Fire Endurance Testing of Floor Systems –
Effects of Scale and Restraint

by

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ABSTRACT

Three standard fire resistance tests (ASTM E 119) were conducted on a composite floor system to study the effects of 1) test restraint conditions, and 2) scale of the test. Two full-scale tests, 35 ft[2] (10.7 m) span, and one half-scale test, 17 ft (5.2 m) span, were conducted. Two tests were conducted under restrained conditions and one under unrestrained conditions. Results showed that the full-scale restrained floor system obtained a fire resistance rating of 1½ h, while the full-scale unrestrained floor system achieved a 2 h rating. Past experience with the ASTM E119 test method would lead one to expect that the unrestrained floor assembly would not perform as well as the restrained assembly, and therefore, would receive a lower fire rating. For the full- and half-scale floor systems tested in the restrained condition, the full-scale specimen obtained a fire resistance rating of 1½ h, while the half-scale specimen achieved a 2 h rating. Both tests would be expected to produce the same fire resistance rating.

KEYWORDS: ASTM E119, fire; fire resistance; fire testing; floor systems; standard fire resistance tests; testing

1.0 INTRODUCTION

NIST's World Trade Center (WTC) investigation (NIST, 2005) allowed the opportunity to conduct full- and reduced-scale tests of the floor system used in the WTC towers. These tests duplicated, as closely as practical, the steel truss-supported composite concrete floor system. In practice, a floor assembly such as that used in the WTC towers is neither restrained nor unrestrained but is likely somewhere in between. Testing under both restraint conditions, then, bounds expected performance under the standard fire exposure, and provides a comparison of unrestrained ratings developed from both restrained and unrestrained test conditions. Also, the spans of the WTC floor system were up to 60 ft (18.3m) while furnaces used in establishing fire resistance ratings in the US allow spans of approximately 18 ft (5.5 m). Thus the extrapolation of results of a reduced-scale test may be an issue.

Full-scale tests were conducted in both the restrained and unrestrained support conditions. Further, a roughly one-half scale test of the restrained floor system was also conducted. A description of the WTC floor system, scaling and conduct of the tests, and results (fire resistance ratings) are presented here.

2.0 FIRE RESISTANCE TESTING

The fire rating of structural materials and assemblies is generally determined through testing, and in the

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[2] The policy of the National Institute of Standards and Technology is to use the International System of Units (metric units) in all its publications. However, in North America in the construction industry, certain non-SI units are so widely used instead of SI units that it is more practical and less confusing to include

measurement values for customary units as the primary units of measure.

United States, such testing is frequently conducted in accordance with ASTM E 119, "Standard Test Methods for Fire Tests of Building Construction and Materials" (ASTM, 2000). This standard was first published in 1917 as a tentative standard ASTM C 19 and was first adopted as ASTM E 119 in 1933. Since its introduction, the test method has been modified and updated, although its essential character has remained unchanged. The test methods described in ASTM E 119 prescribe a standard fire exposure for comparing the test results of building construction assemblies. For the tests of floors and roofs, a test assembly is structurally loaded and the standard fire exposure is applied to the underside of the specimen. The assembly is evaluated for its ability to contain the fire by limiting flame spread and heating of the unexposed surface while maintaining the applied load. The assembly is given a rating, expressed in hours, based on these conditions of acceptance.

Since 1971, versions of the ASTM E 119 Standard differentiate between testing and classifying thermally restrained and unrestrained floor assemblies. According to Appendix A4 of ASTM E 119-73 (ASTM, 1973), a restrained condition is "one in which expansion at the support of a load carrying element resulting from the effects of fire is resisted by forces external to the element." In an unrestrained condition, the element is free to expand and rotate at its supports. It is customary in the United States to conduct standard fire tests of floor assemblies in the restrained condition.

The current standard describes a means to establish restrained and unrestrained ratings for floor assemblies from restrained test samples. For restrained ratings from restrained test samples, the conditions of acceptance are based on limiting flame spread, limiting temperatures on the unexposed surface of the slab, and failure of the assembly to sustain the applied load. For an unrestrained rating determined from a restrained test sample, the conditions of acceptance are based on the same criteria and, in addition, temperature limitations are placed on the main structural members.

In addition, since 1971, the ASTM E 119 Standard describes a means to establish unrestrained ratings from unrestrained test samples. For unrestrained samples, the fire resistance rating is again based on limiting flame spread, exceeding temperatures on the unexposed surface of the slab, and failure to sustain the applied load; there are no limiting temperatures on the steel structural members when the test sample is installed in an unrestrained condition.

