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Designing Fire Protecton for Steel Beams

American Iron and Steel Institute

Subcommittee on Fire Technology of the Committee on Construction Codes and Standards

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DESIGNING FIRE PROTECTION FOR STEEL BEAMS

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I. INTRODUCTION

The ever-present threat to any building is fire. The combustibility of its contents—furniture, furnishings, etc.—makes it virtually impossible to build a truly *fireproof* structure. A more realistic—and attainable—design goal is to make buildings *fire resistant*. For this reason, *building codes* include fire resistance requirements that are based upon the "Standard Methods of Fire Tests of Building Construction and Materials," ASTM E119.

After careful investigation of applicable code requirements for fire resistance, the architect/engineer is then faced with the task of designing a structural system that will meet these requirements. Although information on fire resistance of various construction systems is available from numerous sources, the UL *Fire Resistance Directory*, published annually by the Underwriters Laboratories Inc. (UL), is the single, most widely used reference for design professionals and code enforcement officials. The UL Directory contains fire resistance ratings for literally hundreds of construction assemblies, many of which include protected steel beams. Rarely, however, do beams and girders specified for use in actual building designs exactly match those specified in any given UL Design. Hence, this publication is intended to show how steel beams different from those specified in UL fire resistant designs can be substituted without adversely affecting the rating.

The UL *Fire Resistance Directory* also offers guidelines on beam substitutions in the Design Information Section; much of this was developed directly from AISI-sponsored research. Information presented herein is consistent with the UL guidelines and is intended as supplement to the UL *Directory*. Specific examples covering frequently encountered beam substitution problems are included, as well as a useful Table of beam W/D ratios.

The UL *Directory* is recognized by model building code organizations as an "approved" reference for satisfying fire resistance requirements.*

*See Basic/National Building Code Section 1403.1.2 (1985 Supplement) and Standard Building Code Section 1002.1.

II. FIRE TESTS

As noted, building code fire endurance requirements are based on the "Standard Methods of Fire Tests of Building Construction and Materials," ASTM E119 (NFPA 251 and UL 263). During standard fire tests, "representative" samples of construction assemblies are exposed to a controlled laboratory fire in furnaces specifically designed for this purpose. The fire exposure is defined by the Standard Time-Temperature Curve which specifies the average furnace temperature as a function of time. Furnace temperature rises rapidly during initial phases of the test, reaching 1000F at 5 minutes, 1550F at 30 minutes; and then increases more gradually to 2000F at 4 hours. Floor and roof assemblies are tested with the underside exposed to the furnace fire. During the test, assemblies are loaded so as to develop design allowable stresses. No attempt is made to evaluate the assembly's suitability for continued use following exposure to fire.

Fire endurance is defined as the time during which an assembly continues to perform structurally and resists passage of fire to its unexposed side. Thus, fire endurance is specified in units of time—usually in hours or fractions thereof. In an ASTM E119 test, the fire endurance of an assembly is determined by the time at which any of several endpoint criteria occur:

- Structural collapse—defined as the failure of the assembly to continue supporting the superimposed applied loads.
- The *average* temperature rise of the unexposed surface of the assembly exceeds 250F. Additionally, the temperature rise recorded by any *individual* thermocouple cannot exceed 325F.
- Passage of flames or gases hot enough to ignite cotton waste on the unexposed side of the assembly.
- The occurrence of limiting steel temperatures.

RESTRAINED AND UNRESTRAINED RATINGS

To take into account different end support conditions possible in actual buildings, ASTM E119 was revised in 1970 to include two specific test conditions: *restrained* and *unrestrained*. A restrained condition is "one in which expansion at the supports of a load-carrying element resulting from the effects of fire is resisted by forces external to the element." Restrained test assemblies are constructed with the floor (or roof) slab built tight against a heavily reinforced restraining frame. Typically, steel shims are driven between the ends of steel beams and the restraining frame. In contrast, an *unrestrained* condition is "one in which the load carrying element is free to expand and rotate at its supports." When the dual classification system was developed, an appendix was also included in ASTM E119 to assist architects, engineers, and building officials in determining the proper classification (restrained or unrestrained) of conventional construction systems. Portions of this Appendix are included here in Section IV.

ASSEMBLY TESTS

ASTM E119 specifies two different procedures for determining fire endurance of beams and girders. In most cases, steel beams and girders are tested as part of a complete floor or roof assembly. The assembly must be at least 180 sq ft in area, with neither major dimension less than 12 ft in length. The floor and roof construction, as well as any supporting beams or girders, are all loaded during the test. Fire endurance of the total floor or roof system is evaluated during assembly tests.

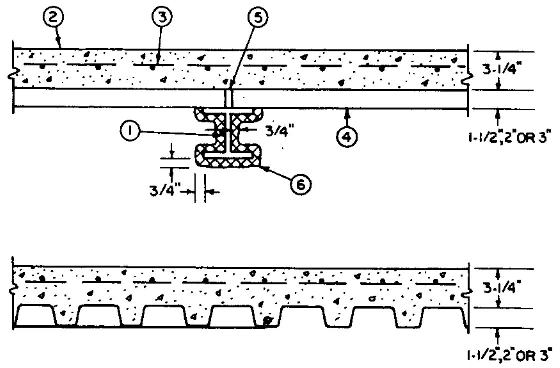
A typical assembly design in the UL *Directory* (Fig. 1) includes Restrained Assembly, Unrestrained Assembly, and Unrestrained Beam Ratings. The Restrained Assembly Rating applies if the floor or roof construction and framing in an actual building is "restrained" as defined in Section IV. Otherwise, Unrestrained Assembly and Beam Ratings apply. Note that "assembly" Designs never include separate Restrained Beam Ratings. For "restrained" construction, the beam is considered as but one element in the Restrained Assembly.

BEAM TESTS

Although beams and girders are usually tested as part of a floor or roof assembly, ASTM E119 includes provisions for testing them as individual members. In such tests, a typical section of floor or roof construction (not more than 7-ft wide) is built on top of the beam. These are frequently referred to as beam-only tests in order to differentiate them from the more common assembly tests. *In beam-only tests, fire endurance of the floor or roof construction is not evaluated.* As a result, minimum thickness slabs are usually used. Beams are always tested restrained. If the floor or roof construction is designed to act compositely with the beam, then the width of the floor assumed to act compositely is also restrained against longitudinal thermal expansion. Otherwise, the floor or roof construction is not restrained. Since fire endurance of the floor or roof is not evaluated during a beam-only test, such tests can seldom be used by themselves. In almost all cases, beam-only tests must be used in conjunction with assembly tests in order to satisfy building code requirements.

As noted earlier, all beam-only tests are restrained. Both *Restrained Beam* and *Unrestrained Beam Ratings* are established. The ratings are determined by the following endpoint criteria: Beam-only Designs are listed in the UL *Fire Resistance Directory* in the N- and S-series. A typical example is shown in Figure 2. Beam-only Designs include both Restrained and Unrestrained Beam Ratings. Since fire endurance of floor or roof construction is not evaluated, beam-only Designs never include assembly ratings; they are intended primarily for use in conjunction with assembly designs. According to ASTM E119, the ratings in a beam-only Design also apply when the beam is used in an assembly design "with floor or roof construction which has a comparable or greater capacity for heat dissipation from the beam than the floor or roof with which it was tested." Guidance on the use of beam-only Designs as given in the UL *Directory*, are discussed in Section V.

Design No. D913 Restrained Assembly Rating—2 Hr., Unrestrained Assembly Rating—0 Hr (See Item 4), Unrestrained Beam Rating—1 Hr.



1. **Beam—W8 x 17,** minimum size.
2. **Light-Weight Concrete**—Expanded shale or slate aggregate by rotary-kiln method or expanded clay aggregate by rotary-kiln or sintered-grate method, 102 pcf unit weight, 2000 psi compressive strength, vibrated, 4 to 7 per cent entrained air.
3. **Welded Wire Fabric**—6 by 6—10/10 SWG.
4. **Steel Floor and Form Units***—Composite 1½, 2, or 3 in. deep galv fluted or cellular units, min gauges are 22 MSG for fluted and 20/20 MSG for cellular. The following combination of units may be used: (1) All fluted; (2) All cellular; (3) Any blend of fluted and cellular. Welded to supports 12 in. O.C. max. Adjacent units button-punched or welded together 36 in. O.C. along side joints.

    Bowman Construction Products, Elwin G. Smith Div., Cyclops Corp.—30 in. wide, Types 1½"V-Grip, 1½"RV-Grip, 2"V-Grip, 2"VW; 24 in. wide, Types 1½"VW2, 1½"VW3, 1½"VW4, 3"V-Grip and 3"VW3.

    Merco Mfg., Inc.—36 in. wide Types B-Lok, B-Lok-R; 24 in. wide Types N-Lok, Lok 2, Lok 3.

    Vulcraft, Div. of Nucor Corp.—24 or 36 in. wide, Types 2.0VL or 3.0VL.

    Wheeling Corrugating Co.—24 in. wide, Type SB-200 or -300.

    The Unrestrained Assembly Rating is 1 Hr.—For unit clear spans of 9 ft 6 in. or less and minimum unit thickness of No. 18 MSG.

