NISTIR 6890

Fire Resistance Determination and Performance Prediction Research Needs Workshop: Proceedings

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- expose engineering students and practitioners to basics of structural fire analysis and computational tools, and sponsor workshops for non-specialists
- codify methods to calculate fire curves for most common scenarios to assist design engineers for routine applications
- examine fire safety of building as a whole and develop practical methods to avoid progressive collapse that could be incorporated into performance-based building codes

A. Astaneh

Astaneh (Appendix III. M) discussed the protection of steel structures against impact, explosion and ensuing fire. An impact is a force applied on a building over a short time interval, and depending upon the geometry and velocity of the impacting object or pressure wave, dynamic forces are generated throughout the building which can cause serious damage at the local and global level to the structure and fire protection systems. The main route to life safety is by preventing collapse of the building directly following the initial impact and after any ensuing fire. The use of catenary action provided by a floor was presented as a possible technology to mitigate collapse. Cables imbedded in a floor specimen were shown to be able to significantly retard the onset of failure. The gross physical behavior was mimicked in a finite element analysis.

The challenge posed by Astaneh was for realistic modeling of the behavior of steel and composite structures exposed to sustained fires. Data are needed on the fire resistance of light weight and high strength concrete and on steel connections. More realistic models of local and overall buckling of steel and composite structures (including composite shear walls) at elevated temperatures are needed. Composite shear walls with a gap between the wall and frame could be used, for example, to protect egress routes. Research is also needed to better predict the performance of various structural systems, especially at elevated temperatures.

STRUCTURAL PERFORMANCE

J-M. Franssen

The frontiers of structural fire modeling were explored by Franssen (Appendix III. N). The temperature in the structure and mechanical behavior are simulated with SAFIR [21], a non-linear, transient finite element model that determines the structure temperature as a function of three directions and the gas temperature, and determines the 3-dimensional displacements as a function of the structural temperature and loads. Limitations on computational resources constrain the capabilities of the mechanical model when 3-dimensional temperature field calculations such as those in Figure 11 are made. Beam finite element calculations provide a link between the thermal and mechanical analysis of the structural frame. Shell finite element calculations work well on thin elements and can successfully predict severe deformations, as shown in Figure 12.

The limits of structural fire modeling are associated with eight factors. (1) The first factor is the lack of thermal properties of structural materials (the thermal conductivity of concrete, for example, is presently under discussion in Europe, as well as the impact of radiative heat transfer to H-steel sections, the so called shadow effect that reduces the radiation to the inner surface of a