3.0 CONDUCT OF TESTS

The floor system design consisted of a lightweight concrete floor slab supported by steel trusses. The main composite trusses were spaced at 6 ft - 8 in. (2.0 m) on center (o.c.) and had a nominal clear span of either 35 ft (10.7 m) or 60 ft (18.3 m). The steel trusses were fabricated using double-angles for the top and bottom chords, and round bars for the webs. The web members protruded above the top chord in the form of a "knuckle" which was embedded in the concrete slab to develop composite action. Additionally, the floor system included bridging trusses (perpendicular to main trusses) spaced 13 ft - 4 in. (4.0 m) o.c. Figure 1 is a cut-away of the composite floor system showing the main and bridging trusses, metal deck and concrete slab.

3.1 Test variables

NIST studied two factors, the effect of (1) scale of the test, and (2) test restraint conditions. To this end, three tests were designed and conducted as follows:

Test #1: Full-scale, restrained test condition
Test #2: Full-scale, unrestrained test condition
Test #3: Reduced-scale, restrained conditions

3.2 Preparation of Test Assemblies

Original shop drawings by Laclede Steel [3] (manufacturer of the steel trusses) were used for the design of the 35 ft (10.7 m) span and 17 ft (5.3 m) span test assemblies. The steel trusses faithfully duplicated the geometry of the original design. Since equipment for making the resistance welds is not available in the United States, metal inert gas (MIG) welding was used and the welds were designed per American Institute of Steel Construction (AISC) Specification (AISC, 2001) to develop the web diagonal capacities in tension or compression. This requirement was based on available test data indicating that weld capacities exceeded proof loads by a factor in excess of 2.0. In addition, the steel angles and round bars, reinforcing steel, welded wire fabric, metal deck, lightweight concrete, and primer paint were all matched as closely as practical. Sprayed Fire Resistant Material (SFRM) was applied to the steel trusses at a specified thickness of 0.75 in (19 mm).

3.3 Description of Tests and Loading

3.3.1 Full-scale Tests - 35 ft (10.7 m) span

The full-scale tests were conducted at the Underwriters Laboratories (UL) furnace facility in Toronto, Canada. Loading of the floor slab with an applied load to "simulate a maximum load condition" as required by ASTM E 119, was accomplished through a combination concrete block and water-filled containers which were tied off to prevent them from damaging the fire brick and instrumentation in the event of a catastrophic failure of the floor system.

3.3.2 Reduced-scale Test - 17 ft (5.2 m) span

For the reduced-scale test specimens, the size of the truss members and thickness of concrete slab were selected to allow the most information to be extracted as practicably possible considering the Standard Fire Resistance Test is a test of the assembly's ability to contain a fire and is based on both thermal response (flame spread and heating of the unexposed surface) and structural response (support the applied load) to the standard fire. The sizes of the steel members, thickness of concrete slab, and truss spacing were selected to be the same as in the full-scale tests. Otherwise, the geometry was scaled by roughly half. This scaling required that the loading be increased by a factor of 2.

The reduced-scale tests were conducted at the UL furnace facility in Northbrook, Illinois. The superimposed uniform load was applied through a combination of concrete blocks, water-filled containers and hydraulic actuators located along the trusses.

4.0 TEST RESULTS

As noted above, prior to 1971, the ASTM E 119 Standard did not differentiate between testing and classifying thermally restrained and unrestrained floor assemblies. The 1961 revision of ASTM E 119, the revision referenced in the 1968 New York City Building Code, is used here for reporting the Standard Fire Test ratings. Using this revision, a single rating is developed. The year 2000 revision of the Standard is used here for reporting restrained and unrestrained ratings.

A photograph of the underside of the full-scale, restrained test specimen after almost 2 h of exposure is shown in Figure 2. Buckling of the compression diagonals can be seen as well as bowing of the metal deck between supports. Upon

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[3] Certain trade names and company products are mentioned in the text or identified in an illustration in order to adequately specify the experimental procedure and equipment used. In no case does such an identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the products are necessarily the best available for the purpose.

cooling, the test specimen recovered at least half of the deflection achieved during the test. Sectioning of the slab revealed that the bowing resulted from spalling of the concrete.

Table 1 shows results for all three tests giving the times (in minutes) to reach the conditions of acceptance, and the Standard Fire Test rating (in hours) for both the 1961 and 2000 revisions of ASTM E119[4]. Note that in none of the tests did the floor assembly fail to support the applied load.

Several observations can be made from the results (ratings) shown in Table 1 as follows:

- The restrained full-scale floor system obtained a fire resistance rating of 1½ h while the unrestrained floor system achieved a 2 h rating. Past experience with the ASTM E119 test method would lead one to expect that the unrestrained floor assembly would receive a lower fire rating.

- A fire rating of 2 h was determined from the reduced-scale test while a fire rating of 1½ h was determined from the full-scale test.

- The above result raises the question of whether or not a fire rating based on the ASTM E119 performance of a 17 ft (5.2 m) span floor assembly is scalable to a larger floor system of, say, up to 60 ft (18.3 m).