    Alternate Construction—Non-composite units of the same type listed above may be used provided allowable loading is calculated on the basis of non-composite design.
5. **Joint-Cover**—2 in. wide pressure-sensitive adhesive cloth tape.

6a. **Sprayed Fiber***—Applied by spraying with water, in one or more coats, to a final tamped or untamped thickness shown on sketch. Steel surfaces must be free of dirt, oil, or scale. When fluted steel deck is used, the area between the steel deck and the beam's top flange shall be sprayed. Tamping is optional. Use of adhesive or surface sealer is optional. Minimum average tamped or untamped density is 12 pcf, minimum individual tamped or untamped density is 11 pcf. For method of density determination refer to Design Information Section.

    United States Mineral Products Co.—Type D-C/F fiber, Type E.B.S. adhesive, Cafco Type 2 or 3 sealer.

6b. **Cementitious mixture***—Applied by mixing with water and spraying one or more coats, to a final thickness as shown in the above illustration, to steel surfaces which are free of dirt, oil or scale. When fluted steel deck is used, the area between the steel deck and the beam's top flange shall be sprayed. Min avg density is 34 pcf with a min ind density of 31 pcf. For method of density determination refer to Design Information Section.

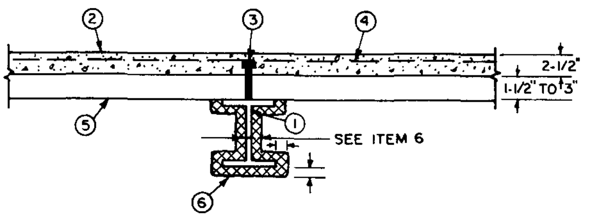
    United States Mineral Products Co.—Type 350.

7. **Shear Connector Studs—Optional**—(Not Shown)—Studs, ¾ in. diam, by 3 to 3½ in. long for 1½ in. deep form units to 5¼ in. long for 3 in. units, headed-type or equivalent per AISC specifications. Welded to top flange of beam through form units.

*Bearing the UL Classification Marking

Figure 1. Typical UL Assembly Design (from UL *Fire Resistance Directory*, 1983).

Design No. N708 Restrained Beam Ratings—1, 2, 3 and 4 Hr.,
Unrestrained Beam Ratings—1, 1½, 2, 3 and 4 Hr.



1. **Steel Beam**—W8 x 28 min size.
2. **Normal Weight or Lightweight Concrete**—Compressive strength, 3000 psi. For normal weight concrete either carbonate or siliceous aggregate may be used. Unit weight, 148 pcf. For lightweight concrete, unit weight 110 pcf.
3. **Shear Connector**—(Optional)—Studs, ¾ in. diam headed type or equivalent per AISC specifications. Welded to the top flange of beam through the steel floor units.
4. **Welded Wire Fabric**—(Optional)—6 x 6-10/10 SWG.
5. **Steel Floor and Form Units***—1 5/16 in. deep corrugated units; or 1½ to 3 in. deep fluted or cellular units, welded to beam.
6. **Cementitious Mixture***—Applied by mixing with water and spraying in more than one coat to the beam to the final thicknesses shown below. When fluted or corrugated steel floor units are used, crest areas shall be filled with cementitious mixture above the beam. Beam surfaces must be clean and free of dirt, loose scale and oil. Min avg and min ind density of 17/15 pcf for Type MK-4 and 15/14 pcf for Type MK-5. For method of density determination, see Design Information Section.

Unrestrained Beam Rating, Hr	**Minimum Thickness, In.**
1	½
1½	⅞
2	1⅛
3	1⅝
4	2

Restrained Beam Rating, Hr	**Minimum Thickness, In.**
1	½
1½	¾
2	1
3	1½
4	2

Construction Product Div., W.R. Grace & Co. of Canada Ltd.—Types MK-4 and MK-5.
Hyde & Co., Ltd., F.—Types MK-4 and MK-5.
Robinson Insulation Co.—Types MK-4 and MK-5.
Southwest Vermiculite Co., Inc.—Types MK-4 and MK-5.
Vermiculite-Intermountain, Inc.—Types MK-4 and MK-5.
Vermiculite Prods., Inc.—Types MK-4 and MK-5.
Zonolite Const. Prods. Div., W.R. Grace & Co.—Types MK-4 and MK-5.

*Bearing the UL Classification Marking

Figure 2. Typical UL *beam-only* Design. (from the UL *Fire Resistance Directory* 1983)

III. BUILDING CODE REQUIREMENTS

Building codes define the required fire resistance level for each of various structural elements, including beams and girders, in terms of "Construction Types." Generally, "Type of Construction" required for any given application is determined by occupancy, building height and floor area. Other considerations such as street frontage or perimeter accessibility, sprinkler protection, and fire limits also affect the required "Type of Construction." In-depth treatment of this subject is beyond the scope of this publication.* It may be presumed that most designers are familiar with those building code requirements that determine the required "Type of Construction." The following discussion covers the application of Types of Construction requirements in the three nationally recognized model building codes to the design of fire protection for steel beams and girders.

*A thorough discussion of "Types of Construction" is included in *Fire Protection Through Modern Building Codes,* American Iron and Steel Institute publication.

BASIC/NATIONAL BUILDING CODE

The Basic/National Building Code is developed and published by the Building Officials and Code Administrators International (BOCA). Structural fire resistance requirements are set forth in Table 401 of that publication. Portions of that Table most pertinent to steel beams and girders are shown in Table I.

Floor construction, beams and girders are generally required to have the same fire resistance rating. An exception occurs in the case of girders which support more than one floor. An example is load transfer girders that directly support columns that in turn support other floors or a roof.

TABLE I FIRE RESISTANCE RATINGS OF STRUCTURAL ELEMENTS (IN HOURS) (From Basic/National Building Code, Table 401)

STRUCTURAL ELEMENT		Type of Construction 1A	1B	2A	2B	2C
8 Interior bearing walls, bearing partitions, columns, girders, trusses (other than roof trusses) and framing	Supporting more than one floor	4	3	2	1	0
	Supporting one floor only	3	2	1½	1	0
	Supporting a roof only	3	2	1½	1	0
10 Floor construction including beams		3	2	1½	1	0
11 Roof construction including beams, trusses and framing, arches and roof deck	15 ft or less in height to lowest member	2	1½	1	1	0
	More than 15 ft but less than 20 ft in height to lowest member	1	1	1	0	0
	20 ft or more in height to lowest member	0	0	0	0	0

STANDARD BUILDING CODE

The Standard Building Code is developed and published by the Southern Building Code Congress International (SBCCI). Structural fire resistance requirements are set forth in Table 600 of that publication. Portions of the Table, most pertinent to steel beams and girders, are shown here in Table II. As in the case of the Basic/National Building Code, beams and girders are generally required to have the same fire resistance rating as floor or roof construction, with an exception for some load transfer girders.

UNIFORM BUILDING CODE

The Uniform Building Code (UBC) is developed and published by the International Conference of Building Officials (ICBO). In that publication, fire resistance requirements are set forth in Table 17-A. Portions most pertinent to steel beams and girders are shown here in Table III. The UBC is unique in that fire resistance requirements are specified for the "structural frame" which is defined in Section 1702 as follows:

The structural frame shall be considered to be the columns and the girders, beams, trusses and spandrels having direct connections to the columns and all other members which are essential to the stability of the building as a whole. The members of floor or roof panels which have no connection to the columns shall be considered secondary members and not a part of the structural frame.

As a result, in Type I buildings, girders and beams that frame into columns are required to have a 3-hour fire resistance rating, whereas floors are required to have a 2-hour rating. In some cases, exterior spandrel girders and beams are required to have a 4-hour rating. Such re-

TABLE II REQUIRED FIRE RESISTANCE (IN HOURS)
(From Standard Building Code, Table 600)

	Type of Construction			
STRUCTURAL ELEMENT	Type I	Type II	Type IV 1 Hour	Type IV Unprotected
BEAMS, GIRDERS, TRUSSES AND ARCHES				
Supporting more than one floor or columns	4	3	1	NC
Supporting one floor only	3	2	1	NC
Supporting a roof only	1½	1	1	NC
FLOOR CONSTRUCTION	3	2	1	NC
ROOF CONSTRUCTION	1½	1	1	NC

NC: Unprotected Noncombustible Construction

TABLE III FIRE-RESISTIVE REQUIREMENTS (IN HOURS)
(From Uniform Building Code, Table 17A)

	Noncombustible			
	Type I	Type II		
BUILDING ELEMENT	Fire-Resistive	Fire-Resistive	1 Hour	N
Structural Frame	3	2	1	N
Floors	2	2	1	N
Roofs	2	1	1	N

N: Noncombustible construction with no general requirements for fire-resistance.

quirements present special problems to the designer, the handling of which will be covered in Section V (Beam Substitutions).

