Restrained Fire Resistance Ratings in Structural Steel Buildings

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ABSTRACT

Unique to North America is a dual classification for fire resistance of supporting members in floor and roof systems in buildings, depending on whether these members are restrained or unrestrained at their ends. When this dual classification was first introduced in 1970, the ASTM E-5 Fire Test Committee clearly recognized that architects, engineers and building code administrators not familiar with the nuances of structural fire testing would have difficulty in properly applying restrained and unrestrained fire ratings in the design of real buildings. As a result, general guidance was added to ASTM E119 Standard Fire Test in the form of Appendix X3, reproduced in its entirety herein as Appendix A, with the permission of ASTM.

The purpose of this paper is to eliminate the confusion that has persisted in some regions of the USA concerning the proper application of restrained and unrestrained fire resistance ratings for steel beam floor and roof assemblies. The ASTM E119 Standard Fire Test and fire test procedures are discussed. Current building code requirements are summarized and results of extensive fire research and analysis of steel beam and concrete floor constructions are reviewed. Recent studies that provide greater understanding of how steel beam and concrete floor systems endure the effects of uncontrolled fire events in real buildings are briefly referenced. The information in this paper will enable architects and engineers to satisfy code provisions requiring justification where fire resistance for steel beam floor and roof systems are based on restrained assembly ratings.

BACKGROUND

ASTM E119 Standard Fire Test

Building code requirements for structural fire protection are based on laboratory tests conducted in accordance with the Standard Test Methods for Fire Tests of Building Construction and Materials, ASTM E119 (also designated NFPA 251 and UL 263) (ASTM, 1970). Since its inception in 1918, the ASTM E119 Standard Fire Test has required that test specimens be representative of actual building construction. Achieving this requirement in actual practice has been difficult since available laboratory facilities can only accommodate floor specimens on the order of 15 ft × 18 ft in plan area in a fire test furnace. For typical steel and concrete structural systems, the behavior of specimens in an ASTM E119 fire test do not reflect the behavior of floor and roof constructions that are exposed to uncontrolled fire in real buildings. The conduct of fire tests of buildings are required to be controlled by the standard time-temperature curve given in ASTM E119 and reproduced here as Figure 1 with permission from ASTM.

In contrast with the structural characteristics of ASTM E119 test specimens, floor slabs in real buildings are continuous over interior beams and girders although this continuity has not been explicitly considered in the structural design. Beam/girder/column connections range from simple shear to full moment connections, and framing member size and geometry vary significantly depending on structural system and building size and layout. Even for relatively simple structural systems, realistically simulating the restraint, continuity and redundancy present in actual buildings is extremely difficult to achieve in a laboratory fire test

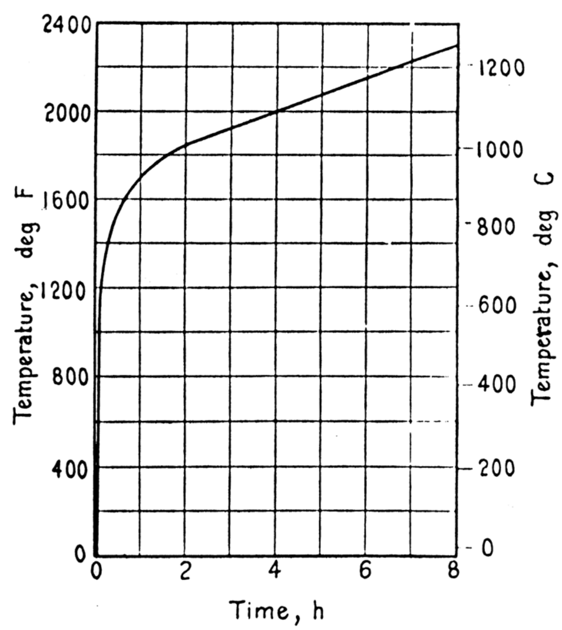

Fig. 1. Time-Temperature Curve.
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assembly. In addition, the size and intensity of a real uncontrolled fire and the loads superimposed on a floor system during that exposure are variables not investigated during an ASTM E119 fire test. Many factors influence the intensity and duration of an uncontrolled fire and the likelihood of full design loads occurring simultaneously with peak fire temperatures is minimal.

It is clear that the ASTM E119 Standard Fire Test was developed as a comparative and not a predictive test. In effect, the Standard Fire Test is used to evaluate the relative performance (fire endurance) of different construction assemblies under controlled laboratory conditions.

In recognition of the variety and complexity of modern structural systems and the practical difficulties associated with realistically modeling appropriate boundary conditions, ASTM E119 was revised in 1970 to include two specific classifications for beams in floor and roof construction: restrained and unrestrained. (Similar terms are frequently used in structural design, but in the context of fire resistance these terms allude to the degree of the beam's resistance to thermal effects, not resistance to rotation of beams due to connection and column or girder stiffness under gravity or lateral loads.) The Appendix X3 in ASTM E119-70 stated that conventional steel beam and column construction qualifies as restrained construction. Identical language appears in the current ASTM E119-98.

UL Fire Resistance Ratings

In North America, the UL Fire Resistance Directory published annually by Underwriters Laboratories, Inc. is the most widely used compilation of fire resistance ratings (UL, 2001). The Design Information Section of this Directory includes useful guidance on the proper application of UL ratings. Prior to 1992, this section included Appendix C to UL 263, Standards for Fire Tests of Building Construction and Materials, which was virtually identical to ASTM E119-70, Appendix X3.

In 1993, Appendix C was deleted from the UL Fire Resistance Directory in favor of an abbreviated discussion that includes a characterization of the UL restraining fire test frames, including stiffness values. However, although the actual text of Appendix C was deleted, the Design Information Section continues to directly reference the UL 263 Appendix C. A review of the 2001 Fire Resistance Directory indicates that UL continues to concentrate on describing its own unique test conditions, but the Directory still defers to nationally recognized standards (e.g., UL 263, virtually identical to ASTM E119-98, Appendix X3).

