The Need for International Collaboration on Structural Fire Endurance Research

by

William L. Grosshandler and Kuldeep Prasad[1]

ABSTRACT

A concerted effort is required to accelerate the development of the engineering tools needed to support the ambitious goal of scientifically-based performance predictions of building materials, products, structural elements, and systems up to the point of imminent fire-caused collapse. This paper reviews the general state of fire/structure test methods and models, identifies the research needed to move building fire codes and standards to a performance basis, and makes the case for the establishment of an international structural fire endurance laboratory as an essential component of this effort.

KEYWORDS: structural fire endurance, testing, fire resistance, research

1.0 INTRODUCTION

Societies dictate that buildings and other structures used routinely by civilian populations need to withstand severe, but anticipated, natural and manmade hazardous events, including earthquakes, wind storms, floods, heavy snows, and fires. The degree of severity anticipated is a choice made at the local, regional or federal government level, depending upon the country. A reliable data base has been established in the U.S. and Japan on the occurrence and severity of natural hazards; however, setting the severity level for manmade fires (accidental or intentional) is complicated by three factors: the historical data base on structural fires is sparsely populated and/or unreliable, extrapolation of historical data to future events is highly uncertain due to changes in human activities, and almost all fires have the potential of being severe given the right set of circumstances that may be out of the control of the building designer.

This article provides a glimpse into how society approaches structural fire safety, its reliance on prescriptive approaches to fire resistance design, the current level of understanding of how structures behave in fires, and the identification of research needed to move building fire codes and standards to a performance basis. Progress hinges on our ability to establish an international structural fire endurance research facility.

2.0 PERSPECTIVE

The enormity of the loss of life and the economic impact caused by the destruction at the World Trade Center (WTC) in New York on September 11, 2001, has caused many jurisdictions to reconsider the degree of severity of a fire that might be anticipated, and has highlighted for the engineering community the need to better understand the technical issues associated with the buildings that collapsed that day, as well as the likely performance of other buildings under severe fire conditions.

Assuming that a level of severity can be established by the appropriate authority having jurisdiction, the challenge for the engineer is to translate a specified fire scenario into heat fluxes onto the boundaries of the structure, into heat fluxes through building lining materials and structural insulation, into temperatures and temperature gradients within the structural elements, into thermal degradation (including phase changes and chemical

[1] Fire Research Division, Building and Fire Research Laboratory, National Institute of Standards and Technology, Gaithersburg, Maryland, 20899-8660, USA

reactions) and breaching of building partitions, into thermally-induced strain of the load bearing elements (including thermal expansion, and elastic, plastic, and creep strains), into redistribution of the loads, into mechanical failure of individual components, and eventually into local or global collapse.

Significant progress has been made in understanding many of the above phenomena, but the time scales and length scales associated with the different processes span a range so large that we are restricted in our ability to model with any certainty the true performance of the whole structure to the imposed fire. To circumvent the difficulty of predicting the performance of the structure under fire conditions, engineers and building code officials have relied upon furnace tests of individual structural elements or structural assemblies to rate one design against another, based upon the amount of time the element or assembly can survive the furnace environment before failing.

3.0 STANDARD TEST METHOD

The predecessor to the current standard fire resistance test for loaded and unloaded structural elements, ASTM E119 (ASTM 200a), was originally released in the U.S. in 1918. While a number of revisions were made to the standard throughout the twentieth century (refer to Grosshandler (2006) for a more complete review of the development of these furnace tests over the past 100 years), the prescriptive nature for the test method remains unaltered, in spite of changing fire loads and significant advances in our knowledge of fire and structural behavior. As early as the 1950s the engineering community was beginning to understand a number of situations that caused the standard fire exposure time-temperature curve, originally established by Ingberg (1928), to vary significantly from reality, including post-flashover fires, ventilation controlled fires, and different insulation properties of wall linings. More was understood about the thermal response of columns and beams to changes in temperature, with new analytical, numerical, and experimental methods being developed to predict column buckling, beam deflection and truss deflection.

In the standard test, full size structural elements, or portions of structural systems, are evaluated by mounting them in a fixture, exposing them to a flame in a furnace whose temperature rises as shown in Figure 1, and by noting the time at which failure occurs. The failure criteria, summarized in Table 1, depend upon the element's function and material, whether the article is load-bearing, and whether it is restrained. The rating of the test article is equal to the time (to the next lowest half-hour increment for times up to two hours, and to the next lowest hour for longer times) when any of the criteria indicated are exceeded.

