6}$/°C). This relatively high coefficient of expansion, compared to concrete or wood, can affect the behavior of the structural system. If the ends of a structural member are axially restrained, the axial expansion due to the heat causes additional mechanical stresses to be induced in the member. These stresses combined with those of the normal loading, can lead to local or global buckling of the member or failure of the member connections. If the structural member is not axially restrained, the free ends of member can move. This movement can cause an eccentrically-loaded bearing condition or potential unseating of the member creating a hazardous condition both for the structure and for fire fighters.

To illustrate the magnitude of movement, consider a beam with a length *L* of 50 ft (15.2 m) that is heated uniformly over its length from 72°F to 972°F (22°C to 522°C); a temperature change $\Delta t$ *of 900*°F (500°C). For a coefficient of linear thermal expansion $\alpha$ of $7.8 \times 10^{-6}$/°F ($14 \times 10^{-6}$/°C) the increase in length $\delta$ is:

$$\delta = \alpha \cdot L \cdot \Delta t = 7.8 \times 10^{-6}\, in./in./°F \cdot (50ft \times 12\, in./ft) \cdot 900°F$$

Thus 4.2 in. (107 mm).

Because unprotected structural steel loses its strength at high temperatures, it typically must be protected from exposure to the heat produced by fires. This protection, often referred to as fireproofing, slows the heat transfer to, and thus the temperature rise in, the steel. Methods of fireproofing structural steel include encasement of the member using concrete or masonry and application of a surface treatment. Installation of a suspended ceiling as part of a floor-ceiling assembly can also increase the fire resistance of the assembly.

Figure 19.3.14 illustrates encasement of a steel beam with concrete. Major disadvantages of this procedure are the cost, both due to the required formwork and concrete, and the increased weight of the members due to the added dead load. To reduce labor costs and weight, surface treatments applied directly to the member have become more popular. Low and medium density sprayed fire-resistive materials (Figure 19.3.15) are widely used today for protecting structural steel. Protection of structural steel with noncombustible coverings such as gypsum wallboard as shown in 19.3.16 is also possible. Encasement using concrete or masonry may still be used for columns.

**FIGURE 19.3.14** Encasement of a Steel Beam by Monolithic Casting of Concrete Around the Beam

**FIGURE 19.3.15** Spray-On Fireproofing

**FIGURE 19.3.16** Furred Steel Beams with Noncombustible Protective Coverings

While the fire protection provide by sprayed fire-resistive materials is excellent when it remains intact, it can be scraped off the member during construction or renovation. Sprayed-on coverings can also spall exposing the underlying steel due to excessive deformation of the structure; for example, during an earthquake or explosion. Thus, the long-term maintenance and integrity after extreme loading events are attributes that should be evaluated in considering sprayed-on coatings.

The proper surface condition of structural steel is critical to assure adequate adhesion of sprayed fire-resistive materials to the steel. The steel surface must be free of dirt, grease, oil, and loose mill scale. Prior to selecting a coating, product information should be reviewed to assure that the coating is appropriate for the conditions of service. Guidance on these tests can be found in ASTM E759, E760, E761, E859 and E937. Intumescent coatings can also be used to increase the fire endurance of structural steel. These coatings intumesce, or swell, when heated, thus forming an insulation around the steel.

Suspended ceilings consisting of lath and plaster, gypsum panels, or acoustical tile supported on a grid system as part of a floor-ceiling assembly can be used for fireproofing. The grid system can be suspended from wire hangers or it can be attached directly to the bottom chord of joists or to the bottom flange of beams. Sometimes ceiling tiles are either mechanically fastened or fitted into splines to prevent the pressures that occur in building fires from lifting them out of place. The effectiveness of this type of barrier protection is questionable because lack of control during construction can result in improper installation, such as inattention to expansion control in the suspension system. In addition, maintenance of ductwork and fixtures in the plenum area may be done by personnel who are not aware of the importance of the integrity of the ceiling to the fire protection system. Removed tiles are sometimes not replaced in a manner that will ensure their integrity during a fire. Consequently, the unprotected steel in the plenum area is exposed to fire and hot gases which significantly reduce its strength.