In the UL test frames, structural connections are rarely included as part of the test assemblies. Beams in fire tests are generally supported on shelf angles with shims driven between the ends of the beam and the test frame, resulting in a highly restrained condition. Concrete slabs are poured tightly against the test frame although some shrinkage typically occurs during curing. Aside from the degree to which restraint occurs as beams and slabs are heated, these support conditions do not accurately model the structural continuity and boundary conditions of typical floor construction.

The unrestrained assembly rating is obtained simply by measuring beam temperatures and assuming the beam ends are totally free to expand and rotate. When certain beam temperatures are reached (1,100°F average, 1,300°F at any one location), the time is recorded and that is the unrestrained fire resistance rating of the beam. The assumption is that, under these temperature criteria, the unrestrained beam will no longer be able to support its own weight and any superimposed dead plus live load. To obtain the restrained rating, the fire test is continued until the entire assembly is judged to no longer support its superimposed load and failure conditions, as indicated by elevated temperatures, are attained in the steel beam and on the top surface of the concrete slab.

Ever since UL included the stiffness characteristics of the restraining test furnace frames in the introductory section of its Fire Resistance Directory, this criterion has sometimes been misapplied (Iaonnides and Mehta, 1997). (The details on the furnace/frame construction are not defined in ASTM E119.) These stiffness values have been used to suggest that they should be the minimum stiffnesses of the steel frame into which steel beams and girders are connected to columns in actual buildings. This implies that providing full axial restraint of beams will reflect actual construction and the behavior of the floor system under uncontrolled fire conditions. As will be shown later in large-scale fire test research and by analytical studies initiated by the American Iron and Steel Institute during the 1960s, this is not the case (Bletzacker, 1966; Chiappetta, Longinow, and Stepanek, 1972; Bresler and Iding, 1982; Gewain, 1982a; Gewain, 1982b; UL, 1984; Bresler, Iding, and Dawsin, 1988).

CURRENT BUILDING CODE REQUIREMENTS

The latest editions of the three model codes have defined restrained assemblies as discussed below.

BOCA National Building Code: 1999

On December 2, 1993, the Building Officials and Code Administrators International, Inc. (BOCA) issued a code interpretation advisory addressing the application of restrained and unrestrained fire resistance ratings. This interpretation indicates that: (1) the support conditions in actual buildings must be considered when applying restrained and unrestrained ratings; (2) in-place construction must be representative of test assemblies; and (3) supporting construction for restrained assemblies must be capable of resisting thermal expansion throughout the range of anticipated temperatures encountered in a fire scenario. In effect, this BOCA Code Interpretation is consistent with ASTM E119, Appendix X3.

SBCCI Standard Building Code: 1997

Prior to 1995 the Southern Building Code Congress, Inc. (SBCCI) issued several nonmandatory interpretations on restraint that relied on the changing guidance in the UL Fire Resistance Directory, since the restraint section in the Standard Building Code (SBC) was largely undefined. In 1995 a significant code change restated portions of ASTM E119 Table X3.1 relative to steel framing in the body of the code.

Section 701.3.2 in the SBC now defines restrained floors, roofs and beams in buildings as those which are surrounded or are supported by construction capable of resisting substantial thermal expansion throughout the range of anticipated elevated temperatures. Construction not complying with this definition is assumed to be entirely free to rotate and expand and must be considered unrestrained. Table 701.3 states that restraint may be provided for steel framing by bolting, welding or riveting steel beams to steel framing members. These connections provide rotational and axial restraint, both (and each) of which will be shown later in this paper, to be sufficient to justify a restrained rating.

ICBO Uniform Building Code: 1997

The Uniform Building Code (UBC) of the International Conference of Building Officials (ICBO) references UBC Standard 7-1 (ASTM E119). However, the UBC has adopted a different approach and requires that, before restrained ratings are used in building design, evidence satisfactory to the building official must be furnished by the person responsible for the structural design. Since the satisfactory evidence may vary from jurisdiction to jurisdiction, architects and engineers are encouraged to consult with the appropriate building official before proceeding with fire protection designs (e.g., thickness of spray-applied fire protection) based upon restrained ratings. It should be noted, however, that the use of restrained ratings under the UBC has been validated for specific, major projects based upon advanced computer modeling and analysis of the results from fire tests and research discussed below.

ICC International Building Code: 2000

The 2000 Edition of the International Building Code, (IBC), developed by the International Code Council (ICC), marks the availability of the first unified national building code supported by the three model code organizations mentioned above. This new building code represents a compilation (and compromise) of the latest editions of the BOCA, SBCCI and UBC codes. The IBC references the ASTM E119 Standard Fire Test, which includes the nonmandatory Appendix X3 guidelines. The IBC includes wording similar to the Uniform Building Code in that evidence of a restrained condition satisfactory to the building official must be furnished by a registered design professional. (By including this language, the ICC was addressing concerns related to design responsibility and code enforcement procedures. Building officials noted that the condition of restraint is often omitted from design drawings, leaving the spray-applied material applicators with little or no guidance from the responsible design professional.) The IBC essentially requires the design professional to designate whether fire resistive floors, roofs and beams are restrained or unrestrained. However, the IBC, like the UBC, does not specify what documentation is required to qualify as sufficient evidence of a restrained condition.

Proposed NFPA 5000 Building Code

The National Fire Protection Association (NFPA) has recently embarked on development of an alternate building code to the IBC. At this time language is being drafted to provide guidance for design professionals and code administrators on the application of restrained fire resistance ratings. Publication of the NFPA 5000 Building Code is targeted for late 2002.

