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

Venkatesh Kodur
Dept. of Civil & Env. Engg.
Michigan State University
East Lansing, MI 48824

Maria Garlock
Dept. of Civil & Env. Engg.
Princeton University
Princeton, NJ 08544

Nestor Iwankiw
Hughes Associates, Inc.
Chicago, IL 60631

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By
Venkatesh Kodur
Dept. of Civil & Env. Engg.
Michigan State University
East Lansing, MI 48824
Maria Garlock
Dept. of Civil & Env. Engg.
Princeton University
Princeton, NJ 08544
Nestor Iwankiw
Hughes Associates, Inc.
Chicago, IL 60631

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Notice

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WORKSHOP REPORT

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Venkatesh Kodur
Professor
Dept. of Civil & Env. Engg.
Michigan State University
East Lansing, MI 48824

Maria Garlock
Assistant Professor
Dept. of Civil & Env. Engg.
Princeton University
Princeton, NJ 08544

Nestor Iwankiw
Senior Consulting Engineer
Hughes Associates, Inc.
Chicago, IL 60631

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National Science Foundation
4201 Wilson Boulevard
Arlington, VA 22230

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Gaithersburg, MD 20899

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Department of Civil and Environmental Engineering
Michigan State University
East Lansing, Michigan

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Executive Summary

Structural fire safety is one of the key considerations in the design and maintenance of built infrastructure. 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. To review the current state-of-the-art and to identify the research and training needs for improved fire safety in the U.S., a two-day National Workshop was organized at Michigan State University. The workshop brought together many academics from U.S universities, in addition to international experts and design professionals in the structural fire safety field. The deliberations from presentations, panel discussions, and break-out sessions formed the basis for this report and the information was used to develop research and training needs for improving the state-of-the-art in the structural fire safety field. Accordingly, the top ten research and training needs are:

- Development of high-temperature constitutive material models
- Development of new sensor technology for fire tests
- Collection and generation of test data for model verification
- Development of acceptable tools and criteria for undertaking structural fire design
- Defining proper fire loads (scenarios) for developing numerical models and design guidelines
- Performing sensitivity analyses and parametric studies to identify factors governing global structural response
- Undertaking full-scale fire tests on decommissioned buildings
- Characterizing connection behavior
- Development of university curriculum related to structures in fire at the graduate and undergraduate levels
- Improving the procedures and specifications to modify the ASTM E119 standard fire test

Full details related to above research and training needs are discussed in the report. It is hoped that the research and training need priorities identified in this report will stimulate significant new research and training activities in the structural fire safety field. Such activities should generate rational design methodologies, numerical models, innovative technologies, high performing materials and better informed practitioners and educators, all of which will improve the current practice of structural fire design to enhance public safety and potentially reduce or reallocate fire protection costs.

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1. Introduction

Fire represents one of the most severe environmental hazards to which the built-infrastructure is subjected. Unfortunately, the U.S. has one of the worst fire-loss records in the industrialized world, as demonstrated by the large number of deaths and property destruction. Within the area of fire science, structural fire safety is least developed [Science News 2007]. Many of the recent reports and white papers have highlighted the numerous drawbacks in the current approach to "structural fire protection" and have called for research and training efforts to advance the state-of-the-art in the structural fire safety field.

Fire is a particularly dangerous event, not only because it is not fully understood, but also because it may be a primary or a secondary event caused by many other hazards such as earthquake, impact and blast. Thus, fire can create severe life-threatening conditions, and hence providing appropriate fire resistance to structural members is a major safety requirement in building design.

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 US, Performance-Based Building (and Fire) Codes are being implemented to augment existing prescriptive standards and regulations. Performance-Based (PB) Codes should allow greater freedom and 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. However, many reports have indicated that the implementation of PB codes requires several key elements. These include improved understanding of materials performance in fires, development of advanced validated tools for alternative fire protection designs, and education of fully trained fire practitioners.

In addition, a new class of materials referred to as high performance materials (HPM), (e.g., fiber-reinforced polymers or FRP), are being increasingly used for strengthening and retrofitting aging and deteriorating infrastructure. Many of these materials have poor or unknown high temperature characteristics. The determination of the fire safety of these materials and their integration into structural systems is critical for ensuring the safety of the built infrastructure.

Addressing the above complex tasks requires significant research and training efforts. However, until recently, there was lack of focused research programs in US universities in the structural fire safety field. In recent years, a few faculties from various universities have initiated some research activity in the structures and fire area. To capitalize on these initiatives, the idea of organizing a National Workshop to develop research and training needs in the structural fire safety field was proposed to the National Science Foundation (NSF). The CMMI division of NSF wholeheartedly supported the idea and provided funding for the workshop. The National Institute of Standards and Technology (NIST) and Michigan State University (MSU) also agreed to co-sponsor and co-fund the workshop.

2. Need for Workshop

The U.S. has one of the worst fire loss records in the industrialized world [Geneva 2006], as demonstrated by the large number of fire-related deaths and the volume of property destruction. As an illustration, recent data shows that 1,550,000 fires occurred in 2004 resulting in 4,003 deaths, 100,000 injuries, and more than $10 billion in direct property losses. Including indirect losses, the total loss due to fire exceeded $50 billion in 2004. While much of these deaths and fire losses occur in residential dwellings, fires do occur in all building types. Thus, fire represents one of the most severe environmental hazards for the built infrastructure and high temperature-resistant (fire safety) design is one of the key considerations in the design and fabrication of civil, mechanical, aerospace and nuclear structures.

In a number of recent reports it has been pointed out that within the area of fire science and engineering, structural fire safety is the least developed. This has been attributed to the lack of research and training in the structural fire safety field. This has been clearly pointed out by the Federal Emergency Management Agency (FEMA) Building Performance Assessment Team which was set up to investigate the destruction and damage of the WTC Twin Towers. The team concluded that there is serious lack of data, tools and qualified personnel to facilitate structural fire safety design [FEMA 2002]. Also, the National Research Council (NRC) of the National Academies and NIST have identified fire safety as an important research area and urged the nation to support university programs related to structural fire performance [NRC 2003, FEMA 2002, Grosshandler 2002, NIST-SFPE 2004, and NIST 2005]. Thus, 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.

This workshop was aimed at identifying the research and training needs for improved structural fire safety in U.S. While this type of effort has been made in some of the previous meetings, such as the NIST workshop in 2002 and NIST-Society of Fire Protection Engineers (SFPE) workshop in 2003, the focus was principally on research needs (rather than on training aspects) and the participation was mainly from research and industry professionals. This workshop brought together many academics from various universities, in addition to experts (researchers and design professionals) in the structural fire safety field. This provided an ideal setting for developing needed research and training efforts for improved structural fire safety in the U.S. The training aspect was thought to be ideal for attracting the attention of U.S. faculty, since some of the schools have recently started a few initiatives in the fire safety area.

3. Objectives

The key objective of this 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:-

- Review the state-of-the-art in structural fire safety (SFS)
- Identify and prioritize research needs
- Improve SFS education and training in the U.S.
- Develop plans to improve provisions in codes and standards

The format selected for the workshop allowed the attendees to better familiarize themselves with the background, current practices, and emerging issues in structural fire engineering, with emphasis on their relationships to the traditional structural engineering field. Some of these topics were prompted or accelerated by the post-9/11 emergency response and public safety concerns, while others have long been acknowledged as matters for future study or professional debate relative to advancements in fire engineering and performance-based design.

4. Organizational Details

4.1 Co-Chairs

This workshop was planned and organized by three co-chairs namely:

- *Dr. Venkatesh Kodur*, Professor in the Department of Civil and Environmental Engineering at Michigan State University (MSU).
- *Dr. Maria Garlock*, Assistant Professor in the Department of Civil and Environmental Engineering at Princeton University (PU)
- *Dr. Nestor Iwankiw,* Senior consulting engineer with Hughes Associates, Inc. (HAI).

4.2 Support

This workshop was supported by NSF under grant no. CMMI 0707360, NIST under grant No. 60NANB706011, and by MSU. The NSF grant included travel support for 30 U.S. faculty members to attend the workshop.

4.3 Venue

The workshop was held on June 10-12, 2007 at the Kellogg Hotel and Conference Center at Michigan State University, East Lansing Michigan. The workshop was held in conjunction with the ribbon cutting ceremony of MSU's new structural fire testing facility for undertaking fire experiments on structural systems such as beams, columns and slabs.

4.4 Participants

The 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 Professors from universities outside the U.S. were invited. These were Jean-Marc Franssen from University of Liege, Belgium; Andy Buchanan from University of Canterbury, New Zealand; and Mario Fontana from ETH, Switzerland. Other speakers at the workshop included fire engineering experts in the U.S. from institutions and firms such as NIST, Arup Fire, HAI., and university professors from various institutions such as MSU, Princeton, Purdue, Worcester Polytechnic Institute (WPI), University of Maryland, Lehigh, and University of Texas at Austin.

Invitations to attend the workshop were sent out to a number of participants through email announcements. Participation from a diverse community was sought. In total there were 57 participants including the workshop organizers. The largest percentage of participants (46%) 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%). The organizers sought to attract some women and underrepresented groups, which represented almost 10% of attendees.

It was important to recruit persons involved in codes and standards, and those who are intimately aware of fire safety needs. To this end, the organizers were successful in recruiting participation 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 (representing 26% of attendees). The variety of expertise present enriched the discussions held during the panel sessions, focus group meetings, and informal discussions held during the workshop. A complete listing of the participants and their affiliation is included in Appendix A.

4.5 Format

The format of the workshop was structured so as to cover a state-of-the-art review on various topics related to structural fire safety and also to develop "research and training needs" based on input from the academics, practitioners and industry. To facilitate this exchange, the workshop was planned for two days, with a welcome reception preceding the main session.

The complete final program for the workshop is provided in Appendix B. The following contains a brief description of the workshop format.

a. On the evening of Sunday, June 10, the workshop opened with a welcome reception.

b. The first day of the workshop (Monday, June 11) was devoted to the presentations. Four sessions were organized with each session representing a key theme. The four sessions were:

   - Structural Fire Safety (SFS): *Current State of the Art*
   - SFS: *Assessment through Numerical Modeling*
   - SFS: *Assessment through Fire Experiments*
   - Treatment of SFS in Codes and Standards, Training and Education

c. Each session on the topics listed above began with a keynote presentation and was followed by three invited speakers. At the end of the session, a "panel discussion" took place. A summary of the keynote presentation and the panel discussions is provided in Appendix C. The day ended with a 'workshop dinner' for all participants. A special presentation on the collapse of a steel-girder highway bridge in the San Francisco-Oakland Bay Area connecting interchange from eastbound I-80 to eastbound interstate I-580 due to fire was organized during the dinner.

d. Tuesday, June 12 was devoted to focus group sessions and deliberations. Each participant was assigned to a group based on their expertise or randomly selected so that the size of each group was essentially the same. The three focus groups were:

   - Group A: *Structural Fire Response Modeling*
   - Group B: *Fire Experiments*
   - Group C: *Codes, Standards, and Education*

A list of the participants in each group is given in Appendix E. Each focus group was assigned two co-chairs (selected by the workshop co-chairs) who were responsible for moderating the discussion and summarizing the deliberations. The groups were assigned the task of identifying the top ten research needs within the focus group topic. One of the two focus group co-chairs presented the outcome of discussions to the entire workshop group. After the focus group presentations and relevant discussion, a 'voting' was held to prioritize the ten most urgent research needs in structural fire safety.

5. State-of-the-Art

Based on the presentations, panel discussions and question answer sessions, a summary of the state-of-the-art in SFS was compiled and is presented below. Further information on the state-of-the-art as presented by key note speakers is included in Appendix C.

