# NISTIR 7133

# NIST-SFPE Workshop for Development of a National R&D Roadmap for Structural Fire Safety Design and Retrofit of Structures: Proceedings

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## Abstract

This report describes the results of the workshop sponsored by the National Institute of Standards and Technology's Building and Fire Research Laboratory that was held on October 2, 3, 2003 in Baltimore, MD. The workshop was planned to assist with the development of a research and development roadmap for structural fire safety design and retrofit of structures,. This report summarizes the content of nine contextual white papers prepared for the workshop and the process and results of the industry discussion and prioritization that took place.



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## Disclaimer

Certain trade names or company products are mentioned in the text to specify adequately the experimental procedure and equipment used. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the equipment is the best available for the purpose.

**Executive Summary**

The National Institute of Standards and Technology's Building and Fire Research Laboratory, as the national laboratory responsible for research into building fires, initiated a program prior to the events of September 11,2001 to put structural fire protection on a stronger scientific footing. The catastrophic collapses of the World Trade center underscored the need to accelerate this effort. As part of this effort, NIST commissioned the Society of Fire Protection Engineers to organize an industry workshop calling on the expertise of the global fire safety engineering community. The purpose of the workshop, held on October 2 and 3,2003 in Baltimore, MD, was to provide industry input for use in the development of a detailed R&D roadmap for structural fire safety design and retrofit of structures. Sixty individuals attended the workshop including structural and fire protection engineers, architects, academia, research and testing laboratory representatives, regulatory offices and representatives of insurance and industry associations.

Nine white papers were commissioned in advance of the workshop to outline the issues and research needs associated with implementing improved structural fire safety design and retrofit methodologies. These papers, providing the perspective of industry users and international experts in the field, set the context for a vigorous one and half day series of discussion sessions where needs for further research and improved practices were identified and prioritized. Two tiers of top priority recommendations were developed, ranging from the need for more research quality experimental data of the behavior of structural components and materials at elevated temperatures to the need to specify professional responsibilities for structural fire protection over the life of the building.

The general consensus of the workshop participants on research needs are summarized as follows:

- Obtain research-quality laboratory and real data, including construction and use of large-scale structural fire test facilities, of engineering material properties at elevated temperature and performance of structural components under load and fire conditions.
- Develop performance goals, criteria and methodologies for implementation in codes and standards, including quantification of safety provided by current prescriptive and performance-based methods, practice guidelines for the enforcement and engineering communities, risk-based methodology for design fires, benchmark problems for validation of analysis tools, standardized test methods, and limit states and failure criteria.
- Specify professional responsibilities for structural fire protection over the life of the building.

# 1. INTRODUCTION

## 1.1 Background

In the wake of the collapse of buildings in the World Trade Center (WTC) complex on September 11,2001, the National Institute of Standards and Technology (NIST), under the authority of the National Construction Safety Team Act (Public Law [P.L.] 107-231), formally initiated the federal building and fire safety investigation of the WTC disaster on August 21,2002. The investigation aims to achieve the following four 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 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.
4. Identify areas in the current national building and fire model codes, standards, and practices that warrant revision.

The first three objectives are short-term and addresses issues specific to the collapse of WTC 1, 2, and 7. The fourth objective is long-term and addresses deficiencies in design practice related to building and fire safety.

Current building design practice does not consider fire as a design condition for purposes of evaluating structural performance in the presence of an uncontrolled fire. Instead, fire endurance ratings of building members or subassemblies, derived from standard fire endurance tests (e.g., ASTM E-119), are specified prescriptively in building codes. In addition, there is no accepted set of verified tools to evaluate the fire performance of entire structures and to achieve engineered fire safety. While current prescriptive methods appear to work satisfactorily in typical compartment fres, the adequacy of such methods in large, uncontrolled fires is questionable. Thus, there is widespread recognition of the need to develop and implement significantly improved tools, practices, and standards that explicitly consider structural fire loads in the design of new structures and the retrofit of existing structures.

Balancing the competing demands for fire safety and economy in a rational manner requires the development of performance-based methods to measure and predict the behavior of full-scale structures under fire conditions. Such performance-based methods must consider the following five key deficiencies in the current building fire safety design practice:

- First, while the current standard fire endurance test methods, which stipulate a prescribed time-temperature exposure, are adequate to compare relative performance of structural components, they do not provide information about the actual performance (i.e., load carrying capacity) of a component in a real fire environment (e.g., involving fire of building contents, hydrocarbon pool fires, or a combination thereof).

- Second, the role of structural connections, diaphragms, and redundancy in enabling load transfer and maintaining overall structural integrity (i.e., preventing progressive collapse) during fire is ignored in structural design. Current structural fire protection design methods are based on fire endurance tests of single components and do not account for the behavior of connections or the complex two- and three-dimensional behavior of the entire structure.

- Third, current analytical tools are inadequate to evaluate the effectiveness of alternative design, retrofit, and fire protection strategies to enhance structural fire endurance (including alternate cementitious spray or board systems, intumescent coatings, high-performance fire protective coatings, active suppression systems, and more sensitive sensing and monitoring). No practical analytical tools exist today that couple the fire dynamics to the structural system response, and the resulting transient, multi-dimensional heat transfer through structural components made with multiple materials.

- Fourth, there is a need to better model and predict the fire hazards to structures and to develop design criteria for evaluating fire hazards from internal and external fires (e.g., due to accidents or terrorist threats). This includes deterministic and probabilistic models for specifying the magnitude, location, and spatial distribution of fire hazards on structures (e.g., design fire **scenarios** defined by the probability of exceeding established criteria by 2% in 50-years); determination of reliability-based load factors for combined dead, live, and fire loads and resistance factors for loss in structural strength and stiffness; and methods for load and resistance factor design (LRFD) under fire conditions.

- Fifth, there is a lack of knowledge about the fire behavior of structures built with innovative structural materials (e.g., high-strength concrete or steel structures) or passive fire protection materials.

## 1.2 NIST R&D Program in Fire Safety Design and Retrofit of Structures

As part of the NIST response plan for the WTC disaster, **NIST** has initiated a major R&D project in fire safety design and retrofit of structures. The project aims to develop and implement significantly improved standards, tools, and practical guidance for the structural fire safety design **and** retrofit of structures in partnership with key stakeholders by integrating knowledge of modem fire science and fire protection engineering with knowledge of modem structural reliability methods and structural engineering. Specifically, the project aims to produce the following eight key products in three major areas, including ***Structural Fire Safety Design of New Buildings, Analysis of Structural Fire Performance,*** and ***Fire Safety Evaluation** and **Retrofit of Existing Buildings,*** over a multi-year period:

<u>Structural Fire **Safety** Design of New Buildings</u>
- Best practices for structural fire safety design of structures.
- Guidelines/pre-standards for fire safety ***design*** of structures.

<u>Analysis of Structural Fire Performance</u>
- Best practices tools for analyzing structural fire performance.
- Load and resistance factor methodology for structural fire safety.
- Selected verified/validated predictive tools for analyzing structural **performance** in **real fires.**

<u>Structural Fire **Safety** Evaluation and Retrofit of Existing Buildings</u>
- Guidelines/pre-standards for structural fire safety evaluation of existing buildings.
- Best practices for fire safety ***retrofit*** of structures.
- Guidelines/pre-standards for fire safety ***retrofitting*** of structures.

## 1.3 NIST-SFPE Workshop on Structural Fire Safety Design and Retrofit of Structures

As part of this R&D project, in June **2003,** the Building and Fire Research Laboratory (BFRL) of NIST commissioned the Society of Fire Protection Engineers (SFPE) to organize an industry workshop to provide input for the development of a detailed roadmap that will identify the R&D gaps for each of the products identified above. A steering team, (Appendix B) consisting of representatives of the design and construction industry, was formed to assist in the planning of the workshop. The team met five times by teleconference over a five month period. Its' activity included:

- Commissioning nine white papers (Appendix 9.1) from authors with acknowledged expertise and leadership in various aspects of structural fire safety design and retrofit and the industry context for it. The purpose of the white papers was to outline the issues and research needs associated with implementing improved structural fire safety design and retrofit methodologies.
- Recommending invited participants (Appendix 9.E) for the workshop who would represent the following sectors of the industry: fire safety design, structural design, architecture, code enforcement, academia, research, and professional and industry associations.
- Developing detailed workshop plan which included a workshop agenda designed to encourage full participation from workshop participants (Appendix 9.C). Breakout sessions were planned to group individuals by their area of expertise: design fires, thermal analysis, structural design, and existing buildings.
- Selecting sixteen recorders and facilitators from participants (Appendix 9.D)
- Developing an outline of a final report to guide discussion at the workshop to the goals of the project.

White papers were sent to all participants in advance of the workshop. Input from participants was sought to gain consensus on a recommended roadmap and provide guidance to NIST for their R&D program. The workshop was held at the Radisson Lord Baltimore Hotel on October **2-3,** 2003. Sixty individuals (Appendix 9.E) participated with a breakdown of employment as:

- Structural engineering – 8
- Fire protection engineering – 8
- Architecture – 3
- Academia – 9
- Research and testing – 6
- NIST – 6
- Regulatory officials – **5**
- Associations – materials, professional – 14
- Insurance- 1

The workshop was divided into 3 sessions, each started with a presentation of the session white papers to all participants. The participants were assigned to four breakout groups: Design Fires, Thermal Analysis, Structural Analysis, and Existing Buildings. Each discussed the session topic according to its particular group focus. Group assignments were made for relatively even representation of all disciplines and background in each group. The groups convened **at** the end of each session to share identified issues and needs. In the sections that follow, a summary of the white papers is followed by a summary of the participants' discussion points. The workshop was opened with an overview of the NIST WTC response plan by S. Sunder, leader of the NIST WTC investigation. Products developed are the summary presentations by each white paper author

**(Appendix 9.H), notes taken within each breakout sessions regarding issues and priorities for research and design guidance (Appendix 9.F), and priorities for the NIST roadmap developed by individual breakout groups and by the group as a whole (Appendix 9.G).**

# 2. STATEMENT OF NEED

## 2.1 Code Enforcement Perspective

Jonathan Siu presented the perspective of the code official when confronted with the need to review and approve building designs based on structural fire safety design principles. The code official must balance the sometimes conflicting demands of the developer and designer, and user and societal goals. In his view, the fire protection engineer often represents the concerns of the developer in terms of seeking approval for a design that does not comply with the building code in effect – either to reduce costs or because the architectural design does not itself conform to the structures envisaged by the codes. The movement to a performance-based approach for structural fire safety requires a paradigm shift in code enforcement away from considering engineered solutions as equivalents to existing prescriptive code provisions, to a new design approach based on mutually agreed upon performance goals. In order to meet these challenges, the enforcement community seeks well validated engineering information which can support a performance approach. Key issues are the selection of performance standards, understanding their implementation, selection of an accepted design event (i.e. size, location and duration of design fires) and the influence of active fire protection systems on the design event, and validation of computer models used for design and analysis. These issues remain a barrier to the ready acceptance of performance-based structural fire safety analysis and design in the enforcement community.

## 2.2 Architectural Perspective

Dave Collins presented the perspective of the architectural community with respect to the current state of the practice in fire safety design. Typically, the architect of record is responsible for many aspects of fire safety design, including the protection of the structure, through the interpretation and application of prescriptive code requirements, for which there is a well-established framework. The architect is often in the unique position of both specifying these features and finding alternative means to satisfy their intent when unique architectural aspects of the design demand other solutions. A concern of the architectural community in moving away from prescriptive code requirements of any kind is a determination of the performance levels currently offered by code complying buildings and a means to assure equivalent performance in "engineered" solutions.

## 2.3 Engineer's Perspective

A specific white paper was not prepared on this topic. However, there was discussion throughout the workshop regarding the role of structural and fire protection engineers in the structural fire safety design process. It was acknowledged that there is a need for structural engineering expertise in structural fire safety design, but concern was expressed by many regarding a business practice model and fee structure for this role. Fire protection engineers have more experience in assisting the architectural community with unique fire safety situations; design and evaluation of structural fire safety must be broadened to include the structural engineer for this aspect of fire safety design.

## 3. FRAMEWORK FOR STRUCTURAL FIRE ENGINEERING AND DESIGN METHODS

### 3.1 Overview

Greg Deierlein presented the structural engineering context for the implementation of fire safety as an integrated component of structural design. The author noted that fire represents a small component of the risk to a structure; further, the primary hazards presented by a fire event are not structural, and speculated that this may be the reason why this aspect of structural design has not been further developed and integrated in the overall design of the structure, but rather left to prescriptive code requirements satisfied in the architectural design. Using the seismic analogy, an overall fiamework for incorporating fire risk into structural design was proposed, including the elements of fire hazard analysis, structural analysis, damage assessment, and loss and risk assessment. *An* example was given of how a risk-based approach to fire safety design could be integrated in parallel with other design loads. This performance-based methodology provides a fiamework to identify research and development needs in a systematic way. These needs include: the further development and refinement of a risk-based design fiamework that is consistent with models and approaches common to both the structural and fire protection engineering communities; validated models for each element of the design process which have a probability basis; and a focus on risk communication and perception.

### 3.2 Discussion

Workshop participants raised several issues with respect to the integration of fire into the structural design context. There is a lack of understanding that fire is different than other natural disaster events. The current level of safety inferred by prescriptive building and fire codes, if considered acceptable, must be defined. This may be accomplished using methods developed for a performance-based approach. Similarly, since ASTM El 19 tests are generally accepted as providing adequate safety, new approaches and levels of acceptable performance should be defined and correlated to this system. Early applications of the approach may include signature buildings, existing or historic buildings, and unique buildings with respect to structure, fire loads, etc. Perhaps a separate performance-based code that would be applicable only for signature or high-risk structures is needed. Simple tools and methods will also be required (as opposed to full probabilistic analysis) if the methods are to see widespread use. It is believed that a significant amount of information can be obtained by analyzing the performance of structures in real fires. A probabilistic approach may not account for certain loads such as terrorism and arson and may need to be addressed. Additionally, for the structural engineer to take on additional liability for fire safety design, responsibilities, business practices, and fee structure will need to be developed. For implementation, standards are needed and documentation of non-U.S. approaches would be a useful first step. Finally, education of the structural engineers must accompany this initiative.

### 3.3 Needed Actions

Based on their discussions, workshop participants identified the following (non-prioritized) needed actions to integrate structural fire safety design into the structural engineering context:

- Archive and mine existing real fire performance data to provide an immediate source of data and identify gaps in needed information
- Identify the full range of accidental fire hazards, in addition to those considered in building codes that may result in hazard to the building structure

- Communicate the concept of risk-based analysis and design as an essential part of rational fire design
- Provide education for the engineering profession on the structural fire performance
- Develop funding resources for implementation of the roadmap
- Leverage resources with other disaster resistance programs
- Understand building performance in fire conditions
- Develop specialized design and analysis tools for signature and high-risk buildings which recognize their unique vulnerability to fire
- Develop data on risk-based design of structures for fire conditions and probabilities of event occurrence
- Incorporate the concept of the difference between large impact events over large area (seismic) versus individual building fire (times number of buildings per year are affected) in risk-based approaches to design and analysis
- Define the relationship between fire safety engineering and structural engineering through the use of probability/event tree analysis
- Normalize ASTM E-119 with respect to engineering based design fires
- Review and compare international codes vs. U.S. codes
- Develop a significant structural code which considers the unique fire hazards that may apply to these structures and provisions for their protection
- Use analytical tools to determine how well existing practice provides structural fire protection and structural safety
- Develop minimum criteria the context for structural fire safety design in the overall fire design context and clarifies the differences between guides, standards and codes
- Develop minimum criteria for a fire safety design go/no go decision to aid in determining whether fire safety design is needed for a specific building (a minimum structural fire safety level that is calculation based)
- Define true cost vs. construction cost – i.e. include maintenance costs, business interruption costs, and other "soft" costs that related to the fire condition
- Consider fire hazards to structures in the context of other hazards
- Society (through building codes) must decide on the method used for fire safety evaluation

**Of these action items, the archiving and mining of actual fire performance data was considered of high importance in the roadmap.**

## 4. RELATIONSHIP BETWEEN STRUCTURAL FIRE PROTECTION DESIGN AND OTHER ELEMENTS OF FIRE SAFETY DESIGN

### 4.1 Overview

Craig Beyler summarized the current elements of comprehensive fire safety design for buildings, including passive and active fire protection, detection and alarm, smoke management, egress systems, contents/finish control and manual fire fighting. Current structural fire protection requirements are based upon assumed fire load densities defined by occupancy as well as building height and area. Structural response is not calculated using advanced analytical methods but rather assumed based on the results of a standard fire endurance test. There are significant science and engineering methods available to apply to this engineering problem; a context within a rational fire safety design method is required to allow them to be implemented. Traditional code requirements implicitly require that overall structural failures need to be prevented in the absence of active fire protection, manual firefighting, or fire barriers; however, inherent assumptions made in implementing this goal may be too conservative in some instances and unconservative in other instances. Thus some assessment of the overall system performance and reliability, on a performance basis, is needed to enable performance oriented structural fire safety design. It was noted that structural performance itself has an impact on barrier integrity. Global fire risk models are available internationally which rigorously account for the performance and reliability of all structural fire design features but much research is needed to quantify/provide input data for these methods. The primary research need is the development of an overall design methodology framework. Additional research needs include the performance of structural and fire barriers, reliability and effectiveness models for sprinkler systems and fire departments, and analysis and test methods to support a risk-based design method.

