Fire Technology, 48, 825–839, 2012

DOI: 10.1007/s10694-011-0247-4

Structures in Fire: State-of-the-Art, Research and Training Needs

V. K. R. Kodur, Department of Civil & Environmental Engineering, Michigan State University, East Lansing, MI 48824, USA*
M. Garlock, Department of Civil & Environmental Engineering, Princeton University, Princeton, NJ 08544, USA
N. Iwankiw, Hughes Associates, Inc., Chicago, IL 60631, USA

Received: 10 February 2009/**Accepted:** 19 October 2011

Abstract. Structural fire safety is one of the key considerations in the design and maintenance of the built infrastructure, yet there are serious limitations in the current approaches to structural fire safety and also severe knowledge gaps in the literature. Two main reasons for these limitations are the lack of significant research activities in this field and lack of educational and training programs in the universities. This paper reviews the current state-of-the-art and identifies the research and training needs for improved fire safety in the U.S. These discussions are based on a two-day workshop organized at Michigan State University which brought together many academics from U.S universities, international experts, and design professionals in the structural fire safety field. This paper summarizes the conclusions of the workshop and identifies the top ten research and training needs in structural fire safety.

Keywords: Structural fire safety, Fire resistance, Fire protection engineering, Research and training needs, Performance based design

1. Introduction

Design for fire is currently based on prescriptive approaches either through standard fire tests on individual building components or empirical approaches. Worldwide trends indicate a shift from these ‘‘prescriptive approaches’’ to ‘‘performance-based’’ design of building systems, with heavy emphasis on validated engineering practice and predictions from computer simulations of ‘‘typical’’, in-service fire scenarios. In the U.S., performance-based building (and fire) codes are being implemented to augment existing prescriptive standards and regulations. However, many reports [1, 2, 3, 4] have indicated that the implementation of performance-based codes requires several key elements that are not fully developed or understood. These include improved understanding of materials performance in fires, development of advanced validated tools for alternative fire protection designs, and education of fully trained structural fire engineering practitioners.

---

* Correspondence should be addressed to: V. K. R. Kodur, E-mail: kodur@egr.msu.edu

Most of the passive fire protection design for structural framing remains within the project architect's responsibility, with little if any input from a fire protection or structural engineer. In the last few years, there has been consensus among the research community that fire should be treated as a "load", a thermal load, just as one may consider an earthquake or wind load. Thermal loads induce stresses and deflections on a structure, together with degradation of material strength and stiffness, and the proper design for such should be considered by engineers with proper knowledge in the field.

Addressing the above complex tasks requires significant research and training efforts. However, until recently, there was lack of focused research programs in U.S. universities in the structural fire safety field. In recent years, a few faculty from various universities have initiated some research activity in the structures and fire area. To capitalize on these initiatives, a National Workshop to identify and develop research and training needs in the structural fire safety field was sponsored by the National Science Foundation (NSF), the National Institute of Standards and Technology (NIST) and Michigan State University (MSU). This paper summarizes the conclusions of the workshop and identifies the top ten research and training needs in structural fire safety.

This paper is important from two perspectives. First, it contains an overview of the state-of-the-art in structural fire engineering area. Such a review is important for both practitioners and researchers that are working in this area and looking for relevant references. Second, it summarizes findings and opinions from dozens of experts working in this field. These experts are from both academia and practice as described in the next section. Such a broad range of experts have not been assembled before to have these important discussions that led to the research and training needs presented in this report.

2. Workshop

The National Workshop on Structures in Fire was held on June 10–12, 2007 at the Kellogg Hotel and Conference Center at Michigan State University, East Lansing Michigan and it was co-chaired by the authors of this paper. The full details of the workshop and the identified research and training needs are discussed in the workshop report [5]. The key objective of the workshop was to enhance the research and training activities in the fire safety area by identifying the needs for research and for state-of-the-art improvement. The specific objectives were (1) review the state-of-the-art in structural fire safety (SFS); (2) identify and prioritize research needs; (3) improve SFS education and training in the U.S.; and (4) develop plans to improve provisions in codes and standards.

The workshop speakers were by invitation only and selected by the workshop co-chairs. Because much of the technology and knowledge base for structural fire engineering resides overseas, three experts from universities outside the U.S. were invited. In total there were 65 participants including the workshop organizers. The largest percentage of participants (50%) was university faculty who are already engaged in structure-fire research and teaching, or are considering beginning such a program. An additional 12% consisted of participants from research organizations such as NIST and Southwest Research Institute. Additionally, several graduate students and post-docs interested in pursuing the field of structural fire safety upon graduation attended the workshop (16%).