5.1 Review - Structural Fire Response Modeling

Typically in the U.S., structural design for fire safety is the responsibility of the architect and is based on prescriptive methods. These prescriptive methods are based on standard fire resistance tests and do not provide realistic assessment of structural performance under fire scenarios encountered in buildings. Recent advances in computational tools and fire science now make it possible, though more complex, to design a structure for fire safety using more rational approaches. This performance-based design approach allows the designer to consider real fire scenarios and the effects of this fire on the structure as a whole (as opposed to individual member behavior not considering the "real" boundary conditions). With such an approach to design, it is possible to have safer and more economical choices. However, it requires education and judgment as related to structure-fire interactions, and it requires knowledge in structure-fire response modeling.

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 2-dimensional (2-D) heat transfer 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 when considering the level of details in the model. The "cost" of the analysis must also be considered: the more detailed, the more computationally expensive it is in terms of setup and run-time. Furthermore, the modeler needs to consider that significant uncertainty exists in the input (the load), i.e. the fire model, as well as in the high-temperature material properties, which need to be considered when interpreting the accuracy of the structural analysis results. A parametric or sensitivity analysis can be employed to at least partially evaluate the range of feasible predicted outcomes.

In the past 10 years, many advances have occurred in software dedicated to structures in fire (such as VULCAN and SAFIR). Other general purpose and commercially available software can be used for structure-fire modeling (such as ANSYS and ABAQUS). However, these programs are quite complex to use (for fire applications) and also do not account for various factors such as spalling in concrete. Further, these software are expensive and, perhaps, too cost prohibitive for engineering firms that do not frequently perform such specialized analyses. As an option to these 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. For example, the fire model can be parametric curves whose equations are straight forward and widely published. The heat transfer model in steel sections with relatively thin plates can be done with a spreadsheet using a lumped mass approach that assumes that the temperature of the steel is uniform (this approach cannot be used for concrete or timber). The structural model can be a beam with the appropriate boundary conditions that represent the surrounding structure.

Many limitations exist for modeling structures in fire in a seamless, efficient, and appropriate way. For example, the links between the fire, thermal, and structural models are not advanced. 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. The same difficulty exists if one wants to transfer data from a 3-D heat transfer model to a 3-D structural model (where typically the heat transfer model will use brick elements and the structural model will use shell elements). 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.

High temperature thermal and mechanical material properties (of steel, concrete, and timber for example) contain much uncertainty. It is not clear how this uncertainty/variability affects the structural response as a whole. 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.

5.2 Fire Experiments: State-of-the-Art

Evaluating the fire behavior of a structural system requires the use of fire resistance experiments and/or numerical models. At present, fire resistance evaluation is mainly undertaken through standard fire tests on structural elements such as beams, columns and slabs, or through prescriptive empirically based methods. There are very few well-validated analytical models that can trace the realistic fire response of structural systems throughout the entire range of behavior – from the initiation of fire to the collapse stage.

A review of the literature clearly indicates that within the area of fire science and engineering, structural fire safety is the least developed. This has been pointed out in a number of recent high profile reports. In the area of fire tests, the reports highlight significant drawbacks in the current fire test methods. The lack of advancements in the area of numerical modeling is attributed to the non-availability of experimental data (for validation) under realistic fire scenarios and also to the lack of established high temperature materials properties and associated constitutive relationships. Thus, further research and improved knowledge in the "fire experiments" area is critical for the advancement in the structural fire safety field.

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. 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.

There are many drawbacks with the standard fire test procedures described above, the most important being 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 state-of-the-art review indicates that there is good amount of data from standard fire resistance tests on isolated structural elements such as beams, columns, walls and floor. However, in many of these tests, only a very limited number of parameters were considered and 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. 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 1980's and 90's. 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. [Bailey et al. 1999; Lennon and Moore, 2004; Gille et al. 2002] 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.

In addition to fire tests on structural elements and systems, the temperature dependent properties of construction 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 [Khoury et al. 2002]. These properties vary as a function of temperature and depend on the composition and characteristics of the material itself.

The literature review indicates that the high temperature properties of conventional construction materials, like steel (structural, reinforcing and pre-stressing steel), concrete and wood are available. Often, there is large variability in the high temperature properties of some materials, such as concrete and wood, and there is very limited property data on new types of concrete (such as high strength concrete) and FRP. Further, there can be large variability in similar data obtained from different sources. This lack of data and the high variation in the reported high-temperature properties of materials can be attributed to:

- 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 constitutive relationships for properties of concrete (mostly normal strength concrete), steel (structural, reinforcing and pre-stressing steel) and wood are available as a function of temperature in the ASCE structural fire protection manual [1992] and in Eurocode-2 [2004]. However, there is a significant lack of reliable high-temperature constitutive relationships for new types of materials, like high strength concrete and 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.

The lack of such high-temperature material constitutive relations is hindering the usage of numerical models for fire resistance evaluation. In addition, the lack of fire test data is further hindering the development and validation of advanced computer models for simulating the fire response of structures. 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.

5.3 Codes, Standards, Training and Education

The current building code provisions in the U.S. for computationally based structural fire engineering and design are essentially non-existent. Apart from the general code allowances for alternative means and methods, the requirements clearly favor and direct users towards the traditional “prescriptively-based” criteria based on empirically developed fire resistance ratings from the ASTM E119 standard fire test [ASTM 2001]. Consequently, most of the passive fire protection for structural framing remains within the project architect’s responsibility, with little, if any, input from a fire protection or structural engineer.

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 interpolations, they have remained substantially unchanged throughout the past 100 or so years. Over the last decade, some performance-based design alternatives have started to emerge. However, in most disciplines, including structural fire engineering, these higher order alternatives in the codes and standards still are not complete or thorough enough to enable widespread use or acceptance. The more advanced structural fire engineering and design applications continue to be regarded as a special exception for experts, to be reviewed and accepted by the authority having jurisdiction on a case-by-case basis.

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, despite the dramatic and tragic evidence of the destructive role of fire in the 9/11 WTC collapses, this long engrained "culture" for prescriptive practice is difficult to change for a variety of reasons.

One obstacle is the fact that structural engineers have little or no knowledge of fire or how heating affects structural behavior, and there is seemingly no tangible interest or motivation to perform such an additional task. Most architects and fire protection engineers are not capable of properly analyzing 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.

There are major needs in all these areas that would improve the subject state-of-the-art in the U.S. These include the development of suitable new standards, code provisions, and design guides with more explicit criteria for structural fire engineering; growth of the very few university courses, faculty, and research projects focused on the topic; increasing the availability of dedicated continuing education programs for professionals and course teaching materials for university faculty; and the increase of relevant publications and media news attention to alert the broader public to its benefits and to major successful projects.

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. It may be feasible to at least generally introduce the subject of high-temperature structural behavior during a limited number of class sessions in selected courses. The best opportunities for a more dedicated course expansion were seen as multidisciplinary electives at the graduate level. 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. Cultivation of greater faculty expertise in this field needs to be accomplished by increased research funding on the subject, faculty grants, and continuing education faculty seminars/workshops, together with textbooks, prepared lecture, course, and curriculum modules that could be quickly and easily adapted for use.

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.

The existing physical "infrastructure" is also lacking the appropriate experimental capabilities at U.S. government, university, and commercial sites to support further innovative research and/or demonstration fire testing. Not only are the laboratory furnaces quite limited in number, they are of relatively small size and are capable of only single member and assembly evaluations.

All these factors present serious impediments and opportunities for structural fire engineering progress towards a mainstream status. They require a well-coordinated plan and systematic resolution in order to provide the requisite fertile climate for the desirable advancements.

6. Research Needs

The second day of the workshop was spent deliberating and discussing topics related to structural fire safety through focus group break out sessions. The objective of these sessions was to identify and prioritize research needs based on the presentations and panel discussions of the first day. Each workshop participant was assigned to one of three focus groups based on their type of expertise, practice area (academia-research, consulting, regulatory/government, emergency services, public), and familiarity with the structural fire safety field. In some cases the participant was randomly selected so that the size and balance of interests/perspectives in each group was about equivalent. The three groups and their designated discussion topics were:

- Group A: *Structural Fire Response Modeling*
- Group B: *Fire Experiments*
- Group C: *Codes, Standards, and Education*

A list of the participants in each group is given in Appendix E. Group A with 23 participants was the largest, while Groups B and C each numbered 15. Each focus group was assigned two co-chairs (selected by the workshop co-chairs) who were responsible for moderating the discussion, staying on the subject, stimulating contributions from everyone, and recording the group's key observations and recommendations. More specifically, these focus groups were assigned the final task of summarizing their deliberations by identifying the top ten research needs within their topic. Before the participants broke out into their groups, several start-up issues were suggested as initial topics. For each focus group, co-chairs subsequently presented the outcome of the discussions to the entire workshop audience.

The focus group sessions went very well with lively exchanges and productive input from all in attendance. These sessions consumed their full assigned time, and the recording co-chair subsequently prepared a written summary of the proceedings and top ten recommendations. There was general difficulty in reducing the many issues raised to only the maximum ten items per group. Each recommended item was to have a descriptive title together with a short paragraph description. There were incidental repetitions and overlapping of issues, however, these proved constructive in highlighting several broader high-priority needs for structural fire engineering. The focus group co-chair presented the highlights of the ten recommendations to all workshop participants.

After the focus group presentations (described in the format section) and resulting discussions, the top ten research needs topics from each group were posted on the wall. Each participant was given 12 stickers and took turns placing a sticker next to their voted topic (only one sticker per research need was permitted). The tabulated votes are listed in

Appendix G. There were some overlaps in identifying research needs in some groups. For example, characterization of material properties was found to be an important need in Groups A and B. These repetitions and similarities were taken into account while identifying the *overall* top ten research needs identified by the workshop participants. The overall top ten topics are described below, with a reference given to each focus group recommendation (in parentheses) as identified in Appendix G.

- ***Development of high-temperature constitutive material models (A1, A2, and B2)***
  Since fire performance of structural members depends on the properties of the constituent materials, knowledge of high-temperature material properties is critical for advancing the state of the art in fire resistance area. At present there is either very limited test data on some high-temperature properties, or there are considerable variations and discrepancies in the high-temperature test data for other properties. Thus there is an urgent need to undertake material property tests to generate reliable property data. Data from such tests should be used to develop constitutive relationships for various properties as a function of temperature. Comprehensive studies are needed to develop high-temperature constitutive relationships for thermal, mechanical and special (such as spalling in concrete, de-bonding of insulation) properties of materials in the temperature range of 20-800^0C (or until the material fails).

- ***Development of new sensor technology for fire tests (B6)***
  At present, there is serious 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.

- ***Collection and generation of test data for model verification (A4, B9, and C5)***
  Models using sophisticated software are sensitive to the input parameters needed to capture the response. Often the user has to make educated judgments and approximations, for example with regard to the actual load (i.e., the fire) and material properties. Such models need to be verified by experimental data or observations taken from actual fire events. Experimental data is particularly valuable for validation of numerical models. However, in the U.S. almost no laboratory facilities exist for such experiments. A large-scale testing facility in one location, or a network of such facilities at several 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 models one constructs.

- ***Development of acceptable tools and criteria for undertaking structural fire design (C4)***
  The current US codes and standards do not provide any substantial criteria for structural fire analysis and design. Most of the provisions remain focused on a 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.

- ***Defining proper fire loads (scenarios) for developing numerical models and design guidelines (A3)***
  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 fire contained in a compartment, many significant fires (e.g. at the WTC and Meridian Plaza) were not contained in a compartment because most of the floor was open. Simple fire models for such spaces 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 computational fluid dynamic modeling are needed for application to structural fire analysis.

- ***Performing sensitivity analyses and parametric studies to identify factors governing global structural response (A6)***
  As mentioned previously, many uncertainties are inherent in the numerical models that predict structural response in a fire, such as the fire load and the high-temperature material properties. Some material properties, for example spalling, are typically not included in models. 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.

- ***Undertaking full-scale fire tests on decommissioned buildings (B10)***
  As discussed above, data from full-scale tests are important for validating models. Buildings that are decommissioned may be a good and economical source for doing full-scale tests that can provide valuable data.