## Wood

Wood construction is preferable option for some architects and designers because of its pleasing appearance, economy, and sustainability. Because wood is combustible, its behavior at elevated temperatures and potential to contribute to the fire load in a structure must be considered in fire safety design.

When thinking about the fire resistance of wood structures, it is useful to distinguish between exposed wood members and protected wood assemblies. Exposed wood members typically have large cross-sectional dimensions and rely on the insulating effect of charring and the protected core of the section to provide sufficient strength in a fire. Protected wood assemblies combine fire resistive membranes, such as gypsum wallboard, and other protective measures, with wood elements. Protected wood assemblies are common for wood-frame construction, but fire resistive membranes are also used to protect larger wood members.

The burning of wood produces charring on the surface at an average rate of about 0.025 in./min (0.6 mm/min). This charring provides a protective coating that insulates the unburned wood and isolates it from the flame, thus retarding further pyrolysis. Therefore, thick members provide more structural integrity over the period of fire exposure than thin ones. Fire-retardant treatments may also be used to delay ignition and retard combustion.

Glue laminated (glulam) and Structural Composite Lumber (SCL), which are composed of smaller pieces of wood that are glued together, are commonly used today where large sections and long spans are needed. In recent years there has been increased used of cross laminated timber (CLT), which are large wood panels comprised of several layers of dimensional lumber oriented at 90 degrees to each other and glued together that can serve as both structural and barrier (wall and floor) elements in a building. Similar to solid heavy timber, these members also provide reserve strength during a fire when adhesives are used that do not result in delamination failures.

Wood-frame construction utilizes dimensional lumber of considerably smaller cross-sectional size than mass timber construction. The exposed area is greater relative to mass and the fire resistance considerably reduced. When this type of construction is exposed to a fire, it offers relatively little structural integrity. Therefore, protective membranes, such as gypsum wallboard or plaster, are important to provide fire resistance. Additional information related this topic can be found in Section 19, Chapter 1, “Types of Building Construction” and Section 19, Chapter 4, “Structural Fire Safety in One- and Two-Family Dwellings.”

# FIRE BEHAVIOR OF OTHER BUILDING MATERIALS

Many materials other than concrete, steel, and wood are used in modern building construction. They frequently make up large portions of the structure. Nonbearing partitions, insulation, building services, and finish materials are all important parts of building construction. Some of the nonstructural, thermally inert materials are used as fireproofing. Others may contribute fuel to a potential fire.

## Glass

Glass is utilized in three common ways in building construction. The most obvious is glazing for windows and doors. In this capacity the glass has little resistance to fire. It quickly cracks because of the temperature difference between the surfaces. Double glazing does not provide much improvement. Wire-reinforced glass is better because it provides somewhat greater integrity in a fire if it is properly installed. However, no glazing should be relied on to remain intact in a severe fire. Ordinary annealed glass has minimal resistance to fire and will break at heat fluxes near or below that required for piloted ignition of ordinary combustibles like wood. Fully tempered glass can resist higher heat fluxes but will break if engulfed in flames.

Glass block and ceramic glass also provide some duration (45 minutes or more) of endurance against fire, although the reduction of heat transmission is limited. The test standard for such assemblies is NFPA 257, *Standard on Fire Test for Window and Glass Block Assemblies.* Only certain types of glass significantly limit heat transmission, such as a special double or triple layer glass with a gel between layers of glass. When exposed to fire, the gel becomes opaque, reducing radiant heat transfer in addition to conductive heat transfer.

A second common use of glass in buildings is in fiberglass insulation. The fiberglass does not burn and is an excellent insulator. Glass fiber is often coated with a combustible resin binder. When used as an insulation, the amount of resin binder and resultant fuel load is such that the insulation is considered limited-combustible (see NFPA 220, *Standard on Types of Building Construction,* and NFPA 259, *Standard Test Method for Potential Heat of Building Materials*). Facings used as vapor barriers over glass fiber insulation, such as asphalt-coated kraft paper and some plastics, generally present more potential for fire spread than the insulation itself.

A third form in which glass is found in buildings is as reinforcement for fiberglass-reinforced plastic building products. The products include translucent window panels, siding, and prefabricated bathroom units. They have distinct advantages of economy and aesthetic appeal. The fiberglass acts as reinforcement for a thermosetting resin, usually a polyester. The resin, combustible even with fire retardants incorporated in the composition, frequently comprises 50 percent or more of the material. Although the fiberglass itself is noncombustible, the products are often quite combustible.