The Uniform Building Code also contains unique provisions on the use of restrained ratings. Section 4302 includes the following restriction:

> *Fire-resistive assemblies tested under U.B.C. Standard No. 43-1 (ASTM E119) shall not be considered to be restrained unless evidence satisfactory to the building official is furnished by the person responsible for the structural design showing that the construction qualifies for a restrained classification in accordance with Section 43.144 of U.B.C. Standard No. 43-1. Restrained construction shall be identified on the plans.*

The "evidence satisfactory to the building official" necessary to substantiate the recognition of restrained ratings will obviously vary from jurisdiction to jurisdiction, and architects and engineers are encouraged to consult with appropriate building officials before proceeding with design. To illustrate differences between restrained and unrestrained ratings, unrestrained ratings based on the UBC are used in the examples given in Section VI.

At the time this provision was adopted, a related section on analytical fire resistant design was also included in UBC Section 4302:

> *As an alternative to Tables No. 43-A, B, and C, fire-resistive construction may be approved by the building official on the basis of evidence submitted by the person responsible for the structural design showing that the construction meets the required fire-resistive classification.*

The stated purpose of both changes was to encourage development and use of analytical methods for designing fire resistant buildings. By discouraging recognition of "restrained ratings," ICBO has adopted a very conservative position with respect to fire resistant construction. For example, unrestrained assemblies often require almost twice as much beam protection as restrained assemblies in order to develop an equivalent hourly rating. At the same time, however, ICBO agreed to permit use of analytical design that can be used to justify classification as restrained construction. As noted in Section VII, AISI sponsored the development of a computer program, FASBUS II, for elevated temperature structural analysis. To date, this program has been successfully used to analyze spandrel girders in two high-rise office buildings designed under the UBC. In both cases, significant reductions in the thickness of required fire protection were realized. As a result, architects and engineers who use unrestrained ratings in accordance with the UBC are encouraged to consider the FASBUS II computer program. This is particularly important in the case of large buildings where the cost of analysis can be recouped many times over through savings in fire protection materials.

IV. FACTORS AFFECTING FIRE RESISTANCE

In the problems discussed here (Section VI), it is assumed that the architect/engineer has already selected a UL Design satisfactory in all respects except beam size. This occurs quite often since tested beams are usually not those found in economic structural designs. Hence, what follows is a discussion of the factors that affect fire resistance of steel beams.

W/D RATIO AND PROTECTION THICKNESS

Heat transfer principles indicate that the rate of temperature change in a body will vary *inversely* with its mass, and *directly* with the surface area through which heat is transferred to the body. Thus, a significant factor influencing a steel member's fire resistance is termed, the *W/D ratio*, where W is the weight per unit length of the member (lb/ft), and D is the inside perimeter of the fire protection material (inches). Expressions for calculating D for both contour and box fire protection profiles are given in Figure 3. When calculating the heated perimeter of beams, it is important to recognize that the steel member is exposed to fire on only three sides. Table XII gives W/D ratios for commonly used beam shapes for both contour and box fire protection profiles.

AISI sponsored a UL research project to develop a beam substitution equation.* The principal objective was to obtain data on the performance of various size beams under conditions of the ASTM E119 Standard Fire Test. The study confirmed the fact that fire resistance of a structural steel beam is a direct function of both its W/D ratio and the thickness of applied fire protection material. On this basis, a beam substitution equation was developed and included in the 1984 UL *Directory*. This equation and its use is explained in Section V.

**Fire Test of Loaded Restrained Beams Protected by Cementitious Mixture*, March 16, 1984 UL Report to AISI, File NC505-11, Project 82NK7962.

STRESS LEVEL

In most cases, Standard Fire Tests are conducted with the assembly loaded so as to develop allowable design stresses in the steel beams. In actual practice, however, stresses present in many beams and girders are often well below maximum allowable values. For example, the critical loading condition for spandrel girders and other rigid members in moment resisting frames is a combination of vertical loads and lateral forces (such as wind and/or seismic) which occur only infrequently—if ever—at allowable design stress levels. Furthermore, in high rise building frames, these structural members have to be designed to limit the lateral motion of the frame, the drift, by requiring an appropriate increase in member stiffness. In most cases, this means a decrease in working stresses. As a result, the actual

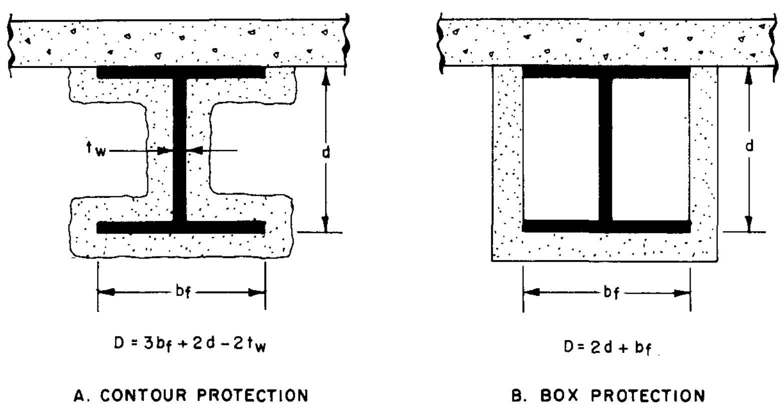


Figure 3. Structural steel beam heated perimeter (D) determination for CONTOUR (A) or BOX (B) fire-protection profiles can be determined by the formula given for the respective type.

Table IV RESTRAINED AND UNRESTRAINED CONSTRUCTION SYSTEMS (From ASTM E119 Table X3.1)

I Wall bearing:

Single span and simply supported end spans of multiple bays:[a]

(1) Open-web steel joists or steel beams, supporting concrete slab, precast units, or metal decking . . . . unrestrained

(2) Concrete slabs, precast units, or metal decking . . . . unrestrained

Interior spans of multiple bays:

(1) Open-web steel joists, steel beams or metal decking, supporting continuous concrete slab . . . . restrained

(2) Open-web steel joists or steel beams, supporting precast units or metal decking . . . . unrestrained

(3) Cast-in-place concrete slab systems . . . . restrained

(4) Precast concrete where the potential thermal expansion is resisted by adjacent construction[b] . . . . restrained

II. Steel framing:

(1) Steel beams welded, riveted, or bolted to the framing members . . . . restrained

(2) All types of cast-in-place floor and roof systems (such as beam-and-slabs, flat slabs, pan joists, and waffle slabs) where the floor or roof system is secured to the framing members . . . . restrained

(3) All types of prefabricated floor or roof systems where the structural members are secured to the framing members and the potential thermal expansion of the floor or roof system is resisted by the framing system or the adjoining floor or roof construction[b] . . . . restrained

III Concrete framing:

(1) Beams securely fastened to the framing members . . . . restrained

(2) All types of cast-in-place floor or roof systems (such as beam-and-slabs, flat slabs, pan joists, and waffle slabs) where the floor system is cast with the framing members . . . . restrained

(3) Interior and exterior spans of precast systems with cast-in-place joints resulting in restraint equivalent to that which would exist in condition III(1) . . . . restrained

(4) All types of prefabricated floor or roof systems where the structural members are secured to such systems and the potential thermal expansion of the floor or roof systems is resisted by the framing system or the adjoining floor or roof construction[b] . . . . restrained

IV Wood construction:

All types . . . . unrestrained

---

[a]Floor and roof systems can be considered restrained when they are tied into walls with or without tie beams, the walls being designed and detailed to resist thermal thrust from the floor or roof system.

[b]For example, resistance to potential thermal expansion is considered to be achieved when:

(1) Continuous structural concrete topping is used,

(2) The space between the ends of precast units or between the ends of units and the vertical face of supports is filled with concrete or mortar, or

(3) The space between the ends of precast units and the vertical faces of supports, or between the ends of solid or hollow core slab units does not exceed 0.25% of the length for normal weight concrete members or 0.1% of the length for structural lightweight concrete members.

stresses in such members under normal loading conditions may be relatively low.

As illustrated in Figure 4, the strength of steel decreases as temperature increases. Thus, the "failure" temperature of steel is a function of applied stress. Hence, on lightly loaded members, the thickness of applied protection can be reduced while still maintaining the protected member's structural fire resistance. Although not specifically recognized, this concept has begun to emerge as a viable design alternative.

At present, designs based on this concept require a structural analysis at elevated temperatures. Such analysis is possible through the use of the FASBUS II computer program described in Section VII. At present, this approach has been successfully applied in two west coast high-rise building designs. Both have moment-resisting frames with large spandrel girders. Using the FASBUS II program, the designers were able to reduce the thickness of fire protection material applied to the spandrel girders by approximately 33 percent when only dead and live loads were considered. Note that these are reductions from the thickness of protection that would otherwise be required by the UBC (3-hour unrestrained girder ratings).