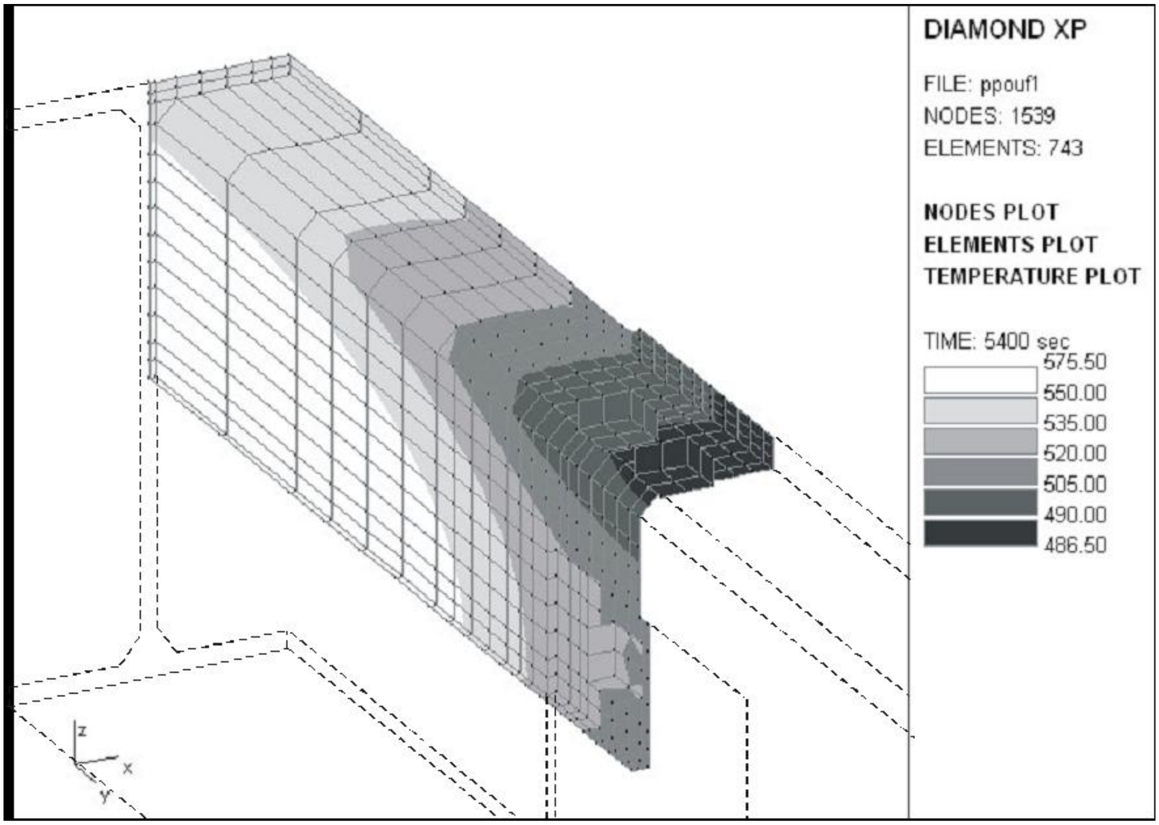

Figure 11. Temperature distribution in two steel beams connected by cover plates (Franssen)

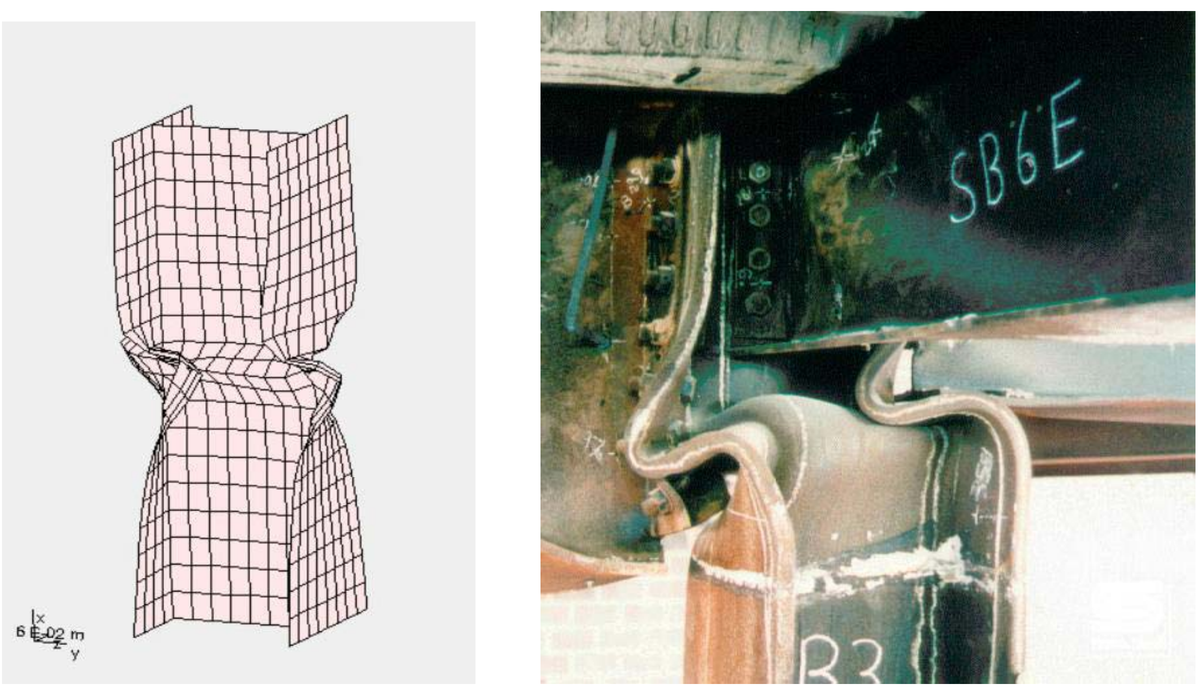

Figure 12. Shell finite element simulation showing severe deformation of a steel column (Franssen)