SYNOPSIS OF FIRE RESEARCH AND ANALYSIS

Early Fire Tests and Analysis of Floor Systems: 1965 - 1966

Prior to incorporation of the restrained/unrestrained criteria into the ASTM E119 fire test in 1970, as a basis for designing spray-applied fire protection for steel beam floor and roof assemblies, fire research on the effect of restraint was conducted for the American Iron and Steel Institute (AISI) by Bletzacker at The Ohio State University (OSU) in 1965 (Bletzacker, 1966). This research was initiated to determine the factors that had produced years of excellent field experience in actual fires, with fire protection thicknesses on steel beams based upon ASTM E119 fire tests and restrained rating criteria.

The basic construction of the OSU test assemblies consisted of 4-in. thick structural concrete on 22-gauge steel floor units supported by a W12×27 steel beam (see Figure 2). The beam and floor deck were protected with a spray-applied cementitious fire protection material. A representative floor construction 3 ft wide and the full length of the beam was assembled and loaded. This research program studied:

1. Connection methods for supporting protected steel beams in the ASTM E119 test furnace—including free-to-expand supports ("unrestrained"), simple double angles and fully welded end plates ("restrained") (see Figure 3);

2. The effect of the concrete slab with ends restrained by the furnace frame;
3. The effect of design and construction—including non-composite action between beam and slab, partial composite action and fully composite action;
4. Comparisons of beam performance—unrestrained expansion and end rotation vs. restrained expansion and end rotation, through the application of various levels of axial thrust and end moment; and
5. The effect of applied vertical load on the resulting working stresses.

Tests on the first three assemblies (Tests B-1 to B-3) investigated the composite action between beams and concrete slab/steel deck. All three assemblies were designed and tested in an idealized unrestrained condition. The floor construction in the next eight beam test assemblies (B-4 to B-11) were all similar in construction with the steel floor deck tack welded to the top flange of the beam. They were loaded assuming no composite action between the slab and the beam. Another beam test assembly (B-12) was designed and constructed as a composite assembly including shear connectors welded to the top flange of the beam and imbedded in the concrete slab. The steel beams in Tests B-4 to B-12 were supported at their ends with bolted clip angle connections, except for Test B-10 in which the beam was welded to 0.75-in. thick steel end plates to provide a moment-resisting connection and a restrained condition.

For Tests B-4 to B-12, all end connections were supported by a jacking frame so that axial and rotational displacements of the beam ends could be limited to different levels, and the axial forces (due to thermal expansion) and moments could be measured during the test.

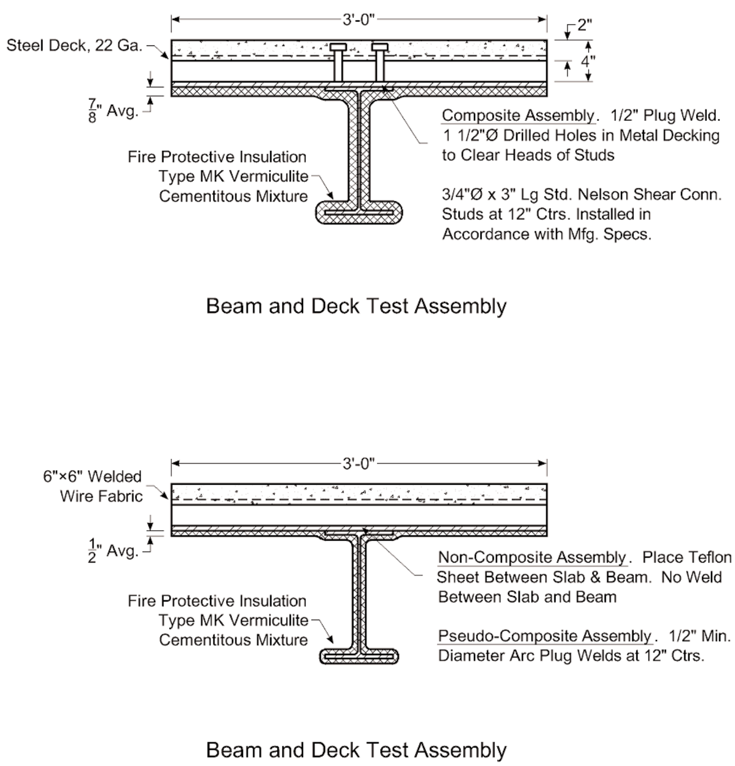

Fig. 2. Details of construction of steel beam and floor assemblies in the Ohio State University fire tests. (Top fig.: B-3; bottom fig.: B-1 and B-2).