### 4.2 Discussion

Workshop participants once again questioned whether these approaches would be used for all buildings or for signature buildings only. The issue of acceptable levels of risk and who determines them was raised as was code equivalent safety. The definition of failure or limit states and a performance envelope are key parameters for a performance approach. Data are required on fuel loads as well as accepted methods for defining them for use in fire safety design.

### 4.3 Needed Actions

Based on their discussions, workshop participants identified the following needed actions to integrate structural fire safety design into the fire protection engineering context:

- Define characteristic fire loads for the design and analysis of structural fire performance.
- Provide professional training for engineers to enable competent structural fire safety design.
- Develop all the needed steps in the process – tools, methods, codes, design guidelines – to provide rational methods and a consensus framework for structural fire protection design.
- Develop outreach program to disseminate the approach to authorities, owners/designers and the public to ensure successful implementation.
- Consider changes in the assignment of professional liability for design engineers as a result of the move to a calculation-based approach to structural fire safety design.
- Provide a performance-based option in building codes to enable this new design approach.

- Maintain the option for prescriptive design approach and quantify the level of protection provided by current prescriptive code requirements using performance-based calculation methods to serve as a performance benchmark.
- Specify performance goals in the building code for both prescriptive and performance-based options.
- Establish general procedures and identify roles for the design and enforcement community in design and maintenance (change of use) of structures in fire.
- Develop and implement more training and education programs for all parties involved in design/construction process in this aspect of fire safety design.
- Conduct outreach program to develop understanding by all parties in the design process that interaction between disciplines early in the design process will optimize the final design.
- Identify those building conditions (complexity, size, function) that should require calculated fire resistance rather than a prescriptive solution.
- Building code performance goals should not require consideration of extreme events in buildings.
- Provide guidance about the types of tools and procedures that should be used in calculating fire resistance (fire load estimation, thermal analysis, structural analysis) – guidance should include the level of complexity and types of tools currently available.

**Of these action items, quantifying the level of protection provided by current prescriptive code requirements was considered of high importance in the roadmap.**

# 5. ANALYSIS TOOLS

Structural fire safety design of new buildings is typically a three-step process: assessment of the thermal input to the structure (i.e. design fire); assessment of the thermal response of the structure and its fire protection; and assessment of the structural response to the design fire. Each of these three topics is addressed separately in sections 5.1 to 5.3 that follow. Section 5.4 addresses the approach to analysis of structural fire safety in existing buildings.

## 5.1 Design Fires

### 5.1.1 Overview

Morgan Hurley summarized the current methods available to predict the fire boundary condition. The application and limitations of closed form algebraic equations and computerized fire models relevant to the modeling of fully-developed enclosure fires, window flames and fire plumes were reviewed. The presenter also addressed probabilistic issues including uncertainty in model inputs, active intervention fiom sprinklers and manual fire fighting and extreme events. Knowledge gaps were identified in the areas of fire load data and fuel characteristics, active intervention, long narrow enclosure fires, window flames with varying fuels, and validation of computer models for more complex geometries and scenarios.

### 5.1.2 Discussion and Needed Actions

Workshop participants extended the discussion on design fires by exploring the topic of frre modeling. It was agreed that one-zone models were the most relevant to the post flashover condition and that the focus should be on enhancing those models, rather than.on more complex models such as NIST's Fire Dynamics Simulator (FDS).

Based on their discussions, participants identified the following research needs:

- Improve models and analysis tools for fire loads and their effects. Priorities identified were: the integration of modeling of heat release rate into fire-development models; modeling of mixed types of combustible materials; and effect of today's internal floor and wall covering combustibility on fire severity.
- Improve models and analysis tools related to ventilation effects. Priorities identified were: predicting the size of broken glass openings based on window types; effects of glazing characteristics and number of panes on ventilation opening; estimating the impact of numerous openings on different walls with various characteristic dimensions; quantifying stack effects; quantifying the impact of mechanical ventilation and air-conditioning systems and wind regimes on ventilation characteristics.
- Develop tools to quantify the effect of active intervention in the form of sprinklers and fire fighters.
- Develop partial safety factors indicating the respective influence of fire loads and boundary conditions and their geometrical features and material properties.
- Improve models and analytical tools that analyze the effects of the building envelope's thermal construction (both thermal mass and insulation properties)
- Improve models and analysis tools for compartment geometry, specifically tall compartments, long and narrow compartments, and concave compartments.

- Improve models and analysis tools for propagation of fully developed fires into other spaces.
- Develop criteria for software validation and benchmarking (by experimental evidence and between models), and identify limits of model validity.
- Improve models and analysis tools for fire spread through window flames.
- Identify and collect data and information needs for fire modeling, specifically a survey of fire loads and their surface areas, including data for various spaces in typical occupancies
- Collect real fire statistical data.

**None of these research needs were identified as of high priority by workshop participants as a whole.**

## 5.2 Thermal Analysis

### 5.2.1. Overview

James Milke presented a survey of heat transfer analysis methods currently available for analyzing the thermal response of a fire-exposed assembly. Lumped heat capacity, steady state heat balance, and semi-infinite slab closed form methods were reviewed with limitations for each described. Graphical methods using temperature profiles on cross-section of structural elements based on ASTM E-119 standard fire exposure, shown as thermal isotherms, were reviewed. Numerical finite element and finite different methods were also reviewed, with a focus on numerical codes developed specifically for the fire condition. The major limitation of all methods identified is the lack of accurate material property data for input, including assumptions regarding homogeneity, moisture movement and gross physical changes (spalling, lack of integrity).

### 5.2.2 Discussion and Needed Actions

Workshop participants concurred with the assessment that current thermal analysis methods are adequate with a few exceptions noted below:

- Thermal analysis methods that respond to unique boundary conditions such as plastics or wood burning adjacent to structural elements
- Thermal analysis methods for timber structures
- Thermal analysis methods to account for water spray on structural elements
- Thermal analysis methods that explicitly account for joints or seams in membranes (for example suspended ceiling systems)
- Thermal analysis methods that account for openings in membranes such as fire doors
- Thermal analysis methods that account for geometry that changes with time in the fire event – eg. spalling, intumescent coatings
- Thermal analysis methods that explicitly account for moisture migration

Workshop participants also identified a range of material property data needs to be used in existing thermal analysis models:

- Wide public availability of material property data in a form suitable for modeling, including results of proprietary tests
- Standard test methods for determining material properties at elevated temperatures

- Specific Elevated Temperature Material Properties
  a) cooling phase properties (when are not reversible)
  b) new materials (new concretes)
  c) glass (windows and structural)
  d) material stickability
  e) material contact resistance

They also noted that there is a need to interface thermal analysis methods with Computational Fluid Dynamic (CFD) models for fire'exposure.

**Of these research needs, the development of standard methods for determining material properties at elevated temperatures was considered to be of high importance by workshop participants.**

### 5.3 Structural Analysis

#### 5.3.1 Overview

James Milke reviewed elementary mechanics approaches for evaluating the performance of structural elements at elevated temperatures, along with limitations for each method. Steel, timber, concrete were treated separately for beams and columns (flexural and compression behavior) A comparison by Hosser et al. was described which rated the various methods available using criteria related to application and accuracy. The currently available numerical analysis methods, which are primarily finite element methods, developed specifically for analyzing the response of structural components to elevated temperature exposure were also presented. A review of a limited number of frame analysis applications was also presented. These are limited by assumptions regarding connection behavior and this area is the subject of several current research initiatives internationally. Research needs identified include the need for a coupling of thermal and mechanical effects, connection behavior, mechanical and thermal properties at elevated temperatures for structural materials, and experimental validation.

#### 5.3.2 Discussion and Needed Actions

Workshop participants reviewed currently available numerical analysis methods and identified several limitations in terms of validation. There was a consensus that, in comparison with other materials, steel behavior is better understood and predicted by current analysis methods. The connection between blast effects and fire was also noted as an area of interest. Finite element analytical tools (ABAQUS, ANSYS, LS-DYNA, etc) provide for the most accurate prediction of structural response under fire conditions. These tools are very useful for research or for design studies by specialized consulting firms. However, such sophisticated analytical tools require a high degree of knowledge by the user, and are costly to develop and interpret the results. Consequently, finite element analytical tools are probably not suitable for routine design applications. However, when they are used, the analytical tools that use explicit integration schemes are likely preferable to those that use implicit integration. Structural element based models (fiame models) are likely to be most suitable for routine analysis of structural response under fire conditions. Such models are very commonly used at present for structural analysis under other load conditions (gravity, wind, seismic) and could potentially be extended to include structural fire response analysis. Commercial software developers would likely incorporate fire response analysis into their frame analysis programs if the basic modeling information were available and if sufficient demand exists for such models.

The following research needs were identified:

- Develop criteria for failure or limit states for predicted structural response under fire. That is, what level of deformation, force or other measures of structural response predicted by a structural analysis model will be considered as failure?
- Develop structural analysis models, starting at the material level, and then work up towards the system level.
- Develop structural analysis models (for materials, members, connections, etc) which must be accompanied by experimental research for understanding, calibration and validation of models.
- Conduct research-quality structural fire experiments.
- Incorporate certain aspects of the response of concrete structures at high temperature, including larger strength reduction of high strength concrete, spalling, post tensioned systems and anchorage, into the analysis methods.
- Construct structural-fire test facilities in the US to develop the needed research quality experimental data. Such facilities must have the capabilities to apply complex structural loads to elements, connections, subassemblies, etc at elevated temperature and at realistic scales.
- Conduct a limited number of full-scale building tests under fire conditions to enhance understanding of system response and to validate structural analysis models (tests similar to those conducted at Cardington). There may be a possibility of conducting such tests on existing buildings that are scheduled for demolition.
- Develop a set of "benchmark" problems for validation as structural element based models are developed for predicting structural fire response.
- Develop a structural analysis method with specific capabilities unique to fire.
- Develop more complete temperature dependent material properties (substantial data already exists for steel and concrete under simple stress conditions; need additional data for material response under complex states of stress, and rate dependent response)
- Develop connection response models (inadequate data available at present to develop reliable connection response models; substantial research is needed on connection behavior at elevated temperature).
- Model element (beams, columns, braces, etc) behavior under complex 3-dimensional loading (e.g., biaxial bending plus compression) and elevated temperatures and temperature gradients; models should include plasticity and post-peak (unloading) response (substantial experimental data and model development work are needed here)
- Improve 3-dimensional modeling capability, including floor slabs and membrane/catenary action (there is some data available on membrane action in slabs, but more is needed)

**Of these research needs, workshop participants identified the need to define failure/limit states, the need to develop benchmark problems for model verification, and the need for large scale structural-fire experimental facilities in the U.S. as having high priority.**

## 5.4 Existing Buildings

### 5.4.1. Overview

Fred Mowrer and Bob Iding described the general approach to analysis of structural fire safety in existing buildings, noting that approaches are similar to those used for new buildings, but that factors such as undocumented design basic, presence of archaic building systems and materials, concealment of design details, and unknown condition of concealed elements complicate the analysis. The seismic retrofit analogy was explored, noting that fire differs from seismic design in that seismic loads can be predicted based on statistical data; in fire, both the frequency and the magnitude of fires are influenced by human interactions and design decisions. Key elements in an analysis of existing buildings which merit further research are the identification of relevant fire scenarios to be considered, means to incorporate uncertainties into analysis and design, and development or adaptation and use of non destructive evaluation technologies for the fire condition.

### 5.4.2 Discussion and Needed Actions

Workshop participants discussed lessons to be learned from seismic retrofit analysis procedures. Tools and methods to evaluate existing structures are needed, as well as a prescribed means to utilize design documentation that may exist. Consideration should be given to load paths, non-visible structural redundancy, and fuel load assessments. Masonry was identified as an area where more information is needed. A multihazard approach to retrofit was recommended.

The following research needs were identified:

- Collect data fiom full scale buildings tests measuring effective properties of existing materials and existing fuel loads which focus on the performance of archaic (not new) materials and systems
- Develop performance metrics for multihazard building robustness

**The development of performance metrics for multihazard building robustness was considered to be a high priority need by workshop participants.**

# 6. BEST PRACTICES AND SUPPORTING TECHNICAL DATA

## 6.1 Overview of Current International Codes and Standards

Andy Buchanan presented an overview of the international status of design standards for structural fire safety, beginning with a review of the international performance based regulatory environment and the context of structural fire design within overall firesafety design. The review included current available information on loads for structural fire design, fire severity and standard fire exposures, fire resistance of building elements, failure criteria, and material specific design standards. It was concluded that the Eurocodes represent the best current source of accepted, authoritative information on structural fire design.

Barbara Lane presented a practice perspective on design methods, analysis tools and regulatory frameworks needed to implement structural fire safety design. Changes to building codes to identify accepted methods and performance criteria for regulators and designers are needed. For routine application of an engineering approach, simple, validated analysis tools are needed and are available in many situations. Gaps include structural system-specific methods (e.g. ribbed slabs), the acceptance by the regulatory community of these methods, and available guidance on their application. Similarly, there must be validation and guidance for regulatory approval of more advanced methods, including compartment fire models, heat transfer to compartments, and structural response to fires. Availability of information on structural fire performance was identified as a key need for the design community; this includes both the development of a robust research base and an information management system to make it easily accessible for routine use. The development of consensus failure and performance criteria for structural fire safety is a key design need, as are simple design approaches for connection behavior at elevated temperatures.

Fred Mowrer and Bob Iding discussed design approaches to building retrofit for fire. There is a need for standards which are unique to the retrofit problem which include retrofit trigger criteria, codification of fire loadings, and approved retrofit technologies to enhance the structural and/or thermal performance of the overall structure. An evaluation methodology and checklist of critical assessment features and retrofit techniques was presented. Needs identified included an assessment of non destructive testing methods, an engineering guide to retrofit options, and evaluation of a multihazard approach to retrofit.

## 6.2 Discussion

Workshop participants discussed the need for best practices and design methods in the areas of design fire exposures, thermal analysis methods, structural design, and retrofit of existing buildings.

For design fire exposures, more accurate statistics are required to calibrate currently available Eurocodes design fire loads and a probabilistic approach must take into account other mitigating measures (e.g. a post flashover fire may not occur).

Although methods are available for thermal analysis, there is no generally accepted design criteria. There is also a need for standardized validation criteria for software and its applicability, and standardized fire test methods for material properties at elevated temperatures.

