

TESTING NEEDS FOR ADVANCEMENT OF STRUCTURAL FIRE ENGINEERING

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ABSTRACT

International standards have long existed and been well recognized for establishing the fire exposure and fire resistance rating features in a standard test of a building construction assembly. However, their primary focus has traditionally been on the thermal protection and performance characteristics of various materials, as recorded by thermocouple measurement of temperatures. Consequently, major voids exist in the documented literature on structural fire response from these prescriptive fire resistance tests, as well as from some research/special testing.

More detailed information on the structural/physical original conditions and response of the test assembly during the fire exposure is greatly needed in order to enable the advancement of structural fire engineering applications. This recorded structural performance information will assist in a better understanding of structural degradation and ultimate failure mechanisms during fire exposures, provide results for validation of analytical models and for the model input properties to structural fire engineering applications. A number of new or revised instrumentation and test procedures, as well as related documentation requirements for these purposes will be outlined. The fire testing issues will principally identify structural performance aspects (such as applied loading, mechanical properties, strength limit states and test termination) and more general needs, though multiple ancillary furnace and fire exposure control variables were also reviewed and considered important to the repeatability and realistic interpretation of the experiments.

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1. INTRODUCTION

The continuing trend in Fire Protection Engineering toward Performance-Based Design (PBD) and rational engineering of structural fire protection in lieu of prescriptive requirements is often limited by the availability of reliable experimental data for analysis/design calibration or verification. The PBD approach requires engineering data that existing test methods, like the ASTM E 119¹, ISO 834², and the like, for prescriptive fire resistive ratings, were not developed almost 100 years ago to provide³. The proprietary nature of most standard fire tests likewise further restricts any such information from being in the public domain of the technical literature. This void of structural engineering data derived from the numerous regular fire resistance tests generally makes it necessary for PBD to utilize results obtained from ad hoc and special test methods performed outside the scope of standard test methodologies. However, special ad hoc tests, by definition, will lack in standardization and possibly in efficiency.

In addition to various limitations with respect to test procedures, number and types of measurements, and reporting, the reproducibility of standard prescriptive fire testing has always been a serious issue. The standard test apparatus and controls are only generally specified in the ASTM E 119 and similar standards. Fuels, burners, furnace linings, furnace dimensions, loading levels, and loading mechanisms are either unspecified or only qualitatively described, thereby allowing for real variances in the fire heating exposure for supposedly identical tests. This has led to situations in which fire test results cannot be reproduced for nominally identical materials and assemblies between different laboratories. Such a lack of experimental consistency and extra source of uncertainty causes significant problems in this PBD environment, which is already difficult due to the nature of normal fire variability.

A number of new or revised instrumentation and fire test procedures, as well as related documentation recommendations for these purposes will be outlined, based on a 2007 NFPA Research Foundation Project⁴ completed by Hughes Associates, Inc.

2. BACKGROUND

Standard fire resistance tests of building construction have been used for decades to assess three key performance parameters of the building assembly: integrity as a fire barrier, structural stability under load, and heat transmission. Despite the fact that two of these three fire performance indices are directly related to the structural, or at least the physical/mechanical response of the assembly, the only measurements explicitly required by ASTM E 119 are thermocouple instrumentation for temperatures. The structural/physical original conditions and response of the assembly during the fire exposure are only ambiguously addressed through general provisions for subjective experimental observations, without requirements for any quantitative recorded data or specific acceptance limits. Consequently, the structural/physical conditions before and during the fire have been evaluated from rather “soft” and qualitative observations, rather than hard data and performance limits.

The derived fire resistive assembly listing does not provide any substantive structural fire performance information. Furthermore, the actual supporting fire test data and documentation (e.g., the test report) for the listing is proprietary and not available as a public document under the current practice; this information can only be obtained and used with the permission of the listing’s sponsor. While these realities may be customary and satisfactory

for prescriptive uses of products and construction assemblies, they seriously hamper the development and application of PBD.