Also in attendance (representing 26% of attendees) were persons involved in codes and standards, and those who are intimately aware of fire safety need such as those from the National Fire Protection Association (NFPA), SFPE, the Structural Engineering Institute (SEI-ASCE), the American Iron and Steel Institute (AISI), the Portland Cement Association (PCA), New York City Fire Department, Underwriters Laboratory (UL), and the New York City Building Department. The variety of expertise present enriched the discussions held during the panel sessions, focus group meetings, and informal discussions held during the workshop.

3. State-of-the-Art Review

The state-of-the-art review that we present is divided into three sections: modeling and predictions, experiments, and materials. Many divisions of this review are possible but these three best represent the topics of discussion at the workshop. This literature review targets the most recent publications, whose own literature review and list of references can be used as another source of information.

3.1. Modeling and Predictions

There are essentially three components to model structures in fire: the fire model, the heat transfer model, and the structural model. A structure-fire interaction model must consider all three components: typically, all three are uncoupled. This means that the three components "talk" to each other in one direction only (in the direction listed above). Each model component can be simple or complex. For example, the fire model can be a time–temperature curve specified in a standard [6] or based on detailed zone or CFD modeling. On the same lines, heat transfer model can be a 2-dimensional (2-D) model through the cross-section of the element being examined, or it can be a 3-D model with temperature varying along the length as well as through the cross-section. Similarly, the structural model can be 2-D or 3-D, and it can use beam elements or more complex shell elements. The modeler needs to consider the limit states that need to be captured, along with the engineering effort and computational cost when considering the level of details in the model.

In the past ten years, many advances have occurred in finite element software dedicated to structures in fire such as VULCAN and SAFIR [7]. Other general purpose and commercially available software can be used for structure-fire modeling (such as ANSYS and ABAQUS). However, these general purpose programs are generally overly complex to use for fire applications, expensive, and perhaps too cost prohibitive for engineering firms that do not frequently perform such specialized analyses.

As an option to these finite element computational tools, simple calculations can be performed using closed-form solutions that consider equilibrium and compatibility. These closed-form solutions can provide a reasonable approximation of the structure-fire response, and they can be used to provide some level of validation for the more complex computational solutions. Structural models with finite axial restraint, or finite rotational restraint can be used to derive the behavior of steel beams and columns under high temperatures. Simple closed-form solutions can be developed from these models assuming thermal loading only, as shown by Usmani et al. [8]. In addition, Quiel et al. [9] have developed a simple analytical model (that can used with a spreadsheet) for predicting the response of a perimeter column in a steel high-rise building subject to fire.

A description of performance-based design for fire and a summary of methods available for predicting the performance of beams and columns subject to fire are given by Milke [10]. In addition, Usmani et al. [8] have developed analytical expressions, confirmed with the results of computational finite-element modeling, which can be used to solve for the moment and midspan deflection in heated horizontal beams. Using finite element computations, Tan and Huang [11] have analyzed a beam under fire considering varying rotational and axial flexibility. They have shown that the axial force that develops in the beam (and hence the connection) depends on parameters such as axial restraint, a utilization factor related to the flexural demand/capacity, beam slenderness, and rotational restraint.

Most methods, however, are limited to a single structural member acting in isolation. In this case, the adjacent members are represented by boundary conditions, but these are not dynamically involved in the time-history of the fire. Recent research (for example [12, 13, 14, 15, 16]) has demonstrated the importance of this dynamic interaction.

Wang et al. [17] described the use of structural subframe finite element models to effectively capture the behavior of a full fire-exposed building frame. More recently, advanced nonlinear analysis methods have been developed to study the performance of steel structures under fire [18, 19, 20, 21, 22].

Many limitations exist for modeling structures in fire in a seamless, efficient, and appropriate way [23]. For example, the links between the fire, thermal, and structural models are not advanced. For predicting fire growth and temperatures, zone models that are well-developed, simple, and computationally inexpensive can be adopted. The merits of zone modeling are well documented in the literature [e.g. 24]. If one wants to do a 3-D computational fluid dynamics model of the fire, it is difficult to transfer that data to the heat transfer model in a seamless and efficient manner. Although CFD modeling may provide a more accurate simulation of the growth phase of the fire, this relatively short time period is usually negligible for a structural fire performance analyses.