- ***Characterizing connection behavior (A7 and B8)***
  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. The connections can play a significant role in determining the response of structural systems during fire as seen in the Cardington full building fire tests [Bailey et al. 1999] and also in the WTC building collapses [NIST 2005]. 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. Detailed experimental and numerical studies are needed on typical connections used in buildings.

- ***Development of university curriculum related to structures in fire at the graduate and undergraduate levels (C6)***
  Though academic interest is increasing, there are still relatively few university courses in the US that partially cover or are fully dedicated to structural fire engineering. In particular, undergraduate programs in the U.S. are at full capacity with their current core requirements and electives, with little room for new content. Elective courses for this specialization in graduate school could provide better opportunities for such new course development and expansion. Model curricula, course modules, and teaching aids are needed to enable a quicker and easier adaptation of this material for class use by interested institutions and faculty.

- ***Improving the procedures and specifications to modify the ASTM E119 standard fire test (B1)***
  There are a number of drawbacks with the with the current test provisions in structural fire standards such as ASTM E119 since they do not properly account for real fire scenarios (e.g. no decay phase), structural interactions, realistic load levels, restraint conditions and failure conditions. While it may not be feasible to change all of the drawbacks, due to complexity and the high level effort required, 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 failure limit state, consideration of all failure limit states (strength, deflection etc.), specifications on pre-test property measurements, observations during the test, and recording of data. It should be noted that E119 fire scenarios represents upper bound to a family of real fire curves.

7. Future Directions

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" [NRC 2003]. One of the key recommendations of the WTC study is the development of performance-based structural design standards for fire conditions [NIST 2005]. Such standards are not possible with an *incomplete understanding* of the structure-fire phenomenon. Further, the state-of-the-art summaries in this report indicate that 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 report 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.

The mobilization of such *research* activity in the field of structural fire safety requires support from granting agencies. However, there also needs to be significant *collaboration*, international and domestic, between academic research institutions, industry and professional societies. Also, there is a strong need to *train and educate* future faculty, researchers, and practitioners through higher education experiences and *technology transfer*. A more detailed discussion of each of these topics is given below.

7.1 Research

Prioritized research needs were identified and are discussed in section 6. Expansion of research in these areas will not only generate the critical results that fill voids in the knowledge base, but it will also attract additional university faculty to structural fire engineering and lead to the development of new graduates well-qualified to undertake research, teaching and structural fire safety design. Successful completion of research will produce new design methodologies, material properties test methods, sensors and fire resistance materials. Dependent on the merits of the research conclusions and recommendations, its subsequent technology transfer may eventually lead to substantive changes in the design codes and standards.

7.2 Collaborations

The implementation of the above recommendations is likely to foster more and closer cooperative efforts among different universities (due to the multi-disciplinary nature of some subjects), various government agencies, structural engineering practitioners, the construction industry, relevant professional organizations, and regulatory bodies. The progression of these coupled interactions will precipitate the evolution of new major field, as it becomes better developed and more widely established. In a broader context, policy-makers, the media, and the general public must also become more involved as active stakeholders in these undertakings to demand improved technologies for minimizing the destructive effects of fire in the built environment.

For achieving faster results, the key collaborations are to be developed at the international level. It should extend beyond just North America to the European community and the Pacific Rim, where much of the recent advancements and proficiency in this field may be found. In this manner, individual country-based advances can be more widely shared for the mutual good of society and the profession. Multi-country partnerships can also be formed for this purpose in order to optimize use of limited resources (including budgets and experimental facilities), similar to past successes in earthquake and wind engineering.

The scope and breadth of needs in this field dictates that a large, well coordinated and multi-year collaborative plan, with significant available resources and expert guidance, will be necessary to move forward. Smaller, intermittent and narrowly focused project work will certainly continue to resolve more limited questions in due time, but this will ultimately not be fruitful in collectively advancing the state-of-the-art in an organized manner.

7.3 Training and Education

Besides the aforementioned corollary benefits from increased research activity on the above listed projects, U.S. universities, faculty and students will greatly benefit from the proposed model curricula, course modules, and other teaching aids. These materials will expedite the transition to increased coverage of structural fire engineering topics within related classes, as well as in fully dedicated new course offerings. Continuing education programs for practitioners and faculty who have not been sufficiently exposed to this subject will increase the profession’s awareness and related knowledge. These efforts should all serve to remove the current obstacles to an adequate understanding of structural fire engineering and enlarge the professional and research base of this unique new specialty.

7.4 Technology Transfer

Technology transfer is an absolutely vital final part of a successful technical endeavor. It typically consists of the dissemination of the research findings, design or material innovations through publications, professional review and discussion, adoption by consensus committee(s) into national code and standard provisions, continuing education, and ultimately implementation for mainstream design and construction practice. Without this process, even the best developments can languish due to lack of general acceptance or understanding.

Therefore, successful technology transfer of major overhauls in design/construction entails contributions from all of the previously listed items - collaboration, research, and training/education from the entire academic, professional, commercial and public sectors. This reality reinforces the need for a well planned and managed U.S. national program, in collaboration with academia, professional societies, industry, and codes and standards writing organizations, to best accomplish this challenging objective.

8. References

ASCE/SFPE29 (1999). "Standard Calculation Method for Structural Fire Protection." American Society of Civil Engineers, Reston, VA.

ASCE (1992). *Structural Fire Protection [Lie T.T. (Editor)]: ASCE Manuals and Reports of Engineering Practice, No 78*. American Society of Civil Engineers, New York, NY.

ASTM (2001). *Standard Methods of Fire Test of Building Construction and Materials. Test Method E119-01*. American Society for Testing and Materials, West Conshohocken, PA.

Barry, C. (2007). "Fire inside: Structural design with fire safety in mind." *Science News*, Vol. 172, pp.122-124

Bailey, C.G., Lennon, T., and Moore, D.B. (1999). "The behavior of full-scale steel-framed buildings subjected to compartment fires." *The Structural Engineer*, Vol. 77, No. 8, pp. 15-21

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.

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, D.C.

Geneva Association (2006). *World Fire Statistics*. Information Bulletin No. 18.

Grosshandler, W.L., ed. (2002). *Proc., Fire resistance determination and performance prediction research needs workshop*. National Institute of Standards and Technology (NIST), Gaithersburg, MD

Gille, M., Usmani, A.S., Rotter, J.M., (2002) "A structural analysis of the Cardington British Steel corner test", Journal of Constructional Steel Research, Vol. 58, No. 4, pp. 427-442

Khoury, G.A., Majorana, C.E., Pesavento, F., Schrefler, B.A., (2002), "Modeling of heated concrete", Magazine of Concrete Research, Vol.54, No. 2, pp. 77-101

Lennon,T., and Moore, D. (2004). *Client Report: Results and observations from full-scale fire test at BRE Cardington*, 16 January 2003 Client report number 215-741.

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, MD.

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, D.C.

Appendix

A. List of Participants

B. Final Program

C. Keynote Presentation Summaries

D. Panel Discussion Summaries

E. Focus Group Members

F. Focus Group Summaries

G. Focus Group Voting Results

Appendix A: List of Participants

No	Name	Appointment	Affiliation*
1	Alfawakhiri, Farid	Senior Engineer	American Iron & Steel Institute
2	Albano, Leonard	Associate Professor	CEE, Worcester Polytechnic Institute
3	Ahmed, Aqeel	PhD Candidate	CEE, Michigan State University
4	Almand, Kathleen	Executive Director	Fire Protection & Research Foundation, National Fire Protection Association
5	Astanesh-Asl, Abolhassan	Professor	CEE, University of California, Berkeley
6	Badders, Barry	Group Leader	Department of Fire Technology, Southwest Research Institute
7	Bagchi, Ashutosh	Assistant Professor	CE, Concordia University
8	Banerjee, Dilip	Research Engineer	Building and Fire Research Laboratory's, National Institute of Standards and Technology
9	Beyler, Craig	Technical Director	Hughes Associate, Inc.
10	Bilow, David	Director	Engineered Structures, Portland Cement Association
11	Buchanan, Andy	Professor	CE, University of Canterbury, New Zealand
12	Chou, Karen	Professor	MCE, Minnesota State University
13	Cramer, Steven	Professor & Associate Dean	CE, University of Wisconsin
14	Dwaikat, Monther	PhD Candidate	CEE, Michigan State University
15	El-Tawil, Sherif	Associate Professor	CEE, University of Michigan
16	Engelhardt, Michael	Professor	CEE, University of Texas at Austin
17	Eschenasy, Dan	Deputy Assistant Commissioner of Safety & Emergency Operations	Department of Buildings, New York City
18	Ezekoye, Ofodike	Professor	ME, University of Texas at Austin
19	Fike, Rustin	PhD Candidate	CEE, Michigan State University
20	Fontana, Mario	Professor	CE, Eidgenössische Technische Hochschule (ETH), Zürich, Switzerland
21	Foutch, Douglas	Program Director	CMMI, National Science Foundation
22	Franssen, Jean-Marc	Research Director N.F.S.R	CE, University of Liege, Belgium
23	Gamble, William	Professor Emeritus	CEE, University of Illinois, Urbana-Champaign
24	Garlock, Maria	Assistant Professor	CEE, Princeton University
25	Grace, Nabil	Professor & Chairperson CE	CE, Lawrence Technological University
26	Gross, John	Research Structural Engineer	Building and Fire Research Laboratory, National Institute of Standards and Technology
27	Grosshandler, William	Chief, Fire Research Division	Building and Fire Research Laboratory, National Institute of Standards and Technology
28	Harichandran, Ronald	Professor & Chairperson CEE	CEE, Michigan State University
29	Hay, Al	Chief of Safety	Fire Department of New York
30	Hurley, Morgan	Technical Director	Society of Fire Protection Engineers
31	Iqbal, Shahid	PhD Candidate	CEE, Michigan State University
32	Iwankiw, Nestor	Senior Consultant Engineer	Hughes Associate, Inc.
33	Jassens, Marc	Director	Department of Fire Technology, Southwest Research Institute
34	Jensen, Elin	Assistant Professor	CE, Lawrence Technological University
35	Kodur, Venkatesh	Professor	CEE, Michigan State University
36	Lamont, Susan	Senior Engineer	Arup Fire, United Kingdom
37	Lin, Feng-Bao	Associate Professor	CE, The City College of New York

Appendix A (Cont): List of Participants

No	Name	Appointment	Affiliation*
38	McGinnis, Michael	PDF	CEE, Lehigh University
39	Meacham, Brian	Principal	Arup, United States of America
40	Milke, James	Associate Professor and Associate Chair	FPE, University of Maryland
41	Mowrer, Frederick W.	Associate Professor	FPE, University of Maryland
42	Pessiki, Stephen	Professor & Chairperson CEE	CEE, Lehigh University
43	Phan, Long	Research Structural Engineer	Building and Fire Research Laboratory, National Institute of Standards and Technology
44	Prasad, Kuldeep	Research Engineer	Building and Fire Research Laboratory, National Institute of Standards and Technology
45	Quiel, Spencer	PhD Candidate	CEE, Princeton University
46	Raut, Nikhil	PhD Candidate	CEE, Michigan State University
47	Ricles, James	Professor	CEE, Lehigh University
48	Rini, Darlene	Senior Engineer	Arup, United Kingdom
49	Rossberg, Jim	Director	Structural Engineering Institute, American Society of Civil Engineers
50	Sasani, Mehrdad	Assistant Professor	CE, Northeastern University
51	Selamet, Serdar	PhD Candidate	CEE, Princeton University
52	Tabaddor, Mahmood	Engineer	Global R&D, Underwriters Laboratories Inc.
53	Thaigarajan, Ganesh	Assistant Professor	CE, University of Missouri
54	Varma, Amit	Assistant Professor	CE, Purdue University
55	Vivian, Megan	MS Student	CEE, Michigan State University
56	Wichman, Indrek	Professor	ME, Michigan State University
57	Zalol, Ehab	Professor	CEE, Carleton University Canada
58	Hong, Sangdo	PDF	CE, Purdue University
59	Huber, Devin	PhD Candidate	CE, Purdue University