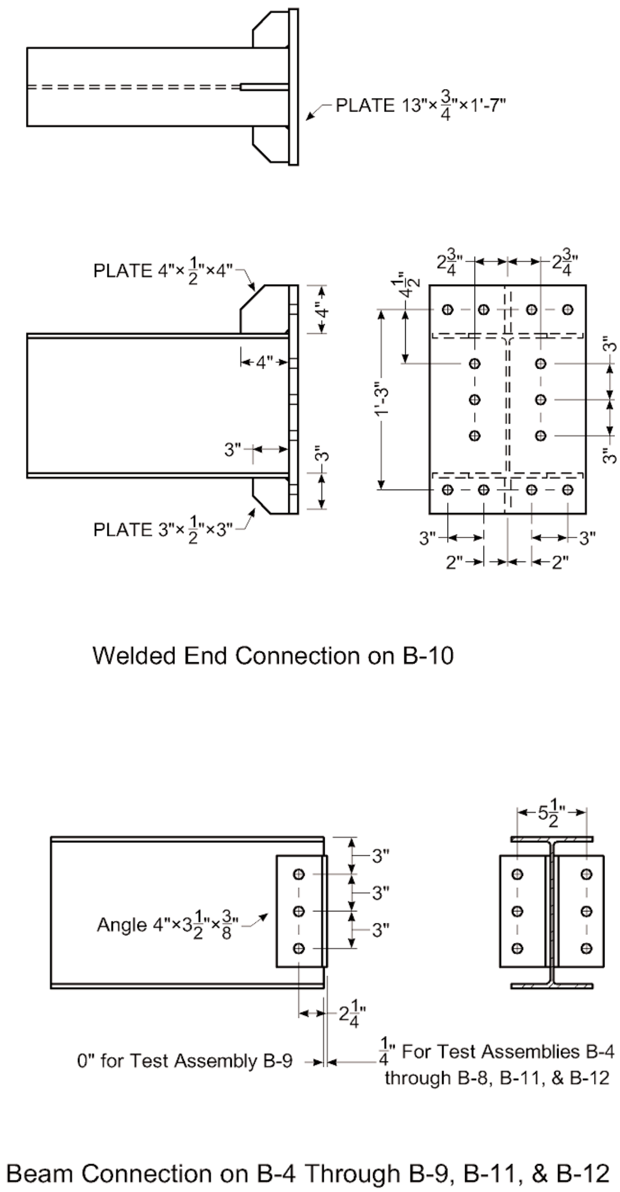

Fig. 3. Connection details for the beam assemblies in the Ohio State University Fire Tests

Results

The Ohio State University fire research program showed that realistic levels of restraint, such as those provided by simple beam-to-column shear connections in typical steel-framed construction, will provide fire endurance equal to or greater than that measured when testing very highly restrained test specimens in a massive ASTM furnace test frame such as UL's. It was observed that even these typical shear connections provide rotational and axial restraint for the beam due to interaction with the concrete floor slab and the inherent stiffness of columns.

Development of a Structural Computer Model: 1968-1981

In 1968, the American Iron and Steel Institute sponsored research at Illinois Institute of Technology Research Institute (IITRI) to develop a nonlinear finite element structural analysis computer program. The goal was to enable engineers to assess the structural performance of steel deck and structural concrete floors supported by steel framing under uncontrolled fire exposure. The program, FASBUS I (Fire Analysis of Steel Building Systems) was completed in 1972 (Chiapetta, Longinow, and Stepanek, 1972). Refinements to the program to make it more user friendly were continued in 1978 at the University of California and later at the consulting firm of Wiss, Janney, Elstner and Associates (WJE). The FASBUS II computer program was completed in 1981 and is described in the WJE Final Report (Bresler and Iding, 1982).

Large Scale Building Fire Test: 1981

In order to demonstrate that FASBUS II could duplicate the interaction of a floor assembly with the surrounding structure using basic principles of structural and material mechanics, there was a need to develop data from large-scale fire tests conducted in real building environments. AISI undertook such a fire research project as part of a Research Associate program at the National Bureau of Standards (NBS, now the National Institute of Standards and Technology—NIST) (Gewain, 1982a; Gewain, 1982b).

In 1981, a two-story, four-bay steel frame structure was erected on the NIST campus in Gaithersburg, MD. The structure had a footprint of 32 ft × 40 ft and was 20 ft high (see Figure 4). The frame was sized to represent a floor at mid-height of a 20-story office building and was fabricated of hot rolled structural steel sections fastened to columns with high-strength bolts. The floor slab at the second floor level was subjected to a design live load of 80 lb/ft^2 and consisted of normal weight concrete on a steel deck. During each of the tests, one 16 ft × 20 ft × 10 ft high bay of the test frame was exposed to fire and the structural steel and metal deck protected with spray-applied fire protection material, ½-in. thick. The assembly used a W12×22 beam framing into a W12×22 spandrel and W12×30 girder and was based upon UL Design No. N805 (UL, 2001), because of its similarity to the construction details being tested (see Figure 5).

Both ASTM E119 fire exposures and ventilation-controlled fires (freeburn, using wood pallets as the fuel) representing exposures expected in an office occupancy were used. Temperature measurements were recorded dur-

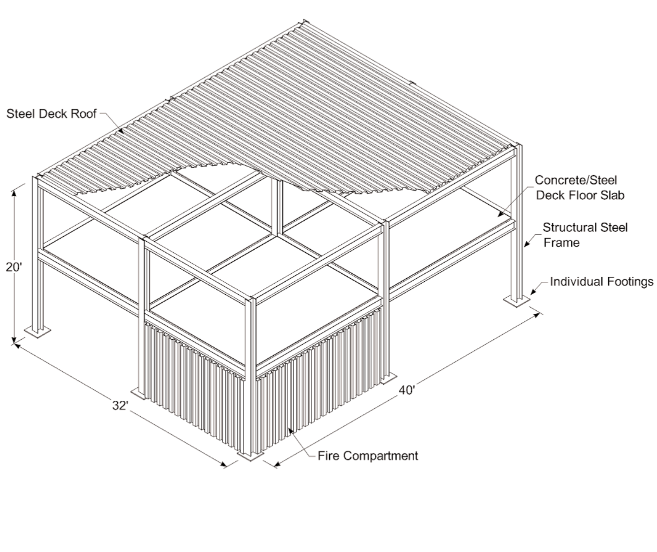

Fig. 4. Schematic of NBS test building.

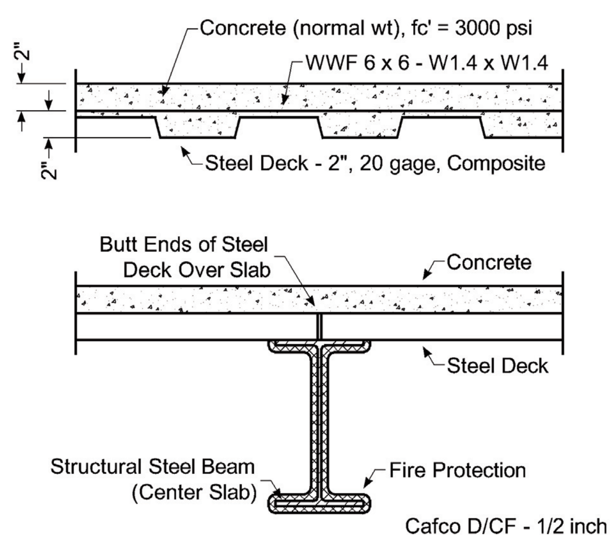

Fig. 5. Details of beam and floor assembly for large scale NBS tests.