The same difficulty exists if one wants to transfer data from a 3-D heat transfer model to a 3-D structural model. However, recent advances in some FEA software packages facilitate transfer of 3D heat transfer results into a 3D structural model (e.g., Abaqus sequentially-coupled thermal stress analysis procedure). In addition, the complete analysis is typically one-way only as described previously. It cannot capture, for example, the change in the fire model if a portion of a floor collapses. Most models will not explicitly capture phenomenon such as concrete spalling, mass transport, fire protection material damage (detachment or cracking) and creep strain. Section 4 identifies other research needs that can advance performance prediction through modeling. For example, more experimental data is needed to validate the numerical models, reducing the uncertainty in the fire load prediction, and more realistic modeling of the beam-to-column connection behavior.

3.2. Experiments

A state-of-the-art review has indicated that there is good amount of data from standard fire resistance tests on isolated structural elements such as beams, columns, walls and floor [25, 26]. However, these standard test data are proprietary and in most of these tests, only a very limited number of parameters were considered, the tests generally followed standard fire conditions without consideration of realistic (design) conditions, such as real fire exposure, specimen size, loading and structural failure conditions [27]. Further, there is a lack of even minimum data on some types of assemblies, such as steel and reinforced concrete beams under restrained conditions. There have been only a very limited number of fire experiments that considered the “system approach” for evaluating global response of structures.

A few tests on portal frames were conducted in the 1980s and 1990s [25]. However, the most notable and significant research in structural fire experiments were undertaken in the last decade by the Building Research Establishment (BRE) in the U.K., which conducted a series of full-scale fire tests in the Large Building Test Facility (LBTF) at Cardington, U.K. [16, 28, 29]. The tests on multi-story steel and concrete buildings provided unique and valuable response data regarding the behaviour of both structural and non-structural elements within a real compartment subjected to real fires.

Connections is a growing research area and one that is recommended by several reports [1, 2, 3, 4]. Experimental studies for extended end plate connections under fire loads have been performed by Lawson [30], Leston-Jones et al. [31], Al-Jabri et al. [32], Spyrou et al. [33, 34]. In addition to experimental research, 3D finite element models of end plate connections in fire have been developed [35, 36, 37] and verified based on the experimental works described above. Research on single plate (i.e., shear tab, fin plate) connections has recently begun [38, 28, 39, 40, 41]. These studies have shown that it is possible to utilize catenary action in unprotected steel beams only if the connections have sufficient resistance to support the tensile forces that develop from this catenary action.

Research needs that can advance the state-of-the-art in experimentation are identified in Sect. 4. For example, new robust reliable sensors are needed to measure the structural response, more experimental facilities are needed, and experimental tests on decommissioned full-scale structures would enhance the database of knowledge. The lack of fire test data is hindering the development and validation of advanced computer models for simulating the fire response of structures.

3.3. Materials

The fire performance of structural members depends on the properties of the constituent materials and hence the knowledge of high temperature properties of

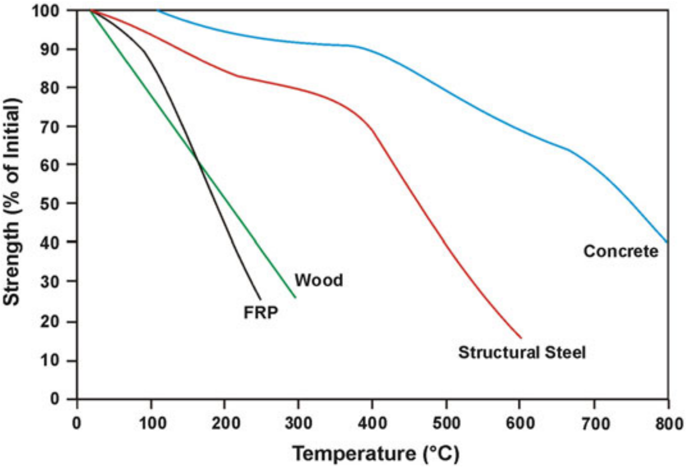

Figure 1. Approximate variation in strength of FRP, concrete, steel, and wood with increasing temperature.

constituent materials is critical for fire resistance assessment under performance-based codes. The temperature dependent properties that are important for establishing the fire-response of structures include: thermal, mechanical and material specific properties (such as spalling in concrete) of constituent materials. Figure 1 illustrates the variation of strength with temperature for commonly used construction materials.

The variation of many of the properties at high temperature is quite sensitive to small changes in materials composition (such as chemical composition in steel or aggregate type in concrete) and environmental conditions (humidity and rate of temperature rise). As an example, the thermal properties are significantly influenced by the type of aggregate and composition of the concrete mix [42, 43].