Acquisition of tangible experimental information on structural fire performance will not only provide a more solid basis for the traditional use of fire resistive ratings, but are an absolute necessity to support PBD developments. However, rather than encumbering or confusing the continuing use of prescriptive fire tests and ratings, a separate series of independent criteria for structural fire performance testing has been suggested.⁴ These structurally oriented testing issues will be presented first and in greater detail. Several recommendations relative to furnace and fire controls, and some other more general experimental needs will then conclude this paper. The complete and original source of these recommendations may be found in the cited NFPA Report⁴, which can be accessed and downloaded via the NFPA Internet site.

Of course, any and all test procedure items require appropriate documentation and data collection. The great value added to PBE of this additional experimental information lies in better understanding of behavior for purposes of its structural fire resistance modeling, model validation, and subsequent design utilization with better input data.

3. STRUCTURAL ISSUES

Several recommendations for implementation and possibly eventual standardization of structural issues for fire performance testing are presented as follows.

3.1 Test to Failure

All assembly fire tests should be conducted under maximum design load until an imminent, or actual, structural failure limit state is attained, or until a major integrity breach occurs, irrespective of the assembly's other thermal conditions. Currently, many of the prescriptive fire resistance tests, and some others, are stopped when certain limiting acceptance temperatures for the materials are reached, without any insights into the ultimate structural fire endurance time and failure mode.

3.2 Applied Maximum Design Load

The maximum assembly design load should be based on the greater of the design load computed from either allowable stress design or limit states-LRFD, and the controlling strength failure mode to be used for each type of assembly construction. Fire tests with no applied load or with light load may gravely distort the construction's integrity under the worst-case of maximum design load.

3.3 Define Criteria for Imminent Collapse

In lieu of reaching full assembly collapse, quantitative limits and guidelines for imminent structural failure in axial compression and bending should be identified. These would help protect safety and minimize damage to laboratory furnaces and test apparatus, while testing to failure.

Ryan and Robertson⁵ had developed in 1959 arguably the first deflection failure criteria for steel beams tested in a standard E 119 fire test under full load. Some prescriptive international fire standards, such as ISO 834, have already included similar type of deflection-based criteria for "loadbearing capacity," but ASTM E 119 has not to date.

3.4 Means of Load Application

Superimposed loading on all assemblies should only be applied through mechanical or hydraulically-controlled equipment, not water-filled tanks, concrete blocks, or sand bags.

Use of such constant weights is inherently less accurate and consistent than load control equipment that has been properly calibrated and serviced. Inconsistencies and differences in the load application methodology alone may lead to discrepancies between tests and/or laboratories. Moreover, in fire tests that reach actual structural failure, the public danger and damage potential to the laboratory furnace is less with controlled loads than with stacked tank, block, and bag weights, whose support and stability cannot be readily maintained after floor collapse.

3.5 Deflections

Record, as a minimum, the time-history of transverse deflections at mid-span in all primary structural members (beams, joists, columns, and wall studs) of the assembly, together with axial shortening of loaded columns and wall studs. The stiffness of a structural assembly is an important performance factor, as is strength. Structural deflections are not only a lead indicator of structural distress in the element tested, but large deflections also can lead to damage of its fire protection materials as well as damage to adjacent construction.

3.6 Strains

Place high-temperature strain gauges at critical sections (typically ends and/or mid-span) of main structural members (beams, joists, columns, wall studs) and of other important load transfer elements (shear studs, metal deck, floor slabs and reinforcement, and connections). Strain data provides key information on load paths, identifies the local member areas where inelastic (yielding) material response is occurring, and whether it is tensile or compressive, thereby revealing the critical structural locations for force redistribution and resistance mechanisms with fire exposure time.

3.7 Loaded Column and Wall Tests (including eccentricity)

Conduct column tests with superimposed compressive load until structural failure; investigate alternative protocol(s) for non-uniform heating of columns and walls, including possible provision for “equivalent” minimum eccentricity of axial load.

The effects of accidental load eccentricity, initial column curvature or imperfections, column mechanical strength properties, length slenderness ratio, and the type of structural failure (squash or stability/buckling) under fire exposures are relatively unknown. Similarly, the effects of non-uniform heating of a column (see Figure 1) or wall can be detrimental to stability and have not been rigorously studied.