5. OBSERVATIONS AND CONCLUSIONS

The tested floor assemblies are similar, though not identical, to steel joist and concrete floor systems that are widely used in low rise construction. The test results provide valuable insight into the behavior of these widely used assemblies and also identify issues regarding scaling and restraint that require further study for floor systems and possibly other types of structural component.

The tests show temperature damage to the bridging trusses and buckling (in the full scale tests) of compression diagonals and the vertical strut near the supports. No evidence of knuckle failures was seen in the tests.

The ASTM E 119 standard test method has been used for several decades and has, for the most part, served its intended purpose well when taken together with the fire rating requirements. This is supported by historical fire loss data for more than half a century for different high-rise building occupancies. In addition, there are extensive data and experience that have been developed using the test method.

The NIST tests have identified areas where further study related to the standard test method may be warranted. The issues related to the test method that NIST will consider in formulating its recommendations include:

- the scale of the test for prototype assemblies that are much larger than the tested assemblies,

- the effect of restraint conditions on test results,

- the repeatability of test results (e.g., do multiple fire resistance tests conducted under the same conditions yield the same results?),

- the acceptance criteria to evaluate the load carrying capacity of the tested assemblies (currently tests are stopped before the load carrying capacity of the assembly is reached

[4] ASTM E 119 contains the following statement regarding precision and bias: No comprehensive test program has been conducted to develop data on which to derive statistical measures of repeatability (within-laboratory variability) and reproducibility (among-laboratory variability). The limited data indicate that there is a degree of repeatability and reproducibility for some types of assemblies. Results depend on factors such as the type of assembly and materials being tested, the characteristics of the furnace, the type and level of applied load, the nature of the boundary conditions (restraint and end fixity), and details of workmanship during assembly.

because other acceptance criteria are met or because the deflection becomes excessive and assembly failure could damage the furnace).

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Table 1. Results of ASTM E119 Standard Fire Tests

Test	Description	Times to Reach Conditions of Acceptance (min)						Standard Fire Test Rating (h)		
		Temperature on Unexposed Surface		Steel Temperatures		Failure to Sup-port Load	Test Termin-a ted (min)	ASTM E 119-61	ASTM E119-00	
		Average Temp Ambient+ 250 ºF (121ºC)	Maximum Temp Ambient+ 325 ºF (163 ºC)	Average Temp 1100 ºF (593 ºC)	Maximum Temp 1300 ºF (704 ºC)			Rating	Restr-aine d Rating	Unrestr-ai ned Rating
1	35 ft (10.7 m), restrained	---	111	66	62	(3)	116(1)	1 ½	1 ½	1
2	35 ft (10.7 m), unrestrained	---	---	76	62	(3)	146(2)	2	---	2
3	17 ft (5.3 m), restrained	180	157	86	76	(3)	210(2)	2	2	1

(1) Imminent collapse
(2) Vertical displacement exceeded capability to measure accurately
(3) Did not occur

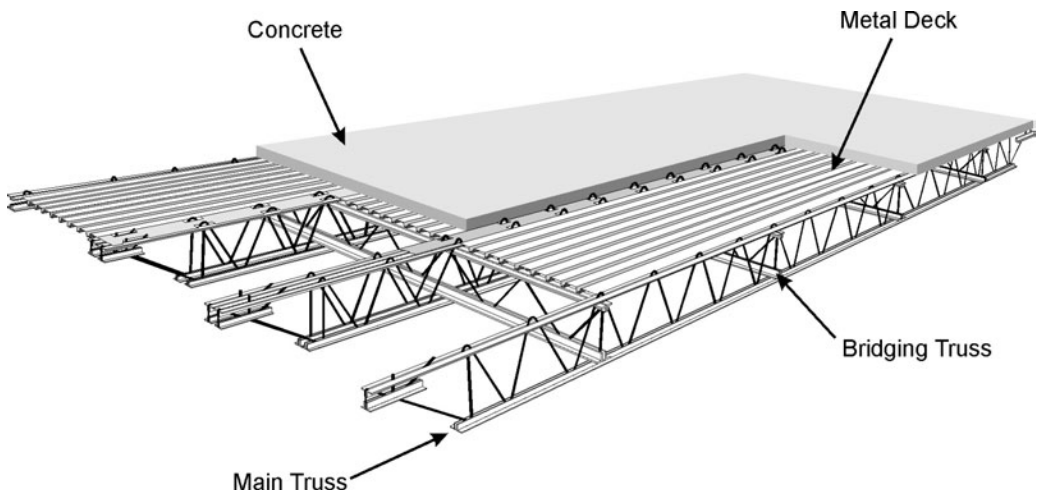

Figure 1. Floor system tested

Figure 2. Buckled truss webs and bowed metal deck