Table 1. Summary of 1984 UL Fire Test Results					
Report	Beam Size	*W/D*	Thickness of Protection Material	Time of 1,100°F Limiting Temperature (*t*), min.	Time of Load Removal (min.)
NC505-11	W14x22	0.52	1 1/8 in.	99	120
NC505-11	W14x22	0.52	2 in.	187	210
NC505-11	W21x101	1.29	1 1/8 in.	165	*

* Beam loaded to 15 percent of design allowable capacity during test. Load not removed during the fire test which was terminated at 258 min.

ing and after the tests through the slab thickness, along the beam profile, on the columns in the test bay, and within the fire compartment. Vertical deflections were measured across the exposed portion of the floor slab and horizontal deflections were measured along the columns and spandrel beams of the test bay and in the fire compartment.

The fire tests were conducted in 1982. During the free-burn test, the compartment peak mean temperature reached 1,938°F, and the maximum temperature on the steel beam, protected by the ½-in. of spray-applied material, reached 1,184°F. See Figure 6 for a view of the fire compartment approximately 35 minutes into the test. At the conclusion of this test, the floor assembly had a deflection of 6.5 in. and continued to carry the load. The data from all three tests showed that the structural framing had equal or better fire resistance than a single beam in the ASTM E119 fire test protected in accordance with the restrained rating criteria. The guidelines in Appendix X3 of ASTM E119 for restrained beams were confirmed by these results.

Fig. 6. NBS test fire compartment after approximately 35 minutes.

Underwriters Laboratories, Inc. Fire Tests: 1983-1984

Fire tests conducted in 1983 at UL for the American Iron and Steel Institute investigated the similarities and differences during UL 263 (ASTM, E119) fire tests in the performance of restrained steel beams with different end conditions (UL, 1984). The end conditions investigated were:

1. Beams restrained in the UL test frame in the traditional manner, by placing steel shims between the ends of the beams and the test frame; and
2. Beams placed in the test frame using typical field bolted clip angle connections (see Figure 7).

Results of these fire tests, based on Table 1 in the UL test report, are summarized in Table 1 in this paper.

In evaluating the test data from these fire tests and other tests, the UL report concluded the following:

> *There does not appear to be significant differences in the fire resistance performance of restrained beams that are shimmed against the test frame as compared to restrained beams that are bolted to clip angles in the manner described in this report. Thus, this test confirmed that beams with bolted connections should be considered as restrained beams.*

Computer Modeling of the 1965 OSU/AISI Fire Tests: 1988

Having been successful in using FASBUS II to analyze the structural performance and fire endurance of steel beam floor systems in full scale fire tests at NIST in 1981, AISI funded an analytical study at Wiss, Janney, Elstner and Associates (WJE) (Bresler, Iding, and Dawsin, 1988) to verify the applicability of this computer program to the 1965 beam/floor fire tests done at OSU (Bletzacker, 1966). The computer program was used to analyze the fire response of beam assembly Test B-3, which was unrestrained, and fully composite with shear connectors. Figure 8 shows the excellent agreement between the FASBUS II calculated and experimental deflections.

The OSU fire test results had indicated that, based on ASTM E119 steel beam tests, the optimum fire endurance was obtained at some low magnitude of restraint rather than in fully restrained specimens. Thus, the WJE analysis of these fire tests using FASBUS II considered two components of end restraint in realistic steel-framed buildings:

1. Rotational restraint, provided by simple bolted connections; and
2. Axial restraint, due to column restraints, floor slabs and adjoining construction.

Rotational Restraint

The minimum restraint condition used in the WJE analysis was a connection generally considered as a pinned or simple shear connection by designers: a 3-bolt single plate framing connection. Figure 9 shows the results of the FASBUS II analysis and the results of corresponding unrestrained and fully restrained beams. Figure 10 illustrates that the end moments due to the bolted end connections reduce mid-span moments and stresses at all stages of the fire test. More highly restraining connectors were not studied since a minimum-sized bolted end connection gave essentially restrained-based fire endurance.

Based on these results, WJE concluded from their analysis that a minimum amount of rotational restraint (no axial restraint considered) provided by simple shear connections produces a fire endurance that approximates that of the identical floor system assembly but with fully fixed, moment-resisting connections.

Axial Restraint

The WJE FASBUS II study for axial stiffness and its effect on fire endurance involved a W12×27 beam-slab assembly from the OSU tests, framed into a single W14×43 column. The column was assumed fixed one story above and one story below. Restraint due to both weak-axis and strong-axis orientation of the column (the latter about ten times stiffer) were studied. The conclusion reached by WJE was that axial restraint in the absence of rotational restraint does not increase fire endurance over that of minimal rotational restraint alone (see Figure 11).

It should be noted that, although the component of restraint to the axial growth of beams provided by column stiffness can increase fire endurance of the floor or roof system, excessive restraint can cause buckling of beam flanges or damage to connections. Contrarily, very flexible columns theoretically could be subjected to significant horizontal deflections at the floor or roof level during heating or cooling. However, there are no known cases of actual uncontrolled fires in which any of these effects have impaired the performance or fire endurance of protected structural steel framing.