It is expected that a 2-hour (h) rated article would resist failure in a real fire for a longer period of time than a similarly functioning 1-h rated article, and this is invariably the case. What can not be expected, however, is that a structure composed of elements that are 2-h rated would necessarily withstand an actual fire for two hours, or that that the structure would necessarily fail after two hours. The inability of the fire resistance rating to act as an absolute predictor of performance in an actual fire was recognized from the beginning when the forerunner of ASTM E119 was published in 1918. Over the years, however, the reference to fire resistance ratings in common time units has become interpreted to relate closely (or at least conservatively) to the actual expected time that a structure or element would be expected to resist a fire.

The fire resistance rating of a structural element or assembly can be greatly enhanced by applying a thermal insulation to the surfaces exposed to the high temperatures of the furnace. Sprayed fire resistive materials (SFRM) were introduced over 40 years ago as a lower labor cost, lighter weight alternative to concrete and lath/plaster. The SFRM derived its fire resistive properties from water of hydration contained in the gypsum or portland cement used to bind various fibers and other fillers. In addition to SFRM, intumescent materials, suspended ceilings and drywall assemblies, concrete encasements, tiles, and plaster/lath are used today to increase the ability of a structure to endure a fire. It is not uncommon for some of these materials, when applied in accordance with the manufacturer's instructions, to increase the fire resistance rating of a structural element by factors of four or more, a result of great consequence for steel construction, but also important for aluminum, timber and composite materials.

The shortcomings of the current methods for rating the fire resistance of structural elements and systems are numerous; some are obvious and have been recognized for years. The obvious shortcomings include:

- The size of the test article is limited to the size of the furnace (on the order of 5 m x 5 m x 2 m).
- The support conditions for the test article do not adequately mimic field use.
- The load conditions for the test article do not adequately mimic field use.
- The thermal environment of the furnace does not mimic a real fire.
- There is no universally accepted definition of the failure-to-meet-load criteria.
- The tests reveal no fundamental information about the performance of the specimen and provide little guidance on how to improve performance.
- The tests require specialized facilities and can be expensive to run.
- The furnaces themselves are not standardized; hence, the same specimen could receive different ratings if tested in two different facilities.
- Ratings are based upon a single test, with no way to quantify the uncertainty or safety factor.

In spite of severe shortcomings, these test methods continue to be used throughout the world. The reasons are based upon the following arguments:

- A massive data base using the standard fire resistance test method has been established and is in continual use.
- The historical record suggests that the test methods are conservative, since the number of losses due to the collapse of commercial buildings in fires is relatively small.
- Alternative methods have not been developed yet that are acceptable to the major parties who have widely divergent interests.

4.0 RECENT RESEARCH

4.1 Real-scale Test Programs

In addition to the standard furnace tests on individual building elements described above, many experiments have been conducted with different assemblies of various sizes and materials for different purposes. One of the largest under a controlled environment was on an eight story steel frame structure constructed within a dirigible hangar in Cardington, UK. Organized through a collaboration of universities, industries and European governments, one of the major objectives was to investigate how load is redistributed from a column or floor weakened by a localized fire to stronger elements that may be adjacent or more distant. A general conclusion from the study was that redistribution improves the robustness of the structure, which suggests that if this phenomena were well understood and predictable in general, that the fire proofing requirements could be lessened. Some representative articles and reports that describe different aspects of the Cardington test program include Kirby (1997), Sanad, et al. (1999), Gillie, et al. (2001), Lamont, et al. (2001), and Lennon and Moore (2003). Moss and Clifton (2004) reported on an effort to model the entire structure during the fire tests.

The literature is filled with tests and experimental measurements of individual structural members at elevated temperatures. Table 2 provides references that represent the kinds of experimental investigations that have been reported recently.