The Eurocodes were considered a good starting point for structural fire design. However, the applicability to U.S. design practices of the data that support the provisions of the Eurocodes is unknown and must be established before the Eurocodes can be accepted in the U.S. The issue of design responsibility over the life of the structure was addressed: i.e. as changes in occupancy or geometry occur, this may have impacts on structural fire safety.

There is little knowledge available on retrofit of existing structures for fire, nor standard inspection procedures. Owner incentives may need to be provided; education is a major component of retrofit best practices and must extend beyond the engineering community.

### 6.3 Needed Actions

The following needs for best practices/design guides and standards were'identified:

***Design Fires***

- Develop design fires using risk-based methodology to account for various fire scenarios; validation with fire tests
- Develop a catalogue of standard or benchmark fire loads for generic occupancies

***Thermal Analysis***

- Develop a design guide using existing thermal analysis methods
- Standardize validation of thermal analysis computer models and clear definition of its applicability
- Publish available material property data in a form suitable for model input
- Codify thermal analysis methodology – agreement on acceptable methods for various applications and limitations
- Publish model output, available in a form suitable for use by various groups (engineers, authorities having jurisdiction, etc)
- Standardize test methods to evaluate thermal properties of materials

***Structural Design***

- Research results to support/validate existing Eurocode methods
- Develop and validate of connection design methods for the fire condition
- Develop codes of practice to assign responsibility for structural fire design over the life of the building
- Develop design methods to account for interaction of structure and the compartment (ie when the structural barrier itself become involved in the fire scenario)

***Upgrade of Existing Buildings***

- Establish design and performance criteria for structural fire safety retrofit
- Develop and implement owner incentives to upgrade the structural fire safety of existing buildings
- Implement education programs to overcome the perception (cultural) that structural fire protection doesn't change with time
- Develop guidelines for the enforcement and engineering communities – e.g. "Evaluation And Remediation Of Structural Fire Performance Of Existing Buildings"

**Workshop participants identified the following as having the highest priorities from the above list:**

- **Design Fires - Develop design fires using risk-based methodology to account for various fire scenarios; validate with fire tests**

- **Structural Design – Develop and validate connection design methods for the fire condition**
- **Structural Design – Develop codes of practice to assign responsibility for structural fire design over the life of the building**
- **Upgrade - Develop guidelines for the enforcement and engineering communities – e.g. "Evaluation And Remediation Of Structural Fire Performance Of Existing Buildings"**

# 7. RESEARCH PRIORITIES FOR DEVELOPMENT OF NATIONAL ROADMAP

Workshop participants identified the following research needs as having the highest priority for development of best practices for structural fire safety design and retrofit of structures (shown with the number of votes given by participants as a percentage of the total votes cast. Note that this list represents the highest priority items only, other items received less than 1% votes):

1. Build and utilize structural-fire experimental facilities in U.S. to apply complex structural loads to large-scale components at elevated temperature – 6%

2. Develop more research quality experimental data on the behavior of the following structural components and material properties at elevated temperature – 6%
   a) multi-axial stress and rate effects (creep) of materials
   b) structural connections
   c) members under complex loading
   d) subassemblies
   e) structural systems

3. Quantify level of protection provided by current prescriptive code requirements – 5%

4. Collect actual fire performance data – 5%

5. Define failure/limit states for structural response in fire – 5%

6. Develop guidelines for enforcement and engineering communities on evaluation and remediation of structural fire performance of existing buildings – 5%

7. Specify performance goals in the building code for prescriptive and performance-based options – 4%

8. Develop performance metrics for multihazard building robustness – 3%

9. Develop a risk based methodology for design fires and the data to support it; place into a standard – 3%

10. Develop standard methods for determining material properties at elevated temperatures – 3%

11. Investigate fire performance of structural connections to and develop and validate engineering methods to predict this performance – 3%

12. Develop benchmark problems for verification of analytical tools – 2%

13. Specify professional responsibilities for structural fire protection over the life of the building – 2%

Table 7.1 shows these priorities for actions mapped against the expected products of NIST Research and Development program in structural fire safety of new and existing buildings.

| Expected Products | Needed Actions |
| --- | --- |
| Structural Fire Safety Design of New Buildings | |
| • Best practices for fire safety design of structures[1].<br>• Guidelines/pre-standards for fire safety design of structures. | 3. Quantify level of protection provided by current prescriptive code requirements – 5%<br><br>5. Define failure/limit states for structural response in fire – 5%<br><br>7. Specify performance goals in the building code for prescriptive and performance-based options – **4%**<br><br>8. Develop performance metrics for multihazard building robustness – 3%<br><br>9. Develop a risk based methodology for design fires and the data to support it; place into a standard – 3%<br><br>13. Specify professional responsibilities for structural fire protection over the life of the building – 2% |
| Analysis of Structural Fire Performance | |
| • Best practices tools for analyzing structural fire performance.<br>• Load and resistance factor methodology for structural fire safety.<br>• Selected verified/validated predictive tools for analyzing structural performance in real fires. | 1. Build and utilize structural-fire experimental facilities in U.S. to apply complex structural loads to large scale components at elevated temperature – 6%<br><br>2. Develop more "research quality" experimental data on structural response at elevated temperature – 6%<br><br>4. Collect actual fire performance data – 3%<br><br>10. Standard methods for determining material properties at elevated temperatures – 3%<br><br>11. Investigate fire performance of connections – 3%<br><br>12. Develop benchmark problems for verification of analytical tools – 2% |

[1] Steel, concrete, and steel-concrete composite construction

Table 7.1 (continued)

| Structural Fire Safety Evaluation and Retrofit of Existing Buildings | |
|---|---|
| • Guidelines/pre-standards for structural fire safety evaluation of existing buildings.<br>• Best practices for fire safety retrofit of structures.<br>• Guidelines/pre-standards for fire safety retrofitting of structures. | 3. Quantify level of protection provided by current prescriptive code requirements – 5%<br><br>5. Define failure/limit states for structural response in fire – 5%<br><br>6. Develop guidelines for enforcement and engineering communities on evaluation and remediation of structural fire performance of existing buildings – 5%<br><br>7. Specify performance goals in the building code for prescriptive and performance-based options – 4%<br><br>8. Develop performance metrics for multihazard building robustness – 3%<br><br>9. Develop a risk based methodology for design fires and the data to support it; place into a standard – 3%<br><br>13. Specify professional responsibilities for structural fire protection over the life of the building – 2% |

## 8. RECOMMENDATIONS

The top 13 research needs identified by workshop participants can be grouped into the following three main categories:

- Obtain/develop research-quality real and experimental data on structural fire performance (priorities # **1, 2, 4,** 11 and **12** – total **22%** votes)
- Codify/standardize performance goals, criteria and methodologies for structural fire design and analysis (priorities # 3, 5, 6, 7, **8, 9,** and **10** – total **28%** votes)
- Specify professional responsibilities for structural fire protection of buildings (priority # **13** – total **2%** votes)

Of the above three categories of research needs, the top two – collection of structural fire performance data and codification/standardization of performance goals and criteria to provide guidance for structural fire design and analysis – received the most number of votes **(22%** and 28%, respectively). Thus, there appeared to be a general consensus that better data and **an** accepted design and regulatory frame work are most needed for progress in structural fire safety.

# 9. APPENDICES

## Appendix 9. A:
## Workshop Prospectus

### National R&D Roadmap for Structural Fire Safety Design and Retrofit of Structures

**Need**
Current building design practice does not consider fire as a design condition for purposes of evaluating structural performance. Instead, structural fire endurance ratings are specified in building codes. In addition, there is no accepted set of verified tools to evaluate the fire performance of entire structures and to achieve engineered fire safety. Thus, there is widespread recognition of the need to develop and implement significantly improved tools, practices, and standards that explicitly consider structural fire loads in the design of new structures and the retrofit of existing structures. Background information on this need is attached.

**Expected Products** of **NIST R&D**
The National Institute of Standards and Technology (NIST) recently initiated a major R&D project to develop and implement significantly improved standards, tools, and practical guidance for the fire safety design and retrofit of structures in partnership with key stakeholders. The project will integrate knowledge of modem fire science and fire protection engineering with knowledge of modern structural reliability methods and structural engineering. Specifically, the project aims to produce the following key products over a multi-year period:

<u>Structural Fire Safety Design of New Buildings</u>
- Best practices for fire safety ***design*** of structures*.
- Guidelines/pre-standards for fire safety ***design*** of structures.

<u>Analysis of Structural Fire Performance</u>
- Best practices tools for analyzing structural fire performance..
- Load and resistance factor methodology for structural fire safety.
- Selected verified/validated predictive tools for analyzing structural performance in real fires.

<u>Structural Fire Safety Evaluation and Retrofit of Existing; Buildings</u>
- Guidelines/pre-standards for structural fire safety evaluation of existing buildings.
- Best practices for fire safety ***retrofit*** of structures.
- Guidelines/pre-standards for fire safety ***retrofitting*** of structures.

**Workshop to Develop R&D Roadmap**
**NIST** plans to hold a three-day workshop[3] to develop a detailed roadmap that will identify the R&D gaps to be filled to achieve each of the products identified above. Workshop participations will include representatives from engineering practice, relevant standards and codes committees, and technical groups as well as experts in structural reliability, fire protection engineering, and structural fire analysis. While the focus of the workshop is on U.S. practice and codes and standards, a limited number of international experts will be invited to provide perspective on important recent developments in these areas elsewhere around the world.

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[2] Steel, concrete, and steel-concrete composite construction
[3] Afternoon of the first day, full second day, and until noon the third day.

The workshop will also invite representatives from codes and standards organizations to develop and present a framework in which the above R&D products will fit and that maximizes their value to the private sector codes and standards development effort.

Background

Balancing the competing demands for fire safety and economy in a rational manner requires the development of performance-based methods to measure and predict the behavior of fill-scale structures under fire conditions.

Five key factors must be considered in developing such performance-based methods:

- First, while the current standard fire endurance test method, which stipulates a prescribed time-temperature exposure, is adequate to compare relative performance of structural components, it does not provide any indication about the actual performance (i.e., load carrying capacity) of a component in a real fire environment (e.g., involving fire of building contents, hydrocarbon pool fires, or a combination thereof).

- Second, the role of structural connections, diaphragms, and redundancy in enabling load transfer and maintaining overall structural integrity (i.e., preventing progressive collapse) during fire is ignored in structural design. Current design methods are based on fire endurance tests of single components and do not account for the behavior of inter-component connections or the complex two- and three-dimensional behavior of the entire structure.

- Third, there is a need to evaluate the effectiveness of alternative design, retrofit, and fire protection strategies to enhance structural fire endurance (including alternate cementitious spray or board systems, intumescent coatings, high-performance fire protective coatings, active suppression systems, and more sensitive sensing and monitoring). No practical, high-level models exist today that couple the fire dynamics to the structural system response, and the resulting transient, multi-dimensional heat transfer through structural components made with multiple materials.

- Fourth, there is a need to better model and predict the fire hazard to structures fiom internal and external fires (e.g., due to accidents or terrorist threats). This includes deterministic and probabilistic models for specifying the magnitude, location, and spatial distribution of fire hazards on structures (e.g., design fire scenarios, extreme events such **as** 10% in SO-years and 2% in 50-years); determination of reliability-based load factors for combined dead, live, and fire loads and resistance factors for loss in structural strength and stiffness; and methods for load and resistance factor design (LRFD) under fire conditions.

- Fifth, there is a lack of knowledge about the fire behavior of structures built with innovative structural materials (e.g., high-strength concrete or steel structures) or passive fire protection materials.

## Appendix 9.B
## Steering Committee Members

Lou Gerschwinder, American Institute of Steel Construction
Jim Rossberg, American Society of Civil Engineers
Steve Szoke, Portland Cement Association
Pravin Gandhi, Underwriters Laboratories, Inc.
Chris Marrion, Arup Fire
Kathleen Almand, Society of Fire Protection Engineers
Robert Duval, National Fire Protection Association

**Appendix 9.C**
**Fire Safety Design and Retrofit of Structures**
**Workshop Agenda**
**October 2,3**
**Versailles Room**
**Radisson Lord Baltimore Hotel**
**Baltimore, MD**

Thursday, October 2,2003

| | |
|---|---|
| 7:00 | Registration opens (continental breakfast provided) |
| 8:00 | Opening remarks, NIST |
| 8:30 | Keynote presentations - Architect and Code Official Perspectives on Need for Structural Fire Safety Design Methods – Jonathan Siu, City of Seattle and Dave Collins, AIA |
| 9:15 | Plenary 1 – Context for Structural Design for the Fire Condition - Greg Deierlein, Stanford University and Craig Beyler, Hughes Associates |
| 10:15 | Break |
| 10:45 | Breakout sessions 1 – Goal: To gain consensus on the context and identify means for the integration of structural design for the fire condition within fire safety design and within framework for reliability based structural design |
| 12:15 | Reconvene to summarize breakout sessions – key ***observations and required actions*** |
| 1:00 | Lunch |
| 2:00 | Plenary 2 – State of the Art in Structural Design for the Fire Condition – New and Existing Buildings - Morgan Hurley, SFPE, Jim Milke, University of Maryland, Barbara Lane, Arup Fire, Fred Mowrer, University of Maryland, and Bob Iding, WJE |
| 3:00 | Breakout sessions 2 - Goal: To identify and prioritize gaps in analysis methods and their technical basis (research needs) for the four components of structural design for the fire condition: design fires, thermal analysis methods, structural analysis methods, and evaluation and retrofit techniques. |
| 5:00 | Reconvene to summarize break out sessions – key ***gaps in research, datu, vaIidation*** |
| 5:45 | Adjourn |
| 5:45 – 7:00 | Reception |

Friday, October 3,2003

| | |
|---|---|
| 7:30 | Continental breakfast |

| | |
|---|---|
| 8:00 | Plenary 3 - International status of development and adoption of design standards for structural fire safety and the overall codes and standards context – Andy Buchanan, University of Canterbury |
| 8:30 | Breakout sessions 3 - Goal: to identify **and** prioritize gaps in best practices, design guidelines, standards etc. for the four components of design for the structural condition: design fires, thermal analysis methods, structural analysis methods, and evaluation and retrofit techniques. |
| 10:00 | Break |
| 10:30 | Reconvene to summarize breakout sessions – key gaps in best practices, standards, guidelines |
| 11:00 | General prioritization of results of Breakout sessions 1, 2 and 3 |
| 12:00 | Discussion/synthesis & Wrap-up |
| 12:30 | Adjourn |

## Appendix 9.D
## Workshop Facilitators and Recorders

Four groups – A, B, C, D assigned as follows

| Breakout Sessions | Facilitators | Recorders |
|---|---|---|
| 1. Context | | |
| A,B Fire Safety Design | Paul Sullivan | Chris Marrion |
| | Milosh Puchovsky | Scott Nacheman |
| C,D Structural Design | Bruce Ellingwood | Steve Szoke |
| | Jim Rossberg | John Ruddy |
| 2. State of the Art | | |
| A Design Fires | Rachel Becker | Chris Marrion |
| B Thermal Analysis | Jean Marc Franssen | Pravin Ghandi |
| C Structural Analysis | Asif Usmani | Mike Englehardt |
| D Evaluation and Retrofit | Bob Weber | Ramon Gilsanz |
| '3. Design Guides and Standards | | |
| A Design Fires | Beth Tubbs | Farid Alfawhakiri |
| B Heat Transfer Design | Bob Berhinig | Tom Izbicki |
| C Structural Design | Charlie Carter | Steve Szoke |
| D Evaluation and Retrofit | Bob Duvall | Dave McKinnon |

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## WORKSHOP ATTENDANCE

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**Appendix 9.F**
**Workshop Breakout Notes**

**Note: No written summaries of Group B, Breakout session 2 and Group B and C, breakout session 3 were submitted by workshop participants**

**Groups A and B, Breakout Session 1**

**Discussion: Context for Fire Safety Design for Fire Conditions**

**Paper by: Craig Beyler**

General

- Where do we want to be at the end of this process regarding fire/structures?
- Guidelines for 'exceptional' versus 'everyday' projects? – What is needed for each? i.e. 'everyday' projects typically prescriptive based design – How will codes be impacted? What is needed.for this approach? Larger projects - what tools/methods/data, etc are needed?
- Should look at structural engineer's process for this.