wide flange section). (2) The second factor is the interaction between the gas and the structure in the case of localized fires, which is a problem for both CFD and zone models of the fire. (3) Spalling in concrete is a third factor that limits structural fire models. (4) The beam finite element models are based upon the Bernoulli hypothesis (that parallel planes remain parallel during deformation), which is a fourth factor limiting modeling in situations with significant rotation, local buckling, shear failure or debonding of reinforcing bars or prestressing tendons. (5) A non-physical local and/or temporary negative stiffness can arise in some situations, which causes the calculation to terminate. (6) Boundary conditions in the substructures are difficult to specify. Which may be more appropriate, fixed or free conditions? (7) A seventh limitation is the definition of failure. How much deformation qualifies as a failure of the element? (Suggested criteria are given by Ryan and Robertson [22].) (8) Finally, structural fire models are limited to structures that do not exceed a certain size because computational resources are finite.

Franssen (Appendix III. N) concludes that

> "for understanding and designing structures submitted to fire, numerical modelling offers capabilities that are unique. The frontiers at the moment are
> - Spalling in concrete
> - Thermal properties
> - Local or temporary failures
> - Very large structures
> - Very large displacements
> - Boundary conditions
> - Interface with environment in localised fires
> - Resources (money, time, people, …)"

J. Ricles

The response of structures to earthquakes and extreme fires was reviewed by Ricles (Appendix III. O). Analysis and experimental testing are essential tools for predicting the fate of a building during an earthquake. Material modeling must deal with cyclic plasticity, cyclic degradation of material stiffness and strength, and fracture, all non-linear phenomena. Geometric non-linearities accompany local buckling and global instabilities (P-Δ).

Experimental testing is required to develop a database on real performance, to demonstrate proof of concept, and to calibrate analytical models. Shake table testing is precisely controlled and provides data in real time; however the specimen sized is quite limited. Reaction wall testing (pseudo-static or pseudo dynamic) allows one to test full-scale specimens, although the building system's response to the loads are not real time (compared to earthquake time scales). Full-scale component tests can also be conducted in multi-dimensional reaction wall facilities, although choosing the most appropriate boundary conditions, and controlling them requires careful attention. Time response remains an issue.

Finite element analysis can be applied to building details such as welded connections to examine the impact of cyclic load in the local region around the joints. Non-linear analysis of the structural system over time can also be performed, with the details of the connections such as panel zone deformations and connector flexibility (i.e., semi-rigid connections) considered.

Elevated temperatures effect the yield strength, the ultimate stress, the modulus of elasticity, and the coefficient of thermal expansion of all structural materials, leading to a dramatic decrease in structural performance of steel above 600 °C. Member restraints change, large displacements can occur, and loads shifted to other parts of the structure. Beam twisting and local buckling, column local buckling, and connection failure are all observed.

Ricles (Appendix III. O) lists the following research issues and needs:
<u>Testing</u>

- determining the effects of structural redundancy, restraint, connections, and non-load bearing elements during structural component vs. structural system testing
- determining how to maintain the proper thermal environment
- developing heat resistant structural response sensors
- establishing proper testing protocol
- constructing and maintaining adequate facilities for fire testing

<u>Analysis</u>

- calibration of models with test data
- structural component vs. structural system modeling, with concern for the effects of structural redundancy, restraint, connections, and non-load bearing elements
- thermal input
- time scale
- non-linearities
  - change in material properties due to thermal input and loading
  - geometric non-linearities (large displacements, local buckling, load shifting)
  - connection modeling (stiffness and strength deterioration, fracture)

Ricles concludes that success has been achieved in predicting the performance of structures to extreme earthquakes using sophisticated analytical models and experimental testing. Predicting the fire resistance and performance of structures is challenged by the physical complexities of structural fires, the level of sophistication needed for analytical models, and the compounding difficulty of experimental testing to calibrate these models.

