Design of

Fire-Resistive Assemblies with Steel Joists

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Selecting the proper fire-resistant assembly using steel joists is easier than you think!

Steel joists are an efficient and economical way of constructing a floor or roof system, but where fire-resistive assemblies are required, structural members must be suitably protected. The two most common ways to protect steel joists are by means of a fire-resistant membrane installed as a ceiling below the floor or roof assembly, or by the direct application of fire-resistive material to the steel joist.

Organizations such Underwriters Laboratories (UL), Factory Mutual, Ohio State University, the University of California, and others have conduced several hundred successful fire tests of floor and roof assemblies using steel joists. These tests are the basis of design listings that show the components required to qualify for fire resistance for a specified time period. Many steel-joist assemblies are designed for fire resistance using the *Fire Resistance Directory* published annually by UL.

The Steel Joist Institute (SJI) has created a complete listing of all assemblies using steel joists, called *Design of Fire-Resistive Assemblies with Steel Joists, Technical Digest No. 10*. This publication contains a number of designs from which the specifying professional can select an assembly that meets the building code requirements. It will be available from SJI in August 2003. Nonetheless, the *Fire Resistance Directory* must always be consulted for a complete description of the assembly.

PROPERTIES OF STEEL

A steel joist designed for room-temperature applications has an inherent factor of safety, which decreases as the temperature of the steel rises. Eventually a temperature is reached where the load exceeds the resistance of the steel joist. This temperature is a function of the type of material being tested, end-support conditions and applied load.

As with other materials, the properties of structural steel members are adversely affected by elevated temperatures. Two of the most important material properties that govern the design are yield stress and the modulus of elasticity. Both of these properties decrease as temperatures increase. These properties can be found in many references, including Ref. 1.

The effect of end conditions is addressed as restrained and unrestrained construction, which ASTM E119 explains more clearly. ASTM Standard E119 requires that the assembly under investigation be loaded so as to develop the full design stress of the steel joist. While this approach is conservative (see Ref. 2), the design based on the material properties of the steel joist at elevated temperatures is not specifically recognized and is just emerging as an alternative approach to fire-resistance design.

FIRE-RESISTANCE TESTS

The fire-resistance ratings published in the UL *Fire Resistance Directory* are based upon the test methods and acceptance criteria described in the "Standard, Fire Tests of Building Construction and Materials," ANSI/UL 263, ASTM E119 and NFPA 251.

The test standard is not intended to model the actual conditions of a real fire but can be viewed as a relative measure of how different assemblies perform under identical laboratory conditions. The intensity of the fire follows the ASTM E119 Standard Time-Temperature curve.

Fire resistance is the ability of a structure to act as a barrier to the spread of fire and to confine it to the area of origin. Fire endurance is the time during which an assembly continues to perform structurally and resist the passage of flame, hot gases and excessive heat to the unexposed surface. Fire-resistance ratings apply to assemblies in their entirety. The test standard determines the rating period by monitoring the assembly's ability to support the applied load, monitoring temperature rise on the unexposed surface of the assembly, and monitoring temperatures of the structural members themselves. Temperature limits for the structural members are different for restrained and unrestrained assemblies, and vary depending on the spacing of the members—more closely spaced members are allowed to reach higher temperatures.

The tested construction duplicates the actual construction, but the spans of the steel joists are limited to the size of the test furnace. The test furnace at UL is nominally 14' by 17'. Suitability for continued use of the structure after a fire, or the damage caused by the fire, is not a consideration of the test methods.

BUILDING CODES

The UL *Fire Resistance Directory* is not a code, but it is recognized by major building codes as an authoritative reference for fire-resistance design. The model building codes establish the fire-resistance requirements for a building based primarily on several factors, including but not limited to: type of occupancy (assembly, business, etc.); building size (height, area); type of construction; and building location on lot.

DESIGN OF ASSEMBLIES

When designing a fire-resistant assembly, it is best to do it carefully and correctly the first time—remedial procedures are expensive! One should consult the building code and consider the economics of percentage increases in area and height permitted, sprinkler protection, and other important factors. Also evaluate fire insurance requirements. The owner's insurance agent might require fire resistance beyond that required by the building code.

After establishing the required fire resistance, consider what type of protection for the assembly is needed. This is either membrane protection (provided by the ceiling) or directly applied protection (provided by spraying fire-resistive material directly to the steel joists).

Next select the type of roof (rigid insulation or fill) or floor (normal or lightweight concrete). This is simply a matter of selecting the materials to be used in the construction of the assembly.

Finally, consult the UL *Fire Resistance Directory* for an assembly that matches the construction materials and meets fire-resistance requirements. It is important to note that the constructed assembly must meet the requirements of the chosen UL assembly, including requirements for joist depth and weight per foot.

SJI's *Technical Digest No. 10, Design of Fire-Resistive Assemblies with Steel Joists*, can assist the specifying professional in quickly selecting a fire resistant design from the UL *Fire Resistance Directory*.