FLOOR AND ROOF CONSTRUCTION

One of the least understood factors affecting fire resistance rating of steel beams is the influence of roof deck or floor slab construction. Concrete

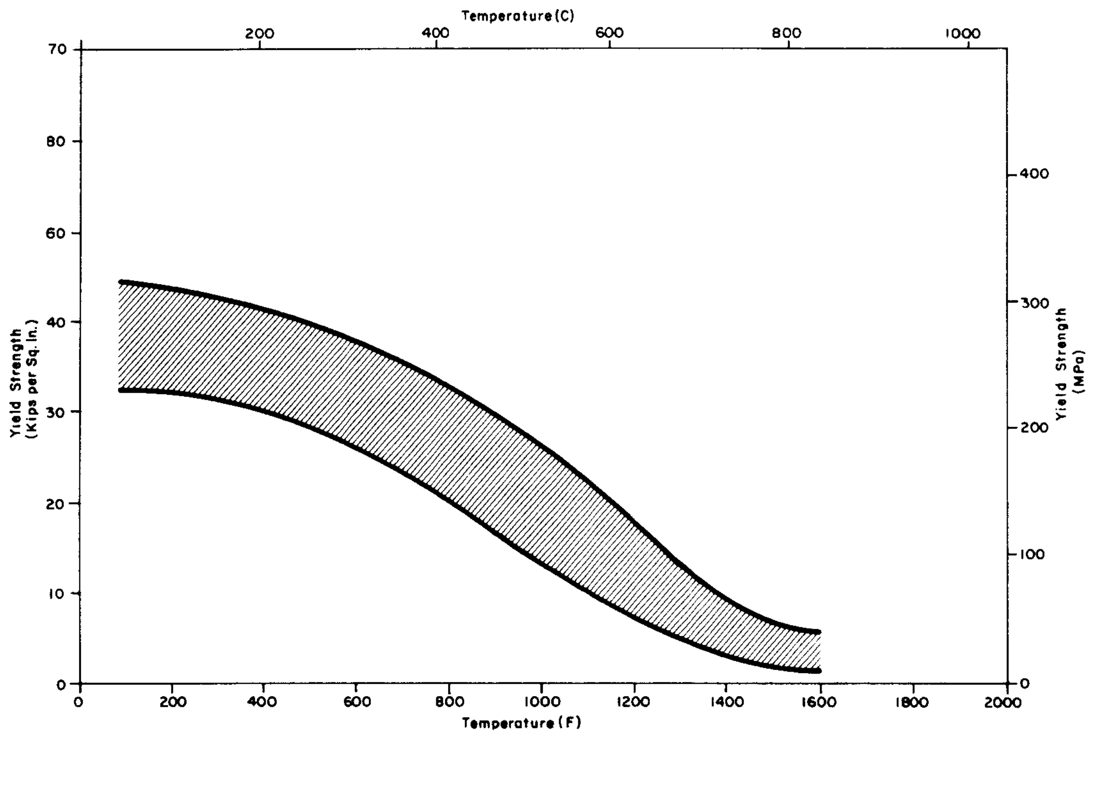


Figure 4. Yield strength of ASTM A36 structural steel at elevated temperatures.

slabs act as a heat sink, absorbing heat from the beam, thus delaying the temperature rise of the beam. In contrast, insulated steel roof decks retard the escape of heat from the beam, resulting in higher beam temperatures. While this is an extreme comparison (an insulated roof deck vs. a concrete slab), it does illustrate the influence that deck/slab construction can have on beam temperature and thus fire resistance ratings.

Other deck/slab construction details can also influence the temperature of protected steel beams. For example, an unprotected steel deck will transmit more heat into the top flange of a steel beam than an identical, protected steel deck. The UL *Fire Resistance Directory* correctly points out that:

> *Beam ratings depend upon the type of floor or roof that the beam supports and the protection, if any, on the floor or roof units, as well as the type and thickness of protection applied to the beam.*

Thus, changes in floor slab or roof deck construction, beyond that specifically permitted in individual UL Designs, are difficult to make without adversely affecting the fire resistance rating. However, this restriction does not pose a major problem provided that the architect/engineer selects UL Designs with floor slab and roof deck construction consistent with that desired.

RESTRAINT, CONTINUITY, AND REDUNDANCY

Structural continuity and redundancy, as well as restraint against thermal expansion, are all factors that significantly affect fire endurance of beams and floor and roof assemblies in real buildings. A typical ASTM E119 test specimen represents a relatively small sample of an actual floor or roof structure. Realistically simulating the restraint, continuity, and redundancy present in actual buildings during a Standard Fire Test is extremely difficult. Furthermore, the degree of restraint, continuity, and redundancy present in an actual building will vary as a function of its geometry, framing system and other factors. Because of this complexity, ASTM E119 was revised (1970) to include two specific test conditions, *restrained* and *unrestrained*, that are intended to simulate two of the many end support conditions found in actual buildings.

When this dual classification system was introduced, recognition was given to the fact that most architects, engineers, and building officials were not familiar with structural fire testing and would, therefore, have difficulty properly applying restrained and unrestrained ratings. Hence, an appendix was added to the Standard Fire Test titled "Guide for Determining Conditions of Restraint for Floor and Roof Assemblies and for Individual Beams." This appendix gives the following definition of restrained assemblies.

> *Floor and roof assemblies and individual beams in buildings shall be considered restrained when the surrounding or supporting structure is capable of resisting substantial thermal expansion throughout the range of anticipated elevated temperatures. Construction not complying with this definition is assumed to be free to rotate and expand and shall therefore be considered unrestrained.*
>
> *This definition requires the exercise of engineering judgment to determine what constitutes restraint to 'substantial thermal expansion.' Restraint may be provided by the lateral stiffness of supports for floor and roof assemblies and intermediate beams forming part of the assembly. In order to develop restraint, connections must adequately transfer thermal thrusts to such supports. The rigidity of adjoining panels or structures should be considered in assessing the capability of a structure to resist thermal expansion. Continuity, such as that occurring in beams acting continuously over more than two supports, will induce rotational restraint which will usually add to the fire resistance of structural members.*

As an aid to users, the ASTM E119 appendix includes a listing of the most common structural systems, and indicates those that can be considered restrained in actual buildings (reprinted here in Table IV). The appendix adds that "having these examples in mind as well as the philosophy expressed in the Preamble, the user should be able to rationalize the less common types of construction."

V. BEAM SUBSTITUTIONS

Individual Designs in the UL *Fire Resistance Directory* specify *minimum* beam sizes. Rarely will the beam(s) in an actual building exactly match those specified. As a result, designers are constantly confronted with the problem of substituting different beam shapes other than those specified. In general, beam substitutions can be made in accord with the UL *Directory* in three different ways.*

1. LARGER BEAMS

Beams with a larger W/D ratio can always be substituted for the shape given in an individual design without changing the thickness of fire protection material.

This general principle applies in *all* cases where steel beams are specified, including both beam-only and assembly designs. In many cases, however, the minimum beam size specified in UL Designs is a relatively shallow, compact shape with a W/D ratio greater than that of many economical shapes commonly used for floor and roof beam applications. As a result, beam substitutions employing this general principle are often not possible. In such cases, designers should use the beam substitution equation that permits replacement of a shape with a smaller W/D provided that the thickness of spray-applied protection is *increased.*

Even when the direct substitution of beams with a larger W/D ratio is possible, designers are encouraged to consider using the beam substitution equation. In these instances the thickness of spray-applied protection can be reduced thereby resulting in a more economical design.

*It should be noted that the UL *Directory* does not permit substitution of composite beams into Designs that specify noncomposite beams. If, however, composite beams are specified in an individual Design, noncomposite beams may be used.

2. BEAM SUBSTITUTION EQUATION

Based on AISI-sponsored research, UL developed an equation that permits substitution of beam shapes different from those specified in individual Designs provided that the thickness of the spray-applied protection is adjusted as a function of the W/D ratios. In other words, beams having smaller W/D ratios require an increase in the protection thickness while a decrease is permitted for beams having larger W/D ratios. Based upon beam temperature limits of 1100/1300F, in a strict sense this equation was derived directly from Unrestrained Beam Ratings. However, the fire resistance of Restrained Assemblies and Restrained Beams are also a function of these temperature limits. Therefore, this equation can also be applied to Restrained Beams and beams in Restrained Assemblies, and was published in the January 1984 UL *Fire Resistance Directory.* To aid in the use of this equation, Table XII gives W/D ratios for commonly used beam shapes for both contour and box fire protection profiles as illustrated in Figure 3.

UL/AISI BEAM SUBSTITUTION EQUATION

$$h_1 = \left[\frac{W_2/D_2 + 0.6}{W_1/D_1 + 0.6}\right] h_2$$

Where h = thickness of spray-applied fire protection (inches).
W = weight of steel beam (lb/ft).
D = heated perimeter of the steel beam (inches). Note, see Figure 3.
Subscript 1 = refers to the substitute beam and required protection thickness.
Subscript 2 = refers to the beam and protection thickness specified in the individual UL Design.

Use of this equation is subject to these limitations:

1) The equation applies to beams having W/D values not less than 0.37,
2) h_1 cannot be less than ⅜ inch, and
3) the Unrestrained Beam Rating in the UL Design is not less than 1 hour.

Table V below illustrates the reduction in protection thicknesses made possible by using the beam substitution equation. This Table is for illustration purposes only and should not be used for design. The reductions possible in specific cases will depend upon the specified thickness of protection and the size of both the substitute and the specified beams.