<u>G. Deierlein</u>

Parallels were drawn by Deierlein (Appendix III. P) between performance-based engineering for fire and for earthquake hazards. Citing the ICC 2000 Performance Code [23], the objective of the design is "to limit the impact of a fire event in the building, its occupants, processes and use; and to limit the impact of an exposing fire on buildings, adjacent properties and processes." A level IV performance group (see Fig. 13) includes vital facilities that can sustain only moderate damage even under the rarest of disasters (earthquake or fire), while a low performing (level I), expendable structure can tolerate design criteria that lead to severe damage for a rare event, and moderate damage for frequent small events.

The qualitative description from the matrix can be made more explicit by relating the damage assessment to replacement cost and/or casualty rate, as shown in Figure 14 based upon the work

	PERFORMANCE GROUPS			
	I	II	III	IV
Very Large (Very Rare)	SEVERE	SEVERE	HIGH	MODERATE
Large (Rare)	SEVERE	HIGH	MODERATE	MILD
Medium (Less Frequent)	HIGH	MODERATE	MILD	MILD
Small (Frequent)	MODERATE	MILD	MILD	MILD

Figure 13. ICC 2000 performance matrix [23].

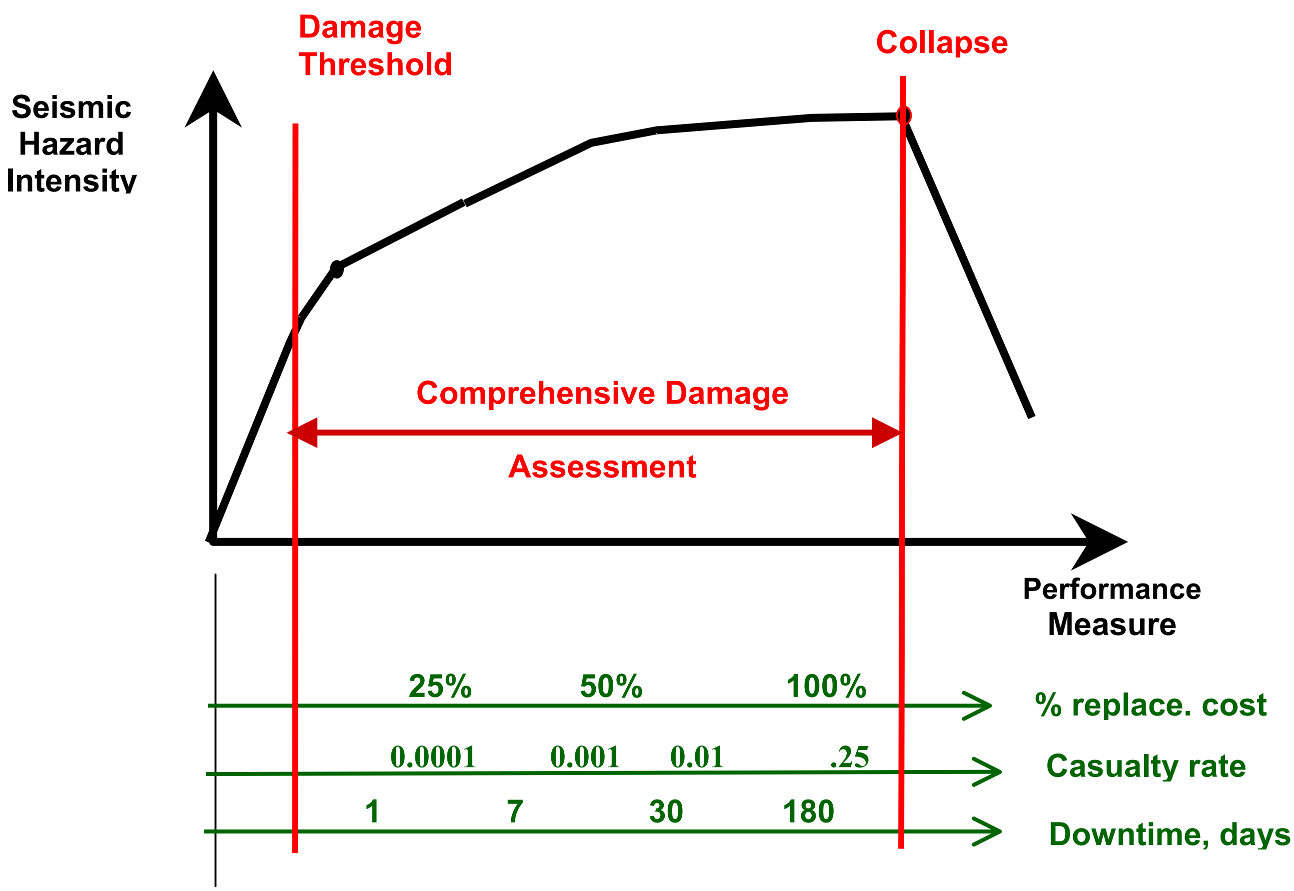

Figure 14. Explicit performance assessment in terms of earthquake intensity [24].