** CE - Civil Engineering*
CEE - Civil & Environmental Engineering
FPE - Fire Protection Engineering
MCE - Mechanical & Civil Engineering
ME - Mechanical Engineering
PDF – Post Doctoral Fellow

Appendix B: Final Program

National Workshop on Structures and Fire: Research and Training Needs
Kellogg Hotel & Conference Center
Michigan State University
East Lansing, MI, USA
10-12 June, 2007

Final Program

10 - June - 2007

	18:00 – 19:00	Registration / Cash Bar	Red Cedar B Lobby
	18:00 – 20:00	Welcome Reception	Red Cedar B

11 - June - 2007

	7:15 – 8:00	Registration	Room 106 Lobby

7:15 – 8:00 Continental Breakfast (Room 106)

Workshop Opening

8:00 – 8:35 Moderator: R. Harichandran, MSU, USA

1.	8:00 – 8:05	Workshop Opening	I. Gray, VP, MSU
2.	8:05 – 8:10	Welcome Remarks	S. Udpa, Dean, EGR, MSU
3.	8:10 – 8:15	Welcome Remarks	D. Fouch, NSF
4.	8:15 – 8:20	Welcome Remarks	W. Grosshandler, NIST
5.	8:20 – 8:30	Workshop Objectives	V. Kodur, MSU, USA
6.	8:30 – 8:35	Announcements	N. Iwankiw, HFI, USA

Session 1: *Structural Fire Safety (SFS) – Current State-of-the-Art; Future Directions (R 106)*

8:35 – 10:15 Moderator: W. Gamble, University of Illinois, USA

1. KP	8:35 – 9:10	Structural Fire Safety- State of the Art and Future Direction	A. Buchanan, University of Canterbury, New Zealand
2. IP	9:10 – 9:25	Role of SFS within the Context of Global Fire Safety	C. Beyler, HFI, USA
3. IP	9:25 – 9:40	Quantifying Fire Hazard on Structure	F. Mowrer, University of Maryland, USA
4. IP	9:40 – 9:55	Design Fire Scenarios for Simulating Fire Resistance of Structures	L. Albano, WPI, USA
5.	9:55 – 10:15	Panel Discussion	Speakers

10:15 – 10:35 Coffee Break

Session 2: ***SFS Assessment through Numerical Modeling (Room 106*****)**

10:35 – 12:15 Moderator: S. El-Tawil, University of Michigan, USA

1. KP	10:35 – 11:10	Modeling the Behavior of Structures-Current Capabilities and Future Trends	J. M. Franssen, University of Liege, Belgium
2. IP	11:10 – 11:25	Simple Calculation Methods for Predicting SFS	J. Milke, University of Maryland, USA
3. IP	11:25 – 11:40	Factors to be Captured in Modeling the Behavior of SFS	M. Garlock, Princeton University, USA
4. IP	11:40 – 11:55	Probabilistic Approach for Evaluating SFS	M. Fontana, ETH, Switzerland
5.	11:55 – 12:15	Panel Discussion	Speakers

12:15 – 12:30 Group Picture
12:30 – 13:30 Lunch (Centennial BC)

Session 3: ***SFS Assessment through Fire Experiments (Room 106)***

13:30 – 15:10 Moderator: M. Janssens, SWRI, USA

1. KP	13:30 – 14:05	Material and Structural Response through Fire Experiments – A Way Forward	V. Kodur, MSU, USA
2. IP	14:05 – 14:20	High Temperature Material Property Tests	L. Phan, NIST, USA
3. IP	14:20 – 14:35	Critical Factors to be Captured in Fire Tests	N. Iwankiw, HFI, USA
4. IP	14:35 – 14:50	Structural Fire Testing Methods: Advantages and Limitations	A. Varma, Purdue University, USA
5.	14:50 – 15:10	Panel Discussion	Speakers

15:10 – 15:30 Coffee Break

Session 4: ***Treatment of SFS in Codes and Standards, Training and Education (Room 106)***

15:30 – 17:10 Moderator: M. Hurley, SFPE, USA

1. KP	15:30 – 16:05	Fire Research Issues Arising from WTC Disaster	B. Grosshandler, NIST, USA
2. IP	16:05 – 16:20	Prescriptive and Performance Based Approaches for SFS	S. Lamont, ARUP, USA
3. IP	16:20 – 16:35	Lessons from Earthquake Engineering to SFS	M. Englehardt, University of Texas, USA
4. IP	16:35 – 16:50	Training and Education in SFS	S. Pessiki, Lehigh University, USA
5.	16:50 – 17:10	Panel Discussion	Speakers

18:30 – 19:30 Cash Bar (Red Cedar AB)
19:30 – 22:00 Dinner (Red Cedar AB)

1.	21:00-21:20	Dinner Presentation " Collapse of Oakland Bridge, CA, Bridge: Preliminary report from data collection study"	Abolhassan Astaneh-Asl, University of California, Berkeley USA
2.	21:20-21:30	Word of Thanks	V. Kodur, MSU, USA

12 - June – 2007

	7:15 – 8:00	Registration	Room 106 Lobby

7:15 – 8:00 Continental Breakfast (Room 106)

Session 5: ***Research Needs Assessment (Room 106)***

8:00 – 8:30 Moderator: J. Ricles, Lehigh University, USA

8:00 – 8:10	Introductions	All Participants
8:10 – 8:15	Focus Group Formation	V. Kodur, MSU, USA
8:15 – 8:30	Tasks for Focus Groups	M. Garlock, Princeton University, USA

10:15 – 10:30 Coffee Break

Session 6: ***Research Needs Assessment - Focus Group Meetings***

8:30 – 11:30

Focus Group A – Structural Fire Response Modeling – Research Needs **(Room 106)** Co-chair: K. Prasad, NIST, USA Co-chair: A. Astaneh-Asl, University of California Berkely, USA
Focus Group B – Fire Experiments – Research Needs **(Heritage)** Co-chair: J. Gross, NIST, USA Co-chair: S. Cramer, University of Wisconsin, USA
Focus Group C – Codes, Standards and Education – Research and Training Needs **(Room 102)** Co-chair: K. Almand, NFPA, USA Co-chair: O. A. Ezekoye, University of Texas, USA

11:30 – 12:00	Travel to MSU Civil Infrastructure Laboratory
12:00 – 12:20	Ribbon-cutting for Structural Fire Testing Facility
12:20 – 12:50	Lunch
12:50 – 13:10	Lab Tour
13:10 – 13:30	Travel to Kellogg's Center

Session 7: ***Research Needs Prioritization (Room 106)***

13:30 – 15:00 Moderator: S. Sunder, NIST, USA

1.	13:30 – 13:50	Research Needs for Structural Fire Response Modeling	Group A
2.	13:50 – 14:10	Research Needs for Fire Experiments	Group B
3.	14:10 – 14:30	Research Needs for Codes, Standards and Education	Group C
4.	14:30 – 14.50	Prioritize Research Needs	N. Iwankiw, HFI, USA
5.	14:50 – 15:00	Future Plans and Workshop Closure	V. Kodur, MSU, USA

Appendix C: Keynote Presentation Summaries

C.1 Structural Fire Safety - State of the Art - Future Directions

Andy Buchanan
University of Canterbury
Christchurch, New Zealand

Where have we come from?

In 1666, the Great Fire of London changed the way that cities considered fire safety. From this time there was slow development for several centuries. In the 20th century we saw the development of prescriptive building codes, Fire Resistance Ratings determined by simple test methods, with very little underlying science.

In the last 20 years there has been lots of change as fire safety science has matured and codes around the world have adjusted accordingly.

What are the changes in structural fire safety?

The main changes in inputs have been in the areas of fire science, and advanced structural analysis under fire conditions, accompanied by a shift to Performance-Based codes.

The resulting changes in outputs have been much more predictable behavior of buildings in fire, better fire science, and safer buildings for less cost.

What are our objectives?

The stakeholders for structural fire safety follow a spectrum from the building owners to the designers, regulators, forensic investigators, researchers, manufacturers, and code writers. The owner and designer consider only one building at a time, whereas the code writers consider whole groups of buildings.

How much time have we got?

For one building during an emergency we have only minutes to predict the structural behavior. In preliminary design we have hours or days. A full design can take weeks, a risk assessment may take months and a forensic study can continue for years.

What do the regulators want?

Much fire design is still based on prescriptive codes which state how to build it – "don't ask any questions". Almost anyone can drive a simple prescriptive code with limited education.

The international trend is now towards performance-based codes where any design can be accepted if the stated performance requirements are met. This requires much better science and the application of engineering judgement.

Performance based codes in New Zealand

Performance-based fire codes have been in use in New Zealand for 15 years - How well have they worked? They were good for a start, with a small number of specialists using them. This resulted in a big shift from property protection to life safety. Some problems arose with new entrants to the field ("cowboys with computers"), which are being addressed with new national standards being set, including the need to prescribe design fires.

Predictive capacity

There is a need to keep things simple, because computing power is out-stripping the ability to do improved analysis of structures in fire. This is because of a combination of limitations on input data, limited ability to handle output, and lack of large scale test results.

What can we do now?

We should work on problems that can be solved, such as computer friendliness, data management, material properties, more test data, thermal analysis, and much better structural analysis.

What can we do about the difficult problems?

There are still many difficult assumptions which have to be made when doing a prediction of structural fire behavior. These include the fire size, the fire location, sprinkler reliability, changes in use of the building. Additional unknowns are the possibility of fire after earthquake, and terrorist attacks. The use of quantitative risk assessment can help with these uncertainties.

Conclusions

- Structural fire engineering remains very challenging.
- Computer analysis of fires and structures is growing fast, but these are not enough on their own to improve predictive capability.
- We need new knowledge about materials at high temperatures, structural behavior in fires, the severity of expected fires, all supported by full-scale test results.
- Design and analysis are two different skill sets which need different approaches.
- Quantitative risk assessment is needed to add a new dimension.
- Education and training is of paramount importance.

C.2 Structural Fire Safety Assessment through Numerical Modelling

Jean-Marc Franssen
University of Liege
Liege, Belgium

When the fire resistance of a structure has to be evaluated, four different families of applicable methods can be identified.

- Experimental testing.
- Tabulated data.
- Simple calculation models
- General calculation models

Experimental testing is the subject of another session and will thus not be discussed here.

Tabulated data are results obtained by another method and presented in a simple form. They are available only for single members subjected to the standard fire. They have been developed for masonry, concrete, and composite steel-and-concrete elements, but not so much for steel elements. Such methods are quite valuable tools at the preliminary design stage, although simple interpolation tools would be useful when the number of parameters is important. The background of certain among these methods is not very clear.

Simple calculation models are methods based on global equilibrium equations. Very often, these methods are the direct extrapolation to high temperatures of the traditional methods otherwise used for ambient conditions. Different methods are available for each combination of a material and an element type; a concrete column, for example, is not designed with the same equations as a steel beam. These methods don't require more than a simple pocket calculator, but they are not very well suited for complex structures. Despite this, they are used commonly for real project applications in combination with an element by element analysis.

Advanced calculation models are models based on the local equations of heat transfer and structural mechanics. These local equations are integrated on space and on time by the now classical methods of finite differences (thermal problems), finite elements (thermal and structural problems) or boundary elements (not widely used in structural fire safety). These techniques can only be implemented numerically in a computer, hence the name of numerical modelling. The rest of this presentation is dedicated to numerical modelling.

Three different families of software can be identified for structural fire modelling. The first one is composed of proprietary software that is constructed by one individual for solving his own problem. They have usually a limited field of application, are generally available to the public and quickly become obsolete when the author turns his attention to another topic.

Another family is composed of programs that are dedicated to the simulation of building structures subjected to the fire. These programs have typically been written by groups of academics, have a wider field of application and tend to become more easily available now.