TABLE V EXAMPLE REDUCTIONS IN PROTECTION THICKNESS BASED UPON THE BEAM SUBSTITUTION EQUATION

Substitute Shape	W/D	Minimum Beam Size Specified in UL Designs: W6 x 12 (W/D=0.51) 2 Hr. Rating	W6 x 12 (W/D=0.51) 3 Hr. Rating	W8 x 28 (W/D=0.80) 2 Hr. Rating	W8 x 28 (W/D=0.80) 3 Hr. Rating
W10 x 30	0.79	20%	20%	—	—
W10 x 45	**1.03**	**32%**	**32%**	**14%**	**14%**
W12 x 79	1.32	42%	42%	25%	27%
W21 x 132	**1.66**	**50%**	**51%**	**25%**	**39%**
W30 x 211	2.00	50%	57%	25%	46%
W36 x 300	**2.47**	**50%**	**64%**	**25%**	**54%**

3. BEAM-ONLY DESIGNS

As explained in Section II, ASTM E119 includes provisions for the testing of individual beams with a representative section of floor or roof construction. In beam-only tests, fire endurance of floor or roof construction is not evaluated. In virtually every instance, building codes require fire resistant floor and roof construction when protected beams are required. Consequently, beam-only tests are of little value by themselves. In certain cases they do, however, provide designers with some useful and necessary options when used in conjunction with assembly designs. As a result, the UL *Directory* provides specific guidance on the substitution of beams from beam-only Designs into assembly Designs. Beam-only ratings are given in the N- and S-Series Designs in the UL *Directory*. These Designs have proven to be most useful in the following cases:

1) When building codes require beams (or girders) to have greater fire resistance than the floor or roof construction supported by the beam.
2) When the assembly Design does not include steel beams. For example, the J-Series Designs with precast concrete floor systems.
3) When it is desired to use beam protection material or a profile different from that specified in an assembly Design.

The following conditions govern the substitution of beam-only Designs into assembly Designs:

— The floor or roof construction specified in the beam-only Design must have a lower capacity for dissipating heat from the beam than the floor or roof construction specified in the assembly Design. For concrete floors, a lower capacity for heat dissipation exists when the concrete has an equal or lower density and volumetric coverage per unit of floor area. In addition, the floor or roof construction must be in accordance with both the assembly and beam-only Designs, keeping in mind that the specified thicknesses of concrete slabs are minimums.

— Beam-only Designs with spray-applied fire protection material on the underside of steel decks may be used in assembly Designs with unprotected steel decks or unprotected precast concrete floors provided that the beam fire protection material is oversprayed to the underside of the deck on both sides of the beam for a distance of 12 inches beyond the edges of the beam flange. The thickness of fire protection material oversprayed to the underside of the deck or slab shall be the same as required for the beam.

— Beam-only Designs with unprotected steel decks may be used in assembly Designs with either protected or unprotected steel decks or precast concrete floors. Overspraying is not required.

— The Unrestrained Beam Rating in the beam-only Design must be equal to or greater than the Unrestrained Beam Rating in the assembly Design.

— For assembly Designs which do not include steel beams, the beam rating (either restrained or unrestrained, as appropriate), is determined directly from the beam-only Design.

VI. BEAM SUBSTITUTION— EXAMPLE PROBLEMS

The following examples illustrate application of the basic principles as set forth in the preceding Section V. Readers are urged to study these examples carefully along with the information in Section V and that of the UL *Fire Resistance Directory*, in order to obtain greater understanding of these principles. To implement this understanding, reference has been made to specific building code requirements. The basic design chosen is a typical corner bay in a steel framed building (Fig. 5).

EXAMPLE 1—RESTRAINED ASSEMBLY-PROTECTED DECK

PROBLEM: Determine the thickness of spray-applied fire protection necessary to satisfy the Basic/National Building Code requirements for Type 1B Construction or the Standard Building Code requirements for Type II Construction. Assume that the designer wishes to use a protected deck and 2½-inch normal weight concrete slab.

REQUIRED: 2-hour Floor Construction
2-hour Floor Beams
2-hour Girders and Spandrel Beams

SOLUTION: Since all framing connections are bolted/welded and the deck is welded to all beams and girders, both floor construction and framing are restrained according to Table V. Therefore, a 2-hour Restrained Assembly will satisfy the code requirements. The architect/

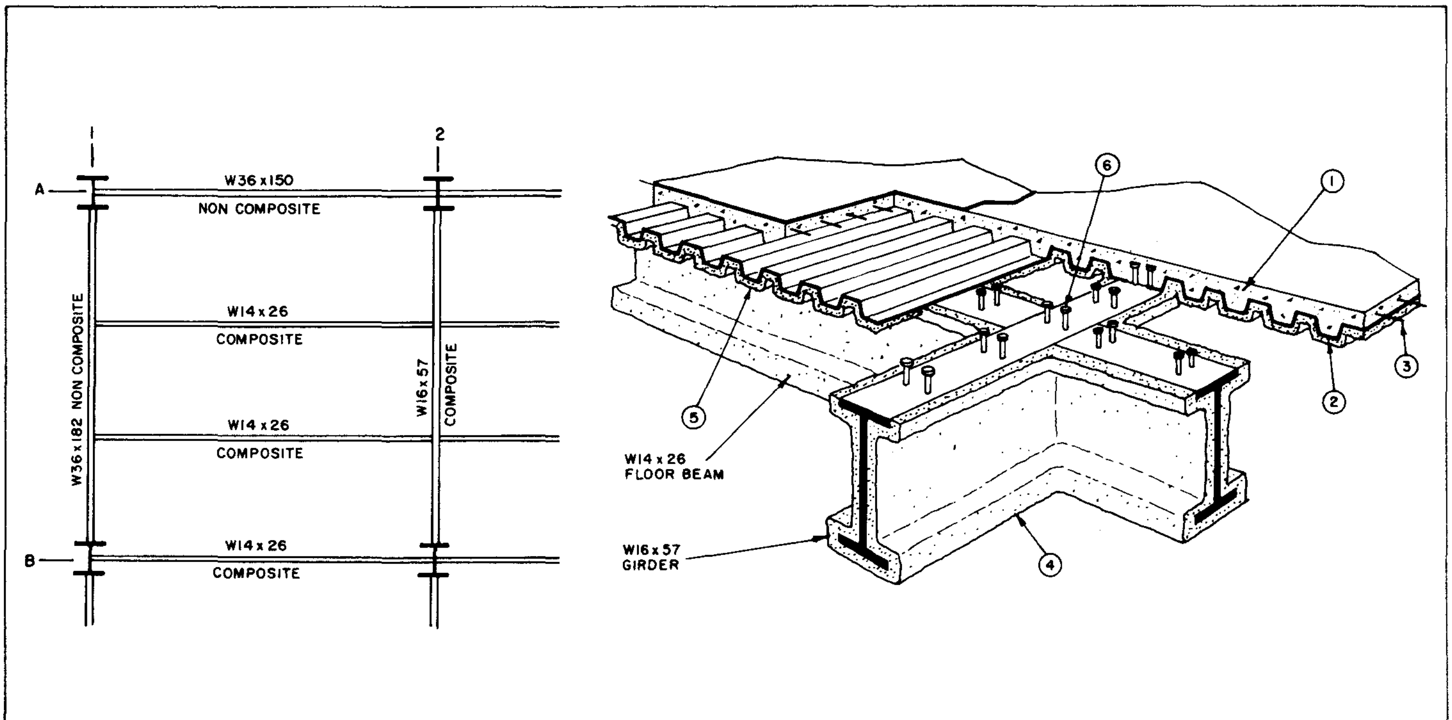


Figure 5. Typical Floor Framing Plan

1. Lightweight or normal weight concrete slab. Thickness determined by structural requirements and the appropriate UL Fire Resistant Design. For examples 1, 2, and 5, use a 2½ inch thick normal weight concrete slab. For examples 3 and 4, use a 3¼ inch thick lightweight concrete slab.
2. Fluted steel deck. Deck depth and thickness determined by structural requirements and the appropriate UL Fire Resistant Design. Use a 3 inch deep, 20 gage deck. Deck welded to all steel beams and girders, 12 inches on center.
3. 6 x 6 - W1.4 x W1.4 welded wire mesh.
4. Spray-applied beam and girder protection as required to satisfy the selected UL Fire Resistant Design (See example problems).
5. Deck protection, if required by the appropriate UL Fire Resistant Design.
6. Shear studs.

TABLE VI

Substitute Beam	W/D	Direct Substitution Thickness	Beam Equation Thickness	Percent Reduction
W14 x 26	0.61	0.75 inches	0.71 inches (Use ¾″)	0
W16 x 57	**1.07**	**0.75 inches**	**0.51 inches (Use ⅝″)**	**16**
W36 x 150	1.41	0.75 inches	0.43 inches (Use ½″)	33
W36 x 182	**1.69**	**0.75 inches**	**0.37 inches (Use ⅜″)**	**50**

engineer selects UL Design D825 since it includes both composite and noncomposite beams, and the floor construction is consistent with that desired. The minimum beam size specified in D825 is a W8X17 (W/D = 0.54) and ¾ inches of spray-applied protection is required. All of the given beam and girder shapes have W/D ratios that are greater than the W8X17. Therefore, a direct substitution according to the "Larger Beam" concept is permitted and ¾ inches of protection will provide the required fire resistance rating for all members in the given framing plan. Since several of the girders are appreciably larger than the W8X17, the required thickness of protection can be reduced through use of the beam substitution equation.

$$h_1 = \left[\frac{W_2/D_2 + 0.6}{W_1/D_1 + 0.6}\right] h_2$$

$$\text{or} \quad h_1 = \left[\frac{0.54 + 0.6}{W_1/D_1 + 0.6}\right] 0.75$$

$$h_1 = \frac{0.855}{W_1/D_1 + 0.6}$$

As evident from Table VI, significant savings in the thickness of spray-applied fire protection can be realized through use of the beam substitution equation.