by Holmes [24]. As presented by Deierlein, the key attributes of performance based approaches are that they are more scientific and transparent, they address stakeholder decision needs at multiple levels, and they provide for a consistent treatment of risk and uncertainties. The methodology has four serial components: input damage intensity measures (e.g., earthquake duration and strength), engineering demand parameters (e.g., drift and acceleration felt by building), resulting damage measures (e.g., condition assessment and necessary repairs), and decision variables (e.g., fatalities and injuries, dollars lost, downtime). By examining each of the components in detail, a probabilistic description of a decision variable can be developed.

A parallel methodology was suggested to guide decisions involving fire safety design. Intensity measures could include fire load and compartment temperatures. Engineering demand parameters might be related to peak structural temperatures and deflections. The damage measures and decision variables would be similar to those used in the performance based earthquake engineering methodology, with the additional special considerations of the fire services. Questions that need to be answered in developing this methodology include the following:

- For whom is the methodology intended: the fire protection engineer, the structural engineer or the mechanical engineer?
- How does one describe the fire scenario, and how many scenarios need to be examined?
- How faithfully must the global analysis be able to predict local degradation of members, connections and composite action?
- Is there a different tolerance of risk for fires vis a vis earthquakes?
- What is the minimum level of protection required, and how does one quantify higher performance levels?

Deierlein summarized the issues and needs for improved fire resistance performance prediction o include a comprehensive methodology that is consistent with other hazards and evolving code provisions; a probabilistic fire hazard assessment; codification of acceptance criteria such as explicit numbers of causalities or dollars lost, component strength checks, and survival duration; structural simulation tools; and validation through laboratory tests and field reconnaissance.

B. Lane

Lane (Appendix III. Q) presented her list of items needed most for a numerical model of structural response to fire conditions, from the perspective of a consultant. She suggested that there were widespread concerns about the standard fire resistance test (temperature/time relationship is not the same as in real fires; structural response and fire protection materials response are important; how to deal with the huge body of existing data; how to relate standard fire test data to numerical structural fire models; the need for a new test). She felt that all could agree that mechanical response is not properly addressed in the current test (single elements tested and single elements analyzed; real frame behavior ignored, including effects of restrained thermal expansion, load transfer through connections to cooler elements, slab actions that sometimes may increase overall strength of composite frame).

Current finite element models are just beginning to capture the complexities of structural fire response. The principles for advanced calculation models are laid out in the Eurocode 3, Part 1.2, Structural Fire Design [25], and in CIB W014 [26], Rational Fire Safety Engineering Approach to Fire Resistance in Buildings. There is also the ASCE/SFPE effort to guide fire model applications, and work sponsored by AISC. The information that needs to come from these studies should lead to a reference document for consultants and authorities having jurisdiction, stating design objectives and means for achieving acceptable results.

Clear guidance is required on the design-basis fires. Do we create a new standard fire resistance test, use temperature-time relationships from real fire data, or calculate the real fire environment from the known fuel load, ventilation, and boundary properties?

Once the design-basis fires are established, the heat transfer to the structural elements can be calculated, which leads to a time varying temperature field in each element. How well have existing heat transfer models been assessed, and are they sufficient for current construction materials and fire proofing? What level of detail is required regarding the temperature field?

The structure responds to the high temperature in a fire with a combination of effects: loss in strength and stiffness of the structural elements, compression forces in the elements produced by restraint to thermal expansion, greater deflections resulting from higher restraint, and curvature in the elements imposed by through-depth thermal gradients. The combination of these can produce a range of deflections and internal force patterns. Non-linear analysis is required to handle these complexities. A means to translate the results of the complex models into simple tables for mainstream design is needed, as is a way to use these models to incorporate new understanding into building codes. An intensive effort over the last decade in Europe is beginning to bear fruit. It is essential to build on this work rather than to start again, and to reformat the input and output to be useful in a design office.