A surrogate approach for simulation of wall and column assembly strength degradation due to additional non-uniform heating effects may be the imposition of a minimum eccentricity for compressive loads. Minimum compressive load eccentricity has been required in some test standards, such as ASTM E 72⁶, as well as in structural design methods, such as ACI 318-02⁷.

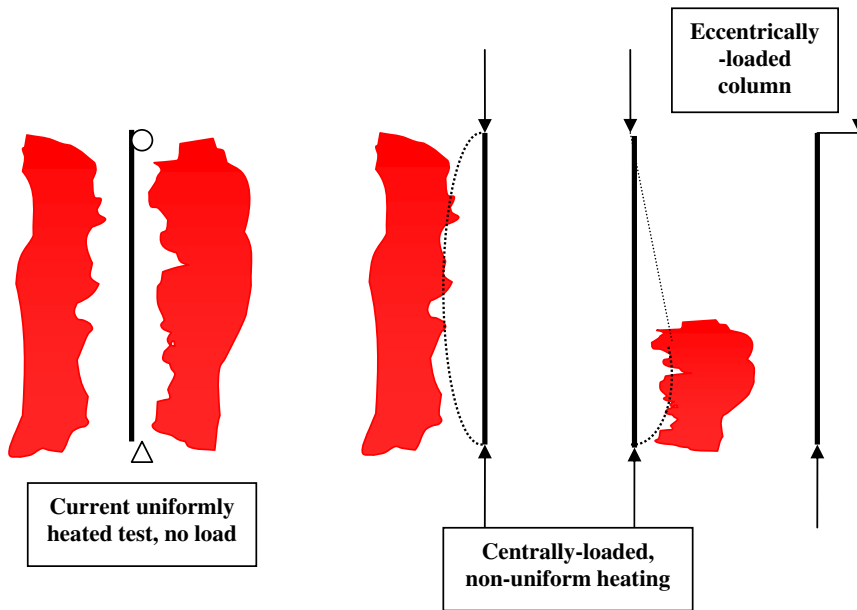


Figure 1 – Column Fire Testing Alternatives

3.8 Actual Mechanical Properties at Ambient

Perform material strength tests on samples extracted from the primary structural assembly members to determine their actual mechanical properties at ambient (including yield and ultimate strength, and elastic modulus). This is more accurate and correct than just relying on the minimum nominal properties of the grade/type of construction material utilized.

3.9 Mechanical Properties at Elevated Temperatures

Perform material strength on samples extracted from the primary structural assembly members to determine their actual mechanical properties at high temperatures (including yield and ultimate strength, and elastic modulus).

3.10 Scaling of Test Results

Develop criteria for when and how furnace- scaled fire tests can be used and interpreted relative to actual construction, as an alternate or supplement to current extrapolation of results to larger and heavier assemblies.

3.11 Thermal End Restraint

Record magnitude of thermal restraining forces on assembly throughout test duration, or at least provide detailed description of the boundary conditions present during the test, especially for floor and ceiling assemblies.

In the US and relative to ASTM E 119 classifications for restrained and unrestrained beam ratings (see Figure 2), this issue presents a common source of confusion, particularly to structural engineers and architects, in that thermal restraint is not necessarily synonymous with structural end restraint. Simple and modest steel shear connections for beam framing,

which are considered to be rotationally unrestrained with negligible moment-resisting strength, have been shown to represent adequate thermally restrained conditions for most cases.⁸