For the corner bay illustrated in Figure 5 and the modified thicknesses given above (Table VI), overall savings of 25% in fire protection material could be realized through use of the beam substitution equation.

EXAMPLE 2—UNRESTRAINED ASSEMBLY-PROTECTED DECK

PROBLEM: Determine the thickness of spray-applied fire protection necessary to satisfy the Uniform Building Code requirements for Type II Fire Resistive Construction. Assume that the designer once again wishes to use a protected deck and 2½inch normal weight concrete slab.

REQUIRED: 2-hour Floor Construction
2-hour Floor Beams
2-hour Girders and Spandrel Beams

SOLUTION: The Uniform Building Code stipulates that assemblies must be considered *unrestrained* unless "evidence satisfactory to the building official is furnished by the person responsible for the structural design showing that the construction qualifies for a restrained classification." Therefore, assume that the floor

TABLE VII

Substitute Beam	W/D	Direct Substitution Thickness	Beam Equation Thickness	Percent Reduction
W14 x 26	0.61	1.44 inches	1.35 inches (Use 1⅜″)	4
W16 x 57	**1.07**	**1.44 inches**	**0.98 inches (Use 1″)**	**31**
W36 x 150	1.41	1.44 inches	0.82 inches (Use ⅞″)	39
W36 x 182	**1.69**	**1.44 inches**	**0.72 inches (Use ¾″)**	**48**

construction and framing are unrestrained. After reviewing the UL *Directory*, the architect/engineer selects Design D825 since it includes both composite and noncomposite beams, and the floor construction is consistent with that desired. The 2-hour Unrestrained Assembly Rating in D825 will satisfy the code requirements and the W8x17 minimum beam size specified in this Design requires 1⁷⁄₁₆ inches of fire protection material.

As in Example 1, the same thickness of fire protection can be applied to all of the beams and girders since all have W/D ratios greater than the W8x17. Again, the use of the beam substitution equation will result in appreciable savings.

$$h_1 = \left[\frac{W_2/D_2 + 0.6}{W_1/D_1 + 0.6}\right] h_2$$

$$\text{or} \quad h_1 = \left[\frac{0.54 + 0.6}{W_1/D_1 + 0.6}\right] 1.438$$

$$h_1 = \frac{1.639}{W_1/D_1 + 0.6}$$

As can be seen from the following Table VII, significant savings in fire protection material can be realized through the use of the beam substitution equation. The overall thicknesses of fire protection are, however, almost twice as much as those required by either the Basic/National or Standard Building Codes for the same hourly rating shown in Example 1.

In this example, for the corner bay illustrated (Fig. 5) and the thicknesses given above, use of the beam substitution equation would result in an overall savings of 29 percent in fire protection material.

EXAMPLE 3—RESTRAINED ASSEMBLY-UNPROTECTED DECK

PROBLEM: Determine thickness of spray-applied fire protection necessary to satisfy the Basic/National Building Code requirements for Type 1B Construction or the Standard Building Code requirements for Type II Construction. Assume that the designer wishes to use an unprotected deck and 3¼-inch lightweight concrete slab.

REQUIRED: 2-hour Floor Construction
2-hour Floor Beams
2-hour Girders and Spandrel Beams

SOLUTION: As in Example 1, a 2 hour restrained assembly will satisfy the code requirements since all framing is bolted/welded and the deck is welded to all beams and girders. The architect/engineer selects UL Design D916 since it includes both composite and noncomposite beams, and the floor construction is consistent with that desired.

The minimum beam size specified in D916 is a W8x28 (W/D = 0.80) and ½ inch of protection is required for the 2-hour restrained rating. Since all girders and spandrel members have W/D ratios greater than that of W8x28, direct substitution based upon the "Larger Beam" concept is possible. The W14x26 shape, however, has a W/D ratio less than the W8x28, hence direct substitution is not permitted for the floor beams. Therefore, the beam substitution equation *must* be used for this shape so as to determine the required thickness of protection.

As in the previous examples, use of the beam substitution equation for the girder and spandrel members results in some savings in fire protection material (Table VIII) in addition to providing a basis for determining the thickness of protection required for the floor beams.

$$h_1 = \left[\frac{W_2/D_2 + 0.6}{W_1/D_1 + 0.6}\right] h_2$$

$$\text{or} \quad h_1 = \left[\frac{0.80 + 0.6}{W_1/D_1 + 0.6}\right] 0.5$$

$$h_1 = \frac{0.7}{W_1/D_1 + 0.6}$$

TABLE VIII

Substitute Beam	W/D	Direct Substitution Thickness	Beam Equation Thickness	Percent Reduction
W14 x 26	0.61	Not Permitted	0.58 inches (Use ⅝″)	—
W16 x 57	**1.07**	**0.50 inches**	**0.42 inches (Use ½″)**	**0**
W36 x 150	1.41	0.50 inches	0.35 inches (Use ⅜″)	24
W36 x 182	**1.69**	**0.50 inches**	**0.31 inches (Use ⅜″)**	**24**

EXAMPLE 4—UNRESTRAINED ASSEMBLY-UNPROTECTED DECK

PROBLEM: Determine the thickness of spray-applied fire protection necessary to satisfy the Uniform Building Code requirements for Type II Fire Resistive Construction. Assume that the designer wishes to use an unprotected deck and 3¼ inch lightweight concrete slab.

REQUIRED: 2-hour Floor Construction
2-hour Floor Beams
2-hour Girders and Spandrel Beams

SOLUTION: The Uniform Building Code stipulates that *unrestrained* ratings must be used unless "evidence satisfactory to the building official is furnished by the person responsible for the structural design showing that the construction qualifies for a restrained classification."

Therefore, assume that floor construction and framing are unrestrained, and that the designer wishes to use spray-applied fire protection material specified in UL Design D916. Unfortunately, D916 has a 0-Unrestrained Assembly Rating and therefore, will not satisfy the code requirements in this example. Hence, the architect/engineer reviews all the other UL Designs in the D900 series with unprotected decks. The only Design with the specified fire protection material and deck/slab floor construction consistent with that desired is D907. For a 2-hour Unrestrained Assembly Rating with W8x28 beams, this Design limits the deck span to 9′-6″ which is slightly less than that provided. Therefore, to use this Design, the floor beams must be redesigned. As a last resort, the designer decides to investigate D906 which is an unprotected deck assembly without floor beams. The floor construction in this Design has a 2-hour Unrestrained Assembly Rating for spans less than 13′-2″ and is consistent with that desired.

In order to use D906, the beam and girder protection must be developed based upon a beam-only Design in the UL N700 series. Design N708 references the desired fire protection material with floor construction consistent with that desired. Furthermore, the floor construction in N708 has a lower capacity for heat dissipation from the beam than D906, a prerequisite for using this beam-only Design in conjunction with D906 (comparable concrete density and lower volumetric coverage per square foot of floor area). Therefore, beam and girder protection for this example can be determined in accordance with N708 which specifies 1⅛ inches of protection for a 2-hour Unrestrained Beam Rating for W8x28 and larger beams.

Since the W8x28 has a greater W/D ratio than the W14x26 floor beams, the beam substitution equation *must* be used in order to determine the required thickness of protection. Furthermore, as in the preceding examples, Table IX shows that the beam substitution equation can be used to reduce the required thickness of protection for the "larger" girder and spandrel members.

$$h_1 = \left[\frac{W_2/D_2 + 0.6}{W_1/D_1 + 0.6}\right] h_2$$

$$\text{or} \quad h_1 = \left[\frac{0.80 + 0.6}{W_1/D_1 + 0.6}\right] 1.125$$

$$h_1 = \frac{1.575}{W_1/D_1 + 0.6}$$

TABLE IX

Substitute Beam	W/D	Direct Substitution Thickness	Beam Equation Thickness	Percent Reduction
W14 x 26	0.61	Not Permitted	1.30 inches (Use 1⅜")	—
W16 x 57	1.07	1.13 inches	0.94 inches (Use 1")	12
W36 x 150	1.41	1.13 inches	0.78 inches (Use ⅞")	22
W36 x 182	1.69	1.13 inches	0.69 inches (Use ¾")	33

EXAMPLE 5—BEAMS/GIRDERS WITH GREATER REQUIRED FIRE RESISTANCE THAN FLOORS

PROBLEM: Determine the thickness of spray-applied fire protection necessary to satisfy the Uniform Building Code requirements for Type I Construction. Assume that the designer wishes to use a protected deck and 2½-inch normal weight concrete slab.