Finally, general purpose commercially available software can be utilized for analyzing structures in fire, even if this application was not foreseen when the software was written. They are widely distributed, used and validated. The utilization in the context of structural fire modelling nevertheless requires a strong experience of the user in the field, not compensable by the quality of the produced graphics.

If we look at the evolution of the discipline in the recent years, the following observations can be made:

- Whereas uniform temperature distributions in the section or linear temperature gradients on the thickness were used, real temperature distribution on the section is now taken into account.
- Three dimensional structures and 3D behaviors are now routinely taken into account, whereas earlier studies were usually restricted to a 2D plane.
- Whereas linear type elements (typically beam elements) where exclusively used in the past, shell elements are now more and more commonly used.
- Whereas ancient programs usually relied on one type of element, and sometimes on one type of material, different types of elements and materials are now routinely mixed in a model.
- In the previous century, the classical modelling approach for these types of structural fire analyses was a series of successive static analyses with the temperature varying from one step to the next. The dynamic aspect of the question is now systematically used in order

to solve some of the convergence problems that were encountered with the previous approach.

In the near future, the following points will have to be addressed. Some are already the subject of serious research works.

- There is still a challenge when very large structures have to be modelled. Software developers will have to continue improving the structure of their programs in order to allow bigger structures to be modelled. Waiting for the increase in hardware capacities will not be sufficient, especially now that 3D analyses are performed more often. Software users will have to better apprehend the consequence of extracting a substructure from a complete structure.
- Our knowledge of the behavior of connections, or joints, between the members still needs substantial improvement. It is especially important to consider the variety of possible connections and the complexity of the transient effects that they have to support, particularly during the cooling phase of a fire.
- Spalling of concrete, although a subject of research for many years, has still to receive a complete answer that would encompass the material and the structural aspects, possibly in a probabilistic approach.
- A lot of material properties and structural behaviors are still not well documented for the cooling phase.
- All the behaviors that involve moisture movements are not easily modelled. Spalling is one of them, but the behaviors of wood or gypsum when heated are other problems with moisture features.
- Most of the concrete structures analysed until now rely on the reinforcing bars to withstand tension. The behavior and the modelling of structures where the tensile strength of concrete is crucial are still an open field of research. Shear or anchorage problems belong to this category.
- Some developments have to be made if the localized nature of the fire has to be taken into account in the thermal and structural analyses of structures. Interfacing computational finite difference (CFD) software and the finite element (FE) software is one such case.

The last part of the presentation is dedicated to a more detailed discussion of the dynamic structural analysis, with the emphasis put on the benefits offered this technique, namely the possibility to continue the simulation for much longer fire duration in some cases and obtain much better insight into the failure mode in other cases. Some specific cases when the dynamic approach yields significant benefits are also presented, specifically cases with small or imposed displacements.

C.3 Material and Structural Response through Fire Experiments – A Way Forward

Venkatesh Kodur
Department of Civil & Environmental Engineering
Michigan State University
East Lansing, MI 48824, USA

The fire response of structural system can be established through the use of fire resistance experiments or numerical models. At present, fire resistance is mostly evaluated through standard fire tests on structural elements such as beams, columns and slabs, or through prescriptive-based empirical methods. The main reasoning for the limited use of a numerical approach to fire resistance evaluation is the lack of validated computer models and due to a lack of high-temperature constitutive models for materials. A state-of-the-art summary and research needs on material and structural response through fire experiments and research needs is presented in this section. The discussion is presented under two categories: elemental/structural systems and material characterization.

Elemental/System Tests

The basic provisions for the standard fire tests were developed in early 20th century. While there have been small changes in some of the provisions, the test method remains essentially unchanged today. In North America different standards, which include ASTME119, NFPA 251, UL 263 and ULC-S101, exist for evaluating the fire resistance of structural members. However, the test procedure in many of these standards is similar in nature and also is equivalent to that of the internationally used test standard of ISO 834 which is widely accepted and adopted by most of the European and Asian countries.

Generally, the process of conducting standard fire tests encompasses the following: (1) Sponsor develops assembly in accordance to the design specifications, (2) Testing laboratory witness all the construction procedure to ensure quality control, (3) Assembly is tested and data collected, (4) The test details are issued in a proprietary report if successful. Tests are conducted in specially designed fire-testing furnaces with specific dimensions for each type of structural assembly. The test specimen should represent actual construction. Standard fire-temperature curves are followed during the test. Based on the duration of the test (to reach failure), the fire resistance rating is assigned for the tested assembly. The three failure criterions that are to be satisfied in most standard fire resistance tests are: (1) insulation (barrier) – to limit the temperature rise or fire spread, (2) stability (strength) – to prevent collapse, and (3) integrity – to limit flame (fire) spread. Often such failure is said to have been reached based on simple rules-of-thumb, such as a critical or limiting temperature in steel.

There are a number of drawbacks with the standard test methods. Some of these include:

- *Scaling Effects:* The size of the testing specimen represents the actual assembly, but this scaling does affect the fire resistance.
- *Fire Scenarios:* The standard fires used in various standards represent only one fire scenario. Further there is no cooling (decay) phase in this fire scenario. Real fires do have a decay phase after the flashover point.

- *Furnace Parameters:* Heat flux from the fire exposure is not consistent. The actual flux required to maintain a certain level of temperature depends upon the material used in the assembly. Heat flux is a function of furnace volume, surface area, thermal properties of the furnace boundaries and fuel gas properties. ASTM E119 does not specify any furnace pressure requirements. Typically for floors and columns, negative pressure is maintained. However, ISO 834 does specify a positive pressure of 10 Pascal for floor (horizontal assemblies) and a linear pressure for vertical assemblies. During the test, it is very difficult to maintain constant pressure, temperature and emissivity. In addition, the relative humidity cannot be controlled in furnace tests.

- *Test Specimens:* Small test specimens representing part of actual beam, column or slab assembly are tested in the furnace. These specimens do not take into account the interaction between assemblies. Thus the connections of the system as a whole are not accounted for during testing. Also, the support conditions do not reflect the true restraint/unrestraint support conditions in reality.

- *Loads:* Loading during tests is applied using hydraulic jacks, sand bags or water cans. Under hydraulic loads, it is difficult to maintain the load level. Assemblies are normally tested unloaded.

- *Instrumentation:* To measure the relative humidity of the specimen before testing, drilling is required, which damages its surface. Any damage then becomes a weak link during testing. High temperature strain gages are not available. Gauges used give varying data depending upon the bond condition at high temperatures. Spalling is common phenomenon in concrete at high temperatures and that may effect the instrumentation near the surface.

- *Failure Criterion:* The current test methods do not give due consideration to various failure limit states such as strength, stability, deflection and rate of deflection as failure criterion. Often the failure is said to have been reached based on simple rules of thumb such as a critical or limiting temperature in steel, which is not a true representation of failure for different load levels.

Due to the above drawbacks, the current test methods are not realistic, applicable only under restrictive scenarios, provide minimum data for validation, too expensive, quite time consuming and provide only prescriptive solutions.

The state-of-the-art review indicates that there is good amount of data from standard fire resistance tests on some structural elements such as beams, columns, walls and floors. The available data set is particularly large for steel, concrete and composite columns, as well as for floors and walls. These tests, which considered a very limited number of parameters, generally followed standard fire conditions and no realistic (design) conditions such as fire exposure, specimen size, loading and failure conditions were considered. But there is serious lack of data on some structural element such as steel and reinforced concrete beams, as well as connections.

There have only been a limited number of fire experiments that considered a "system approach" for evaluating the response of structures to fire. A few studies have investigated assemblies such as portal frames and steel beam-concrete slab assemblies to illustrate the beneficial effect of structural interaction under fire exposure. The most significant system studies were undertaken by the Building Research Establishment (BRE) in U.K, who carried out a series of full-scale fire experiments in the Large Building Test Facility (LBTF) at Cardington, UK. The tests on 7-storey steel and concrete buildings provided valuable data on behavior of both structural and non-structural elements within a real compartment subjected to real fires.

Data from the six full-scale fire tests on a steel framed building (as well as a concrete building) confirmed that the fire resistance of complete buildings (structural systems) is significantly higher than that of single elements from which fire performance is usually assessed. These experimental studies at LBTF also provided valuable information on the feasibility of unprotected steel structures. The tests have demonstrated that in composite floor systems it is possible to achieve higher fire resistance than when the beams are tested as individual elements.

Way-Forward: Fire resistance experiments are absolutely necessary for understanding the system response, model validation, and drawing comparisons. The system approach under realistic conditions, as compared to the current elemental approach under standard scenarios, is a more effective way of conducting fire experiments. However, the current standards, construction practices, and regulatory environment do not offer incentives to move towards a system approach. There is a need to revise the testing procedures to address the aforementioned drawbacks. Such improvements in standards should incorporate specifications pertaining to the consideration of real fire scenarios (with a cooling phase), measurement of various material properties and conditions (such as strength, relative humidity in concrete), instrumentation (cross-sectional thermocouples and high-temperature strain gauges), monitoring data throughout the test (with intervals at every minute) and continuing the tests until the assembly fails. Furnace parameters like inside pressure, temperature, fuel type, lining material and emissivity should be deliberated upon and reported from each tests. Small and intermediate scale testing equipment which may allow testing portal frames and connections needs to be commissioned. During the test, all types of data possible should be collected and reported to improve the data base. Many of these changes can be incorporated in the standards tests with moderate effort and resources.

However, changing to a full system approach (i.e. testing whole buildings) requires significant effort and resources. Such an approach should be limited to a few tests for validation of models. The validated models can be used to study the overall structural behavior.

There is a need to develop high-temperature sensors, new test equipment and relevant resources for advancing the state of the art in the area.

Material Property Tests

Since the fire performance of structural members depends on the properties of the constituent materials, knowledge of high-temperature material properties is critical for fire resistance assessment. There is either no (or very limited) test data on some high-temperature properties, or there are considerable variations and discrepancies in the high-temperature test data for other properties, especially in the nonlinear range of behavior. This is mainly due to the differences in test methods, conditions and procedures, and the environmental parameters accompanying the tests. Thus, at present, some of the constitutive relationships for high-temperature properties of materials (such as concrete, steel or wood) that are present in codes and standards are not fully verified, or there are no reliable constitutive relationships for many other high-temperature properties of insulation materials or high strength concrete.

Fire performance of assemblies depends on the properties of each material, and these vary with the temperature. Material properties at elevated temperature like thermal and mechanical properties, deformations, bonding and pore water pressure for concrete, bond for steel, charring for wood, and adhesion of insulating material are required to develop the models and study variability effects. Such data is usually obtained through tests.

Much of the current knowledge regarding high-temperature material properties of normal strength concrete (NSC) is based on very limited material property tests. While some limited information is available on high-temperature properties such as strength, modulus of elasticity, thermal conductivity and specific heat, there is no reliable data on properties such as high temperature creep and porosity. Further, until recently there were no standard test methods for evaluating the high-temperature thermal, mechanical and deformation properties. Only in the last few years, efforts are underway by RILEM and other organizations to develop test methods for obtaining high-temperature properties. Thus the current available test data, where researchers used different variables such as heating rate and loading conditions, can not be compared with one other.

This lack of data and the high variation in the reported high-temperature properties of materials can be attributed to:

- Lack of standard test methods.
- Need for specific (different) testing procedures for new materials.
- Lack of specifications for heating rate, loading, residual strength and steady/transient state.
- Varying temperature and load ranges.
- High cost and complexity of expanding the reporting procedures to include relative humidity, heating rate, and strength of specimen on testing day and mix design proportions including type of aggregate used.
- Test equipment is not easily available.
- Complexity in instrumenting small scale specimens.
- Lack of instrumentation to measure the bond and strains.
- Lack of interest (by researchers) in the development of constitutive models.