Today's paradigm

- Working w/authorities, insurers, designers, owners, public – all with various issues/concerns.
- Fire/structures studies are safety and economics driven.
- Looking to move from equivalencies to understanding overall performance.
- More knowledge needed in undertaking fire/structures studies
- Performance criteria – 'as-safe' as code design. How safe is this though?
- Who decides what level of risk is acceptable?
- Objectives/risk – fire protection engineers may frame this, however, public should decide what level of risk is acceptable. How does this process happen though?
- Need capability to predict the 'performance envelope' of buildings or structure so we know what we have, i.e., does a 2 hour fire rated column fail at 2 hrs and 1 minute, or continue to bear its load?
- Should we look at providing a conservative first estimate, and refine the process/tools/information as knowledge level increases?
- May want to look into using the Eurocodes as a starting point.

Limitations

Fire/Fuel Load

- The fire/fuel load is not defined for fire as it is for other loads.
- How should this be defined?
    - o $Lb/ft^2$ or energy/unit area?
    - o Duration?
    - o Maximum heat release rate
- Need to improve deterministic approach to determining this, and develop probabilistic approach that is simplified.

Performance Design Criteria

- What is failure?
- How is this defined? Local? Global? Failure of structure? Failure of compartmentation?
- Comparative analysis – against what code requires, versus 'absolute' analysis which would be driven more by objectives/performance criteria.

Calculation methods

- Are 'approved' calculation methods available?

Different types of models – large models available treating all phenomenon, while small models available for sub-system assessment.
Scaling is a factor.
Risk/decision making tools are important and needed.
Validation of models is important and needed.

- Should predict structural performance to failure so one knows what they have and not just to say **2** hours, as may fail at 2 hrs and 1 minute.
- Effect of compartment (**i.e.** compartment size) on fire induced environment is important.

Data/Information

- **Is** data/information available to undertake these assessments?
- Data is needed including for materials effects and response.
- Process, assumptions, model information, etc. needed as well.

Performance codes/standards/Guidelines

- Are they available?
- Methodology for design/analysis is needed.

Marketing/Selling

- Challenges exist with regards to selling to authorities, public, owner/designers.
- How do we market/sell this?
- To whom?
  Authorities – acceptability of process, tools, results, etc.
  Public – level of safety provided
  Owner/design team – benefits
- Benefits
  - cost-effective solutions,
  - aesthetics,
  - assessing whether code required protection **is** adequate
  - being able to provide equivalent levels of safety between buildings

Vision for tomorrow

Vision for tomorrow should include developing:

- Methodologies
- Tools
- Fire Loads
- Address the above
- FPE's assist Structural engineers **with** defining fire loads

Steps

Steps **to** getting there should include the following:

- Defineloads
- Training
- Tools
- Data
- Codes/guidelines
- 'Marketing'/selling

**Priorities**

- **Defining fuel loads**
- **Probabilities**
- **Reliability**
- **Liability**

**Group A, Breakout Session 2**

**Design Fires (for structural fire safety design) – Analysis Methods**

**Paper by: Morgan Hurley**

Aim of workshop: Identify and prioritize gaps in analysis methods and their technical basis (research needs). The group was requested to focus on analysis during this session, as session 3A would be devoted to design and codes.

The discussion included the following items:

1) State-of-the-art
2) Gaps in methods, validation, and data
3) Priorities

**1) State of the art**

The White Paper by Morgan Hurley summarized the state-of-the-art on modeling of realistic fires, while referring to an extensive list of 45 references. Three main types of design fires have been discussed:

- Post flashover ventilation-controlled compartment fires, which are relevant for the design of the general structure and its parts.
- Window flames that stem from flashed over ventilation-controlled compartment fires, which are relevant for the design of external steel construction.
- Fire plumes, which are relevant for the design of structural elements when exposed to localized fuels in large compartments.

Two additional White Papers (Andy Buchanan, Barbara Lane) have devoted some sections to the topic of fire modeling.

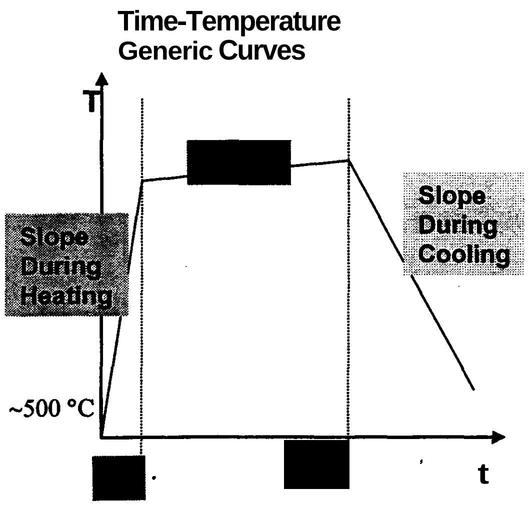
Three types of modeling tools have been distinguished:

- 1-zone models, for which there are some well known available computer models. It was mentioned that these models are sufficiently accurate but conservative, and are thus the most adequate for the sake of structural design. Being based on simple equations they are sufficiently simple and in essence there should be no difficulty for most design offices to write their own computer code, and integrate it into their design procedures.
- Fire dynamics simulators (FDS) using computational fluid dynamics (CFD). These are usually developed for simulating the initial stages of fire development, and do not seem to

add significant information for the post flashover stage. The group decided thus that there is no need to discuss research needs in this area.

- Algebraic formulations and standardized graphs. These are simplistic approximations to realistic fires that may be used in very simple cases, but are not suitable for the cases where a performance-based or fire safety engineering approach would usually be applied. It was thus agreed that there is no need for NIST to devote research efforts in this direction.

The group has consequently reached consensus that the 1-zone models are the most adequate for the sake of structural design in the anticipated performance-based fire safety engineering environment. It thus devoted the discussion to this type of fire modeling in the context of its ability to predict the main features of the post-flashover temperature-time curve, which are significant for structural design (slopes during heating and cooling, Tmax, time fiom flashover to Tmax, duration of Tmax).




**2) Gaps in methods, validation, & data**

A. Gaps & research needs

Towards the discussion the facilitator prepared a preliminary list of the gaps and needs for further research that have been raised in the mentioned white papers, as well as, in some other papers (mainly: V. Babrauskas, "Fire modeling tools for FSE: are they good enough?", J. Fire Protection Eng. 8, 87-95 (1996)).

In its discussion the group reached consensus that NIST research in this area should be devoted to items that are needed for advancement of design tools, rather than to the general refinement of the scientific basis of fire modeling. Consequently, many items on the list have been graded as insignificant, as explained below, and only five items were identified as requiring further research, with two of them gaining high priority, while the other three medium to low priority, as indicated below.

The list of items and the ensuing discussion and decisions were:

***A.1) Fire loads & their effects* (integrating modeling of heat release rate into fire-development models; mixed types of combustible materials; internal coverings' combustibility):** The group stated that the fire of interest is ventilation-controlled, and as such, only fire loads' energy content is significant. Consequently, HRR is of no interest, and combustible covering materials should be added to the fire load. Combustible construction and its time dependent contribution to the fire load was raised as a significant topic to be mentioned later, under item 7.

***A.2) Ventilation* (size of broken glass areas depending on window types, glazing characteristics, and number of panes; numerous openings on different walls with various characteristic dimensions; stack effects; existence of mechanical ventilation and air-conditioning systems; wind regime around the building):** It was agreed that, as design tools should be conservative, the possible variations in the size of broken glass areas should be incorporated into the safety factors and/or design scenarios, and there is no need to gather information on actual windows' behavior. In addition, it was stated that multiple openings are represented sufficiently well in the current models, stack effects are rare and usually not relevant in most buildings, mechanical ventilation and air conditioning systems are blocked during fire by means of dampers and do not contribute to the fire ventilation, and wind has almost no effect on fully developed fires. It was thus concluded that this item is well represented in existing models and needs no further research.

***A.3) Effects of intervention means* (sprinklers and fire fighters):** Activated sprinklers prevent the development of a fully developed fire and as such there is no need in their incorporation in models for structural design. Fire fighters' intervention may reduce the fire severity, and would lead to unconservative design. Taking into account the lack of uniformity in fire fighting intervention, it seems that this cannot be incorporated into the fire modeling.

***A.4) Partial Safety Factors (for fire loads, for geometrical features, for material properties):*** It was argued that this topic should be discussed by the Design Tools group, and not by the Analysis group. No further discussion ensued.

***A.5) Effects of building envelope's thermal construction (location of mass and insulation):*** It was agreed that these may affect the fire growth rate and maximal temperature and their incorporation into the models is needed. However, the item has been identified as of low priority.

***A.6) Compartment geometry (tall compartments, long and narrow compartments, concave compartments):*** There was consensus that the knowledge regarding the fire behavior in these types of compartments needs further research, but the item was regarded as of medium priority.

***A.7) Propagation of fully developed fires into other spaces:*** This item has been recognized as of high priority. Modeling should include spread of fire due to heat transfer through barriers, as well as via existing openings (doors and windows) and those developing with time by perforation, degradation, breakage or dismantling of separation elements (walls and floors). The group concluded that it would be best to integrate the fire modeling with the construction fire-performance modeling (thermal and structural) so that time-dependent damage to building elements on one hand, and exposure of structural combustible materials on the other hand and their contribution to the growth of fire, would automatically be incorporated in the predictions. It was also suggested that a methodology should be established for the incorporation of tested fire properties of building separation elements into the models.

***A.8) Validation and benchmarking (by experimental evidence and between models),*** *and* ***identification of validity limits of models:*** It was suggested to use the term Calibration instead of Validation as the models are not intended to be accurate, but rather a pessimistic representation of possible real fires. The item was considered as of high priority. It was also suggested to recommend that the activity will be linked as much as possible with information derived from real fire, as mentioned in item B.2 below.

***A.9) Window Flames:*** There was consensus that this item is currently covered by very little research, and the only available model is the one developed by Margaret Law and implemented in the EC 1, Part 2: Actions on Fire. Further research is required.

B. Data and Information Needs

***B.1) HRR – Data for various spaces in typical occupancies:*** The group argued that this information is not relevant for the modeling of fully developed fires, and its gathering is not important in the context of structural fire design.

***B.2) Fire loads and their surface areas – Data for various spaces in typical occupancies:*** The group recognized that there is an urgent need to gather statistically valid information on the fuel loads (in energetic terms) in the various typical spaces of most typical occupancies. It was suggested that the information should be then used as a basis for the codification of the Fire Loads in a standard. Data should include distributions in order to enable evaluation of probabilities and partial safety factors.

***B.3) Glazing breakage during fire (linked to window type, glass properties and number of panes):*** As mentioned in A2 above, the group concluded that although not fully available, this information will be of no significance for structural design. The size of openings should be taken as maximal window area in most design cases, as this pessimizes the fire. When longer and cooler fires may be more threatening to the structure, the designer should consider scenarios with parametrically smaller openings.

***B.4) Real fire statistical data:*** the group suggests that NIST should develop a methodology for the extraction of valid information from real fires. The methodology should address, on one hand, how to extract more information from existing information bases on past fires, and, on the other hand, how to handle the interrogation and extraction of information from future fires.

**3) Conclusions**

The following research and data needs and priorities were identified:

High priority:

Items A.7 - Integration of fire analysis and models with fire performance of the construction in order to enable the prediction of the time-dependent fire spread beyond the compartment of origin as well as the fire load imposed by combustible construction.

Item A.8 - Validation and benchmarking (by experimental evidence and between models), and identification of validity limits of models.

Item B.2 - Collection of statistically valid data regarding fuel loads distributions (in MJ) per floor **and** envelope area, and their surface areas. Information should be specific for the various spaces in as many **as** possible of the typical occupancies.

Item B.4 - Development of methodologies for the extraction of valid information from real past and future fires. Implementation of the methodologies for the existing information bases, and in future fires.

Medium to low priority:

Item A.5 - Effects of building envelope's thermal construction (location of mass and insulation. Although of low priority this item can easily be integrated into item A.7.

Item A.6 - Compartment geometry (tall compartments, long and narrow compartments, concave compartments).

**Group C, Breakout Session 2**

**Discussion: Structural Analysis – Issues And Needs**

**Paper by: James Milke**

- Need better definition of "failure" or limit states for predicted structural response under fire. That is, what level of deformation, force or other structural response quantity predicted by a structural analysis model will be taken as failure?

  Possible limit states:
  - global collapse of structure;
  - local collapse of structure;
  - excessive deformation that will impair fire rated compartment walls;
  - excessive deformation that will lead to excessive repair costs.

  In a performance based design approach, various limit states may need to be considered, corresponding to various performance objectives. Associating predicted structural response quantities (deflection, force, etc) with corresponding damage conditions in the structure will be a particularly difficult task (the same has proven true for performance based seismic engineering).

- Development of structural analysis models should start at the material level, and then work up towards the system level. That is, models should be developed for:
  - material response ( simple and complex states of stress)
  - member response (simple and complex loading conditions)
  - connection response
  - subassembly response (frame subassembly of two or more members with connections)
  - frame response
  - 3-dimensional system response

  By starting at the material level and working upwards to more complex behaviors, we progressively build our knowledge, modeling capability, and our ability to use and interpret the results of the models.

- Development of structural analysis models (for materials, members, connections, etc) must be accompanied by experimental research for understanding, calibration and validation of models.

- Need "research" quality structural-fire experiments:
  - apply complex structural loads to elements, connections and subassemblies under elevated temperatures;
  - thorough instrumentation
  - test elements to "failure"

  Whereas a great deal of test data is available for standard ASTM El 19 fire endurance tests, these standard tests do not, in general, provide the type of loading, data collection and analysis needed for development of structural analysis models.

- Certain aspects of the response of concrete structures merit investigation. These include:
  - high strength concrete (need very large load capacity test facilities to obtain meaningful data at realistic scales)
  - spalling behavior
  - post-tensioned systems and anchorages
  - behavior during cool-down (may be critical in some cases).

- Need structural-fire test facilities in the US to develop the needed research quality experimental data. Such facilities must have the capabilities listed above; i.e., apply complex structural loads to elements, connections, subassemblies, etc at elevated temperature and at realistic scales. It appears that no such facility exists in the US.

- Need a limited number of fill-scale building tests under fire conditions to enhance understanding of system response and to validate structural analysis models (tests similar to those conducted at Cardington). There may be a possibility of conducting such tests on existing buildings that are scheduled for demolition.

- Finite element models (ABAQUS, ANSYS, LS-DYNA, etc) provide for the most accurate prediction of structural response under fire conditions. Finite element models are very useful tools for research or for design studies by specialized consulting firms. However, such finite element models require a high degree of knowledge by the user, and are costly to develop and to interpret the results. Consequently, finite element models are probably not suitable for routine design applications. However, when finite element models are used, models that use explicit integration schemes are likely preferable to those that use implicit integration.

- Structural element based models (fiame models) are likely to be most suitable for routine analysis of structural response under fire conditions. Such models are very commonly used at present for structural analysis under other load conditions (gravity, wind, seismic) and could potentially be extended to include fire structural response analysis. Commercial software developers would likely incorporate fire response analysis into their frame analysis programs if the basic modeling information were available and if sufficient demand exists for such models.

- As structural element based models are developed for predicting structural fire response, need to develop a set of "benchmark" problems for validation. Benchmark problems of selected elements, fiames and systems would be solved by more advanced and exact methods (fmite element, etc) and be used to evaluate the accuracy of the simpler element based models.