REQUIRED: 2-hour Floor Construction
2-hour Floor Beams
3-hour Structural Frame
(Includes all girders and spandrel beams, and floor beams with direct column connections)

SOLUTION: This example is identical to Example 2 except that the "structural frame" requires 3-hour protection. As a result, assume that the architect/engineer has selected UL Design D825 and has determined that 1⅜ inches of protection is required for the W14x26 floor beams which do not frame into columns. The new part of this example is the 3-hour protection required for structural frame elements. According to the Uniform Building Code, all girders and beams directly connected to columns are part of the structural frame. Hence, the three girders and spandrel members shown in the given framing plan are part of the structural frame. In addition, the W14x26 floor beam at column line B must also be considered part of the structural frame. Since all these members require 3-hour protection, a beam-only Design must be used. Again, it is assumed that unrestrained ratings apply under the Uniform Building Code.

The first task is to find a beam-only Design in the UL N800 Series that meets the following criteria:

1) Has the same fire protection material as specified in Design D825.
2) Has floor construction with comparable or *lower* capacity for dissipating heat from the beam than the floor construction specified in D825. Since the designer wishes to use normal weight concrete, the beam-only Design may specify either a normal- or lightweight slab with a maximum thickness of 2½ inches. The deck can be either protected or unprotected. If the designer wishes to use a cellular deck, the beam-only Design must also permit the use of cellular decks.
3) Since several of the girders are composite, the beam-only Design must include composite beams.
4) The beam-only Design must obviously include a 3-hour unrestrained beam rating.

UL Design N815 satisfies all the above criteria. In addition, N815 permits the protection thickness over the toe of the bottom flange to be cut in half.

Design N815 specifies a W8x28 beam (W/D = 0.80) and 2⅛ inches of protection for a 3-hour Unrestrained Beam Rating. Using the "Larger Beam" concept, the W16x57 (W/D = 1.07), W36x150 (W/D = 1.41) and

$$h_1 = \left[\frac{W_2/D_2 + 0.6}{W_1/D_1 + 0.6}\right] h_2$$

$$\text{or} \quad h_1 = \left[\frac{0.80 + 0.6}{W_1/D_1 + 0.6}\right] 2.125$$

$$h_1 = \frac{2.98}{W_1/D_1 + 0.6}$$

W36x182 (W/D = 1.69) shapes can be directly substituted into this Design with 2$\frac{1}{8}$ inches of protection. The W14x26 (W/D = 0.61) cannot, however, be directly substituted into this Design since it has a smaller W/D ratio than the specified beam shape. Therefore, use the beam substitution equation to determine the required thicknesses of protection.

The following Table X gives the thicknesses of protection calculated according to the beam substitution equation. These protected beams all have a 3-hour Unrestrained Beam Rating and can therefore be substituted into D825 which includes 2-hour Unrestrained Beam Ratings.

TABLE X

Substitute Beam	W/D	Direct Substitution Thickness	Beam Equation Thickness	Percent Reduction
W14 x 26 (2 hr)	0.61	From Table VII	1$\frac{3}{8}$"	—
W14 x 26 (3 hr)	**0.61**	**Not Permitted**	**2.46 inches (Use 2$\frac{1}{2}$")**	**—**
W16 x 57 (3 hr)	1.07	2.13 inches	1.78 inches (Use 1$\frac{7}{8}$")	12
W36 x 150 (3 hr)	**1.41**	**2.13 inches**	**1.48 inches (Use 1$\frac{1}{2}$")**	**29**
W36 x 182 (3 hr)	1.69	2.13 inches	1.30 inches (Use 1$\frac{3}{8}$")	35

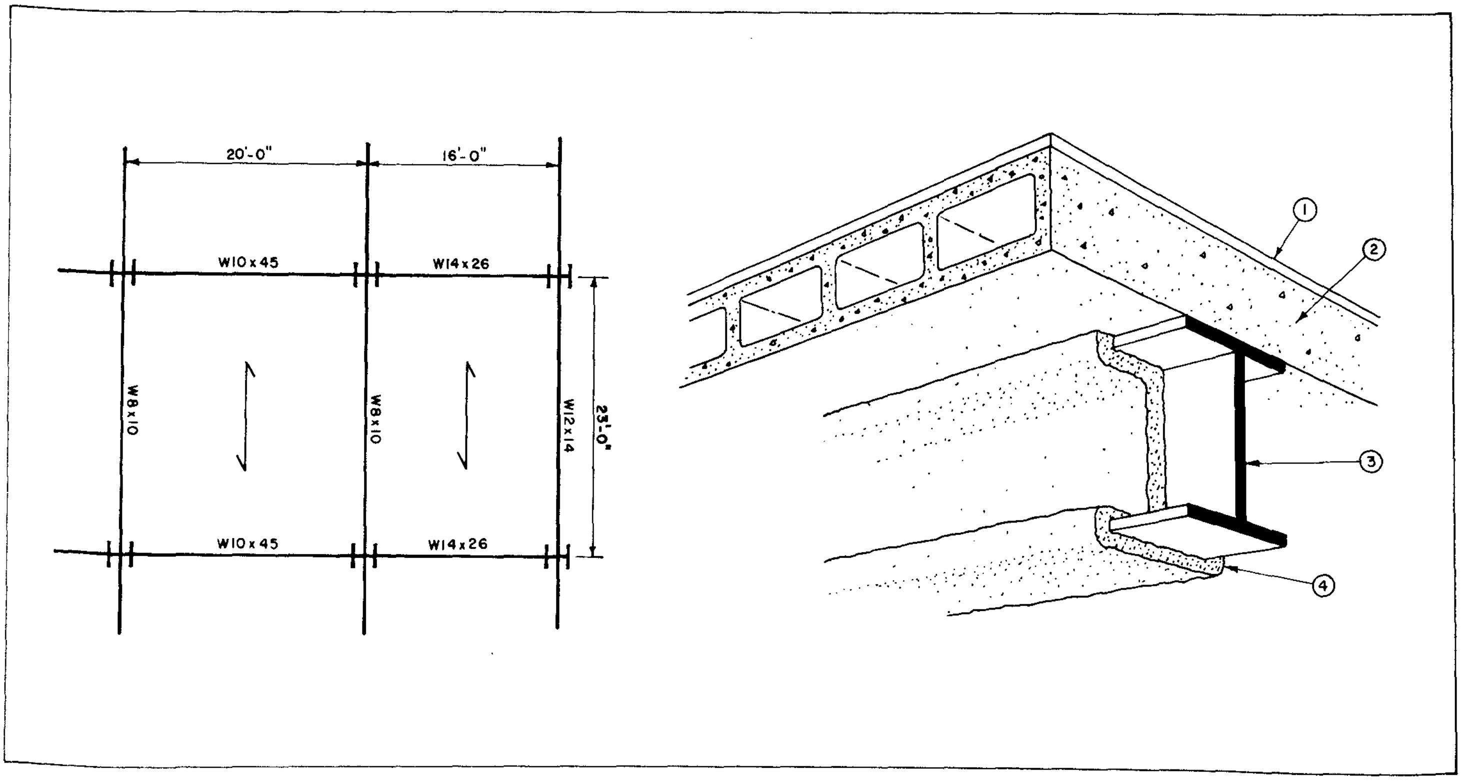


Figure 6. Example Residential High Rise framing plan with precast concrete floor slab.

1. Concrete topping.

2. Precast concrete floor slab.

3. Steel beam

4. Spray-applied fire protection.

EXAMPLE 6—PRECAST CONCRETE FLOORS

PROBLEM: Using the framing plan shown in Figure 6 determine the thickness of spray-applied fire protection necessary to satisfy the Basic/National Building Code requirements for Type 1B Construction or the Standard Building Code requirements for Type II Construction. Assume that the designer wishes to specify precast concrete floor slabs in accordance with UL Design J914.

REQUIRED: 2-Hour Floor Construction
2-Hour Floor Beams
2-Hour Girders

SOLUTION: It is presumed that the design satisfies the requirements in J914 for a 2-hour rating (either restrained or unrestrained, as appropriate). The problem considered in this example is the 2-hour protection required for the W12x14, W14x26, W8x10 and W10x45 girders. Since J914 does not include a steel beam, a UL beam-only Design must be used in order to determine the required thickness of protection; N708 has been selected. As explained in Section V, this substitution is permissible provided that the floor construction in the beam-only Design N708 has a comparable or lower capacity for heat dissipation from the beam than the floor construction in the assembly Design J914 (equal or lower density and volumetric coverage per unit floor area). Since J914 does not include detailed information on the precast concrete slabs, the designer must check with the manufacturer(s) to determine if this criterion is satisfied.

Assuming that the precast concrete slabs have an adequate heat dissipation capacity, the 2-hour Restrained Beam Rating in N708 will satisfy the code requirements. Since all connections are bolted, the girders may be considered "restrained" in accordance with Table IV regardless of whether or not the precast concrete floor slabs are restrained or unrestrained. The minimum beam size specified in N708 is W8x28 (W/D = 0.80) and 1 inch of spray-applied protection is required. The W10x45 shape has a greater W/D ratio than the W8x28 so that a direct substitution according to the "Larger Beam" concept is permitted. The W8x10, W12x14 and W14x26 are, however, smaller. As a result, in all cases use the beam substitution equation.

$$h_1 = \left[\frac{W_2/D_2 + 0.6}{W_1/D_1 + 0.6}\right] h_2$$

$$\text{or} \quad h_1 = \left[\frac{0.80 + 0.6}{W_1/D_1 + 0.6}\right] 1.00$$

$$h_1 = \frac{1.40}{W_1/D_1 + 0.6}$$

As can be seen from the following Table XI some savings in the thickness of spray-applied fire protection can be realized through use of the beam substitution equation. Note that overspraying of the precast slabs is not required since an unprotected steel deck is specified in N708.