## Gypsum

Gypsum products, such as plaster and plasterboard, are excellent fire protection materials. The gypsum has a high proportion of chemically bound water. Evaporation of this water requires a great deal of heat energy, making gypsum an excellent, inexpensive, fire-resistant building material. A detailed description of numerous fire-rated assemblies using gypsum can be found in the *Fire Resistance Design Manual*[20] by the Gypsum Association.

## Masonry

Brick, tile, and concrete masonry products behave well when subjected to the elevated temperatures of a fire. Hollow concrete blocks may crack from the heat, but they generally retain their integrity. Brick can withstand high temperatures without severe damage. The fire resistance of masonry can be determined based on the type of aggregate used and the equivalent thickness of material.

# SUMMARY

Two important considerations in designing for structural integrity of a building during a fire are the ability of the structure to avoid collapse and the ability of barriers to prevent the fire from spreading to adjacent spaces. Three approaches to structural frame and barrier design for fire resistance include (1) standard fire resistance testing, (2) fire resistance ratings based on empirical equations, and (3) structural fire engineering design methods based on real fire exposure characteristics and structural system performance. Testing of structural members and assemblies determines the fire resistance rating, and indirectly, the behavior of structural materials at elevated temperatures. Tests to establish relevant thermal and mechanical properties of individual materials in assemblies is useful to understand behavior and is often required for structural fire engineering calculations.

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**NFPA Codes, Standards, and Recommended Practices**

*Reference to the following NFPA codes, standards, and recommended practices provide further information on the fire resistance of structural members and assemblies discussed in this chapter. (See the latest version* of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 80, *Standard for Fire Doors and Other Opening Protectives*
NFPA 220, *Standard on Types of Building Construction*
NFPA 221, *Standard for High Challenge Fire Walls, Fire Walls, and Fire Barrier Walls*
NFPA 251, *Standard Methods of Tests of Fire Resistance of Building Construction and Materials [withdrawn in 2010]*
NFPA 257, *Standard on Fire Test for Window and Glass Block Assemblies*
NFPA 259, *Standard Test Method for Potential Heat of Building Materials*
*NFPA 5000®, Building Construction and Safety Code®*

**References**

ACI 216.1, *Code Requirements for Determining Fire Resistance of Concrete and Masonry Construction Assemblies*
ACI 318, *Building Code Requirements for Structural Concrete and Commentary*
AISC 360, *Specification for Structural Steel Building*
ANSI/AWC NDS, *National Design Specification® (NDS) for Wood Construction*
ASCE/SFPE 29, *Standard Calculation Methods for Structural Fire Protection*

ASTM C33, *Standard Specification for Concrete Aggregates*
ASTM C140, *Standard Test Methods for Sampling and Testing Concrete Masonry Units and Related Units*
ASTM C330, *Standard Specification for Lightweight Aggregates for Structural Concrete*
ASTM C331, *Standard Specification for Lightweight Aggregates for Concrete Masonry Units*
ASTM C516, *Standard Specification for Vermiculite Loose Fill Thermal Insulation*
ASTM C549, *Standard Specification for Perlite Loose Fill Insulation*
ASTM C567, *Standard Test Method for Determining Density of Structural Lightweight Concrete*
ASTM E119, *Standard Test Methods for Fire Tests of Building Construction and Materials*
ASTM E759, *Standard Test Method for Effect of Deflection on Sprayed Fire-Resistive Material Applied to Structural Members*
ASTM E760, *Standard Test Method for Effect of Impact on Bonding of Sprayed Fire-Resistive Material Applied to Structural Members*
ASTM E761, *Standard Test Method for Compressive Strength of Sprayed Fire-Resistive Material Applied to Structural Members*
ASTM E859, *Standard Test Method for Air Erosion of Sprayed Fire-Resistive Materials (SFRMs) Applied to Structural Members*
ASTM E937, *Standard Test Method for Corrosion of Steel by Sprayed Fire-Resistive Material (SFRM) Applied to Structural Members*
*IBC, International Building Code*
UL 263, *Fire Tests of Building Construction and Materials*