- Required attributes of a structural analysis model capable of predicting response under fire conditions:

  - need to model large deformations
    (such modeling capability already exists; no significant research needs for this)
  - need temperature dependent material properties
    (substantial data already exists for steel and concrete under simple stress conditions;

need additional data for material response under complex states of stress, and rate dependent response)

- need connection response models
  (inadequate data available at present to develop reliable connection response models; substantial research needed on connection behavior at elevated temperature).
- need to model element (beams, columns, braces, etc) behavior under complex 3-dimensional loading (e.g., biaxial bending plus compression) under elevated temperatures and temperature gradients; models should include plasticity and post-peak (unloading) response
  (substantial experimental data and model development work needed here)
- need 3-dimensional modeling capability, including floor slabs and membrane/catenary action
  (some data available on membrane action in slabs, but need more)

**Group D, Breakout Session 2**

**Discussion: State of the Art in Evaluation and Retrofit for Fire Safety**

**Paper by: Fred Mowrer and Bob Iding**

Issues:
What triggers a retrofit?
Look at seismic retrofit as an example
Code trigger by architect/ structural. Fire – change of use
Code lacks triggers to upgrade – building official call vs. scoping engineering standards/guides
What is retrofit?
Consider use of other strategies – existing and life safety, seismic

Needs:
20 year roadmap/plan
New procedures/standards – tools to evaluate the fire resistance of archaic materials, criteria to access structures
Tools that would be relevant for both new and retrofit conditions – analysis, evaluation
Methodology to use of existing construction documents
Education
Thermal analysis of archaic materials

Plan of Action:
Develop design guides/standards/tools – retrofit for unsafe buildings, optional upgrades – convince the architect/engineer and owner of value
Develop evaluation checklist, assessment criteria – elements, connection. load paths, non visible,
Develop existing building performance objectives – levels, measurement, validations. Develop means to make fuel load assessment.
Carry out full scale building testing – develop test criteria, consider available buildings, fuel loads
Develop performance measures – metrics, multihazard robustness, redundancy

**Group A, Breakout Session 3**

**Discussion:** **Design Fires**

**Paper by:** **Morgan Hurley**

**Attendance**
Beth Tubbs, Facilitator
Farid Alfawakhiri, Recorder
Jonathan Barnett
Rachel Becker
Craig Beyler
Doug Carpenter
David Collins
Joel Kruppa
Chris Marrion
Bud Nelson
Long Phan
Robert Thomas
Wei Zhang

**Opening**
Beth Tubbs opened the session at 8:50 am
The goal of the session was to identify and prioritize gaps in best practices, design guidelines, standards, etc for the **Design Fires** for use in the structural design for the fire condition:
(1) Current design methods, codes and standards
(2) Gaps
(3) Priorities

**Discussion**

- It is important to develop meaningful codes and standards that would allow more routine structural design for fire – this will improve AHJ confidence and streamline the approval process.
- Eurocodes contain provisions for design fires.
- More accurate statistics are required to calibrate the codes
- Current state – there is no code or standard in US for design fires
- Methods of establishing fire (energy) loads were discussed
- Eurocodes use 80% fractile fire loads for occupancies
- Discussion went on whether the client (and the design team) or the code/standard establish the design fire load
- Factors that would affect fire loads and load factors were discussed – probabilistic approaches were discussed
- It is important to develop a probabilistic standard on fire loads based on the current state of knowledge, and then maintain and update the standard as more research is done in this field.

**Flipchart Outlines**

*Questions*
What do code officials (or other stakeholders) need
Should it be probabilistic
In a code or standard
Methodology or more of a list
Fire load studies

***Factors that affect fire loads***
Ventilation/openings
Active protection systems/interaction
Combustibility of construction
Use/occupancy
Height/area
Level of compartmentation
Separation between buildings

**Group D, Breakout Session 3**

**Discussion:** **Retrofit Best Practices, Guides and Standards**

**Paper by:** **Fred Mowrer and Bob Iding**

Robert Duvall – Facilitator
David MacKinnon – Recorder

Note: Group believes upgrade is a better term than retrofit.

Gaps

- No case studies available
- Few engineers, if any, have ever done a structural retrofit for fire performance
- Fire performance is not being considered when doing other, multi-hazard (seismic, etc) upgrades for other purposes.
- Triggers
  - West coast, seismic
  - East coast, any time you do an upgrade, maybe for a change in tenancy if a problem is identified
- No standardized/published inspection procedures
  - Criteria
  - Could trigger upgrade
  - Method to prioritize problems
  - Check list
  - Primarily a self regulatory process but could be adopted by a community that has severe problem
  - No guideline for redundancy and toughness
- Same (maybe) procedures for inspection of fire protection materials
- Existing Building Codes have triggers, are focused on reuse, assume building fire protection features are as per code when built
- Owner incentives to evaluate building
  - Evaluation upon sale of building
  - Disclosure
  - But no published criteria
  - Financing institution
  - Internally driven
  - Due diligence, comprehensive, price negotiation
  - Quality Index for Fire, rating like LEEDS, part of structural evaluation (NYC)
  - Employees
- Knowledge of practicing structural engineers
- Even if not regulated will be used by owners and purchasers but building department will not get involved unless legislated
- Life Safety work is being done in hospitals, self-evaluation, plan for improvements, effects accreditation. Hospitals are now more open, and want to know what is wrong with their building. Not presently regulated.
- Understanding of responsibility, who responsible for what.
- Fire safety inspections are not focused on consequences of degraded structural fire protection

- Perception that once regulatory agencies sign off on building, owners no longer need to think about structural fire protection.
- Accountability: owner required to maintain and operate a facility that meets requirements
- Insurance companies do evaluation of life safety systems and fire hazards but don't go into hidden things like structural fire protection issues. Perception is that when structure is built, it is OK and nothing ever changes. Only visual inspection are conducted (if done at all), protection materials are not measured or tested.

Design Guidelines and Standards

- Guideline for the evaluation and remediation of structural fire performance of existing buildings.
  - Toughness/robustness
  - Egress routes
  - Redundancy
  - Keeping fire separated from critical elements
  - Systems, components, connections
  - Fire spread, barriers, all passive systems
  - Roles of design team members - who is responsible for what
  - Communication of findings, legal issues, professional codes of ethics
- Tools to identify weak links in structural fire performance.
- Guidelines to identify problem components based on consequence of failure
  - Need measures? - Affected area.
- Document that describes when a structural engineer should be called in to evaluate structural fire protection
  - Upgrades are complaint driven
  - Owner and allied professions need guidance
- Non-technical guide for communities who want to upgrade their building stock
  - Tax incentives, etc.

## Appendix 9. G
## National R&D Roadmap for Structural Fire Safety Design and Retrofit of Structures
## Research and Development Priorities

Workshop participants identified the following research needs as having the highest priority for development of best practices for structural fire safety design and retrofit of structures (shown with the number of votes given by participants as a percentage of the total votes cast. Note that this list represents the highest priority items only). On the following pages, under Research and Development Needs, the entire list of research needs are presented, with the number of votes received by each.

1. Need structural-fire experimental facilities in U.S. – 35
   a) apply complex structural loads to large scale components at elevated temperature

2. Need more "research quality" experimental data on structural response at elevated temperature – 34
   f) material behavior - need some additional data on multi axial stress and rate effects (creep) – 1
   g) connection behavior - need substantial work – little data available at present) – 3
   h) member behavior under complex loading – need substantial work – current data mostly for simple loading – 1
   i) subassembly behavior – need substantial data – 6
   j) system behavior – need additional data to supplement Cardington – 9

3. Quantify level of protection provided by current prescriptive code requirements – **32**

4. Actual fire performance data – 32

5. Need definition of failure/limit states for structural response in fire – 29

6. Guideline needed – for public community and engineering community "Evaluation and remediation of structural fire performance of existing buildings" - 29

7. Specify performance goals in the building code for prescriptive and performance-based options – 21

8. Develop performance metrics for multi-hazard building robustness – 18

9. Design Fires: needs – risk based methodology - 18
   - data to support with future considerations - 12
   - development of a standard – 7

10. Standard methods for determining material properties at elevated temperatures – 16

11. Fire performance of connections for codes and standards - 15

12. Need benchmark problems for model verification – 14

13. Whose role is fire protection including over the life of the building – **13**

**Research and Development Needs**

Listed below are the research and development needs identified by workshop participants accompanied by the number of "votes" assigned to each during the general prioritization session.

**IA – Context for fire safety design**
Define loads
Training - 1
Tools
Data- 1
Codes/design guidelines
Marketing/selling – authorities, owners/designers, public - 6
Probabilities
Reliability
Liability

**IB – Context for fire safety design**
Provide a performance based option in building code – 1
Maintain option for prescriptive design option – 5
Quantify level of protection provided by current prescriptive code requirements – 32
Specify performance goals in the building code for prescriptive and performance-based options – 21
Establish general procedures and identify roles (design team and enforcement)
Implement more training and education programs for all parties involved in design/construction process
Enhance interaction between disciplines early in design process – 8
Identify those building conditions (complexity, size, function) that should require a calculated fire resistance
Building code performance goals should not require consideration of extreme events
Provide direct reference to the types of tools and procedures that should be used in calculating fire resistance (fire load, thermal analysis, structural analysis)

**IC – Context for Structural Design**
New buildings – current practice seems ok but we don't really know
Existing buildings – we don't know
Poor data available on performance of active systems, performance of structural components and barriers - 1
Lack of understanding that fire is different than natural disaster events. – 2

Need Actual Fire Performance data - 32
Identification of fire hazards (accidental) - 1
Risk communication – rational fire design
Professional education component
Develop funding resources - 7
Capitalize on other disaster resistance programs
Understand building performance
Tools for signature buildings
Measure of what is intended to be applied
Limited data on risk based design and probabilities - 1
Large impact over large area (seismic) versus individual building fire (times no. of buildings)

**ID – Context for Structural Design**
Understanding of the relationship between fire safety engineering and structural engineering –
"probability/event tree – 2
Normalization of E-119 – 4
Review/comparison of Int'l codes vs. us
Significant structure code?
Reverse engineering from existing to new; use analytical tools to verify existing practice
Context/preamble of effort within societal beliefs (public perception) – difference between guides/stds and codes
Handling the unpredictable
Develop a fire safety go/no go – 4
Define true cost vs. cost – i.e. cost to society
Structural engineering and fire safety engineering collectively define the unknown"
Multi hazard considered with fire
"Society" selection of method

IIA – **Design Fires**
Compartment fire model gaps:

1) integration with construction performance in order to enable:
    a. fire spread to other compartments (via thermal conduction, holes, dismantled partitions, openings) - 10
    b. involvement of combustible construction materials (with time) – *3*

2) Calibration, benchmarking (experimental, between models). An identification of limitations - 8
3) geometry (tall, long, concave)
4) envelope (mass and insulation)

Window flames

Data: fuel loads (per typical spaces) - 5

Methodology for gathering statistical information from past and future fires.

**IIIA – Design Fires**
Current status – Non existent in USA
Gaps – lack of data and methodology – 8
Needs – risk based methodology - 18
- data to support with future considerations - 12
- development of a standard – 7

Establish benchmark fire loads for generic occupancies - **4**

**IIB – Thermal Analysis**
Analysis methods are adequate for modeling conduction
- are not ok for
    - FRP or wood burning around the structure – define boundary conditions
    - Wood
    - Water spray on structures
    - Membranes (joints0
    - Fire doors

- o Changing geometry (spalling, intumescent materials) – 1
- o Moisture movement

Material Properties availability – 7

Elevated Temperature Material Properties – 2

- f) thermal and boundary conditions
- g) cooling phase (Properties are not reversible0
- h) new materials (new concretes)
- i) glass (windows and structural)
- j) proprietary results
- k) material stickability

Standard Methods for determining material properties at elevated temperatures – 16
Contact Resistance
Interface CFD fire modeling to the structure - 2

**IIIB – Thermal Analysis**

Lack of a design guide for thermal analysis methods – 6
Standardized validation of software – clear definition of software applicability – 5
Lack of published material property data – 3
Acceptance of codified thermal analysis methodology (i.e. sprinkler hydraulics, smoke control, etc) – published software output, published results tailored to various groups (engineers, AHJ. Etc) - 6
Standardized fire test methods

**IIC – Structural Analysis Methods**

Need definition of failure/limit states for structural response in fire – 29
Need to develop structural element based models (i.e. frame analysis type models) for routine analysis/design of structural fire response – 2
Need benchmark problems for model verification – 14
Need more "research quality" experimental data on structural response at elevated temperature – 34

- k) material behavior - need some additional data on multi axial stress and rate effects (creep) – 1
- l) connection behavior - need substantial work – little data available at present) – 3
- m) member behavior under complex loading – need substantial work – current data mostly for simple loading – 1
- n) subassembly behavior – need substantial data – 6
- o) system behavior – need additional data to supplement Cardington – 9

Need structural-fire experimental facilities in U.S. – 35

- b) apply complex structural loads to large scale components at elevated temperatures

Need limited number of full scale "Cardington-like" tests to evaluate system behavior – use actual buildings – 8

**IIIC – Structural Analysis Methods**
Euro codes methods seem good but need to validate supporting data - 5
Connections - 15
Whose role is fire protection including over the life of the building – 13
Interaction of structure and the compartment – 4

**IID** - Retrofit
Identify what data is needed – 2
Identify what data is not available – 2
Database collection – full scale buildings tests, properties of existing materials, fuel loads – 9
Analyze data
Develop performance metrics for multihazard building robustness – 18
Validate the results
Start over

**IIID** - Retrofit
Develop and publish criteria for retrofit
Owner incentives to upgrade
Perception (cultural) – structural fir protection doesn't change with time
Guideline needed – public community and engineering community
Evaluation and remediation of structural fire performance of existing buildings

## Appendix 9.H

## White Papers

1. Challenges Facing Engineered Structural Fire Safety – a Code Officials' Perspective – Jonathan Siu, P.E., SE
2. Challenges Facing Engineered Structural Fire Safety – the Architect's Perspective – Dave Collins, AIA
3. Framework for Structural Fire Engineering and Design Methods – Greg Deierlein, Ph.D. and Scott Hamilton
4. Relationship between Structural Fire Protection Design and Other Elements of Fire Safety Design - Craig Beyler, Ph.D.
5. Design Fire Scenarios – Morgan Hurley, P.E.
6. Analysis Tools and Design Methods: Current Best Practices – Jim Milke, Ph.D.
7. Thermal and Structural Analysis Methods and Tools – Gaps in Knowledge and Priority Areas for Research **fiom** a Practice Perspective – Barbara Lane, Ph.D.
8. Evaluation and Retrofit of Existing Buildings for Structural Fire Safety – Fred Mowrer, Ph.D., and Bob Iding, Ph.D.
9. International Status of Design Standards for Structural Fire Safety – Andy Buchanan, Ph.D.

## White Paper 1
## Challenges Facing Engineered Structural Fire Safety – A Code Official's Perspective

**Jonathan C. Siu, PE, SE**[1]

## INTRODUCTION

In 1973, construction was completed on two highrise office buildings—the 62-story First Interstate Bank building in Los Angeles, California, and the 38-story One Meridian Plaza building in Philadelphia, Pennsylvania. Fifteen years later, on May 4, 1988, a fire destroyed four floors of the First Interstate building after burning for four hours. Nearly three years later, on February 23, 1991, a fire burning for over 19 hours gutted eight floors of the One Meridian Plaza building. Although the resources of the Los Angeles Fire Department were severely challenged, they were successful in controlling the first fire, and the resultant damage to the structure was very minor. In the One Meridian Plaza fire, the Philadelphia Fire Department was unable to control the fire before the onset of major structural damage. Due to fear of imminent structural collapse, firefighting personnel were pulled out of the building eight hours before an automatic fire sprinkler system finally controlled the fire. Shortly after the 9-11 terrorist attacks in 2001, the World Trade Center 7 building, completed in 1987, became the first modern fire-protected steel highrise building to collapse due primarily to fire damage. In all three cases, the buildings were built in accordance with the latest prescriptive codes in effect at the time of construction.