The literature review indicates that the high temperature properties of conventional construction materials, like steel (structural, reinforcing and pre-stressing steel), concrete (mostly normal strength) and wood are available (e.g., ASCE structural fire protection manual [44] and in the Eurocode-2 [45, 46]. Often, there is large variability in the high temperature properties of some materials, such as concrete and wood [42, 47, 48]. In addition, there is significant lack of information on properties related to high temperature creep, transient strain, or spalling related properties in concrete [49]. Due to this, many of these properties are not fully accounted for in current fire resistance calculations [47].

In the last two decades, there has been significant research and development activity in the construction materials area. This has led to the introduction of a new class of materials referred to as high performance materials (e.g., fiber-reinforced polymers (FRP), high performance concrete), which are being increasingly used in the built infrastructure, which includes buildings, bridges, tunnels and transit systems. Many of these materials have poor, or unknown, fire resistance characteristics and knowledge of their high temperature properties is critical for evaluating fire safety of structural systems [42].

These new types of materials such as FRP, unlike steel and concrete (NSC), are often combustible and might even alter the fire exposure characteristics. Further, there is wide variation in the composition of FRP (glass, carbon, aramid) and the orthotropic nature of these materials makes the fire resistance evaluation quite complex. Thus, conventional measurement techniques and failure limit states may not be applicable, such as the critical temperature concept, in their property/performance measurement/evaluation.

Standard fire tests typically provide only the final fire resistive ratings of the overall construction assembly without requiring more detailed property documentation of the protection material(s) that were employed. Thus, while generic information has been published on the thermo-mechanical properties of the various fire protection materials (spray-ons, gypsum board, intumescent/mastic paints, wraps, batts and blankets), this is limited and often not accurate for specific manufactured products.

Therefore, there is a critical need for research in this area as identified in the next section.

4. Research and Training Needs

This section identifies the top ten research and training needs as identified and voted upon by the workshop participants, which consisted of academic and practitioner experts in the field of structural fire safety as indicated in Sect. 2. Three breakout groups were defined, each with a different theme (Structural Fire Response Modeling, Fire Experiments, and Codes, Standards, and Education). Each group identified the top ten research needs for the theme. When all groups reconvened, the 30 recommendations were voted upon by all workshop participants to identify the top ten overall recommendations that we discuss below in order of decreasing number of votes.

4.1. Development of High-Temperature Constitutive Material Models

The temperature dependent properties of construction and fire protection materials are critically important for establishing an understanding of the fire-response of structures. These properties include: (a) thermal (b) mechanical and (c) material specific properties, such as spalling in concrete and charring in wood. The thermal properties, (thermal conductivity, specific heat, thermal expansion, mass loss and vapor pressure) determine the extent of heat transfer through the material, whereas the mechanical properties (strength, modulus of elasticity, and creep) determine the extent of strength loss and stiffness deterioration. In addition, spalling can play a significant role in some types of concrete. These properties vary as a function of temperature and depend on the composition and characteristics of the material itself.

While the literature review indicates that the high temperature properties of conventional construction materials are available, often, there is large variability in the high temperature properties of some materials, such as concrete and wood. Furthermore there is a significant lack of reliable high-temperature constitutive relationships for new types of materials, like high strength concrete, FRP, and the various insulation materials. No or limited systematic tests have been carried out to develop high-temperature properties for pore (vapor) pressure in high strength concrete, creep in steel, or charring in wood under realistic fire, loading and failure scenarios. This lack of data and the high variation can be attributed to several factors such as:

- Lack of standardized test methods to test high-temperature properties,
- No standardized equipment to measure properties,
- Diversity in available materials and their composition (such as different concrete mixes and its constituents),
- Non-uniformity of the test parameters and environmental conditions (such as humidity and heating rate).

The lack of such high-temperature material constitutive relations is hindering the usage of numerical models for fire resistance evaluation. Thus, there is a significant research need to develop high-temperature material property and fire resistance test data to advance the state-of-the-art in the structural fire safety field.

4.2. Development of New Sensor Technology for Fire Tests

At present, there is a lack of instrumentation (strain gauges, heat flux gauges, deflection gauges) and devices to measure the various structural response parameters during fire tests. This is not limited to the simple application of heat, but also includes the ability to handle heat flux. While significant progress has been made in the development of strain gauges and sensors, there has been very little progress in high temperature range. Such instrumentation and sensors are critical for capturing the response parameters during fire tests. In addition, there is a need for advanced remote monitoring techniques (such as wireless sensors) to capture data under extreme temperatures. Also, the reliability issue of the current instrumentation (thermocouples) has to be improved to address frequent failures.