Way Forward: Given the above variations (for NSC) and lack of information (for HSC) with regards to high-temperature properties, there is an urgent need to undertake material property tests and to develop constitutive relationships for various properties as a function of temperature. Comprehensive studies are needed to develop high-temperature constitutive relationships for thermal, mechanical and special properties of different materials (especially insulation) in the temperature range of 0-800^{0}C. The availability of constitutive relationships for high-temperature properties is critical for facilitating the use of rational approaches to fire engineering of structures and to promote performance-based fire safety design.

Summary

- Fire resistance assessment continues to be based on standard fire tests.
- There is an urgent need to develop additional test procedures, guidelines and standards for undertaking rational fire experiments.
- There is lack of test data for validating computer models.

- Material properties at elevated temperatures are critical for performance-based fire design and there is large variation in the available data.
- With moderate effort and resources, some of the drawbacks in current fire test standards can be overcome.
- The current fire test methods have significant drawbacks with respect to fire scenarios, instrumentation, test conditions, loading application and data collection. Thus, there is a need for updating the test provisions for validation of numerical tools for use under performance-based codes.

C.4 Structural Fire Safety through Improved Building Codes and Standards: Recommendations from the Technical Investigation of the WTC Collapse

William L. Grosshandler
Building and Fire Research Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899-8660, USA

Following the tragedy at the World Trade Center (WTC) in 2001, the topic of structural fire resistance jumped abruptly from the specialized vernacular of the fire protection engineer to almost daily coverage on television, in newspapers, and on the internet. The technical investigation[1] conducted by the National Institute of Standards and Technology (NIST) has stimulated significant new efforts to put our understanding of fire/structural interactions on a sounder foundation.

The NIST investigation had four specific objectives: (1) determine why and how WTC 1 and WTC 2 collapsed following the initial impacts of the aircraft and why and how WTC 7 collapsed; (2) determine why the injuries and fatalities were so high or low depending on location, including all technical aspects of fire protection, occupant behavior, evacuation, and emergency response; (3) determine what procedures and practices were used in the design, construction, operation, and maintenance of WTC 1, 2, and 7; and (4) identify, as specifically as possible, areas in current building and fire codes, standards, and practices that warrant revision.

To meet these objectives, NIST and its contractors reviewed thousands of documents, conducted interviews, analyzed pieces of steel that were obtained from the wreckage, performed laboratory tests, measured material properties, and performed computer simulations of the sequence of events that happened from the instant of aircraft impact to the initiation of collapse for each tower. Because the buildings had been totally destroyed and remnants removed from the site, along with the documentation they contained on the buildings' design and operation, NIST relied heavily on the photographic and video material that were gathered by the media and individuals.

The behavior of each tower on September 11, 2001 was simulated in four steps:

[1] http://wtc.nist.gov

- The aircraft impact into the tower, the resulting distribution of aviation fuel, and the damage to the structure, partitions, thermal insulation materials, and building contents;
- The evolution of multi-floor fires;
- The heating and consequent weakening of the structural elements by the fires; and
- The response of the damaged and heated building structure, and the progression of structural component failures leading to the initiation of the collapse of the towers.

The output of these simulations was subject to uncertainties in the as-built condition of the towers, the interior layout and furnishings, the aircraft impact, the internal damage to the towers, the redistribution of the combustibles, and the response of the building structural components to the heat from the fires. Based on its investigation findings, NIST identified a broad set of issues related to practices, standards, and codes that provided the basis for thirty specific recommendations that were grouped into the following general categories:[2] (1) increased structural integrity, (2) enhanced fire endurance of structures, (3) new methods for fire resistant design of structures, (4) improved active fire protection, (5) improved building evacuation, (6) improved emergency response technologies and procedures, (7) improved procedures and practices, and (8) education and training. The recommendations in groups (2) and (3) have direct relevance to the current workshop; other recommendations also bear, at least indirectly, on the topics. For brevity, only an excerpt of the directly relevant recommendations is paraphrased below:[3]

- **R4.** Evaluate/improve the technical basis for determining appropriate construction classification and fire rating requirements by explicitly considering factors including: timely access by emergency responders and full evacuation of occupants; the ability of the structure and local floor systems to withstand a maximum credible fire scenario without collapse; and the extent to which fire control systems should be credited as part of the prevention of fire spread.
- **R5.** Improve the technical basis for fire resistance testing of components and assemblies through a national effort, and develop guidance for extrapolating the results of tested assemblies to prototypical building systems.
- **R6.** Develop criteria, test methods, and standards for the performance of spray-applied fire resistive material and ensure that these materials conform to conditions in tests used to establish fire resistance ratings.
- **R7.** Adopt, nationwide, the structural frame approach to fire resistance ratings.
- **R8.** Enhance the fire resistance of structures by requiring a performance objective that uncontrolled building fires result in burnout without local or global collapse.

[2] *Final Report on the Collapse of the World Trade Center Tower*, NIST NCSTAR 1, National Institute of Standards and Technology, Gaithersburg, MD, September 2005.
[3] The recommendation numbers correspond to the numbering in the NIST NCSTAR 1, and the reader should refer to the full text of the recommendations found in that report.

- **<u>R9.</u>** Develop performance-based standards and code provisions to enable the design/retrofit of structures to resist real building fire conditions, including their ability to achieve the performance objective of burnout without structural or local floor collapse, and tools and test methods necessary to evaluate the fire performance of the structure as a whole system.

- **<u>R10.</u>** Develop/evaluate new fire resistive coating materials, systems, and technologies with significantly enhanced performance and durability to provide protection following major events.

- **<u>R11.</u>** Evaluate the performance/suitability of advanced structural steel, reinforced and pre-stressed concrete, and other high-performance material systems for use under conditions expected in building fires.

NIST, being a non-regulatory agency, does not prescribe specific technologies or threshold levels that should be set in standards and codes. NIST encourages competition among different systems that can meet performance requirements, and recognizes that the responsibility for establishment of threshold levels belongs in the public policy setting process, in which the standards and codes development process plays a key role.

Technical barriers exist to the adoption of the NIST recommendations. To put these barriers into perspective, note that structural engineers design buildings to handle loads due to gravity and specified building contents. In addition, buildings must handle loads caused by severe natural occurrences (high winds, snow levels and earth-quakes), with the loading probability established through historical data. How does one set the severity level for manmade fires (accidental or intentional)?

Setting the severity level of fires for building design is complicated by three factors: the historical database 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 not in control of the building designer. The technical problems manifest themselves in two ways:

- There are no agreed upon protocols for establishing the maximum fire load (analogous to wind and earthquake loads) that a building ***should*** be designed to resist.

- There is no systematic framework or sufficiently robust scientific foundation upon which to predict, with an established certainty, the maximum fire load that a building ***could*** withstand.

Policy makers, ultimately, will make the decisions to adopt or modify the NIST recommendations. The research community must provide the codes and standards making organizations and the authorities having jurisdiction with the knowledge, data, and predictive tools to make well-informed decisions, and to enable structural engineers and architects, materials manufacturers and building equipment suppliers to construct innovative, safe and economically viable buildings.

The key issue to be tackled by researchers related to structural fire safety is the enhancement of procedures used in fire resistance design associated with the desire that uncontrolled fires result in burnout without local or global collapse. This outcome will require improving the technical basis for construction classifications and fire resistance ratings and testing methods; using the structural frame approach to fire resistance ratings; developing in-service performance requirements and conformance criteria for spray-applied fire resistive materials; developing and evaluating new fire resistive coating materials and technologies; and evaluating the fire performance of conventional and high-performance structural materials.

There are two specific research areas that, as a minimum, need to be addressed before the recommendations can be implemented: (1) measuring the properties of construction materials at elevated temperatures, and (2) designing/measuring/predicting structural fire performance in well-controlled real-scale fire/structure experiments. New experimental methods and protocols are needed to make accurate high temperature measurements of the thermal/mechanical properties of construction materials, up to the point of failure. Materials of interest include: normal/high strength concrete, normal/fire-resistant steel, timber, aluminum, steel/concrete composite, fiber-reinforced polymer composites, gypsum partitions, glazing, fire stops, intumescent coatings, and structural fireproofing. Standardized measurement methods must be developed and used to accumulate a consistent, reliable, high temperature (> 500 ^{o}C) database on the thermal/mechanical properties of these materials, with the database including thermal conductivity, specific heat, enthalpy of phase change and decomposition, thermal diffusivity, and stress-strain relationships as a function of strain-rate as well as temperature.

A new real-scale, structural fire endurance national users facility is required: for exposing floor and wall composite assemblies to controlled fires under measured loads all of the way to mechanical failure; for measuring the behavior of fireproofing as installed and when degraded by time, temperature, and stress; for the response of structural connections, welds, bolts, rivets and adhesives when exposed to severe fire conditions and loads, including during the cool-down period; for developing more efficient non-linear structural algorithms which accommodate a wide range of length scales and include creep, concrete cracking, spalling, and fireproofing damage; and for verifying sub-grid models to better resolve heat transfer from the fire environment to structural elements, and failure of structural connections and interfaces at elevated temperatures.

The ultimate scientific goal of structural/fire safety research is to have validated models that resolve heat transfer from the fire environment to the structural elements, and that predict the failure of structural components and systems at elevated temperatures, up to the point of local or global collapse, with sufficient accuracy to discriminate performance among alternative designs, construction materials, and active fire protection systems.

Appendix D: Panel Discussion Summaries

D.1 Discussion: Session 1

Panel: A. Buchanan, C. Beyler, F. Mowrer, L. Albano

- How do we move forward in terms of defining fire loading? (Grosshandler)
- Fire load is not like wind load – it is transient, including a heat-up and cool-down phase. (Albano)
- How do you decide what conditions or scenarios you are designing for?
- The designer is working for the owner, which poses a potential conflict.
- For practicing engineers, a load factor in LRFD and a design fire with a specified number of compartments are currently in question.
- Mahmoud?? article published in China indicates policy adjustments in the direction of structural-fire design. This is needed if our efforts are to be successful.
- Clear focus currently doesn't exist. (Beyler)
- Does it exist in Sweden? (audience)
- Many variables still exist, but some countries are further along. (Buchanan)
  - For example, N.Z. is the size of one US state, so it is easier for them to have a coordinated approach.
  - However, it doesn't mean they have all the answers – we still have to improve the science, and moving ahead is not so easy.
- Following up on "cowboys with computers" comment, pioneers in the US need new ways to develop new materials.
- We need to be able to categorize our buildings
- How do we link the fire in our analyses to experiments?
- What do we want to accomplish as structural engineers?
  - For example, localized fire vs. average description of that fire

D.2 Discussion: Session 2

Panel: J.M. Franssen, J. Milke, M. Garlock, M. Fontana

- Can probabilistic approaches be applied for structures in fire? (Astaneh)
  - There exists a lack of fire-related data and statistics. (Milke)
  - There is also a lack of special studies of actual structural-fire events. (Garlock)
  - These decisions can become very political, so we need to identify the important variables. (Fontana)
- Is there unresolved uncertainty in material properties under fire exposure? (Kodur)
  - We should test for the exact properties if the funding is available, otherwise just use generic published values. (Franssen)
  - Limitation: We cannot accurately predict failure by analysis
- How do we characterize the probability of failure? (Buchanan)
  - Structural, property, and life safety affects must be accounted for. (Fontana)
  - We need simplified models for regular practice. (Milke)
- Comment to FDNY and NYC Building Officers:
  - Combustible vs. non-combustible materials → occupant escape → firefighter safety

- UL → use modeling to reduce variability of material properties (curve fitting, inverse methods, etc.).
  - Differences exist between different versions or samples of the same material. (Fontana)
  - For example, f'_c for concrete cylinder tests can vary for the same material. (Franssen)
- Implicit vs. Explicit integration for solution convergence (El-Tawil)
  - SAFIR only uses an implicit method. (Franssen)
- Analogous to earthquake research, a reliability approach should be used to push modeling progress and further experimental testing. (Foutch)
  - To obtain research funding, a similar program to NEES could be established.