4.2 Material Properties

The response of a structure to fire differs greatly with the selection of materials for construction. While mechanical properties of most structural materials at ambient conditions are well documented, the properties of these same materials at temperatures that they might reach in a fire are sparse at best, and often non-existent. During the conduct of the investigation into the collapse of the WTC towers (NIST 2005), an extensive database was developed of the physical, thermal and mechanical properties of structural steels at elevated temperatures (Luecke, et al., 2005; Banovic, et al., 2005). Outinen and Makelainen (2004) also compiled the mechanical properties of structural steel at elevated temperatures. The mechanical properties at elevated temperatures of high strength concrete have been reviewed by Phan and Carino (1998), and the thermal properties of reinforced concrete at high temperatures have been examined by Lie and Kodur (1996) and by Kodur and Sultan (2003). A heat flux gauge was developed by Jansson (2004) specifically for determining the thermal conductivity, thermal diffusivity and heat capacity of structural materials, including wood, concrete, gypsum, and SFRM at temperatures up 725 ^{o}C. Extensive measurements of the thermophysical properties of gypsum panels and SFRM were also conducted in connection with the WTC investigation (Carino, et al., 2005).

4.3 Fire Modeling

Within the discipline of structural engineering it has been customary to treat fire as a quasi-steady, homogeneous bath that increases the temperature of a structural member or assembly in a uniform manner. Hence, structure temperature becomes an independent variable against which force, stress, strain and deflection are plotted. Neither time nor thermal gradients are considered as first-order parameters. The key to design, then, is to keep the temperature below a limit such that the demand-to-capacity ratio does not exceed unity. For such an approach, the details of fire growth and spread are irrelevant.

In many cases time is a primary factor that can act either to increase or decrease the performance of a structure in a fire. The temperatures in a real fire builds up more quickly than the temperature in a standard furnace test; however, the fire cannot sustain these high temperatures at any one location because the fuel is consumed (unless the fire is being fed by a continuous fuel source such as a broken natural gas line). A uniform bath and homogeneous temperature model cannot capture either of these phenomena. In addition to the transitory nature of the fire, creep, which is irreversible and time dependent, can play a significant role in the response of the structure.

Zone fire models have been developed that allow one to account for a growing fire in a room and the transport of hot gases and smoke to other locations in a building. Olenick and Carpenter (2003) identified almost 50 different zone models in their survey of the field. These include, for example, BRANZFIRE (Building Research Association of New Zealand, 2000), MAGIC (Gautier, et al., 1999), and CFAST (Peacock, et al., 2005). Because these models lead to algebraic and ordinary differential equations, they can rather quickly solve for the time varying temperature within a particular volume (usually divided into an upper and lower zone) in a multi-room building. Many of the zone models will also predict the heat flux to the boundaries of the compartment, although the heat transfer into the walls and structure is not computed in any detail.

The complexity of problems that can be solved using computational fluid dynamics models has increased in direct proportion to the speed of computers, which is now to the point that meaningful engineering calculations of room fires can be done on a personal computer. McGrattan (2005) elegantly described where we are and where we are going with CFD fire modeling in general. The Fire Dynamic Simulator (FDS) (McGrattan, 2004) has been developed specifically for doing realistic fire calculations and currently is used throughout the world for fire protection engineering design purposes.

4.4 Structural Modeling

The development of finite element modeling techniques provided engineers a tool that could begin to deal with complex solid mechanics problems. While mechanical engineers applied finite element analysis (FEA) techniques to heat transfer and thermo-mechanical designs associated with power systems and manufacturing processes, civil and structural engineers were mostly concerned with buildings and large civil structures that could be treated as fixed at the environmental temperature.

Models have been developed over the past 20 years to predict the fire endurance of specific structural elements or materials, and these are briefly reviewed by Olenick and Carpenter (2003). Examples of more general codes include TASEF (Sterner and Wickstrom, 1990), THELMA (Spearpoint, 2001), and SAFIR (Franssen, 2003).

The Proceedings of the International Association of Fire Safety Science (IAFSS) archive many of the significant advances in the analysis and numerical prediction of how structures behave in fire. The IAFSS symposium held in Beijing in 2005 was particularly rich in this area, and an examination of the proceedings of this symposium greatly simplifies anyone's effort to review the topic. An excellent assessment of our capability to numerically model the behavior of structures, and a look into the future, was provided by Franssen (2005). Baum (2005) assessed the current state of our ability to predict the response of a complex structure to a fire. The algorithm called the Fire Structure Interface (Prasad and Baum, 2005a; Prasad and Baum, 2005b), or FSI, allows coupling of the FDS finite volume model output to an ANSYS (2003) finite element model, an exercise made difficult by the shear magnitude of the degrees of freedom and the discontinuity of the element structures at the interface. Additional references on structural/fire models and experiments are provided in the review article by Grosshandler (2006).