4.3. Collection and Generation of Test Data for Model Verification

An extensive set of experimental data is essential for validation of numerical models, which need to be verified by experimental data or observations taken from actual fire events. As discussed previously, use of the proprietary limited results of standard fire tests is usually insufficient for model validation purposes. There is also a lack of U.S. laboratory facilities for such non-standard fire experiments. A large-scale testing facility in one location, or a network of such facilities at several US universities, would be a great benefit for structural fire safety research. Data for real fire scenarios can also be collected through building incident reporting after an actual fire event. All data regarding experiments or actual fire events needs to be archived, perhaps in a public repository, that can be used by anyone to verify the computer models.

4.4. Development of Acceptable Tools and Criteria for Undertaking Structural Fire Design

The current US codes and standards do not provide any substantive criteria for structural fire analysis and design. Most of the provisions remain focused on the traditional prescriptive fire resistance approach. Appropriate basic information on fire loads, heat transfer, structural response at high temperatures, and the thermo-mechanical properties of construction and insulation materials must be developed and compiled into usable forms for practitioners. Computer software for these more sophisticated applications should be further refined/validated and made commercially available for research and practice. Finally, additional publications and design guides regarding relevant practical issues are needed to complement the evolving performance-based design criteria.

4.5. Defining Proper Fire Loads (Scenarios) for Developing Numerical Models and Design Guidelines

The greatest uncertainty encountered while modeling a structure in fire is typically the load itself, i.e., the fire. While several parametric fire models exist for a typical fully-developed fire contained within a single compartment, many significant fires (e.g. at the WTC and Meridian Plaza in Philadelphia) were not contained in a compartment because most of the floor was open. Also, the WTC fires occurred simultaneously on multiple floors. Simple fire models for such spaces and scenarios are not established. More complex computational fluid dynamic models could be used, but these are not practical for design purposes due to their complexity, computational expense, and the lack of a link to the thermal analysis in available software. Simplified, parametric representations of the results of zone modeling or computational fluid dynamic modeling are needed for application to structural fire analysis.

4.6. Performing Sensitivity Analyses and Parametric Studies to Identify Factors Governing Global Structural Response

As mentioned previously, high temperature thermal and mechanical material properties (of steel, concrete, and timber for example) contain much uncertainty as does the fire load. It is not clear how this uncertainty/variability affects the structural response as a whole. Studies, both experimental and computational, should be performed to evaluate the sensitivity of structural response to such properties so that the modeler can determine which parameters need to be precisely measured and captured in the analysis.

Probabilistic approaches may be able to quantify these material property uncertainties. It may also provide a risk assessment measure as to the structure's level of safety given a certain fire scenario. Future directions in structural fire response modeling are, therefore, looking towards probabilistic approaches for identifying risk levels in a performance-based design approach to structural fire safety. Since this entails gathering data from thousands of analyses, it is important to further enhance our computational modeling capabilities as well as improve our understanding of the important phenomena that need to be captured in these models.

4.7. Undertaking Full-Scale Fire Tests on Decommissioned Buildings

As discussed in Sect. 4.3, data from full-scale tests are critical for validating models and there is a lack of such data. Buildings that are decommissioned may be a good and economical source for doing full-scale tests that can provide valuable data.

4.8. Characterizing Connection Behavior

The current approach to fire resistance evaluation is based on the exposure of individual structural elements of specific dimensions, such as beams, columns, floors or walls, to the standard ASTM E119 fire. However, member/assembly connections are usually not included in the standard fire test. The connections' load transfer capabilities and ductility can play a significant role in determining the response of structural systems during fire, as seen in the Cardington full building fire tests [16] and also in the WTC building collapses [4]. At present, there is lack of data on the behavior of connections under high temperature. Such data, both at small-scale and full-scale as part of a structural system, are critical for understanding the behavior of connections in fire. Also, the floor assemblies and steel connections used for the Cardington testing were designed in accordance with the British building code and reflects local construction practices, some of which are not consistent with conventional US applications. In particular, the beam connection types used in Cardington and their capacity to resist axial tensile loads were not fully representative of the common U.S. construction practices. Thus detailed experimental and numerical studies are needed on typical connections used in buildings.