After each of these three major fires, the question has been raised whether prescriptive building codes provide adequate protection for the structure. It can be argued that the code-required (prescriptive) fire protection for the structure in the first two fires performed adequately, since neither structure collapsed, and no loss of life occurred as a result of damage to the structure. On the other hand, even though the First Interstate building was put back into complete service within a few months, the economic losses along with the attendant costs to society in all three cases would argue equally that the prescriptive building code requirements are lacking.

The First Interstate and One Meridian Plaza fires eventually resulted in changes being made to the prescriptive codes to require automatic fire sprinkler systems to be installed throughout all new highrise buildings. Changes to the building codes are currently being discussed in various forums as a result of the World Trade Center 7 collapse. At the same time, the organizations that promulgate building codes are trying write codes that are more "performance-based" and less prescriptive, to increase design flexibility. Increasingly, analysis and reports from fire protection engineers are being provided to code officials in lieu of traditional fire protection of structures.

In the atmosphere of increasing demand for fire protection engineering and the increasing sophistication of the analytical tools available to the fire protection engineer, it must be recognized that code officials will ultimately decide what will be permitted for protection of structures. There are many challenges facing the code official (and by extension, the fire protection engineer) before engineered fire protection can become widely accepted. The four example buildings below will be used to illustrate how engineered fire protection is being used in lieu of prescriptive code requirements in the city of Seattle, Washington, and will also serve as examples of the challenges facing the code official.

## EXAMPLES OF ENGINEERED STRUCTURAL FIRE PROTECTION IN SEATTLE

The Department of Design, Construction and Land Use (DCLU) is the agency in the City of Seattle government that regulates construction. DCLU enforces the Seattle Building Code (SBC), a locally-amended version of the Uniform Building Code™. The SBC allows alternate materials and methods to be used in lieu of prescriptive code requirements, on the condition the alternates provide protection equivalent to that required by the code. The four projects discussed below **are** examples of structures where engineered fire protection was approved by DCLU **as** an alternate for the protection ordinarily required by the code.

1. Glass/steel bridge; Seattle City Hall

   Earlier in 2003, the City of Seattle completed construction of a new City Hall building. One of the more striking architectural features of the new building is a bridge spanning the public lobby space, used **as** one of the routes connecting the City Council offices to their meeting chamber. The bridge floor and rails are constructed of glass panels with steel supports, and the entire structure is stabilized laterally with steel rods. Given the type of construction of the building, the prescriptive provisions of the SBC require any structure supporting floor loads to be protected by 3-hour fire rated construction. For most steel structures, this protection is provided by spray-applied fireproofing. However, that method would have destroyed the architecture of the bridge. Instead, the fire protection engineer was able to demonstrate that an "expected" fire, uncontrolled by sprinklers, and placed in the "worst" location would not raise the temperature of the steel to the point where the bridge would collapse.

2. Mesh structure; Seattle Central Library

   As of this writing, the new Central Library for the City of Seattle is under construction. A steel mesh structure on the outside of the building provides support for the exterior glazing, **as** well **as** lateral bracing for the building against earthquakes and wind. In one portion of the building, the mesh structure is canted at an angle such that it also acts as part of the roof framing, transferring vertical loads to the primary frame of the building. The **SBC** requires secondary roof framing members (those not directly connected to columns) to have a protection rating of two hours, although there are allowances in the code to lessen the protection if the structure is far enough away from potential fire sources. Again, sprayed-on fireproofing was not acceptable to the architect, and given the nature of the mesh structure, sprinkler protection of the structure was impractical. The ultimate resolution was the product of teamwork between the fire protection engineer and the structural engineer. Once the fire protection engineer was able to show how many members of the mesh structure would be expected to fail under fire conditions, the structural engineer was able to demonstrate the highly redundant structure was capable of transferring the loads around the failed portion. As added protection, the sprinkler system was designed to provide a greater density of water onto the source of **fuel** (primarily bookshelves) below the canted portion of the mesh structure, in order to control **any** fire before it would endanger **the** structure.

3. Roof framing and walkways; Fred Hutchinson Cancer Research Center Building

   A four-story atrium connects two wings of the Fred Hutchinson Cancer Research Center Building, which is nearing completion at the time of this writing. The roof of the atrium is constructed **of glass** supported by a steel beam grid. Walkways supported by steel beams cross the atrium to connect the wings at each floor level. Mid-span support for the walkways and the roof grid is provided by a group of four steel columns. The architectural design called for the roof and the walkway beams to be unprotected, whereas the SBC required them to be protected for two hours (roof) or three hours (walkways). The fire protection engineer considered the likely fuel loading in the atrium and was able to convince the code official the design fire would not damage the structure.

4. Columns; Space Needle

   The Space Needle at the Seattle Center was constructed in the early 1960's as the centerpiece of the 1962 World's Fair, and is Seattle's defining landmark. Originally, the only occupied space in the structure was on the restaurant and observation levels in the saucer-shaped structure at the top. The main columns are in a tripod configuration, and constructed of steel sections with flanges in excess of 1% inches thick. Each leg of the tripod consists of two steel sections. In the 1980's, a lower restaurant level was added, being attached to the inside of the tripod structure. In the 1990's, a new retail and ticketing structure was constructed at the ground level, enclosing the base of the tripod. Because the columns were no longer fully open to the atmosphere, DCLU was concerned that heat from a fire would build up sufficiently to damage the columns. Although the SBC would have required 3-hour rated protection to be provided for the columns, the fire protection engineer demonstrated the columns would not heat up enough to fail under design fire conditions, due to their large size.

The common thread running through the four cases above is the desire of the architect to leave the steel structure exposed, without code-required (prescriptive) fire protection. In each case, the fire protection engineer was able to demonstrate the structure would not be damaged by a design fire. However, also common to each case, the code official for DCLU had to decide what the goals were, what parameters needed to be addressed, and whether the fire protection engineer had adequately addressed the issues.

## CHALLENGES FACING THE CODE OFFICIAL

**I. The Balancing Act.** When a building is built, the main stakeholders are the developer, the designers, the users of the building, and society in general. The code official is placed in the position of balancing the needs of these stakeholders, and managing the impacts and risks associated the compromises made to maintain that balance.

On the developer's side, while many are interested in more than their bottom line, ultimately, any building and therefore any solutions to building code issues must make economic sense to them. In the example of the Central Library steel mesh above, protecting the mesh with a sprinkler system would have been acceptable by the code, but would not have been economically feasible to the owner/developer (in this case, the City of Seattle) as it would have taken hundreds of extra sprinkler heads to provide adequate coverage of the structure.

As another stakeholder, in many building designs, the architect is focused on the aesthetics of the space, or the need to make an architectural/artistic "statement". The unprotected structures in all four cases above are expressions of this artistic nature of architecture. Another example is in old, historic buildings where certain architectural features such as large timber beams and columns must remain exposed to preserve the historic character of the building.

The third set of stakeholders, the users of the building, want to be safe but my experience is if they are lessees or owners, they are also very concerned with the economics of the building.

Many times the concern to minimize dollar costs of construction override safety concerns. In those cases, they are essentially willing to gamble that a fire, an admittedly somewhat rare event, won't affect them. This is usually less of an issue with new construction, but is a larger issue in older (lower rent) existing buildings.

Finally, society demands life or economic losses in a single event be minimized—buildings must provide some level of life safety for occupants as well as property protection. (Note that since the World Trade Center collapses, there has also been a heightened public concern for the safety of emergency responders.) Public outcry does not occur over the many, many deaths in fires in single family residences each year, but single events with large losses of life such as the 9/11 terrorist attacks will generate an outcry. This is recognized in the building codes, which require higher levels of protection for buildings housing large numbers of people. On the economics side, the loss of a large building such as One Meridian Plaza leads to other societal impacts--economic strain on businesses (those formerly housed by the building and those dependent on the business generated by the building), not to mention the cost of demolition and rebuilding. Again, society is willing to endure many small losses, but does not tolerate large single losses. On the other hand, similar to the developer's need, society wants solutions to make economic sense. In general, the public is not willing to pay the price for complete safety—such construction would not be attractive or affordable. However, after a large-loss event, there is a danger that societal demands will be used to inappropriately influence (i.e., politicize) changes to codes.

Even though many code officials recognize their role in balancing the stakeholder needs, they also view their main purpose for existence in the construction process as representing the needs of society and the users of the building. Thus, they tend to err on the side of life safety for the occupants of buildings. Fire protection engineering consultants are viewed by many code officials as advocates for the developer or architect, and not necessarily for safety. This lack of trust by the code official is due to many factors that may include:

- Lack of code official expertise. Many code officials lack the expertise to properly evaluate engineered fire protection proposals. Because they are not comfortable making the evaluation, they are more likely to depend on the prescriptive codes rather than shifting paradigms, as discussed in the next section.
- Credibility of the fire protection engineer. The profession of fire protection engineering is relatively new to most code officials. As a whole, code officials don't know what type of training or other exams a fire protection engineer must take in order to be called an "engineer". Is there a core set of courses a college graduate in fire protection engineering must take, regardless of where he/she goes to school? In most states, there is not a separate professional license for fire protection engineers. Is there a nationally recognized standardized testing program for licensure? Because there isn't the "comfort level" with the fire engineering professionals as there is with other design professionals (architects or engineers), the code official is less likely to approve engineered solutions for structural fire protection. In addition, as in any profession, there are those fire protection engineers who are credible, and those that aren't. The code official has to discern whether or not the fire protection engineer is knowledgeable and credible. To establish credibility, the fire protection engineer must be able to explain what the prescriptive code requires, why it's required (what's the intent of the code), and most importantly, how their proposal is justified, or how the proposal mitigates the hazards the prescriptive code is trying to address. An engineered fire protection proposal that is not adequately justified is unlikely to inspire code official confidence in the engineer.

Another reason for code official reluctance to deviate from the prescriptive code is the fear of litigation or media exposure. It is my opinion that this fear is somewhat irrational, as lawsuits involving building code decisions are practically non-existent. Even so, it is viewed by many code officials (with encouragement from their attorneys in many cases) as being a safer course to stay with the strict wording in the code. Additionally, in his/her mind's eye, any failure reflects poorly on the professionalism of the code official, and failures resulting from poor code provisions are easier to live with than failures resulting from risky decisions.

**II. The Paradigm Shift.** In order for code officials to consider engineered structural fire safety solutions, they must be prepared to consider new methods that are not neatly codified— performance requirements. The prescriptive code requirements are familiar, and easy to enforce. Deciding whether performance goals are met requires judgment, and the knowledge of the goals. Unfortunately, this shift is difficult for many code officials, as many do not have a professional background that prepares them to make these judgments.

These first two challenges are not under the control of the fire protection engineer. However, there are other challenges that hinder wider acceptance of engineered solutions, even for the professionally-trained code officials who are willing to make the paradigm shift.

**III. Performance Standards.** The code official's first challenge from a technical standpoint (as opposed to philosophical) when presented with a proposal for engineered fire protection is to determine what standards must be met. Attempts are being made in various forums to define performance standards to which buildings can be designed and evaluated. One example is in the ICC ***Performance Code for Buildings and Facilities"***, promulgated by the International Code Council. This code sets general standards indicating occupant lives, property, and fire fighters and emergency responders are to be protected. A more specific performance standard for structures in fire is stated as follows:

> "Structural members and assemblies shall have a fire resistance appropriate to their function, the fire load, the predicted fire intensity and duration, the fire hazard, the height and use of the building, the proximity to other properties or structures, and any fire protection features." ($1701.3.1 1)

Performance requirements relevant to this discussion are stated in the ***Building Construction and Safety Code" (NFPA 5000™)*** promulgated by the National Fire Protection Association as follows:

> "Buildings shall be designed and constructed to reasonably prevent structural failure under fire conditions for a time sufficient to protect the occupants." (§5.2.2.3)

> ""Buildings shall be designed and constructed to reasonably prevent structural failure under fire conditions for a time sufficient to enable fire fighters and emergency responders to conduct search and rescue operations." (§5.2.2.3)

While the standards in both these codes are of some help to the code official, they are still vague, and don't provide a basis for evaluating or approving a particular proposal. What is "appropriate"? What is "reasonable" prevention of failure? As a result, there is still much left to be decided and negotiated with the fire protection engineer on a particular building.

IV. Design Event. The most difficult challenge facing the code official is evaluating the design event being proposed. To do this, there are at least three questions that need to be answered:

- What is the size of the design fire? For designing exiting systems for building occupants, the prescriptive building codes assume there is one fire burning at a time, and it does not fully involve a floor in the building. This may be a reasonable design event for engineered structural fire protection, but in reality, the First Interstate and the One Meridian Plaza fires fully involved floors, and more than one floor was burning at the same time. Preliminary studies of World Trade Center 7 indicate a strong possibility a larger-than-normal fuel load (a ruptured diesel fuel line for emergency generators) was a contributing factor in the collapse of the' building. However, these are extraordinary events, and I do not think they represent reasonable design events, especially given the performance standards in the codes. In each of the four examples of engineered fire protection in Seattle, the fire protection engineer assumed a localized fire, with fuel provided by expected furnishings or hazards (books and bookshelves, combustible furniture, retail goods, etc.) None were in an environment that was likely to have high fuel loads.

- What is the duration of the design fire? The prescriptive codes require protection for structures ranging fiom a rating of zero to a rating of three hours, depending on the size and use of the building. (Note that these ratings are based **on** a standardized fire test, and don't necessarily reflect how long the structure would last in a real fire.) Emergency systems are generally required to operate for **two** hours. The NFPA 5000 code says the goal is to "reasonably" avoid structural failure until occupants are evacuated and search and rescue operations are accomplished. In a large building, search and rescue operations could amount to several hours. In the First Interstate fire, search and rescue operations were not **started** until the fire was knocked down, nearly four hours after it had started. The design fire durations **used** to justify the unprotected steel in the Seattle examples were built around the expected fuel load. For example, for the City Hall glass bridge design, the fire protection engineer analyzed the structure for a fire in the adjacent office area, and a furniture/kiosk fire immediately below the bridge. The furniture/kiosk fire was determined to be the worst case fiom the standpoint of heat impingement on the 'structure. However, the duration of the design fire was less than 10 minutes since the fuel for the fire was consumed in that time, and therefore, the heat released by the fire decreased.

- What other assumptions are associated with the design event? While the prescriptive codes generally assume the only protection for structures is the passive protection (e.g., sprayed-on fireproofing or gypsum wallboard enclosures), they do allow fire sprinkler systems to substitute for one hour of required protection. Some fire protection engineers will **try** to justify performance-based designs by saying fire sprinkler systems will control the fire before it gets hot enough **to** affect the structure. There is some merit to this idea—if sprinklers are operating properly, then, no **fire** protection is really needed for the structure. However, there is debate among code officials **as** to how much these active systems should be relied upon. The question is, how subject to failure (human-caused or otherwise) are they? The First Interstate fire started on a floor that had operable sprinklers—the problem was they had been shut **off** and drained in order to work on the system. With this in mind, there is a question **as** to whether or not it should be assumed that the sprinkler system is operable when engineering fire protection of structures. For the examples in Seattle, DCLU required a "belt and suspenders" approach—the design fire was assumed to be burning without being controlled by sprinklers, but the sprinklers were still required in order to further reduce the hazard.