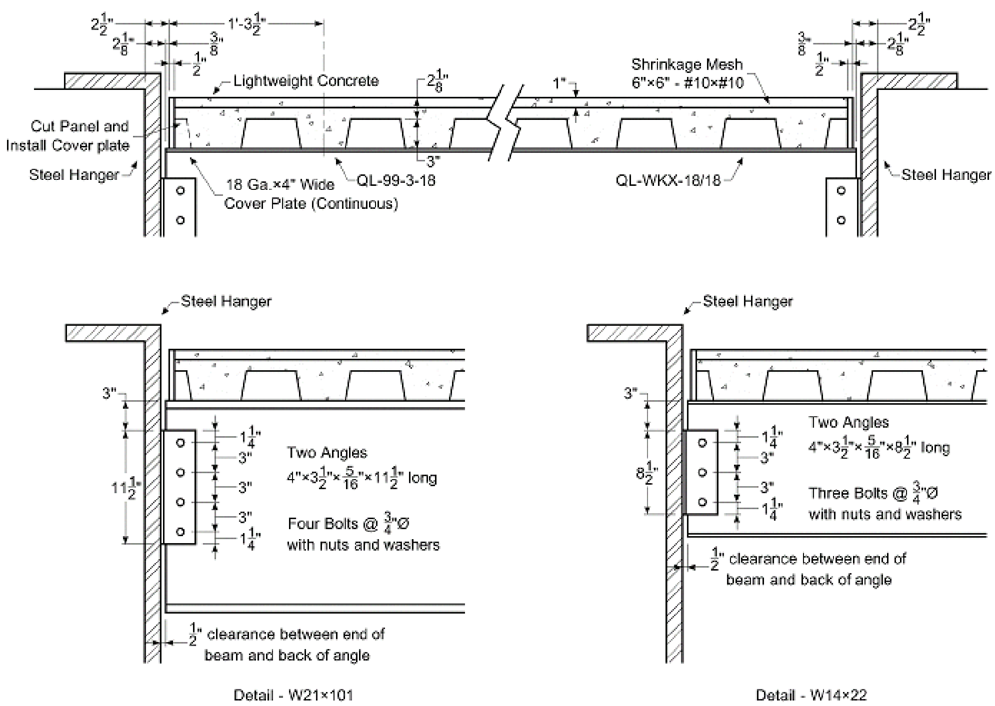

Fig. 7. Steel beams in Underwriter's Laboratories, Inc. fire tests.

Combined Axial and Rotational Restraint

Results from analysis of combined axial and rotational restraint (weak-axis column orientation) are shown in Figure 12 and compared with unrestrained and fully restrained connections. Again, the conclusion drawn by WJE was that if minimal rotational restraint is provided by standard shear connections at the ends of the beam, restrained-based fire endurance is achieved even if there is little or no contribution from axial restraint. Steel framing in both interior and exterior bays will behave as restrained assemblies as long as the connectors are attached to columns or other members to develop some degree of rotational restraint, typically achieved with standard shear connections.

Other Findings

WJE found that the results of their analysis of the 1965 OSU tests using FASBUS II validated the practical classification of restrained construction for structural steel in ASTM E119, Table X3.1. WJE also noted other practical factors that further support this conclusion, such as: continuity and redundancy; lower load levels during actual fires; and, composite action between steel and concrete. It was also concluded, based on these verification studies that FASBUS II provides an accurate prediction of the performance of steel deck and beams in composite floor systems exposed to fire. As a result of the excellent correlation between FASBUS II analysis and fire tests (including ASTM E119 tests and full-scale fire tests), FASBUS has

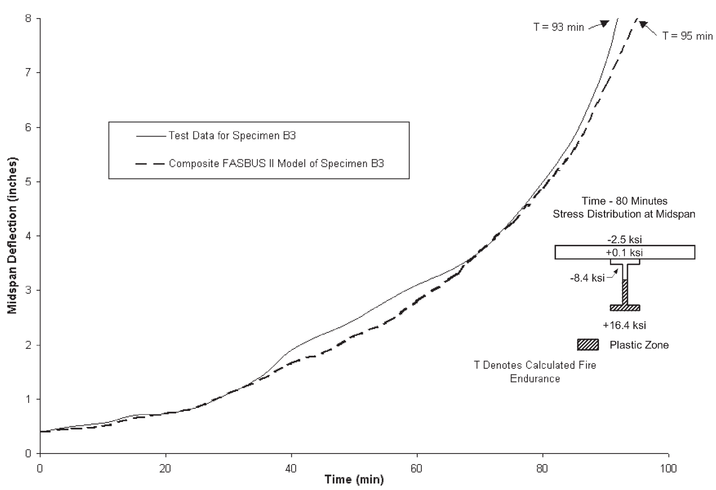

Fig. 8. FASBUS II model analysis: fire endurance of unrestrained composite W12×27 beam specimen B-3, 1965 test data (Bletzacker, 1966).

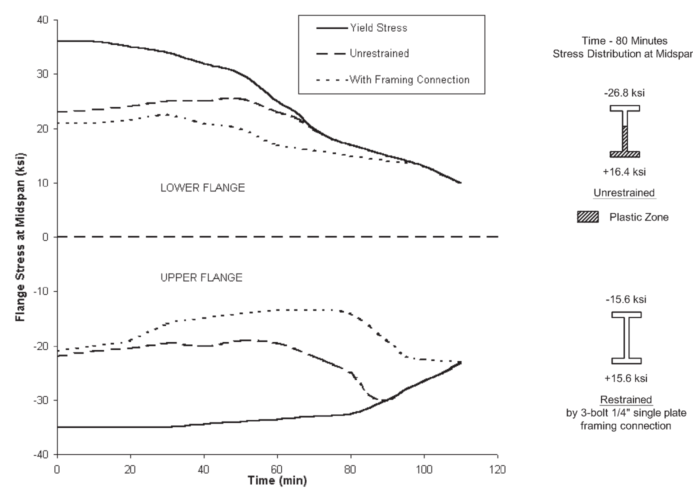

Fig. 10. Effect of rotational restraint on stress history of W12×27 beam.