4.9. Development of University Curriculum Related to Structures in Fire at the Graduate and Undergraduate Levels

One obstacle to performance-based design for structural fire safety is the lack of knowledge by most structural engineers on how to analyze or design for a fire load. Furthermore, there is seemingly no tangible interest or motivation to perform such an additional task. Most architects and fire protection engineers are not trained to properly analyze such complex effects on structures. This multi-disciplinary aspect of structural fire engineering will place extra burdens on its lead profession, which appears to be most appropriately suited for structural engineers. In addition, most building officials, building owners, and occupants, as well as the general public, are lacking in adequate awareness of these realities. These groups are thereby skeptical on recent advances and are not demanding the application of newer technologies in this field.

One prerequisite for improvement and advancements in this field is the development of a critical base of human expertise. Growth of university faculty, new graduates, and experienced professionals well versed in the field are needed to drive this design progress and technological innovations. An existing obstacle to the education of students—future engineers—in structural fire safety is that university core curricula in the related U.S. undergraduate civil, structural, architectural, and mechanical engineering programs are already full, with little room for addition of specialized courses in structural fire safety. However, an even more fundamental constraint is the availability of interested and knowledgeable faculty who would be qualified to develop and teach such new courses. A greater emphasis on practitioner training offerings, in the form of continuing education and special programs, is also necessary to inspire and provide the requisite knowledge for those who are interested in broadening their work to include structural fire engineering.

4.10. Improving the Procedures and Specifications to Modify the ASTM E119 Standard Fire Test

The current approach to fire resistance testing is to subject structural elements, such as beams, columns, floors or walls, of specific dimensions to standard fire exposure in a specially designed fire test furnace. Test procedures, including fire (time–temperature) curves, are specified in standards such as ASTM E119 [50]. Often, the assemblies are not loaded during the tests. Generally, the end point (failure) criterion is based on a simple limit, such as unexposed side temperature or critical limiting temperature in steel assemblies. The most important drawbacks to standard fire test procedures is that they do not account for real fire scenarios (and no decay phase), structural interactions with adjacent framing, realistic load levels and restraint conditions. Further, the current test methods and their acceptance criteria do not give due consideration to various limit states, such as strength, stability, deflection, and rate of deflection for assembly failure.

The genesis and origins of this standard fire test method and its applications are of early 20th century. Apart from evolving fire resistance requirement levels in the codes and related test result interpretations, they have remained substantially unchanged throughout the past 100 or so years. While the prescriptive methods based on ASTM E119 have been generally safe and relatively easy to implement, they are not capable of predicting actual structural fire performance. Various limitations and assumptions are inherent to this approach, which render it to be overly conservative in many conditions and un-conservative in some, but these differentiations are not discernable. The movement towards alternative advanced techniques in structural fire engineering attempts to resolve these shortcomings with a modern knowledge base and engineering tools. However, this long engrained "culture" for prescriptive practice is difficult to change for a variety of reasons.

Attempts should be made to improve the fire test provisions in these standards. Such changes should include installation of additional instrumentation to capture the detailed structural response, testing up to a structural failure limit state, consideration of all failure limit states (strength, deflection etc.), specifications on pretest property measurements, observations during the test, and recording of data. It should also be noted that the E119 fire scenarios represents upper bound to a family of real fire curves.

5. Summary and Conclusions

The National Research Council of the National Academies believes that "an *incomplete understanding* of the phenomenon of fire, the strategies and technologies to control it, and human behavior in chaotic, life-threatening situations contributes to unnecessary human and economic losses" [1]. One of the key recommendations of the WTC study is the development of performance-based structural design standards for fire conditions [4]. Such standards are not possible with an *incomplete understanding* of the structure-fire phenomenon. Further, there is not enough reliable experimental data, numerical modeling tools are underdeveloped, and few specifications for performance-based structural fire safety design exist. The research needs identified in this paper are specific examples of what is needed to advance the state-of-the-art, close the knowledge gap, and increase our understanding of structural fire safety.

It is common practice for engineers to design a structure to withstand large forces imposed by wind (perhaps due to hurricanes) and earthquakes. However, engineers do not typically design for forces imposed by fire (thermal loads), which is another low probability—high consequence event. An example of designing for fire means designing the amount of fire protection that the structural elements require based on a targeted *structural response*. This is an example of the performance-based methodology that the profession is trying to develop. It is not expected that research in this area will lead to higher cost of construction. Actually, performance-based codes will allow greater freedom, encourage innovative designs and open markets for alternative materials and new products, as long as such materials and products are shown to exhibit acceptable levels of fire safety performance.

To achieve this goal of performance-based design, more research is required as outlined in this paper. Collaboration, international and domestic, between academic research institutions, industry and professional societies would advance such studies. Also, there is a strong need to train and educate future faculty, researchers, and practitioners through higher education experiences and technology transfer. Since high temperature-resistant (fire safety) design is one of the key considerations in the design and fabrication of civil, mechanical, aerospace and nuclear structures [51], the establishment of research and training programs for developing design tools and producing trained personnel is a matter of national prestige, public safety, and high priority.