D.3 Discussion: Session 3

Panel: V. Kodur, L. Phan, N. Iwankiw, A. Varma

- As an application to real structures, is it worthwhile to have some kind of monitoring system to know of imminent collapse of structures? (Mahmoud)
- Other researchers have used accelerometers to monitor stability as it decays over time. (Varma)
- The main difficulty in predicting experimental structural failure is that 95% of deflection occurs in the last few second before collapse. (Kodur)
  - Also, we are unable to predict when spalling will occur.
  - Such a system is also being pursued in the UK. (Lamont)
- At ambient temperature, material properties are determined via small scales tests (e.g. from coupons). Can material data at high temperature also come from small scale tests? (Hurley)
  - Yes – this is already being done with concrete. (Phan)
  - This form of testing needs to be standardized.
  - If the size of the specimen is reduced too much, then properties become difficult to capture (e.g. beam spans). (Kodur)
- We are confident that the state-of-the-art will advance with more research and testing. (Iwankiw)
- Tests to failure and testing in the cooling period is incongruent. (Beyler)
- Structural fire safety is very important to fire fighters. (Kodur)

D.4 Discussion: Session 4

Panel: B. Grosshandler, S. Lamont, M. Englehardt, S. Pessiki

- What do you have to give up in a structural engineering curriculum to teach coursework on structures in fire? (Cramer)
  - Rotating graduate classes is a solution.
  - These courses are difficult to include at the undergraduate level
  - Cramer had taught a course at the University of Wisconsin using Buchanan's book.
  - At Michigan State University, undergraduates take 2 ½ weeks of structures in fire within another course. (Kodur)

- We want exposure at the undergraduate level, at least by comparing the same calculations done at ambient to those done with high temperature conditions. (Buchanan)
- NIST would like to see the study of heat flux introduced to structural engineering. (Grosshandler)
- At the University of Illinois, no undergraduates ever took a structural fire course taught by Gamble because their schedules are too constrained.
- It is important to point out in other courses that there are other loads than gravity, earthquake, and wind. (Gamble)
- Can we introduce the earthquake approach of performance based objectives to structural fire engineering? (Buchanan)
- Codes should be made explicit, and tall buildings should be built as fire resistant. (Mowrer)
- Should we take the WTC performance and still make statements that burnout is the desired criteria for performance? (Astaneh)
- The burnout requirement should be explicit. (Mowrer)
- The process of change has been at lightspeed since 9/11 – we are seeing more significant changes. (Grosshandler)
- Models based on small compartment fires help to more accurately define the fire. (Janssens and Lamont)

Appendix E: Focus Group Members

E.1 Focus Group A: *Research Needs for Structural Fire Response Modeling*

Title	*Last Name*	*First Name*	*Affiliation*
Prof.	Astaneh-Asl	Abolhassan	CEE, University of California, Berkeley
Dr.	Bagchi	Ashutosh	CEE, Concordia University
Dr.	Buchanan	Andy	CE, University of Canterbury
Dr.	Chou	Karen	M&CE, Minnesota State University
Mr.	Dwaikat	Monther	CEE, Michigan State University
Prof.	Fontana	Mario	CE, ETH Zurich
Dr.	Foutch	Doug	National Science Foundation
Prof.	Franssen	Jean-Marc	CE, University of Liège
Prof.	Gamble	William	CE, University of Illinois at Urbana-Champaign
Prof.	Garlock	Maria	CEE, Princeton University
Mr.	Hong	Sangdo	CE, Purdue University
Mr.	Iqbal	Shahid	CEE, Michigan State University
Dr.	Jensen	Elin	CE, Lawrence Technology University
Dr.	Lamont	Susan	Arup, UK
Dr.	Lin	Feng-Bao	CE, The City College of New York
Dr.	Mowrer	Frederick	FPE, University of Maryland
Dr.	Pessiki	Stephen	CEE, Lehigh University
Dr.	Phan	Long	BFRL, NIST
Dr.	Prasad	Kuldeep	BFRL, NIST
Mr.	Raut	Nikhil	CEE, Michigan State University
Prof.	Ricles	James	CEE, Lehigh University
Dr.	Thiagarajan	Ganesh	CE, University of Missouri
Prof.	Wichman	Indrek	ME, Michigan State University

E.2 Focus Group B: *Research Needs for Fire Experiments*

Title	*Last Name*	*First Name*	*Affiliation*
Mr.	Ahmed	Aqeel	CEE, Michigan State University
Mr.	Badders	Barry	Southwest Research Institute
Dr.	Banerjee	Dilip	BFRL, NIST
Mr.	Bilow	David	Portland Cement Association
Dr.	Cramer	Steven	CE, University of Wisconsin
Prof.	Engelhardt	Michael	CEE, University of Texas at Austin
Mr.	Fike	Rustin	CEE, Michigan State University
Dr.	Gross	John	BFRL, NIST
Mr.	Hay	Al	Fire Department of New York
Dr.	Iwankiw	Nestor	Hughes Associates, Inc.
Dr.	Janssens	Marc	Southwest Research Institute
Dr.	McGinnis	Michael	CEE, Lehigh University
Mr.	Quiel	Spencer	CEE, Princeton University
Dr.	Varma	Amit	CE, Purdue University
Prof.	Zalok	Ehab	CEE, Carleton University

E.3 Focus Group C: *Research Needs for Codes, Standards and Education*

Title	*Last Name*	*First Name*	*Affiliation*
Prof.	Albano	Leonard	CE, Worcester Polytechnic Institute
Dr.	Alfawakhiri	Farid	AISI
Ms.	Almand	Kathleen	FPRF, NFPA
Dr.	Beyler	Craig	Hughes Associates, Inc.
Mr.	Eschenasy	Dan	New York City Department of Buildings
Dr.	Ezekoye	Ofodike	ME, University of Texas at Austin
Dr.	Grosshandler	William	BFRL, NIST
Mr.	Huber	Devin	CE, Purdue University
	Hurley	Morgan	Society of Fire Protection Engineers
Dr.	Kodur	Venkatesh	CEE, Michigan State University
Dr.	Meacham	Brian	Arup, USA
Ms.	Rini	Darlene	Arup, UK
Mr.	Rossberg	Jim	SEI of ASCE
Mr.	Selamet	Serdar	CEE, Princeton University
Ms.	Vivian	Megan	CEE, Michigan State University

Appendix F: Focus Group Summaries

F.1 Focus Group A: *Research Needs for Structural Fire Response Modeling*

K. Prasad[1] and A. Astanesh-Asl[2]
1. *Research Engineer, BFRL,NIST*
2. *Professor CEE, University of California, Berkeley*

The aim of the "National Workshop on Structures and Fire" organized by Dr. Venkatesh Kodur, was to identify and prioritize research needs in the area of structures and fire. During this two day workshop, a focus group session was organized to identify research needs in the area of "Structural Fire Response Modeling". The focus group session was attended by well known experts in the area of structural-fire engineering and had good representation from the industry, academia, and the national laboratories.

The goal of the focus group session was to identify and prioritize a list of ten research needs in the area of Structural Fire Response Modeling. A list of the ten research needs in Structural Fire Response Modeling, identified by the focus group members, is listed below in no particular order.

- *Constitutive models for materials*
  The focus group identified the development of appropriate constitutive models for various construction materials as a major research need that has a critical effect on numerical modeling of structures under fire loads. Constitutive models are needed for concrete, masonry, steel, wood and fire-proofing. The models should not be limited only to the heating phase, but instead should cover the entire heating / cooling cycle. It was also noted that creep at high temperature can result in structural collapse and that the constitutive models should include the effects of creep. Furthermore, constitute models for the first as well as the second (subsequent) heating / cooling cycle are needed to model the effect of fire on structures.

- *Models for predicting spalling of concrete*
  Concrete when subjected to fire loading can undergo spalling. It is well know that numerical models for structural analysis under fire loading include the effect of spalling in an empirical manner. Development of appropriate models for predicting spalling and including the effect of spalling in structural fire response modeling was identified as a critical research need that will have a significant effect on the accuracy of the models.

- *Development of interfaces for coupled fire, thermal, structural analysi*s
  The first step in structural fire response modeling is to identify the thermal loads on a structure due to the fires. The thermal loads on a structure are closely coupled to the radioactive and convective heating from the fires to the structure. Development of appropriate interfaces that couple the fire dynamics to the thermal response of a structure and link the thermal models to the structural models are a critical research need for structural fire response modeling.

- *Model validation for structural response*
  The numerical models that are currently being used for studying the response of structures under fire loading are extremely complex and there is a clear need to validate the models with experimental data. The focus group members expressed a

need for component testing as well as for full scale / real scale testing of structures under fire loading.

- *Performance-based definition for failure*
  The focus group members discussed at length on the definition of failure and what constitutes failure of a structural system or member. It was suggested that new techniques need to be developed for distinguishing local failure of a structural component from global failure. The group believed that research was needed to identify performance-based criteria for defining failure.

- *Sensitivity analysis and parametric studies*
  A typical structural fire response analysis of a complex structure could require many input parameters. A sensitivity analysis should be performed to identify those input parameters that are critical for the analysis. The focus group members also identified the need for parametric studies to determine which physical processes have the biggest influence on the observed structural response.

- *Connection behavior under fire effects*
  In a typical structural analysis under fire loads, the strength of the connections and its degradation due to thermal heating plays a very important role in the stability of the structure. Currently analysis of structures under fire loads is performed by assuming that the connections have infinite amount of strength. The focus group members voiced strong support for modeling activities and experimental data to validate the observed connection behavior.

- *Modeling non-structural elements under fire effects*
  In order to model structures under fire loading, it was essential to fully understand how fires grow and spread from one compartment to another. The spread of fire can be significantly affected by the presence of partitions, doors, wall etc. Furthermore, breaking of glass windows can affect the ventilation patterns and influence the growth and spread of a fire. The focus group members believed that new research activities must be initiated in the area of modeling non-structural elements, such as partitions, doors, walls, window breakage etc.

Since damage to SFRM can have a significant effect on the computed thermal response, adhesive and cohesive properties of SFRM products was also identified as a critical research need.

- *Improving structural detailing, retrofit of structures*
  Research is needed to develop a sound theoretical basis for retrofit of structures under fire loading.

- *Effect of fire fighting / cooling on structures*
  Structures often collapse during the cool-down phase and new research is needed to study the role of fire fighting and cooling of structural components and their effects on the computed structural response.

The top ten research needs identified by the focus group are listed above. Major topic areas that were not included in the top ten research needs, but were discussed during the focus group session are listed below.

- Fire effects on composite structures.
- Post-fire assessment of structural condition.
- Structural performance monitoring.
- Probabilistic analysis.
- Risk assessment.
- Sub-structure analysis
- Open source fire structure software.

F.2 Focus Group B: *Fire Experiments – Research Needs*

J. Gross[1] and S. Cramer[2]
1 Research Structural Engineer, BFRL,NIST
2 Professor & Associate Dean, University of Wisconsin

To frame the discussions on the broad topic of "fire experiments," the co-moderators suggested that the scope of discussions be limited to testing necessary to support a performance-based approach to structural design for fire. Beyond this, the following questions were posed to stimulate discussions:-

- What testing is required for
    - Determination of fundamental material properties?
    - Understanding of complex behaviors?
    - Characterization of structural performance for validation of computational methods (either advanced or simplified)?
- Are test standards (or universally recognized test protocols) available?
- What scales of tests are required (material, component, system) – reduced scale?
- Under what types of exposure (ovens, furnace "fires", burning fuels or combustibles)?
- Are adequate testing facilities available?
- What instrumentation is required? – is the technology adequate?
- What are the structural types (configurations) that are least well understood, or are most critical to understand?