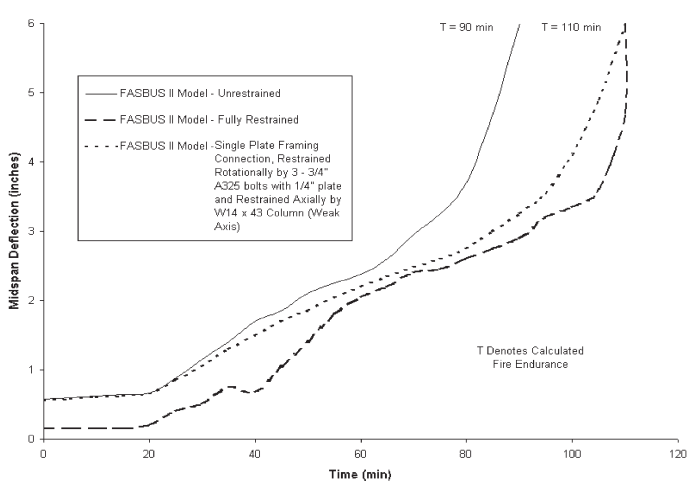

Fig. 9. FASBUS II model analysis: effect of rotational restraint on midspan deflection and fire endurance of W12×27 beam.

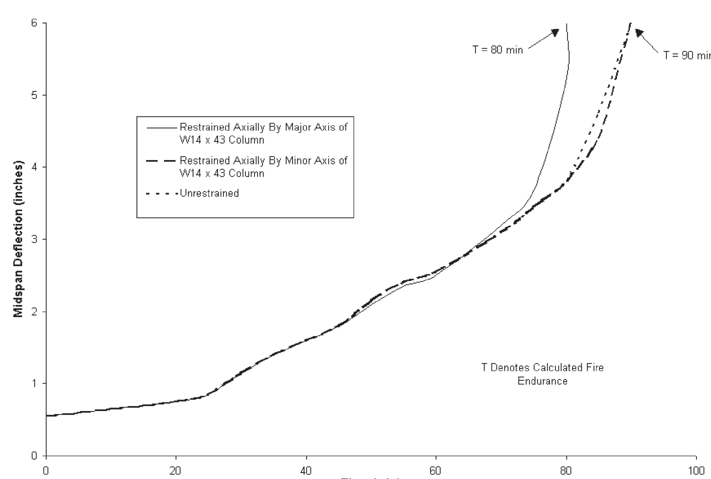

Fig. 11 FASBUS II model analysis: effect of axial restraint on midspan deflection and fire endurance of a simply supported W12×27 beam.

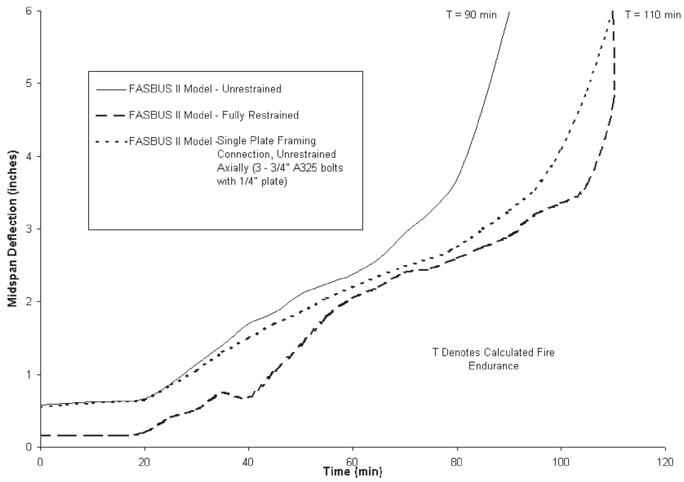

Fig. 12. FASBUS II model analysis: effect of combined rotational and axial restraint on midspan deflection and fire resistance.

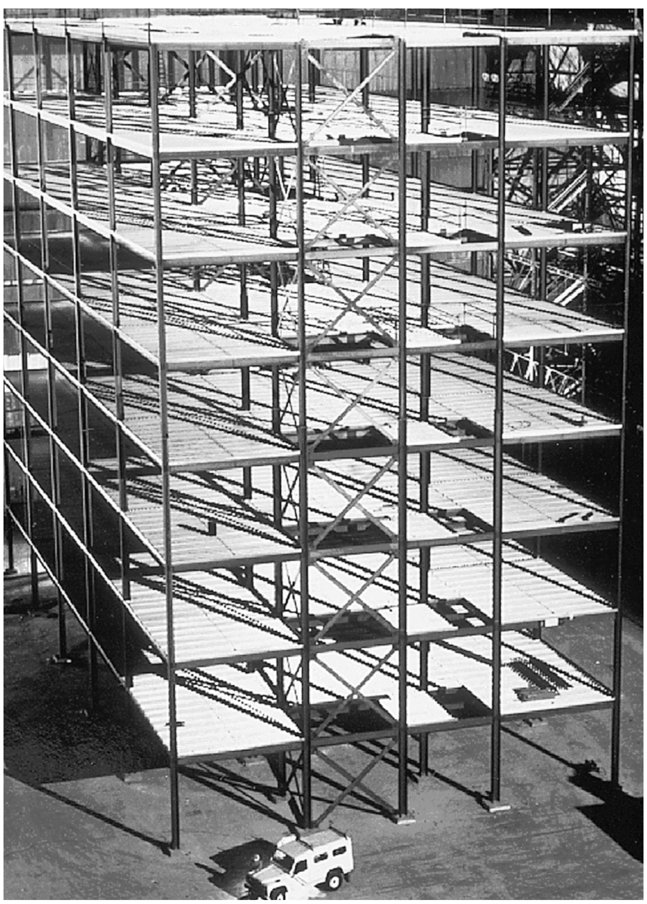

Fig. 13. Eight-story steel-framed building used in Cardington Tests.

been accepted by building officials requesting confirmation of the restrained fire rating classification to determine thickness of spray-applied fire protection materials for steel framing in high-rise office buildings on the West Coast and in Canada.

RECENT STUDIES AND FIRE TESTS

The authors have included the following remarks about several recent studies that reinforce the findings of the AISI-sponsored fire research discussed previously.