Acknowledgements

This workshop was supported by NSF under Grant No. CMMI 0707360, NIST under Grant No. 60NANB706011, and by MSU. Any opinions, findings, and conclusions expressed in this material are those of the authors and do not necessarily represent the views and opinions of the sponsors.

References

1. NRC (2003) Making the nation safe from fire, a path forward in research. National Research Council (NRC) of the National Academies, National Academies Press, Washington
2. FEMA (2002) World Trade Center building performance study: data collection, preliminary observations, and recommendations. Federal Emergency Management Agency (FEMA), Federal Insurance and Mitigation Administration, Washington, DC
3. Grosshandler WL (ed) (2002) Proceedings of fire resistance determination and performance prediction research needs workshop. National Institute of Standards and Technology (NIST), Gaithersburg
4. NIST (2005) Final report of the national construction safety team on the collapse of the world trade center twin towers. NIST NCSTAR 1. National Institute of Standards and Technology, Gaithersburg
5. Kodur VKR, Garlock MEM, Iwankiw N (2007) Structures in fire: state of the art, research and training needs. NIST Report GCR 07-915. National Institute of Standards and Technology, Gaithersburg
6. SFPE (2011) Engineering standard on calculating fire exposures to structures. Society of Fire Protection Engineers, Bethesda
7. Franssen J-M (2005) SAFIR: a thermal/structural program for modeling structures under fire. Eng J AISC 42(3):143–158
8. Usmani AS, Rotter JM, Lamont S, Sanad AM, Gillie M (2001) Fundamental principles of structural behavior under thermal effects. Fire Saf J 36:721–744
9. Quiel SE, Garlock MEM, Paya-Zaforteza I (2011) Closed-form procedure for predicting the capacity and demand of steel beam-columns under fire. J Struct Eng 137(9):967–976
10. Milke JA (1999) Analytical methods to evaluate fire resistance of structural members. J Struct Eng 125(10):1179–1187
11. Tan K-H, Huang Z-F (2005) Structural responses of axially restrained steel beams with semirigid moment connection in fire. J Struct Eng 131(4):541–551
12. Garlock M, Quiel SE (2007) The behavior of steel perimeter columns in a high-rise building under fire. Eng J AISC 44(4):359–372
13. Dong YL, Zhu EC, Prasad K (2008) Thermal and structural response of two-storey two-bay composite steel frames under furnace loading. Fire Saf J 44(4):439–450. doi:10.1016/j.firesaf.2008.09.005
14. Flint G, Usmani A, Lamont S, Lane B, Torero J (2007) Structural response of tall buildings to multiple fires. J Struct Eng 133(12):1719–1732
15. Lamont S, Lane B, Flint G, Usmani A (2006) Behavior of structures in fire—a case study. J Fire Prot Eng 16(2):5–35
16. Bailey CG, Lennon T, Moore DB (1999) The behavior of full-scale steel-framed buildings subjected to compartment fires. J Struct Eng 77(8):15–21
17. Wang YC, Lennon T, Moore T (1995) The behaviour of steel frames subject to fire. J Constr Steel Res 35:291–322
18. Liew JYR, Tang LK, Choo YS (2002) Advanced analysis for performance-based design of steel structures exposed to fires. J Struct Eng 128(12):1584–1593
19. Liew JYR, Chen H (2004) Explosion and fire analysis of steel frames using fiber element approach. J Struct Eng 130(7):991–1000
20. Ma KY, Liew JYR (2004) Nonlinear plastic hinge analysis of three-dimensional steel frames in fire. J Struct Eng 130(7):981–990