Discussions were organized around the following topical areas:-

- Determination of fundamental material properties
    a. Physical properties
    b. Mechanical properties

- Characterization of structural performance in fire for either understanding of complex behaviors or validation of computational methods
    a. Component tests
    b. Sub-system tests
    c. System tests

- Testing requirements
    a. Facilities

b. Protocols
c. Instrumentation

After lengthy and lively discussions, the workshop participants developed narrative descriptions of eleven research needs. They are presented here without edit and reflect the ideas put forth by the participants. They are not presented in any priority but have been organized according to the topical areas identified above.

- *Characterization of fundamental material properties*
  Large gaps exist in our characterization of materials in fire testing. Significant gaps exist in traditional material such as concrete, steel, wood and wood based materials, adhesives, fiber-reinforced plastics and protection materials. Understanding system fire performance data and fire modeling require detailed knowledge of materials under a variety of fire and load conditions.

- *Testing components and columns under load*
  This research project will:-
  - Formalize experimental procedures for conducting fire tests on columns
  - Include columns subjected to different loading conditions (concentric, eccentric, and combined loading) and different end conditions.
  - Include different heating scenarios (one sided, multiple sided), and cooling phases as needed.
  - Include columns made from different materials
  - Measure the thermal and structural behavior of the specimens up to failure

- *Structural behavior of composite floor systems*
  The goal here is to investigate and quantify the effect of composite behavior has on structural fire resistance. This includes but is not limited to: shear interactions and catenary action in composite floors, tensile field action in slabs, slip of concrete within steel tubes and pullout strength of steel reinforcing.

- *Characterization of connection behavior*
  Almost all standard fire tests have not included direct evaluation of structural connections. Basic fire response of connectors (bolts welds, studs, truss plates, adhesives) in all materials needs to be determined. Load transfer, stiffness and ductility are needed in addition to ultimate limit states.

- *Modifications to E119 standard fire test*
  Hundreds of standard ASTM E119 tests conducted in North America each could be extremely useful for model validation. This will require that instrumentation be added beyond what the standard requires and the test be continued until the structure fails. Research is needed to determine the additional measurements that should be made, and a funding mechanism is required to obtain the additional information from commercial fire resistance tests.

- *Resolving scale issues*
  Verify small and medium scale testing configurations and how they correlate to large-size tests and ultimately to full scale building performance.

- *Establish a comparison for test exposure*
  Define and provide guidance on types of exposures, especially related to cooling curves.

- *Establish testing guidelines and protocols*
  - Need to harmonize the definition of failure and uncertainty in reporting test data.
  - Need to develop guidance on heating characteristics and temperature gradients, including establishing recommendations on the use of heat flux versus temperature.
  - Provide guidance on defining structural boundary conditions and measurement of structural loading.

- *Develop new sensor technology*
  Establish limits of existing sensor technology and develop new sensor technology for quantifying physical behavior up to 800°C. Quantities, sensors and techniques of interest include strains, displacements, moisture content and movements, pore pressures, load cells, heat flux, and optical techniques. These types of information are crucial for calibrating and verifying complex analysis models.

- *Establish a large scale test facility*
  Although the Cardington tests provided much data in full scale building fires, there is still a need for more data on how large system performs.

- *One-time testing of decommissioned buildings*
  Decommissioned buildings that are scheduled for demolition represent a unique opportunity to gather large scale test data. A funding mechanism and means to rapidly deploy the necessary expertise and equipment to dispersed sites offers an opportunity to greatly increase our understanding of building fire performance without creating a specialized testing facility.

F.3 Focus Group C*: Codes, Standards and Education*

K. Almand[1] and O. Ezekoye[2]
1 Executive Director, FPRF, NFPA
2 Professor, University of Texas

1. Barriers/Weaknesses in Today's Codes and Standards and Education Frameworks

a. Codes and standards

- *Building codes.* The current regulatory structure in the United States does not foster performance-based design approaches. There are no incentives to move from the current prescriptive approach toward an engineering methodology. Although the ICC has published a performance-based building code, there is little infrastructure or tools to use it. This would include, at a minimum, agreed upon goals and acceptable levels of risk. See the attached conceptual drawing (Figure F.1) of a risk based framework for structural fire engineering.

- *Standards.* For widespread implementation of performance-based design methods, these methods must be codified into recognized national standards. These standards generally do not exist, although some are under development.

- *Professional Framework.* There is no clearly defined role for the structural engineer in the design of structures for fire; typically the architect has responsibility for this aspect of safety in building design. The architect may call on a fire protection engineer; recognition for the role for the structural engineer will be necessary for widespread implementation.

- *Tools & Data.* Data is incomplete on fire loads, potential thermal exposure of structural components, and properties of structural components at high temperature. Tools have been developed at only the most complex (single user, multiple tools) level; standard case study (intermediate level analysis) methods have not been developed or promulgated by appropriate parties.

b. Education

- *Structural Engineering Curricula.* There is little available room in the undergraduate schedule for additional courses in specialties. Awareness level training (through one or more lectures) is likely the only way to introduce the subject to junior undergraduates. A limited number of schools offer one course at the graduate or senior undergraduate level but there are no standard faculty resources/curricula.

- *Fire Protection Engineering Curricula.* The undergraduate and graduate fire protection engineering programs in the United States include structural fire engineering courses. This is considered sufficient at this time.

- *Practitioner Training.* The Society of Fire Protection Engineers offers introductory structural fire engineering courses for non-engineers but these are not widespread in implementation.

2. Research Needs

The top ten priority research needs arising from discussion are given in Appendix G. The following are the high priority research tasks needed to improve the overall context for structural fire engineering and to address the barriers above.

a. Tools and Data

- Development of accepted (e.g. standards) design methods, tools, criteria (see diagram)
- Development of generally accepted methods for determining properties of materials at elevated temperatures to serve as input for calculation methods and models
- Development of a new Building Incident Reporting System for structural fire design (forensic)
- Development of standardized information on fire loads in buildings.

b. Education

- Curriculum development at undergraduate level – course modules or lectures
- Curriculum development at graduate level – core group of courses – thermodynamics, fluid mechanics, heat transfer, include experimental modules

- Curriculum development for the 30 hour to PE requirement – one or more courses for graduates seeking PE license
- Faculty workshops to develop and encourage implementation of curriculum modules – old FEMA model

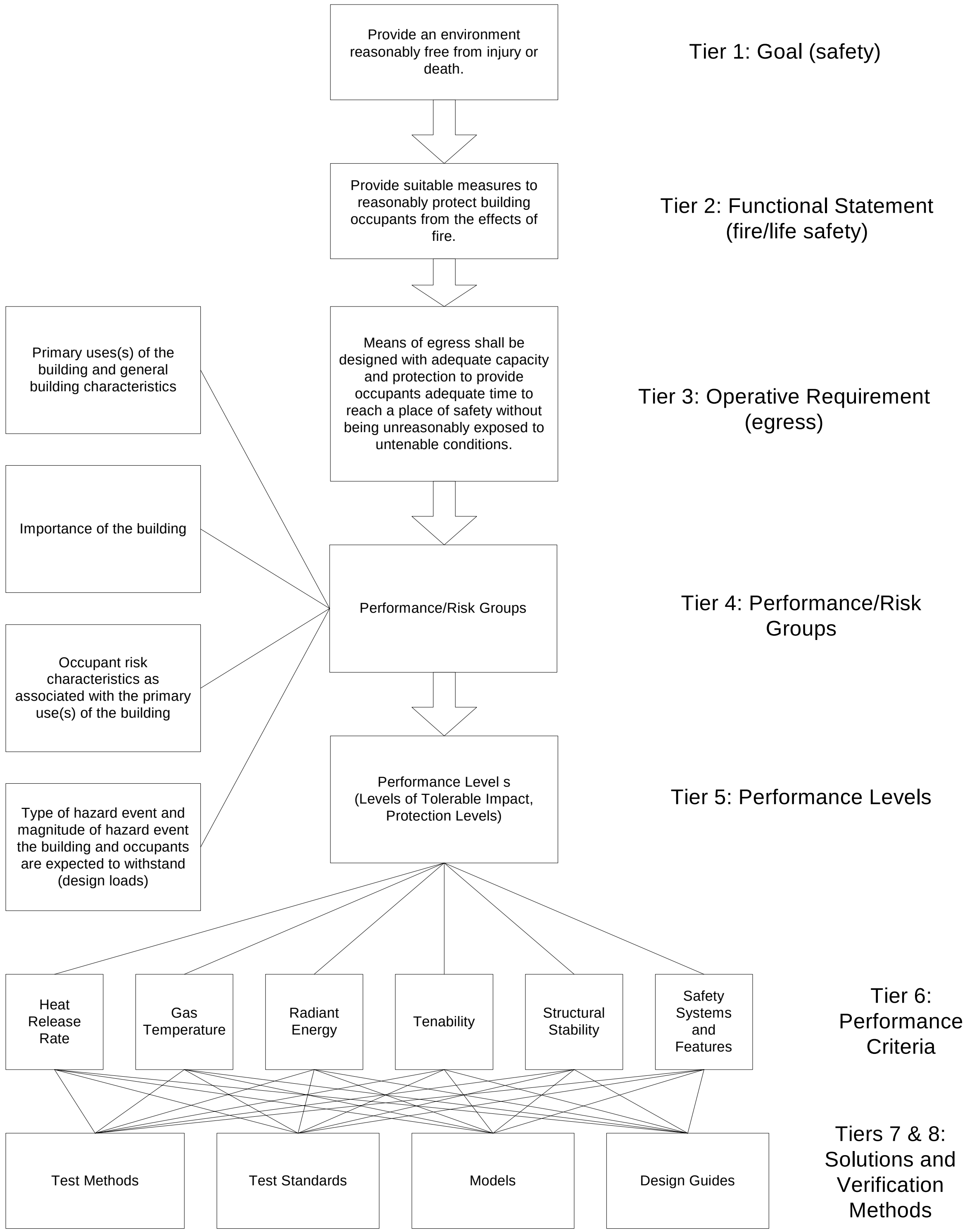

Figure F.1: Interaction of Goals, Objectives and Criteria in the IRCC Performance-Based Building Regulatory System Hierarchy (Meacham, B.J., "Performance-Based Building Regulatory Systems: Structure, Hierarchy and Linkages," *Journal of the Structural Engineering Society of New Zealand*, Vol. 17, No. 1, pp.37-51, 2004)

Appendix G: Focus Group Voting Results

Group A: Structural Fire Response Modeling

	Topic	No of Votes
A1	Constitutive Models of Materials	31
A2	Concrete Spalling	19
A3	Fire Models(Loads on Structures)	24
A4	Model Verification for Structural Response	26
A5	Performance Based Definition of Failure	14
A6	Sensitivity Analysis and Parametric Studies	24
A7	Connection Behavior	23
A8	Modeling Non-Structural Elements	12
A9	Improving Structural Detailing/Retrofit/Post-Fire Assessment	11
A10	Effects of Fire Fighting and Cooling	17

Group B: Fire Tests

B1	Modification to the E119 Standard Fire Test	20
B2	Characterization of Fundamental Material Properties	30
B3	Testing Components and Columns under Load	18
B4	Resolving Scaling Issues	18
B5	Establish Testing Guidelines and Protocol	14
B6	Develop New Sensor Technology	27
B7	Establish a Comparison for Test Exposure	3
B8	Characterization of Connection Behavior	19
B9	Establish a Large Scale Testing Facility	19
B10	One-Time Testing of Decommissioned Buildings	24
B11	Structural Behavior of Composite Floor Systems	13

Group C: Code Standards and Education

C1	Barriers to the Implementation of Performance-Based Design	2
C2	Regulatory Push to Accept Performance-Based Design	5
C3	Acceptance and Implementation of SFE	8
C4	Development of Accepted Tools and Criteria	25
C5	Data Accumulation – Building Incident Reporting	15
C6	Curriculum Development- Graduate and Undergraduate	23
C7	Faculty Workshop	11
C8	Awareness Level Training of AHJ's	3
C9	Architect Awareness	2
C10	Case Studies to Demonstrate Performance-Based Design	3