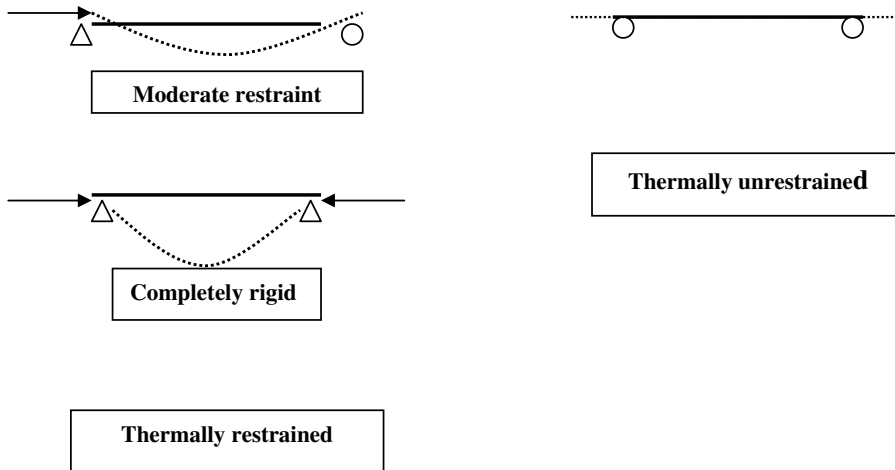


Figure 2 – Thermally Restrained and Unrestrained Floor/Roof Assemblies

4. FIRE/FURNACE ISSUES

The NFPA Report 4 contains an extensive discussion and justification for various recommendations related to the furnace and fire exposure variables, such as:

- Lining
- Gas type
- Burners
- Secondary air flow rate
- Target fire time-temperature curve
- Furnace temperatures
- Furnace temperature controls
- Pressure
- Oxygen concentration
- Tolerances from prescribed exposure

All these generally serve to establish better consistency of the actual heating environment to which the specimens are subjected. Due to the structural focus of this presentation, no more will be said about these, except for the fire time-temperature curve. The latter is a key driving force in the heating and high temperatures of the structural materials, and must commonly be assumed as single or a series of inputs to any structural fire engineering analysis.

4.1 Fire Time-Temperature Curve

In some PBD applications, the standard building fire test curve from ASTM E 119 or ISO 834, or from other more severe exposures based on petrochemical and tunnel incidents shown in Figure 3, is simply used as the design basis exposure. For more in depth studies,

natural fire curves based on the expected combustible fuel content and ventilation in a compartment can be developed.⁹ There is not only inherent uncertainty in these fire development parameters, but also variability in the modeling time-temperature predictions for the same set of inputs. This creates a practical quandary about what fire exposure(s) is most appropriate for both PBD and structural fire performance testing.

Review of the literature has confirmed this large variability in actual natural compartment fires in buildings, both in terms of intensity and duration. (see Figure 4) It should be evident that in a number of reported cases, the standard building fire curve (E 119 and similar), which represents the mildest exposure of all the standard fire curves given in Figure 3, can substantially underestimate the temperatures, especially during the 1st hour of burning.

This information indicates that the worst-case scenario for PBD and testing for buildings fires is really a fairly constant and maximum 1,200°C fire exposure. This has been startling news to many in the building construction profession, including the lead author of this article, given that such high exposure temperatures have been normally associated with only the special hydrocarbon and tunnel fires.

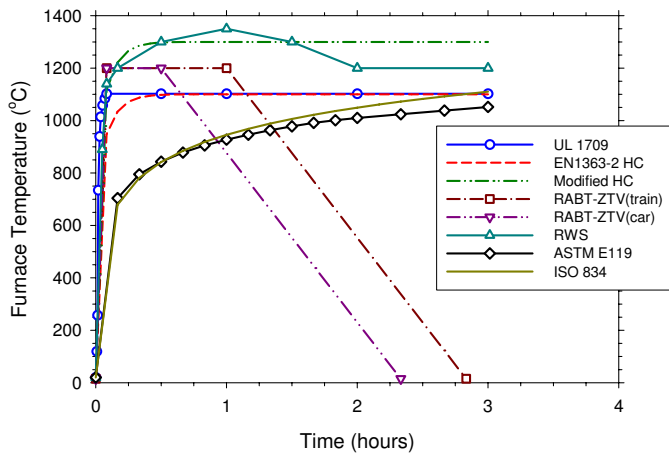


Figure 3 – Different Standard Furnace Time-Temperature Exposure Curves

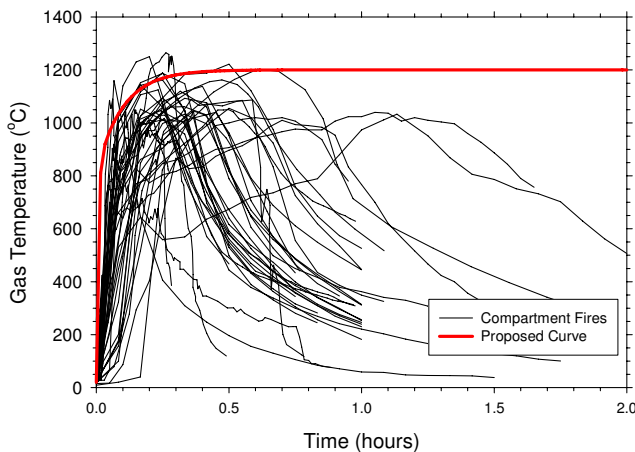


Figure 4 – Average Gas Temperature in Compartment Fires as Function of Time, Compared with 1,200C Maximum Time-Temperature Curve