TABLE XI

Substitute Beam	W/D	Direct Substitution Thickness	Beam Equation Thickness	Percent Reduction
W 8 x 10	0.37	Not Permitted	1.44 inches (Use 1½")	—
W12 x 14	**0.40**	**Not Permitted**	**1.40 inches (Use 1½")**	**—**
W14 x 26	0.61	Not Permitted	1.16 inches (Use 1¼")	—
W10 x 45	**1.03**	**1.00 inches**	**0.86 inches (Use ⅞")**	**12**

VII. ADVANCED DESIGN CONCEPTS

The Standard Fire Test is predicated on the assumption that the test assembly is "representative" of actual field construction. As explained in Section IV, stress, restraint, continuity, and redundancy all have a significant effect on the fire resistance of floor and roof assemblies. In a test it is virtually impossible to accurately simulate these factors because of the limited size of available facilities, as well as the difficulty of modeling end-support conditions. Recognizing these problems, ASTM E119 includes provisions for testing floor and roof assemblies with either of two end-support conditions: restrained and unrestrained. The intention is to simulate just two of the many support conditions possible in actual buildings; an indication that fire testing is still very much an art or, at best, a somewhat inexact science. Furthermore, the fire exposure specified in ASTM E119 does not accurately reflect the conditions present in many real fires.[1] As a result, most researchers in the field of structural fire protection have come to the conclusion that the best hope for determining fire resistance of structural systems lies in analytical methods.

To this end, AISI has sponsored the development of a second generation nonlinear finite-element computer program—*F*ire *A*nalysis of *S*teel *B*uildings *S*ystems (FASBUS II)[2]—which predicts structural response (i.e., stresses and displacements as a function of specified fire exposure) based upon support conditions, material properties, loading and temperature distributions in actual building floor systems. Temperature distributions can be determined by *F*ire *R*esponse of *S*tructures *T*hermal-*3* Dimensional Version (FIRES-T3),[3] a finite-element heat transfer computer program, or ASTM E119 test results.

Analytical predictions using FASBUS II were compared with slab and beam deflections recorded during ASTM E119 fire tests conducted at UL and at The Ohio State University, and with full scale fire tests conducted at the National Bureau of Standards, Center for Fire Research, in a fully instrumented two-story building with four bays. The comparison showed good agreement between the analytical predictions and experimental results. The NBS study focused on the performance of noncomposite framing and floor construction in a corner bay when exposed to fire. The complete report of the NBS study, and information on the FASBUS II and FIRES-T3 computer programs, are available from AISI. To date, two case studies, funded by AISI, have been made using FASBUS II.

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[1] "Fire Protection Through Modern Building Codes," Fifth Edition, American Iron and Steel Institute, 1981.

[2] Iding, R.H., and Bresler, B., "Analysis of Fire Response of Steel Floor Systems," Wiss, Janney, Elstner and Associates Inc.

[3] Iding, R.H., Bresler, B., Nizamuddin, Z., FIRES-T3 "A Computer Program for the Fire Response of Structures—Thermal 3-Dimensional Version," Report *No. UCB-FRG 77-15*. Fire Research Group, Division of Structural Engineering and Structural Mechanics, Department of Civil Engineering, University of California, Berkeley, 1977.

VIII. Table XII WEIGHT TO HEATED PERIMETER RATIOS W/D FOR COMMONLY SPECIFIED WIDE FLANGE BEAM SHAPES

Structural Shape	W/D Contour	W/D Box
W36 x 300	2.47	3.33
x 280	2.31	3.12
x 260	2.16	2.92
x 245	2.04	2.76
x 230	1.92	2.61
W36 x 210	1.94	2.45
x 194	1.80	2.28
x 182	1.69	2.15
x 170	1.59	2.01
x 160	1.50	1.90
x 150	1.41	1.79
x 135	1.28	1.63
W33 x 241	2.11	2.86
x 221	1.94	2.64
x 201	1.78	2.42
W33 x 152	1.51	1.94
x 141	1.41	1.80
x 130	1.31	1.67
x 118	1.19	1.53
W30 x 211	2.00	2.74
x 191	1.82	2.50
x 173	1.66	2.28
W30 x 132	1.45	1.85
x 124	1.37	1.75
x 116	1.28	1.65
x 108	1.20	1.54
x 99	1.10	1.42
W27 x 178	1.85	2.55
x 161	1.68	2.33
x 146	1.53	2.12
W27 x 114	1.36	1.76
x 102	1.23	1.59
x 94	1.13	1.47
x 84	1.02	1.33
W24 x 162	1.85	2.57
x 146	1.68	2.34
x 131	1.52	2.12
x 117	1.36	1.91
x 104	1.22	1.71

Structural Shape	W/D Contour	W/D Box
W24 x 94	1.26	1.63
x 84	1.13	1.47
x 76	1.03	1.34
x 68	0.92	1.21
W24 x 62	0.92	1.14
x 55	0.82	1.02
W21 x 147	1.83	2.60
x 132	1.66	2.35
x 122	1.54	2.19
x 111	1.41	2.01
x 101	1.29	1.84
W21 x 93	1.38	1.80
x 83	1.24	1.62
x 73	1.10	1.44
x 68	1.03	1.35
x 62	0.94	1.23
W21 x 57	0.93	1.17
x 50	0.83	1.04
x 44	0.73	0.92
W18 x 119	1.69	2.42
x 106	1.52	2.18
x 97	1.39	2.01
x 86	1.24	1.80
x 76	1.11	1.60
W18 x 71	1.21	1.59
x 65	1.11	1.47
x 60	1.03	1.36
x 55	0.95	1.26
x 50	0.87	1.15
W18 x 46	0.86	1.09
x 40	0.75	0.96
x 35	0.66	0.85
W16 x 100	1.56	2.25
x 89	1.40	2.03
x 77	1.22	1.78
x 67	1.07	1.56

VIII. Table XII WEIGHT TO HEATED PERIMETER RATIOS W/D FOR COMMONLY SPECIFIED WIDE FLANGE BEAM SHAPES

Structural Shape	W/D Contour	W/D Box
W16 x 57	1.07	1.43
x 50	**0.94**	**1.26**
x 45	0.85	1.15
x 40	**0.76**	**1.03**
x 36	0.69	0.93
W16 x 31	**0.65**	**0.83**
x 26	0.55	0.70
W14 x 132	**1.83**	**3.00**
x 120	1.67	2.75
x 109	**1.53**	**2.52**
x 99	1.39	2.31
x 90	**1.27**	**2.11**
W14 x 82	1.41	2.12
x 74	**1.28**	**1.93**
x 68	1.19	1.78
x 61	**1.07**	**1.61**
W14 x 53	1.03	1.48
x 48	**0.94**	**1.35**
x 43	0.85	1.22
W14 x 38	**0.79**	**1.09**
x 34	0.71	0.98
x 30	**0.63**	**0.87**
W14 x 26	0.61	0.79
x 22	**0.52**	**0.68**
W12 x 87	1.44	2.34
x 79	**1.32**	**2.14**
x 72	1.20	1.97
x 65	**1.09**	**1.79**
W12 x 58	1.08	1.69
x 53	**0.99**	**1.55**
W12 x 50	1.04	1.54
x 45	**0.95**	**1.40**
x 40	0.85	1.25
W12 x 35	**0.79**	**1.11**
x 30	0.69	0.96
x 26	**0.60**	**0.84**
W12 x 22	0.61	0.77
x 19	**0.53**	**0.67**
x 16	0.45	0.57
x 14	**0.40**	**0.50**
W10 x 112	2.14	3.38
x 100	**1.93**	**3.07**
x 88	1.72	2.75
x 77	**1.52**	**2.45**
x 68	1.35	2.20
x 60	**1.20**	**1.97**
x 54	1.09	1.79
x 49	**0.99**	**1.64**
W10 x 45	1.03	1.59
x 39	**0.90**	**1.40**
x 33	0.77	1.20
W10 x 30	**0.79**	**1.12**
x 26	0.69	0.98
x 22	**0.59**	**0.84**
W10 x 19	0.59	0.78
x 17	**0.54**	**0.70**
x 15	0.48	0.63
x 12	**0.38**	**0.51**
W8 x 67	1.61	2.55
x 58	**1.41**	**2.26**
x 48	1.18	1.91
x 40	**1.00**	**1.63**
x 35	0.88	1.44
x 31	**0.79**	**1.29**
W8 x 28	0.80	1.24
x 24	**0.69**	**1.07**
W8 x 21	0.66	0.96
x 18	**0.57**	**0.84**
W8 x 15	0.54	0.74
x 13	**0.47**	**0.65**
x 10	0.37	0.51
W6 x 25	**0.82**	**1.33**
x 20	0.67	1.09
x 15	**0.51**	**0.83**
W6 x 16	0.66	0.96
x 12	**0.51**	**0.75**
x 9	0.39	0.57
W5 x 19	**0.76**	**1.24**
x 16	0.65	1.07
W4 x 13	**0.65**	[illegible]