V. **Validation of Models.** Another hindrance to code official acceptance of engineered structural fire protection is the lack of data to validate the models and assumptions made by the engineers. Sophisticated programs and modeling techniques are available and can be used by the engineer to calculate, for example, whether or not a certain component of a structure will fail given a specific fire in a specific room configuration. For the glass/steel bridge in Seattle City Hall, the engineer used a computer program to model the spread of heat fiom the fire source through the open lobby area up to and across the ceiling where the structure is attached. However, the results of engineered structural fire protection have not been tested in real-life situations enough (if at all) to assure the code official the solutions will really work, as opposed to working in a computer program or in a limited, controlled test. The three fires discussed in the introduction are the 'only major fires in modem highrise buildings resulting in any kind structural damage. From an overall societal standpoint, this is good news. However, these fires are not tests of engineered solutions, but of the prescriptive code provisions, and so do not contribute to any sort of validation of fire engineering methods. In fact, it can be argued that the prescriptive solutions met the performance goals discussed above—one only collapsed after seven hours of uncontrolled burning, and the other two did not collapse at all despite long fire exposures. Based on the performance of these buildings, many code officials will prefer to rely on the tested prescriptive solutions than on theoretical and unvalidated engineered solutions.

The lack of data to validate models also means factors of safety are unknown. Structural engineering uses factors of safety ranging from 1½ to 6 to account for uncertainties in loading or material properties. When a fire protection engineer shows the code official a particular beam will not be affected by a particular fire, the code official does not know if there is any sort of safety factor built in to the engineer's analysis to account for uncertainties in the design fire or the structural materials. Even if the engineer does provide a safety factor, there is no standard to guide the code official as to what factor is appropriate.

## FURTHER STUDY

In my view, the challenges discussed above must be addressed before research on specific issues will be useful. Without the standards, research provides data, but not information to the code official. Once the code official is willing to use his/her judgment, he/she needs a standard basis on which to manage the risk of his/her decisions. As a possible model for engineered structural fire safety, here are some examples that may be used in seismic design by structural engineers that attempt to address these same challenges.

| Issue | Structural Engineering Example |
|---|---|
| Performance Standard | • Collapse prevention in a major event. Local collapses may occur, but global collapse does not.<br>• Life safety in a moderate event. Building may be heavily damaged, but occupants can evacuate the building.<br>• Light damage in minor event. Limited to cosmetic and minor non-structural damage only. |
| Design Event | • Major event: Earthquake with 2% chance of exceedance in 50 years (1 in 2500 year event)<br>• Moderate event: Earthquake with 10% chance of exceedance in 50 years (1 in 450 year event)<br>• Minor event: Earthquake with 50% chance of exceedance in 50 years (1 in 100 year event) |
| Model Validation | • Tested several times a year by Mother Nature |
| Factor of Safety (examples) | • Global overturning: 1.5<br>• Specific structural components: Varies with materials used for construction. Ranges from 2 to 6 or more. |

Notice that there are several levels of performance standards, depending on the design event, and even the most extreme design, while based on a remote event, is not based on the largest, worst-case event. This is a concept that I have not seen in the engineered structural fire safety proposals presented to the DCLU.

Once the code officials and fire protection engineers can come to an agreement as to what are the appropriate standards, design events, models, and factors of safety, then there two areas of research that would have been helpful to DCLU in evaluating the proposals in the four examples above:

1. Effectiveness of fire sprinkler system protection of structures. As discussed in the challenges above; sprinklers are a primary component in any engineered structural fire safety design presented to DCLU. Usually, they end up as adding some extra safety factor as part of the "belt and suspenders" approach. However, a preliminary request was made on the Fred Hutchinson building to use sprinklers to "wet" the columns supporting the stairs, walkways, and roof in the atrium, in lieu of providing code-required 3-hour rated protection. DCLU raised many objections to this concept, and ultimately, the architect provided an approved intumescent paint for protection, hidden by some architectural finishes. However, for the expected fuel load in the atrium, it is probable the sprinklers would have been adequate. There is a question, though, about how far this concept can be pushed. Further research is also required on the reliability of sprinkler systems if they are to be used as the sole source of protection of structures.

2. Validation of computer models of heat release/spread. DCLU approved the Seattle City Hall glass bridge on the basis of such a model, as discussed above, and similar models have been used to justify other engineered fire safety designs (not necessarily structural).

## CONCLUSION

Engineered structural fire protection is increasingly being utilized as an option to prescriptive code requirements for protection of steel structures. As a result, code officials first are in need of guidance as to the standards by which the engineering solutions can be evaluated. Second, in order to raise the confidence level of code officials in engineering solutions, research is needed to validate the models used by the engineer as justification for deviating from the prescriptive code. Once those have been developed, the philosophical barriers still need to be overcome, but at least the fire protection engineer is dealing from a sound technical basis. Technical research can then be guided by the standards.

## REFERENCES:


***"First Interstate Bank Building Fire, Los Angeles, California,"*** Technical Report Series; United States Fire Administration

*"Highrise Office **Building Fire, One Meridian Plaza, Philadelphia, Pennsylvania,"*** Technical Report Series; United States Fire Administration

***"World Trade Center Building Performance Study"***, Chapter 5; Federal Emergency Management Agency

***Uniform Building Code™***; International Conference of Building Officials

***ICC Performance** Code **for Buildings and Facilities™;*** International Code Council

***Building Construction and Safety Code™ (NFPA 5000™)***; National Fire Protection Association

**White Paper 2**
**The Need for Structural Fire Safety Design Methods**
**An Architect's Perspective – *The Who, What, Where, When and How of doingfire safety design.***

**David S. Collins, FAIA**

**A premise: Most** of the public assumes that there is structural fire safety involved in the design of most major buildings. Do we actually understand the risks we face each time .we walk into a building or structure? The architect's role in development of construction documents and the subsequent process of making a building that is safe and will remain safe has varied over time. Our understanding, and by that I mean the entire construction industry's understanding, of the necessary level of fire safety and the means to design to achieve it isn't absolute, nor is it as clear as most of us would like.

A **standard of care:** The typical approach to frre safety design in virtually 100% of major projects constructed today is to rely heavily on a standard of care that has been established through the model building codes. That standard has been an evolving, moving target which responds relatively rapidly to changes in technology and materials development, largely fueled by the materials or systems manufacturing communities, and even responds to disasters with or without adequate justification.

Examining the earliest standards, we know that the value was placed on the ability of the builder to adequately deliver the project that the owner wanted. The penalties for the lack of performance were rather severe, and were simply aimed at the collapse of the structure. An interesting part of Hammurabi's Code is the admonition to the fire fighter to not take any property while fighting the fire.

If fire break out in a house, and some one who comes to put it out cast his eye upon the property of the owner of the house, and take the property of the master of the house, he shall be thrown into that self-same fire.

## WHO

Registration laws throughout the United States and much of the world put the responsibility on the design professional that they approve to be responsible for designing buildings and structures in a safe and sanitary manner. Even the building regulatory system recognizes this approach by referencing "referenced design professionals" directly into the codes.

However, there is a prevailing attitude within our culture that anyone may build or modify his own home without the benefit of a design professional. The statistical results might point out the fallacy of that attitude. Unfortunately, many of the laws have reinforced this and enforcement allows anyone to build their own home with or without the expertise to determine what is necessary or even what is needed. There is little wonder that when these same persons are working in positions of responsibility within corporations and businesses that they may also take a rather cavalier attitude toward the elements of a building structure that may be vital to saving their lives or the lives of the employees and customers that may be in the space.

Later in this paper I will discuss the issues that further compound the design professional's inability to actually determine whether their original design is carried out, leaving to question if there is a valid system for delivery of safe structures.

There is typically a team involved in the design of any project. In the simplest of them, the team may be the architect and the owner making all the decisions. Other more complex projects may involve large numbers of consultants. Focusing only on active fire protection systems, the team may use a consultant, or even a system vendor to assist in the decision making process. The level of involvement and ability to influence the design decisions depend largely on the scope of the project and the ability of the owner and team leader to see the need for added participation.

ARCHITECTURAL TEAM
***Non-Structural***
Consultants – Fire Safety, Sprinkler Designer, Sprinkler Installer

***Structural***
Manufacturers – DOW, 3M
Agencies – UL, Warnock Hersey
Associations – AISI/AISC, PCA/PCI, Gypsum Association, NF&PA

Structural fire resistance is almost exclusively based on the standards within the code and the specifications of the materials provided in the listings. There is very little to guide the designer in making a choice of materials or methods except for the information provided by the specific manufacturer and the various agencies that may also be a part of the manufacturer's product approval process. Compounding the problems for designers is a confusing network of jargon associated with various materials and the information that is provided with respect to the performance characteristics.

For example, there are rules associated with performance of **a** structural member relating to the coverage of the reinforcement of the concrete beam or the thickness of coverage for the fire protected steel beam. The basis for measurement of the performance is the ASTM E119 test procedure which has been under review and has received criticism from various materials interests for several years. Such debate raises questions in the minds of the designer and the specifier regarding the basis for their decision making.

Building codes have also contributed to the level of confusion regarding the appropriateness of protection features. Terminology such **as** "fire-retardant", "fireproof', "fire blocking", "fire stopping", "combustible", "limited combustible" and "fire resistant" are used in various contexts to the point that ASTM E176 says that fireproof is "an inappropriate and misleading term" which was used (and still is today) to describe buildings of a certain characteristic.

All too often the designer depends on the fire protection contractor to provide the necessary design document in order to obtain a building permit. This practice, in my opinion, is paramount to allowing the building contractor to design the building. Again, later in the paper the issues of delivery will be further explored.

**WHAT**

No standard existed in Hammurabi's Code for the fire safety of a structure or the manner of building it except that the walls must be stable to prevent them from falling and killing the members of the owner's household. With the advent of modem building codes the creation of standards for fire protection came into play more and more.

Earliest versions of the modem building codes we use today included both the passive and active fire protection features. The codes have vacillated between which of these systems is the more important to providing the level of safety felt to be appropriate. Hearings are held on a tri-annual basis to determine what changes are necessary to the codes to achieve what?

This systematic process of review and modification could be seen as facilitating changes that aren't necessary, but the reality is that a very high percentage of proposals never make it beyond being introduced for an initial hearing. At the recent International Code Council's Committee meetings in Nashville, there were *598* changes considered to the building and fire codes that in some way would affect how buildings are designed. Of these changes, well over half were rejected by the committee.

What are we hoping to achieve with constantly changing the standard of care we call a building code?

WHERE

We are accustomed to the environment we are working in where the need for fire protection is fairly well laid out in the model buildings codes. Other interests also may initiate additional requirements for protection due to the nature of the property being protected. Insurance companies will often ask for additional levels of protection in order to offset a perceived exposure.

Various standards are in existence which is also useful to provide guidance for certain special types of facilities such as fireworks and explosives. Other conditions such as medical and environmental dangers are not as well explained or understood as part of the development of safety features in building design.

The codes tell us specifically the aspects of the structure that must be protected by passive means. Is there evidence to show that these means are inadequate for normal exposures? At a recent conference in Washington, DC, sponsored by the TISP (The Infrastructure Security Partnership), the conclusion was that there was no need for such a change.

Perhaps one of the most difficult parts of the process of designing for fire resistance is in existing structure that are unpredictable. I have been involved in three major projects over the past five years that involved issues of the predictability of existing construction fire resistance parameters and fire safety design issues.

- University of Cincinnati Medical Sciences Building
- Shillito Lofts Apartments
- Federal Reserve Bank

In each there were unique problems associated with the existing structure that'were major challenges to the design team now charged with retrofitting the buildings for ongoing use.

**WHEN**

Decisions regarding the use of materials and their application to create a fire resistive structure can come at any time during the preliminary design process. There are guides for such decision making, which again leads us back to the building code as the font for all knowledge on the subject

The AIA is involved with the development of MASTERSPEC" as a primary service to architects in preparation of their construction documents. Some interesting excerpts from that document include:

*Several methods, both active (sprinklers) and passive, are possible for protecting steel structures from fire. Designing for fire protection might include dividing a building into isolated modules with a limited number of penetrations for fire-rated doorways, electrical conduits, and ducts. Modules could be protected....*

*Specific fire-resistance design decisions can affect the cost, scheduling, and complexity of sprayed fire-resistive material applications. Careful design for fire protection can avoid some common problems. For example, to forestall problems with warranty limitations and with the vulnerability of roof assemblies protected by applied sprayed fire-resistive materials when subject to construction, maintenance, or repair activities on the roof, roof-ceiling designs might be limited to those assemblies protected by materials other than sprayed fire-resistive materials....*

There is always the listed assemblies to fall back upon as the most easy means of acceptance.

A general outline of the specification section from MASTERSPEC© on sprayed fire –resistance materials would include the following:

General
Related documents
Summary
Definitions
Submittals
Qualifications
Delivery, storage, and handling
Project conditions
Coordination
Warranty

Products
Manufacturers
Concealed sprayed fire –resistive materials
Exposed fire-resistive materials
Exposed foamed magnesium oxychloride fire-resistive materials
Exposed intumescent mastic fire-resistive coatings
Auxiliary fire-resistive materials

Execution
Examination
Preparation
Installation, general
Installation, concealed sprayed fire-resistive materials

Installation, exposed sprayed fire -resistive mat4erials
Field quality control
Cleaning, protecting and repair

**HOW**

The methods by which the contracts are executed are often the most important part of the entire process fi-om my perspective. **AIA** has taken positions on the various means of delivering designs. Following this section are various statements regarding those methods and the federal governments documents for securing design services **as** well as the ABA's model procurement procedures.

Generally, the procedures follow one of the following procedures.

- Qualifications based Selection
- Fee Based Selection

Methods of Delivery

- Design Bid Build
- Design Build
- Multi Prime Contractors
- Construction Management
- Quality Control
- Value Engineering

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## White Paper 3
## Framework for Structural Fire Engineering and Design Methods

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## PREFACE

This paper was developed for the NIST/SFPE workshop to develop a National R&D Roadmap for Fire Safety Design and Retrofit of Structures. The scope is to review overall methodology aspects of structural fire engineering within the context of design methods, procedures and standards for structural engineering, including probabilistic and risk aspects. Many sources of material were reviewed in preparing this paper, only a portion of which are formally referenced in the paper. Other sources, which are not specifically referenced, but are useful background are listed in the bibliography

## INTRODUCTION

In the broad scheme of things, ***structural fire engineering*** encompasses only a small but essential aspect of fire protection engineering and risk management. By definition, structural fire engineering should involve close coordination between fire protection engineers and structural engineers, but this has not generally been the practice in the United States. Instead, requirements for structural fire protection are largely handled through prescriptive building code provisions, which are often employed under the architect's scope of work. There are other reasons for the lack of coordination. Compared to other structural loadings, fires are usually not a primary structural design consideration, except for instances where fire considerations impose constraints on the design, such as relating to the choice of structural materials for high hazard facilities or minimum thickness of floor slabs for thermal barriers. Moreover, as compared to other design loads, the life safety and economic losses due to fires are usually governed by "non-structural" considerations (smoke, burning of contents, egress, etc.) where the structural response is not a major factor. This is in contrast to most other load effects (gravity, wind, earthquake), where the losses begin with the structural response, i.e., where excessive structural deformations or collapse will precipitate events that lead to significant economic losses, injuries, and potentially casualties. In these cases, the external hazards (the loads) are largely pre-determined, such that the only way to affect performance is through structural design. In fires, on the other hand, there are many factors associated with fire ignition, suppression, fuel loads, compartmentalization, etc., which can be altered through fire protection engineering that affect the imposed risk (through fire loads) on the structure. This is illustrated in Figure 1, where the topic "provide structural stability" is one of many "leaves" in the fire safety concepts tree. Indeed, one of the important incentives for performance-based building codes is to tailor structural fire protection requirements based on other measures taken to reduce the chance of structurally significant fires.

In terms of overall economic and life-safety risks, the "optimum" structural performance targets for fire conditions should be considered relative to other risks and overall cost/benefit considerations. Assessment and design procedures for structural fire engineering should permit alternative approaches to achieving the desired safety, which has the potential to dramatically change current practice. Evidence, which will be cited later, suggests that for certain construction types and occupancies, structural risks from fire are considerably smaller than from other hazards. Thus, in some cases, it may be appropriate to relax structural fire requirements from current practice, provided that one can quantify and demonstrate the benefits of such changes. The first priority for research and development should be to develop procedures, models and criteria to assess performance in terms of meaningful economic and life-safety metrics. The next priority would then be to develop minimum building code requirements, considering relative risks to other hazards and cost/benefits of alternative fire protection measures. Ideally, the performance framework should inform rather than mask fire risk management decisions.