21. Toh WS, Tan KH, Fung TC (2000) Strength and stability of steel frames in fire: Rankine approach. J Struct Eng 127(4):461–469
22. Toh WS, Fung TC, Tan KH (2001) Fire resistance of steel frames using classical and numerical methods. J Struct Eng 127(7):829–838
23. Franssen JM, Kodur VR, Mason J (2004) User manual for SAFIR 2004: a computer program for analysis of structures subjected to fire. Research Report, University of Liege
24. Kim H-J, Lilley DG (2002) Structural fire modeling with the zone method. ASME 2002 international design engineering technical conferences and computers and information in engineering conference, IDETC/CIE2002, vol 1, pp 337–346
25. Nwosu DI, Kodur VKR (1999) Behaviour of steel frames under fire conditions. Can J Civil Eng 26:156–167
26. Kodur V, Raut N (2008) Fire resistance of reinforced concrete columns—state-of-the-art and research needs. In: ACI SP-255 CD-ROM: designing concrete structures for fire safety, pp 1–24
27. Kodur VKR, Fike RS (2009) Guidelines for improving the standard fire resistance test specifications. J ASTM Int 6(7):1–16
28. Lennon T, Moore D (2004) Client report: results and observations from full-scale fire test at BRE Cardington. 16 January 2003 Client report number 215-741
29. Gille M, Usmani AS, Rotter JM (2002) A structural analysis of the Cardington British Steel corner test. J Constr Steel Res 58(4):427–442
30. Lawson RM (1990) Behaviour of steel beam-to-column connections in fire. J Struct Eng 68(14):263–271
31. Leston-Jones LC, Burgess IW, Lennon T, Plank RJ (1997) Elevated-temperature moment-rotation tests on steelwork connections. Proc Inst Civil Eng 122(Nov):410–419
32. Al-Jabri KS, Lennon T, Burgess IW, Plank RJ (1998) Behaviour of steel and composite beam-column connections in fire. J Constr Steel Res 46(1–3):308–309
33. Spyrou S, Davison JB, Burgess IW, Plank RJ (2004) Experimental and analytical investigation of the ‘compression zone’ components within a steel joint at elevated temperatures. J Constr Steel Res 60(6):841–865
34. Spyrou S, Davison JB, Burgess IW, Plank RJ (2004) Experimental and analytical investigation of the ‘tension zone’ components within a steel joint at elevated temperatures. J Constr Steel Res 60(6):867–896
35. Liu TCH (1996) Finite element modelling of behaviours of steel beams and connections in fire. J Struct Eng 125(10):1188–1197
36. Liu TCH (1999) Moment-rotation temperature characteristics of steel/composite connections. J Constr Steel Res 36(3):181–199
37. Ramli-Sulong NH, Elghazouli AY, Izzuddin BA (2007) Behavior and design of beam-to-column connection under fire conditions. Fire Saf J 42(6):437–451
38. Wang Y, Ding J (2006) Experimental behaviour of steel joints to concrete filled steel tubular columns in fire. In: Proceedings of fourth international symposium on steel structures, Seoul, Korea, 16–18 November
39. Yu H, Burgess IW, Davison JB, Plank RJ (2008) Experimental investigation of the behavior of fin plate connections in fire. J Constr Steel Res 65(3):723–736. doi:10.1016/j.jcsr.2008.02.015
40. Yu H, Burgess IW, Davison JB, Plank RJ (2007) Numerical simulation of bolted steel connections in fire using explicit dynamic analysis. J Constr Steel Res. doi: 10.1016/j.jcsr.2007.10.009
41. Selamet S, Garlock MEM (2010) Robust design of single plate shear connections for fire. Eng Struct 32(8):2367–2378

42. Kodur VKR, Harmathy TZ (2002) Properties of building materials. In: DiNenno PJ (ed) SFPE handbook of fire protection engineering, 3rd edn. National Fire Protection Agency, Quincy
43. Lie TT (1992) Structural fire protection: manual of practice, No 78. ASCE, New York
44. ASCE (1992) Structural fire protection. In: Lie TT (ed) ASCE manuals and reports of engineering practice, No 78. American Society of Civil Engineers, New York
45. Eurocode 2 (EN1992-1-2) (2004) Design of concrete structures. Part 1.2: general rules—structural fire design. Commission of European Communities, Brussels
46. CEN (2004) Eurocode 2: design of concrete structures. Part 1–2: general rules—structural fire design (ENV 1992-1-2:2004). European Commission for Standardization (CEN), Brussels
47. Kodur VKR, Dwaikat MMS, Dwaikat MB (2008) High-temperature properties of concrete for fire resistance modeling of structures. ACI Mater J 105(5):517–527
48. Khoury GA, Majorana CE, Pesavento F, Schrefler BA (2002) Modeling of heated concrete. Mag Concr Res 54(2):77–101
49. Khaliq W, Kodur V (2011) Thermal and mechanical properties of fiber reinforced high performance self-consolidating concrete at elevated temperatures. J Cem Concr Res 41:1112–1122
50. ASTM (2001) Standard methods of fire test of building construction and materials. test method E119-01. American Society for Testing and Materials, West Conshohocken
51. Barry C (2007) Fire inside: structural design with fire safety in mind. Sci News 172:122–124