5.0 RESEARCH NEEDS

A workshop held at NIST (Grosshandler, 2002) identified areas where efforts should be focused that would lead to the goal of scientifically-based performance predictions of building materials, products, structural elements, and systems up to the point of imminent fire-caused collapse. These included the need for more data on the properties of building materials, more measurements on the behavior of connections and assemblies, improved computational models, and standard test methods that supported performance-based codes.

5.1. Properties of Materials

Scientifically-based performance predictions require detailed knowledge of the thermal and mechanical properties of materials. Specifically, the workshop recommended research to:

- identify experimental techniques for measuring the thermal and mechanical properties of structural materials (normal and high strength concrete, normal and fire resistant steel, steel/concrete composite, aluminum, fiber-reinforced composite, timber) at temperatures up to their failure point;
- standardize measurement methods and use them to accumulate a consistent, reliable high temperature data base on the thermal and mechanical properties

that dominate the response of a structure to a severe fire , to the failure point; and

- develop experimental protocols for measuring, at elevated temperature, the thermal and mechanical properties of non-structural building materials (gypsum partitions, glazing, fire stops, intumescent coatings, structural fireproofing) that impact structural integrity during a fire, and accumulating a consistent, reliable high temperature data base.

5.2 Real-scale Laboratory Facilities

Facilities exist nowhere in the world for measuring the response to load of real-scale structural connections and assemblies in closely controlled, realistic fire environments (Beitel and Iwankiw, 2002). These measurements are essential to support the development of models and predictive tools for demonstrating the benefit of new materials and designs, and to assist understanding how a structure might fail in a severe case of arson or terrorist attack that exceeds the design threshold.

Current practice in the construction industry is to test structural components and assemblies at full-scale. However, this is most often not possible because of the size of a full-scale specimen and the high temperatures of the fire. In addition, one needs to account for the structural frame surrounding the element. As a result, insufficient data exist to properly extrapolate the response of a reduced-scale specimen in a test to the performance of that component full-size in a building system subjected to real fires. A structural fire endurance research facility is needed to develop a comprehensive understanding of the effects of length-scale on performance.

A real-scale structural fire endurance facility that permits, and promotes, international research would, for example, lead to:

- experimental methods and protocols for measuring the thermal and mechanical behavior of fireproofing as installed and when degraded by time, temperature, and stress;
- experimental methods and protocols for measuring the response of structural connections (including welds, bolts, rivets and adhesives) when exposed to severe fire conditions and loads, including during the cool-down period;
- fully instrumented experimental facilities for exposing floor and wall composite assemblies to controlled fires under measured loads, to failure;
- larger-scale test facilities to the extent necessary to extrapolate the behavior of connections and assemblies to the behavior of whole building frames;
- development of more efficient non-linear structural and CFD algorithms to expand the number of significant physical phenomena (e.g., creep, concrete cracking and spalling, fireproofing damage) and the range of length scales that can be practically accommodated; and
- development of efficient and verified subgrid models to better resolve the heat transfer from the fire environment to the structural elements, and for failure of structural connections and interfaces at elevated temperatures, eventually leading to full collapse analysis.

6.0 CONCLUDING REMARKS

A concerted effort is required to accelerate the development of the engineering tools needed to support the ambitious goal of scientifically-based performance predictions of building materials, products, structural elements, and systems up to the point of imminent fire-caused collapse. New experimental facilities are needed that will provide tight control over the thermal and mechanical loading of structural assemblies at real scale to support the development of the new measurement and predictive methods that will enable the development of these tools. Increased international collaboration in this area would permit leveraging of scarce resources.

A properly designed and equipped structural fire endurance laboratory will provide the following benefits:

- a scientific basis for assessing the response of buildings to extreme threats, the integrity of buildings that have experienced an extreme fire, and performance of alternative remediation approaches;
- acceleration of the development of cost effective materials and technologies into building practices and of engineering tools that support performance-based design alternatives;
- harmonization of best practices in testing laboratories and mitigation of the erection of technically unfounded international trade barriers for building products and materials; and
- safer, more flexible, and possibly less expensive buildings.