Cardington Fire Tests: 1995-1996

During 1995 and 1996, large-scale fire tests were conducted on an eight-story, steel-framed office building at the Cardington Laboratory of the Building Research Establishment in the United Kingdom (Newman, 1999) (see Figure 13). The purpose of these tests was to investigate the behavior of a real structure under real fire conditions and to collect data that would allow computer programs, which are capable of analyzing structures in fire, to be verified. The structure was five bays long (148 ft) by 3 bays wide (69 ft) by 108 ft high, and beams in most of the tests were designed as simply-supported acting compositely with a concrete slab cast on metal deck. Columns were protected up to the underside of the floor slab and the beams, deck and floor slab in this unsprinklered building were unprotected.

Although the test program included one test on a restrained beam assembly on the seventh floor, it was noted that restraint as a variable in fire tests is largely unheard of in Europe. During this restrained assembly test, the maximum beam temperature reached was about 1,650°F and the maximum deflection was about 10 in. (see Figure 14). Although distress was noted in the bottom flange of the beam and at the connections (during cooling), the floor assembly continued to support its applied load at the conclusion of the test (see Figure 15).

Ioannides and Mehta: 1997

An analytical study on restrained/unrestrained fire ratings used the measured temperatures at various locations along the depth of the beam and slab to determine nominal flexural strength and capacity of a beam during the ASTM fire test (Ioannides and Mehta, 1997). The authors offered an analytical procedure, using an assumed time-temperature history for the particular assembly and beam rating coupled with the known properties of the steel at various elevated temperatures, to calculate the nominal flexural strength of the beam. They also provided methods to increase the nominal flexural strength (if needed) by accounting for the effects of rotational restraint (due to connections and slab reinforcement) and thrust restraint. Their study showed that, considering the combination of factors that occur in real buildings during real fires, steel beams, protected with spray-applied fire protection material thicknesses for restrained beams, can have sufficient load-carrying capacity without even counting on any restraint.

An Extreme Fire Event

Experience from intense, uncontrolled fires in *unsprinklered* structural steel high-rise buildings with spray-applied fire protection during the past few decades is limited. However, these few events have borne out the ability of steel and concrete floor systems to mobilize the surrounding structural elements and prevent collapse under the most intense of fire exposures. Perhaps the most dramatic example of steel's fire endurance occurred in a high-rise fire in an East Coast city in 1991—probably the most intense high-rise fire ever experienced in the United States (Klem, 1991). The fire was reported to have caused a complete burnout of eight upper stories over an 18-hour period, being halted at the 30th floor by sprinklers that were being retrofitted into the building from the top floor downward. Although there was considerable distress to steel floor assemblies (originally fire protected based upon a restrained rating classification), there were no reported floor collapses. Dexter and Lu (Dexter and Lu, 2000) later studied the effects of high temperatures and horizontal expansion/contraction and rotation of floor beams on the restraining columns.

Fig. 14. View of Cardington Test Building during fire exposure.

Fig. 15. Beam in Cardington Tests after reaching temperature in excess of 1,600°F.

CONCLUSIONS

1. The unrestrained assembly fire resistance rating for structural steel beam floor and roof systems, based on ASTM E119 temperature criteria only, has no relevance to the behavior of these systems under uncontrolled fires in real buildings.
2. The fire endurance of structural steel beam floor and roof construction under uncontrolled fire is enhanced by the interaction of the beams with the other structural elements and constructions that are integral with or surround the exposed assembly.
3. All steel beam connections to other structural steel members exhibit both axial and rotational restraint. The least stiff connection typically used for steel framed construction (such as a three-bolt single plate connection) is adequate to develop restrained performance.
4. Conclusions drawn from the fire research and computer modeling that have been performed by various agencies, including Underwriters Laboratories, Inc., support the conclusion that a restrained assembly classification and fire protection design is most appropriate for steel beam floor and roof assemblies, and verify the guidance contained in ASTM E119-00, Appendix X3.
5. The performance of structural steel beam and concrete floor systems exposed to uncontrolled fires observed during the research and analysis studies conducted during the past 25 years largely explains the excellent performance of these systems during severe fire exposures in unsprinklered, modern high-rise buildings.

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APPENDIX A

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X3. GUIDE FOR DETERMINING CONDITIONS OF RESTRAINT FOR FLOOR AND ROOF ASSEMBLIES AND FOR INDIVIDUAL BEAMS

X3.1 The revisions adopted in 1970 have introduced, for the first time in the history of the standard, the concept of fire endurance classifications based on two conditions of support: restrained and unrestrained. As a result, most specimens will be fire tested in such a manner as to derive these two classifications.

X3.2 A restrained condition in fire tests, as used in this test method, is one in which expansion at the supports of a load carrying element resulting from the effects of the fire is resisted by forces external to the element. An unrestrained condition is one in which the load carrying element is free to expand and rotate at its supports.

X3.3 Some difficulty is recognized in determining the condition of restraint that may be anticipated at elevated temperatures in actual structures. Until a more satisfactory method is developed, this guide recommends that all constructions be temporarily classified as either restrained or unrestrained. This classification will enable the architect, engineer, or building official to correlate the fire endurance classification, based on conditions of restraint, with the construction type under consideration.

X3.4 For the purpose of this guide, restraint in buildings is defined as follows: "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 are assumed to be free to rotate and expand and shall therefore be considered as unrestrained."

X3.5 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.

X3.6 In Table X3.1 only the common types of constructions are listed. 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.

X3.7 Committee E-5 considers the foregoing methods of establishing the presence or absence of restraint according to type and detail of construction to be a temporary expedient, necessary to the initiation of dual fire endurance classifications. It is anticipated that methods for realistically predetermining the degree of restraint applicable to a particular fire endurance classification will be developed in the near future.

TABLE X3.1 Construction Classification, Restrained and Unrestrained

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.