Some specific models currently in use were mentioned by Lane. VULCAN [27], an implicit scheme developed by the University of Sheffield, applies to steel-framed buildings only, and was used to interpret the results of the Cardington full-scale tests. Geometric and material nonlinearities are included, and plate elements are used to simulate floor slabs. Beam-column elements are used to simulate beams and columns, and spring elements simulate the steel-to-steel connections. The heat transfer analysis is not a part of VULCAN. The University of Edinburgh used ABAQUS [10, 28], a non-linear model specifically for composite steel-framed buildings, to compare with the results of the Cardington fire tests. A stress resultant approach is used to describe the behavior of the shell elements simulating the floor slabs. Shear connectors are incorporated with rigid elements and pins joins approximate steel-t-steel connections. Reinforcements within the slab are included using a smeared model. ABAQUS includes heat transfer, assuming uniform temperature across elements but not necessarily along elements. Both an implicit and explicit version exist. Other models that should be examined are explicit such as LS-DYNA [29]. These models may be able to anticipate collapse because the can cope with highly non-linear situations. A thermal analysis may be conducted in parallel with the mechanical analysis. More computing time and power are obviously associated with these capabilities.

Lane's wish list consists of the following:

- come to agreement on the concerns, issues and inaccuracies
- develop a reference document laying out acceptable principles required for AHJs and consultants
- establish the criteria for choosing a design fire, and the data, model, and input for codes
- establish heat transfer analysis capabilities
- compare and contrast existing 3D finite element models
- further develop these models to address complex behaviors associated with structural response to fire (beyond Cardington)
- develop usable commercial analysis tools
- develop the means to translate results into building codes and simple design methods

SUMMARY

Following the expert presentations described above, the participants broke into three parallel teams to discuss research issues and raise additional ones as they saw appropriate. Each team came up with their own list of priorities and shared them with the whole group on the second day. Their presentations are include in Appendices III. R. through III. T and summarized in the following paragraphs.

Lack of communication among disciplines was expressed by the first team as a hindrance to the introduction of new methods and technologies to structural fire safety. The proper education of young engineers and building designers would eventually overcome this hindrance, but it was felt to be critical to get the right information on structural fire performance to the structural engineering community and the authorities having jurisdiction in a more expeditious fashion. Establishing a full-time position at NIST dedicated to this problem, making use of steering committees to better define project goals and objectives, and development teams with fire modelers, structural engineers, computer scientists, and materials scientist were recommended as ways to increase communications across disciplines. The need to publish and to disseminate new research results across disciplines was also highlighted.

Construction materials were a second focus of recommendations. What is our current state of knowledge? Where gaps exist, we need to acquire basic thermal and physical properties using well thought out principles and accepted test methods, including under conditions likely to exist within a fire. The effects of material variability on installed performance need also be assessed. New information is required to characterize durability and reliability of fireproofing materials during normal operation and in the event of a fire, and the implication of these properties on inspection and maintenance protocols. Is there a role for new sensing methods?

There is a general lack of understanding of the science underlying existing test methods and the proper use of data derived therefrom. In fact, many current test methods are not well suited to collecting useful data; at the same time, the vast amount of test data that has been accumulated cannot be ignored. New fire test methods may be needed to address data gaps and to allow proper interpretation of the ratings generated from flawed or incomplete existing test methods.

Although the tools used most often in design have an over reliance on empirical data and a general lack of scientific basis, a review and summary of the current generation of predictive methods would be useful. A recognized procedure for specifying the design fire is required. Integration of the gas phase fire models with structural response models is the key to progress, and we should borrow freely from computational methods generated outside the fire community as appropriate. Extending capabilities of current CFD models to better address flashover conditions is also required. All improved predictive capabilities will require full scale, fully instrumented validation tests with interaction between modellers and experimentalists. As a first step, a prototype simulation methodology could be developed joining a selected specific choice of existing software for fire simulation, thermal/mechanical properties, and structural response. Eventually, one would need a practical predictive tool for progressive collapse in fire, as well. The practical difficulty of blending structural numerical codes that are primarily commercial with fire numerical codes that are primarily public will need to be addressed as well

The second team listed validated engineering tools, a design framework for new construction, design for retrofitting existing construction, integration of structural and fire performance-based design, and education of engineers, designers and AHJs as the desired end products of a coordinated research effort. Tools for modeling fire growth include space independent models, a simplified approach that includes space/opening effects, and CFD models. The latter can not be used for direct routine design but can be used to develop design tools and for special design issues. A need-based approach must be established for fire growth models. The objective and amount of uncertainty that is acceptable helps define the need, which points out the utility of a standardized process for uncertainty quantification and analysis techniques.