JOIST SUBSTITUTION

UL has conduced numerous fire-resistance tests on steel-joist-supported assemblies in accordance with the recognized standards. The majority of these tests were conducted using small, lightweight joists (normally from 8" through 14" deep). This practice established the minimum acceptable joist. Consequently, any joist in that same joist series that was equal or greater in depth and weight could be substituted into the fire-rated assembly.

The introduction of the K-Series Joists created a need to qualify these joists for use in the existing rated assemblies that employed S-, J- or H-Series Joists. In response to this need, UL and SJI cooperated in designing assemblies, setting stringent temperature-deflection criteria, and conducting tests to qualify the K-Series Joists. The outcome of these tests resulted in the following K-Series qualifications in the UL *Fire Resistance Directory*:

"K-Series Joists, specified in floor- or roof-ceiling assemblies, shall be designed and manufactured in accordance with the Steel Joist Institute's Specifications adopted November 4, 1985, and revised November 5, 1989.

K-Series Joists may be substituted for other joists specified in floor- or roof-ceiling designs as follows:

Floor-Ceiling Assemblies

K-Series Joists of equal or greater depth and weight per foot may be substituted for any S-, J- or H-Series joists in any floor-ceiling design, which employs a structural concrete floor and a suspended membrane ceiling.

Roof-Ceiling Assemblies

K-Series joists of equal or greater depth and weight per foot may be substituted for any S-, J- or H-Series joists in any roof-ceiling design, with the following restrictions:

a. Minimum Nominal Depth = 10 in.
b. Maximum Tensile Stress = 26,000 psi.

Any stress limitation specified in floor or roof designs containing S-, J- or H-Series Joists shall remain if a K-Series Joist is substituted."

To clarify, when a K-Series Joist is specified in an individual fire-resistance design, that joist shall have the design stress limited only if the individual fire-resistance design specifically limits the design stress for K-Series Joists. As an example, UL design number P251 specifies 10H3 or 12K1 joists. However, the design stress is limited to 26,000 psi for the H-Series Joist. The K-Series Joist in this design can be stressed to 30,000 psi.

The following procedure can be used to substitute the proper K-Series Joist for a fire-resistant design:

1. If a fire-rated design that specifically employs a K-Series Joist cannot be used, determine the uniform load per foot the joist is required to support.
2. Select a design from the UL *Fire Resistance Directory* that matches the building construction and has the required fire-resistance rating. From this determine:

Depths and Weights of Various S-, J- and H-Series Joists Specified in the UL *Fire Resistance Directory*

Joist Designation	Joist Depth, in.	Joist Weight, lb/ft	Joist Designation	Joist Depth, in.	Joist Weight, lb/ft
8S2	8	4.0	8J2	8	4.2
10S2	10	5.0	10J2	10	4.2
			10J3	10	4.8
8H2	8	4.2	10J4	10	6.0
8H3	8	5.0	12J2	12	4.5
10H2	10	4.2	12J3	12	5.1
10H3	10	5.0	12J4	12	6.0
10H4	10	6.1	12J5	12	7.0
12H4	12	6.2	12J6	12	8.1
12H5	12	7.1	14J5	14	7.3
			14J7	14	9.7

   a. min. joist depth (D_{min}), in.
   b. min. joist weight (W_{min}), plf
   c. max. joist design stress (F_{max}), ksi. $F_{max} \leq 30$ ksi.

3. Modify the required loading for the stress limitations for floor-ceiling assemblies with a structural concrete floor and a suspended ceiling or a roof-ceiling assembly by ($30/F_{max}$).

4. With the modified loading, enter the economical joist guide and select the K-Series Joist.

5. Ensure that the K-Series Joist selected has:
   a. A depth equal to or exceeding 8″ for a floor-ceiling assembly or 10″ for a roof-ceiling assembly and the minimum joist depth, D_{min}.
   b. A weight equal to or exceeding 5.0 plf and the minimum joist weight, W_{min}.

6. If these criteria are not satisfied, select the next most economical joist that does satisfy the above requirements.

7. To assist in the substitution of K-Series Joists, the depths and weights of various S-, J- and H-Series Joists specified in the UL *Fire Resistance Directory* are listed in the table above.

N- SERIES BEAM DESIGNS

There is a series of N7-- and N8-- designs in the *Fire Resistance Directory* that are not floor assembly designs, but rather deal with the fire resistance of individual structural joists. Following the procedures of the *Fire Resistance Directory*, or using *Design of Fire-Resistive Assemblies with Steel Joists*, these beam designs can be substituted into D7--, D8-- and D9-- assemblies to extend their application to include joists. The substitution into A, G, and J assemblies is also permitted. Refer to the *Fire Resistance Directory* for further information on the proper substitution of these beam designs and for special requirements in the beam design that describe these joists.