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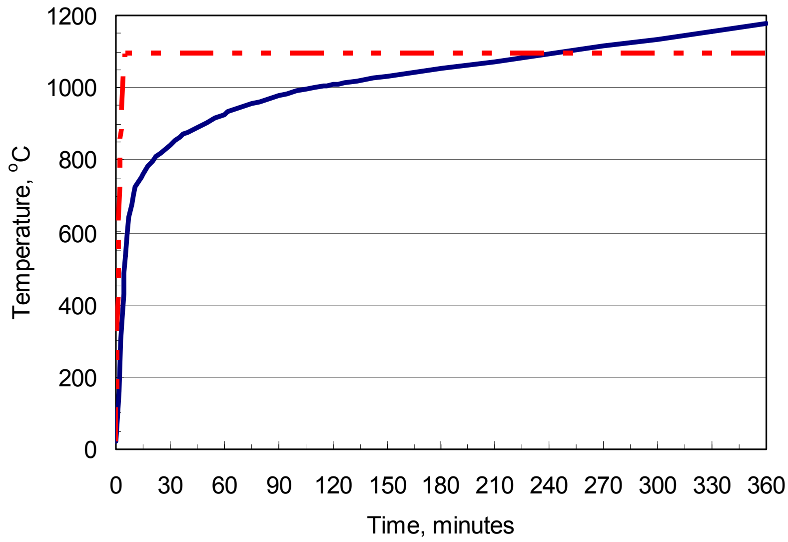

Figure 1: Standard furnace heating curves (ASTM, 2000a; 2000b)

Table 1: Example Failure Criteria for Various Structural Elements (ASTM, 2000a)

Element	**Load Criteria**	**Temperature Criteria**	**Breach Criteria**
floor systems*	Unable to maintain max design load	• Ave. temp. increase on unexposed side > 139 °C. • Max temp. increase on unexposed side > 181 °C. steel structural support • Ave. temperature of steel > 593 °C • Max temperature measured on steel > 704 °C concrete structural support • Ave. temperature of tension steel > 427 °C • Ave. temperature of reinforcing steel > 593 °C	Hot gases able to ignite cotton target on unexposed side
beam*	Unable to maintain max design load	• Average temperature > 593 °C • Max temperature measured > 704 °C	na
column	Unable to maintain max design load	none	na
steel col. or beam	none	• Ave. temperature of column > 538 °C • Max temperature measured on column > 649 °C	na
bearing wall	Unable to maintain max design load	• Ave. temperature increase on unexposed side > 139 °C. • Max temperature increase on unexposed side > 181 °C.	Hot gases able to ignite cotton target on unexposed side
non-bearing partition	na	• Ave. temperature increase on unexposed side > 139 °C. • Max temperature increase on unexposed side > 181 °C.	Hot gases able to ignite cotton target on unexposed side
*The rating of an element tested in a frame that restrains it from bending or expanding may be reduced by a factor of 2 over the same element tested in an unrestrained fashion.			

Table 2: Representative recent experimental investigations of heated structural elements

Materials	Element	Citation
steel	joists	Alfawakhiri, F., and Sultan, M., 2001
steel + insulation	floor trusses	Chang, et al., 2005
steel	H-columns	Hirashima, and Uesugi, 2005
steel	columns	Kamikawa, et al., 2003
steel	cellular beams	Liu and Liew, 2004
steel	columns	Korzen, et al., 1999
steel	joints	Spyrou, et al., 2004
concrete	columns	Ali, et al., 2003
reinforced concrete	beams	Bernhart, et al., 2005
high strength concrete	columns	Kodur, et al., 2003
precast concrete	walls	Lim and Buchanan, 2003
reinforced concrete	beams	Williams, et al., 2005
timber	structures	Frangi and Fontana, 2005
wood	structural members	Janssens, M., 2004
wood	structural members	Jong and Clancy, 2004
wood studs	shear walls	Kodur and Sultan, 2000
wood frame	exterior walls	Takeda, 2005
timber-concrete	slabs	Frangi and Fontana, 2003
gypsum-metal studs	partitions	Manzello, et al., 2004
glass	partitions	Wu et al., 2005
glass	facade	Delin and Walmerdahl. 2001
glass	windows	Harada, et al., 2000
glass	windows	Pagni, 2003