The impact of this potential high temperature exposure could be immense, in that such a rapid and intense heating can result in both premature structural and protection material damage that has not been previously apparent when subjected to the milder standard fire. This damage, such as early spalling and cracking of concrete, delamination/detachment of low-density spray-on protection, and shrinkage-distortion of gypsum boards, can thereby substantially degrade the overall structural fire performance.

The NFPA Report⁴ concludes that the 1,200°C fire exposure curve is the most appropriate one to use for PBD testing, again since it does represent a worst-case scenario. However, because this is a very severe exposure, it will be over-conservative for some building constructions and occupancies, just like the current E 119 fire curve can be un-conservative for some others. Further work should be undertaken to develop a limited number of standard fire curves for different exposure classes, say light, moderate, and severe, with a good descriptive delineation of their range of applicability, similar to what has been done in the simplification of structural design provisions for seismic and wind loads. In the interim, it should at least be acknowledged that PBD and fire testing to the current standard building fire curve, like ASTM E 119, may not necessarily be a conservative exposure.

5. GENERAL FIRE TESTING RESEARCH NEEDS

5.1 Development of Test Procedure and Data on Fire Performance of Common Structural Connections

In the aftermath of the 9/11 World Trade Center collapses, more attention has been directed at the uncertainties of the high-temperature behavior of structural connections. These include not only the thermally-induced material degradation of welds, bolts, fasteners, adhesives and rebar details, but also the effects of large strains and deformations, together with a possible change in the basic mode of connection load transfer, e.g. from simple shear to tension for catenary action. The standard fire resistance tests essentially address members and small subassemblies, not connections. It would be beneficial to better understand the fire response of the common structural connections, in all materials – flexible/shear and rigid/moment, in order to assess whether they are more or less robust than their supported members, and what detailing and/or fire protection features can be optimized for fire performance.

5.2 Develop, Improve and Standardize Test Methods for High Temperature Thermal, Physical, and Structural Properties of Materials

Test methods for high temperature thermal, physical, and structural properties of materials are needed. Thermal properties (conductivity, specific heat capacity, heat of decomposition) need to be measured at temperatures as close to the highest temperature the material is expected to reach. Physical properties (density, moisture content, expansion/contraction, decomposition kinetics) also need to be measured as a function of temperature up to temperatures the material is expected to reach. Material strength tests need to be performed on materials used in the primary structural assembly members to determine their actual mechanical properties at high temperatures (including yield and ultimate strength, and elastic modulus). Research is needed to develop and evaluate the available methods, and provide suggestions for their improvement.

5.3 Compile Fire Test Database

A central compilation of a comprehensive database on all structural fire tests of members and assemblies, including those that were not successful, is recommended. This database should be regularly updated and also include any prescriptive fire resistance test results that were released to the public.

5.4 Analyze Repeatability (Scatter) of Tests

Once a sufficiently large and diverse database has been compiled, a rigorous statistical study of the random variations in similar fire tests should be performed to determine the expected probability distribution of experimental results.

6. CONCLUSIONS

Standard fire test methods and prescriptive ratings will probably continue to have a place in building design and construction for some time to come. In order to supplement the limited structural fire performance information that can be gleaned from such, a different and more scientific approach to structural fire testing is necessary to assist in the implementation of PBD for projects that so warrant. A parallel perspective has been adopted in seismic engineering. A list of recommendations has been outlined in this paper towards this end, mostly on structural issues, but also touching on fire/furnace controls and general experimental research needs.⁴ These should provide a rational path forward to advance PBD and its underlying test validation through enhanced test planning, further standardization, broadened results and better documentation for the future.

7. REFERENCES

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