Insulating and fire proofing materials dictate the amount of heat that will enter the structural elements. One needs to measure the thermal properties of insulating materials as a function of temperature, the adhesion/cohesion properties, and the tendency toward destructive decomposition due to abrasion and thermal degradation. Understanding the role of geometry (of the insulation and underlying structure) on durability is critical as well. The thermal/mechanical properties of structural materials as a function of temperature are a basic need. These include all properties of special steels (light gage steel, high strength/performance steels, welds, bolts, rebar, pre-stressing), high strength concrete, normal strength concrete , FRPs, aluminum, timber, and glazing.

Validation is needed of existing structural response tools for assemblies (including connections) and systems under fire conditions (including soot and other fire phenomena effects). Structural response engineering sub-models for specific fire phenomena and fire barrier models need to be developed. Structural response models need incorporation of high strength concrete behavior in analysis and design, and guidance on how to apply the “fire load” as a load combination to the entire structure. What are the design limit states (i.e., objectives of design)?

Performance criteria for insulating materials need to be developed for in-service use, including impact, maintenance and inspection over the life of the structure. The same is required for structural materials, products and systems.

Improved fire measurement technologies (especially for heat flux) are required, along with standardized test methods for material property determination and for structural components such as connections. The possible use of existing ASTM E119 for standard fire model validation should be evaluated.

The third group listed fire exposure, thermal response, structural response, mitigation strategies (including the use of redundancy, prevention, and design with fire safety in mind) and improved communications among engineers, and regulators as critical needs. Instrumentation of real fires is needed to obtain better fuel load characterization, the impact of spatial distribution, temperature/oxygen histories, heat flux, products of combustion, and full cycle (heating and cooling) data. The behavior of fire proofing and non-structural elements (including glazing) needs to be modeled, including material properties and the thermal response of slabs, dehydration and cracking, improved high temperature performance data (modification of high strength concrete with polymer inclusion, composites), hysteresis, and the difference in response to "short-hot" and "long-cool" fires.

To predict structural response one needs to understand deflections and stresses, the behavior of connections, fire proofing materials, the impact of heating and cooling cycles, and to develop an efficient means to merge fire and structural models (zone with frame models). The models need also to be coupled with experiments for validation and to properly design the experiments and measurement methods. Detailed phenomenological models of chemistry, molecular dynamics, crack development, and pyrolysis behavior will aid the development of new materials and a better understanding of the thermal environment created by the fire.

Validation experiments and measurements are needed for basic material properties (especially the effect of temperature), constitutive properties of slabs (concrete), single step experiments, (ignition, fire spread), multiple step experiments (corner fires, flashover), and integrated tests (enclosures, building fires). Proper instrumentation is required to capture spatial and temporal aspect of fires, behavior of non-structural components (glazing), local stresses and deflection, and heat transfer through connections. The "real world" provides opportunities for validation through analysis of accidental fires.

Performance objectives should include the ability to relate test conditions to the real world. A danger with testing to traditional temperature-time curves arises from the dimensionality of the real world, which has the important implication that it determines the response; e.g., a plume impacting on the ceiling combines convection and radiation loads on the structure; flash-over has not been modeled, and yet the transition can significantly modify the heat transfer; and ill-defined air availability changes the dynamics of the fire. There is a need to translate test results into real world situations. The integrity of fire walls is a major factor. Fire test data need to be used to validate models, but there are little data on more complex structures.