MISCELLANEOUS ITEMS

1. Penetrations. Penetrations are important to the fire resistance of an assembly. Volume II of the *Fire Resistance Directory* has a large number of examples of penetrations and how to deal with them.

2. Concrete. The required compressive strength of the concrete is specified in the individual design. This compressive strength can be reduced by 500 psi from the value specified. The thickness of the concrete specified is a minimum. Interchanging lightweight concrete for normal weight concrete is not recommended due to the differing thermal characteristics of the concrete.

3. Floor inserts. Floor inserts are similar to penetrations in how they are to be handled in a fire-resistant design. A review of the "Outlet Boxes and Fittings Classified for Fire Resistance" of Volume I of the *Fire Resistance Directory* will indicate the provisions required to handle these devices.

4. Spacing of floor joists. A large number of the floor/ceiling assemblies indicate that the spacing of the floor joists is 2′ on center. Spacing between the joists can be increased from that specified to a maximum of 4′ on center if the floor slab meets the structural requirements, and if the spacing of wire hangers supporting the ceiling is not increased.

5. Bridging. The bridging bars or angles specified in the individual designs are a minimum. Larger bridging might be necessary in order to meet the structural and/or code requirements. For designs requiring application of coating materials to steel joists, the bridging members shall be protected with the coating-material thickness required on the joist for a minimum distance of 12″ beyond the joist.

6. **Cavities**. The cavities between the top chord of the joist and the floor or roof deck should be filled with fire-resistive material applied to the beam.
7. **Ceiling clearance**. The dimension from the bottom chord of the joists to the ceiling, whether given or calculated, is a minimum.
8. **Painted joists**. Painted joists generally do not present a problem for directly applied fire protection. The fire-resistive material encapsulates the joist members. Thus the adhesion and adherence problems associated with deck are not encountered. Application method and thickness must be in accordance with the proposed fire-resistance design and the *Fire Resistance Directory*.
9. **Joist area**. When the directly applied fire-resistive material is applied to a steel joist, there is a question concerning the amount of material that is required. AISC has tabulated areas for beams, but steel joists do not have a similar tabulation. However, the following equation can be used to predict the surface area for application of fire resistive material (within 10%):

$$A = 0.852 + 0.730\sqrt{w}$$

where A is the area (sq. ft) of the joist per foot of length and w is weight of the joist, plf. This equation is plotted on the following page.

10. **Modification of fire resistant designs**. Modifications to a fire-resistance design are best accomplished either by UL through an engineering study or by consultation with the local building code authority.
11. **After a fire**. Reuse of steel joists after a fire needs to be investigated on a case-by-case basis. Refer to Reference 3 for a good general discussion of this subject.

EXAMPLE

From design P251, the following are the minimum joists:

12K1, 10H3 with bending stress limited to 26,000 psi and 10K1 if span is a maximum of 12′. Joist spacing is 6′-0″ maximum.

Solution 1: With no restrictions on joist depth: select the 12K1 (note there is no stress restriction).

Solution 2: With a 10″ restriction on joist depth, and a span of 12′-0″ or less: select a 10K1 (no stress restriction).

Solution 3. With a 10″ restriction on joist depth, and a span larger than 12′, following the substitution procedure previously outlined and using the 10H3 as the basis of the substitution:

D_{min} = 10″ (depth of the 10H3)
W_{min} = 5.0 plf (weight of the 10H3)
F_{max} = 26 ksi (stress restriction of the 10H3)

At this point the loading for the joist is required. Assuming the joist is required to carry 244 plf. Modifying the loading to account for the stress restriction:

$$244\text{ plf}\,\frac{30\text{ ksi}}{26\text{ ksi}} = 281\text{ plf}$$

Refer to the Standard Load Table (Reference 4): if the span of the joist is greater than 12′ but less than or equal to 15′, a 10K1 can be selected. If the span exceeds 15′ a special joist can be selected. The special joist would be designated 10K281/LL. (LL = required live load, plf.) ★

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Visit SJI at www.steeljoist.org to order Technical Digest No. 10, Design of Fire-Resistive Assemblies with Steel Joists.

REFERENCES

1. Lie, T. T., and Almand, K. H., "A Method To Predict the Fire Resistance of Steel Building Columns," *Engineering Journal*, Volume 27, No. 4, American Institute of Steel Construction, Fourth Quarter 1990.
2. Ellingwood, B., and Corotis, R. B., "Load Combinations for Buildings Exposed to Fires," *Proceedings, 1990 National Steel Construction Conference*, Kansas City, March 14-17, 1990, American Institute of Steel Construction, 1990.
3. Newman, P., "Answers to Some Frequently-asked Technical Questions," *Proceedings, 1987 National Engineering Conference and Conference of Operating Personnel*, New Orleans, April 29 - May 2, 1987, American Institute of Steel Construction, 1987.
4. *Standard Load Table Open Web Steel Joists, K-Series*, Steel Joist Institute, 1985.

Plot of Joist Area for Fire Protection vs. Joist Weight