RECOMMENDATIONS

The stated objectives of the workshop were to review current practices for achieving fire resistance; to explore the promise of fire dynamics simulations and structural behavior predictions; to identify new fire resistance options coming from materials science; to identify opportunities and needs in advanced computational methods; and to identify applications and needs for emerging measurement, instrumentation and test methods. The first objective was clearly met as documented in this report and referenced material. A better appreciation was achieved across the multiple disciplines represented of what can and cannot be done with the current generation of fire dynamics and structural behavior models. No new fire resistance options nor materials technologies were revealed, although the paucity of technical data on current fireproofing materials and the inadequacy of test methods to evaluate their performance were themes that emerged continuously. The need to measure additional variables during structural fire testing and to quantify the uncertainty of parameters regularly measured were identified as problems worthy of study. An issue not originally raised but which emerged naturally during the discussions was the need to increase communications and education horizontally across technical disciplines and vertically from the research community to the regulator.

The following recommendations are the editor's synthesis of the discussions and opinions expressed by participants of the workshop:

Communication/Education/Training

- Cross-train practicing structural engineers, architects and fire protection engineers involved in new building construction and retrofit projects to ensure that rational fire safety is inculcated into the profession.
- Modify engineering and architecture curricula to increase student exposure to cross-disciplinary team work to enhance awareness of the other disciplines' capabilities in, and constraints to, assuring practical fire safe designs.
- Develop innovative techniques to better educate building code officials, AHJs, and the fire service of the capabilities and limitations of standard test methods and computational tools.

Thermal and Mechanical Properties of Materials

- Identify existing and/or develop new experimental techniques for measuring the thermal and mechanical properties of structural materials (normal and high strength concrete, steel, steel/concrete composite, aluminum, fiber-reinforced composite, timber) at temperatures up to their point of failure.
- Standardize measurement methods and use them to accumulate a consistent, reliable high temperature data base on the thermal and mechanical properties that dominate the response of a structure to a severe fire up to the point of failure.
- Develop experimental protocols for measuring, at elevated temperature, the thermal and mechanical properties of non-structural building materials (glazing, fire stops, intumescent coatings, structural fireproofing) that impact structural integrity during a fire, and accumulate a consistent, reliable high temperature data base.

Measured Behavior of Connections and Assemblies

- Develop experimental methods and protocols for measuring the thermal and mechanical behavior of fireproofing as installed and when degraded by time, temperature, and stress.

- Develop experimental methods and protocols for measuring the response of structural connections (including welds, bolts, rivets and adhesives) when exposed to severe fire conditions and loads.
- Develop fully instrumented experimental facilities for exposing floor and wall composite assemblies to controlled fires under measured loads up to the point of failure.
- Develop large-scale test facilities to the extent necessary to extrapolate the behavior of connections and assemblies to the behavior of whole building frames.

Computational Models

- Develop a guide for AHJs and designers detailing the range of fire and structural models that currently exist, including limitations and constraints.
- Establish a framework (or more likely a patchwork) of models to couple the fire exposure, the heat transfer, and structural behavior.
- Develop more efficient structural and CFD algorithms to expand the number of significant physical phenomena and the range of length scales that can be practically accommodated.
- Develop subgrid models to better resolve the heat transfer from the fire environment to the structural elements, and expand fire models to include post-flashover conditions.
- Develop efficient submodels for failure of structural connections and interfaces at elevated temperatures.
- Use numerical models to design experiments and standard test methods, and use results of experiments and tests to improve computational models.

Standard Test Methods and Codes

- Establish as a goal the need to predict the performance of coupled building systems to the point of impending failure in a fire.
- Determine the extent to which ratings from current standard fire resistance tests indicate the reserve capacity of structural assemblies under moderate and severe fire conditions.
- Modify standard test methods or develop new ones to demonstrate our ability to predict reserve capacity from computational models and measured behavior of connections and assemblies.
- Identify which existing engineering tools and fire-proofing materials that have been developed and evaluated in the past 50 years provide an opportunity to significantly upgrade our ability to design fire resistance into buildings, and work to fast-track their acceptance into current building codes.
- Develop a strategy to effectively incorporate technological advances in structural fire resistance into engineering tools that support performance-based design alternatives.

By acting on these recommendations, we will move towards the vision put forth at the workshop of buildings whose designs balance competing demands for function, aesthetics, fire safety and economy, using scientifically-based performance predictions that are so sound that the predictions can be endorsed by all major stakeholders.

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