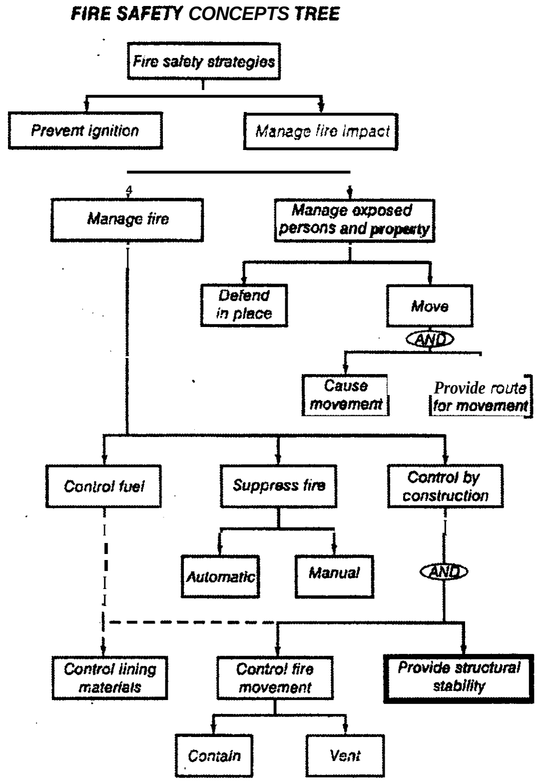


Figure 1 – Conceptual framework for **fire** ***safety*** (Buchanan 2001)

Risk is often conceived of as the probability or likelihood of an event coupled with the consequences resulting from that event. However, translating this general concept of risk into a quantifiable methodology is not straightforward. In particular, how one defines the "event" and "consequences" depends upon ones perspective. In the most general sense, the event of interest should be the likelihood fire ignition with the consequences being injuries, deaths, and economic losses resulting from fire. Alternatively, from the standpoint of ***structural*** frre engineering, the "event" could be conceived of **as** excessive structural deflections with the "consequences" being breach of a barrier between fire compartments. While this general concept of risk can help guide the discussion, the risk framework needs much more specificity to articulate and quantify the many events and consequences that make up fire engineering. Ideally, the framework will permit one to achieve desired outcomes of reduced risk through alternative means, e.g., providing the means to trade-off measures that affect the likelihood of a structurally significant fire (e.g., use of sprinklers) against other measures to limit the impact of such a fire (e.g., thermal insulation of structural members). Indeed, this is is one of the motivations behind the ***ICC Performance Code*** (2001). Quoting from the ***User's Guide*** to this code, "Under prescriptive codes, the typical failure rates of systems are sometimes compensated for by requiring redundancy. One of the perceived advantages of a performance based design is that it might allow the designer to minimize redundancy in order to achieve efficiency by increasing the reliability of the systems and/or strategies used to implement the design." (pg. 119, ICC 2001).

Performance-based engineering and standards should ultimately enable more transparent and direct assessment of risks, which in turn will lead to more informed and effective risk management. This goal, however, is not equally recognized or embraced by all those working on performance-based engineering. To many, performance-based engineering simply represents the move away from prescriptive design requirements to ones that are more scientifically based. This view is particularly appealing to researchers (including the author) interested in developing and applying technologies to simulate structural response to extreme loadings. Simulation technologies are an essential part of performance-based engineering, however, they are only part of the overall goal to provide a methodology that can inform risk decision-making. An equally important challenge to performance-based methods is the development of statistical data and models to characterize hazards and uncertainties throughout the entire process – from the fire hazard through to the consequences of fire. Quantification of risk should be in terms of parameters or metrics that can inform the relevant decision makers, including building owners, building code officials (representative of society at large and emergency responders), insurance and finance organizations, and other stakeholders.

***Overview of Paper Organization:*** With the objective to contribute to establishing an overall framework for performance-based structural fire engineering, this paper is structured along the following lines. First, the key structural behavioral effects and design parameters associated with fires are briefly reviewed. These effects, along with models and criteria to assess them, will be dealt in greater detail in other papers at the workshop. The discussion here is intended to set the stage for this paper's main emphasis on a methodology for performance assessment and design. Second, the issue of "acceptable risk" is discussed, with the objectives to first consider how to phrase the question of risk and then look at fire risks relative to the failure probabilities implied by current practice for other structural loadings. Third, the concepts of the International Code Council's proposed Performance Code (ICC 2001) are summarized and discussed. Next, and perhaps most central to this paper, a comprehensive framework for performance-based structural fire engineering is introduced. The proposed framework is modeled after a comparable framework for performance-based earthquake engineering under development by the Pacific Earthquake Engineering Research (PEER) center. Apart from providing a methodology for codes and standards development, the framework provides an effective means to organize research for developing the data, models and criteria necessary for implementing the framework. Following the presentation of the detailed methodology, some concepts are proposed to envision adaptations of the framework for simplified design provisions appropriate building code implementation. Included is some discussion of design approaches taken by the Eurocodes and recent initiatives of the American Institute of Steel Construction. Finally, the paper concludes with a summary of recommendations for research and development priorities.

## BEHAVIORAL EFFECTS AND DESIGN PARAMETERS

Fire effects on structures primarily have to do with structural response of materials, members and systems under high temperatures that occur during a "structurally significant" (post-flashover) fire. An accurate structural fire assessment will generally require information describing the time history of elevated temperatures in all of the structural members and the applied gravity loads. Temperature distributions in the structural members are, in turn, a function of (a) the fire compartment(s) temperatures, often described through a time versus temperature curve, (b) spreading of the scenario (or design basis fire) to adjacent compartments through convection and or destruction of compartment boundaries, and (c) heat transfer models to relate temperatures in the compartment to those in the structural members and connections. Generally speaking, the fire temperature response can be calculated independently of the structural response, with the exception of cases where excessive structural deformations or collapse lead to breaching of'fire barriers and fire spread and growth.

The basic effects of high temperatures on steel and concrete are thermal expansion, reduced stiffness (elastic modulus), and reduced strength. In addition, concrete may be subject to temperature induced cracking and spalling, which depend on the build up of internal pressure associated with the formation of water vapor from inherent moisture and whether the vapor can be dissipated. Studies of high strength concrete (50 to **120** MPa) have shown it to have a higher rate of strength loss under high temperatures and more susceptibility to spalling due to higher cement paste density (Buchanan 200**1).**

## ACCEPTABLE RISK

In debating minimum standards for structural safety, the establishment of an "acceptable risk" level will invariably arise. Though relevant to the issues in performance-based codes, phrasing the issue in terms of "acceptable risk" can be more distracting than it is helpful. In a report on organizational and societal considerations for performance-based earthquake engineering, Peter May (a political scientist at the University of Washington) writes, "The notion of acceptable risk, while common in engineering, is one of the more disputed notions within the risk literature itself." (May 2002). Quoting risk scholar Baruch Fischhoff, May goes on to note, "Many debates turn on whether the risk associated with a particular configuration of a technology is acceptable. Although these disagreements may be interpreted **as** reflecting conflicting social values or confused individual values, closer examination suggests that the acceptable-risk question itself may be poorly formulated."

May argues against attempting to establish "acceptable risk" in an absolute sense, because this approach is not consistent with how risk management decisions are made. Rather than focusing on what risk is "acceptable", May argues that development of performance-based guidelines and standards should emphasize tools and strategies to evaluate risk in a manner to permit the stakeholder to make informed choices about how to manage the risk. The question of "acceptable risk" should be recast into a "discussion of desired safety goals, the costs involved of achieving these, and the trade-offs imposed". Thus, the "challenge is not only one of assembling collective views about safety but also of effectively communicating the trade-offs in attempting to achieve different levels of safety".

While heeding May's caution not to become pre-occupied with defining what the "acceptable risk" is, it is nonetheless useful to contrast structural fire safety risks with those implied by current building codes and standards for other hazards.

***Gravity loads and wind:*** In a recent reassessment of wind loading provisions, Ellingwood and Tekie **(1999)** propose matching the strength limit state under combined gravity and wind loads to the implied safety under gravity loads. As a basis, they use provisions developed in about twenty-five years ago (Galambos et al., **1982;** Ellingwood et al., **1982;** Ravindra **&** Galambos, **1978),** which established the still current ASCE **7 (2003)** gravity load combination of **1.2D +** 1.6L and design resistance factors for steel structures (AISC-LRFD **1999).** They report the *mean annual probability of failure* ($MAP_f$) under dead and live loads to be approximately $MAP_f =$ 0.0007 **($7 \times 10^{-4}$),** where "failure" is defined **as** the strength limit state associated with exceeding the nominal plastic yield strength of a structural member. Their proposal for a new gravity plus wind load combination (1.2D + 0.5L + 1.6W) targets a comparable failure rate ($MAP_f = 0.0007$). The specific load factors are chosen to result in a failure probability of (0.0007) where the nominal wind load is based on wind speeds with a roughly 500-year recurrence interval (approximately 0.002 mean annual probability of exceedence). The difference between the wind load probability and the failure probability is the result of the load factors, the statistical combination of three loads (D, L and W), and the resistance factor applied to the nominal strength. Their load combination recommendation has since been adopted into ASCE 7 **(2003).**

***Earthquakes:*** The target failure probability under combined gravity loads and earthquakes is more difficult to quantify due to the assumptions regarding dynamic inelastic behavior that are built into the earthquake loading and design provisions. Given the fact that the earthquake risk to buildings is dominated by the earthquake hazard, a first-order approximation to the failure probability implied by current codes is the return period associated with "maximum considered earthquake" under which structures are not expected to collapse. Roughly speaking, the "maximum considered earthquake" used as the basis for ASCE 7 **(2003)** is based on a 2,500 year return period, which translates to an annual probability of exceedence of 0.0004 ($4 \times 10^{-4}$). While this is about half the failure probability associated with the gravity and wind load limits, one must remember that the definition of "failure" is different in this case. For earthquakes, the target performance under the maximum considered earthquake is structural collapse, as opposed to the yielding limit state used to evaluate failure probabilities for other loads. Thus, in terms of overall structural collapse, the associated failure probability for gravity and wind loads is probably less than that for earthquakes.

***Nuclearpowerplants:*** Another reference point to gage minimum performance targets are the failure rates for nuclear power plants – an area which as received significant attention and scrutiny. The target safety goal for standards of the Nuclear Regulatory Commission are based on a mean reactor core damage probability of **IO·′** per year from all causes (Cornel1 **2003).** Using as the design basis and earthquake hazard recurrence rate of $10^{-4}$, the expected failure rate from seismic effects is estimated at $10^{-5}$. Comparing these to the figures cited above (0.0007 for gravity and wind load limit states and 0.0004 for collapse under earthquakes), the reactor core failure target from all events is about four to seven times less, and the failure target from seismic effects is about 40 to 70 times less. One should be cautious about making a literal comparison of these rates, since the definitions of "failure" are different for each situation, and the standards applied in design and construction are more stringently controlled for nuclear power facilities. Nevertheless, the comparisons provide some basis to evaluate what is deemed "acceptable".

***Fire:*** How do the limits mentioned above compare to the structural risks due to fire? In a paper looking at load factor combinations for fire, Ellingwood and Corotis (1991) cite a mean annual probability of a structurally significant (flashover) fire in modern office buildings of about $10^{-6}$. This is based on an assumed mean annual ignition probability of $10^{-4}$ for a $100m^2$ office building and a conditional probability of flashover given ignition of **IO·′.** They go on to propose a load combination for combined gravity and fire effects, which reduces the probability of failure by another order of magnitude – down to $MAP_f = 10^{-7}$, which is generally held to be the minimum threshold for perceiving risks. The proposed load combination of 1.OD + 0.5L + 1.OF (where F denotes the fire-induced effects) represents the "arbitrary point in time" gravity loads, with a mean annual exceedence probability of about $10^{-1}$. Similar criteria to this are used in ASCE 7 **(2002)** for design against "extraordinary events" (e.g., blast or fire) with assumed mean annual probabilities of occurrence of $10^{-6}$ to $10^{-5}$.

***Risk Informed Decision Making:*** Taken at face value, the statistics cited above indicate the probability of *occurrence* of a significant fire occurring is roughly one to two orders of magnitude less than the probability of *structuralfailure* for other hazards. Thus, one might conclude that the *structural* fire hazard is a non-issue. This is in stark contrast to current practice, where structures are designed to resist the rare structurally significant fire events. The obvious question is, why should one design against a hazard with such a low probability of occurance relative to other significant hazards? In light of the comments made previously about "acceptable risk", the point here is not to attempt an answer to this question. But it is important to raise this question, since the notion of "risk informed" and "risk consistent" decision-making is central to the gains to be realized through performance-based design.

There are many arguments one can make for and against using calculated risk to argue for changes in current practice. Complicating these discussions is the fact that the risk argument would suggest relaxing current practice, which in light of September 11 is contrary to the direction of public sentiment on fire safety. Without going into great detail, the following are some factors to consider in advancing risk-informed decision-making:

- *Accuracy offailure probabilities:* To have any credence, failure probabilities need to be backed up with solid data and verifiable models to quantify all significant aspects of the fire safety problem, from the likelihood of fires through to evaluation of their consequences. This is a key challenge throughout performance-based engineering methodologies and technologies.

- *Identifying stakeholders and their interests:* Collective consensus on minimum safety or other issues, requires that the key constituencies be identified and their concerns voiced in a productive manner. Firefighters, for example, will not necessarily see their individual risk mitigated by a low probability of the occurrence of a significant fire, as compared to the structural performance given a fire.

- *Communication of risk andperformance metrics:* Measurements of risk and performance need to reflect the ways that stakeholders relate to risk. For some stakeholders, a rigorous probabilistic presentation (i.e., mean annual probabilities or expected values) are appropriate, whereas for others, scenario descriptions would be more effective.

- *Benefit-cost tradeoffs:* Risk decisions are best made in the context of considering trade-offs of benefits and costs, For example, increasing the risk of one consequence may be considered acceptable if it results in reductions of other risks or improvements in other performance, e.g., trading off fire insulation of a steel frame in favor of sprinklers and improved alarms to detect and suppress the likelihood of a fully developed fire.

- *Quality and assurance in design, construction and operations:* Performance-based design solutions often involve increased reliance on predictable and reliable performance. For structural fire engineering this could range from accurate calculations of fire loads and heat transfer in design to reliable operation of fire suppression equipment. Thus, acceptance of the calculated risk will often require increased trust in the process of design, construction and operation.

- ***Comprehensive assessment of performance and consequences:*** A common dilemma in developing building code provisions concerns the tradeoff between crafting general provisions that are practical to apply versus provisions that are best tailored to a specific situation. As a result, building codes tend to emphasize a "one size fits all" approach, which are too conservative in some cases and not conservative enough in others. One can imagine, for example, that in setting minimum failure probabilities for structural collapse, one would need to know the consequences of collapse. To some extent, codes address this through the designation of building "use groups" or "performance groups". Ideally, performance-based approaches should articulate performance metrics that will provide more accurate and comprehensive measures of performance in terms of a common set of metrics related to safety (injuries and casualties) and economic losses.

## INTERNATIONAL CODE COUNCIL'S - PERFORMANCE CODE

Building code provisions can generally be considered to serve three basic purposes. First, the codes articulate minimum standards and criteria by which buildings should be designed and constructed. Implied by these minimum requirements are desired levels of performance for functionality and safety. Second, the codes and underlying specifications establish the responsibilities and limits of liability between the various parties (e.g., design professionals, code officials, manufacturers, and contractors) involved in the design and construction. For example, ASTM material testing standards provide a basis upon which the design engineers, material manufacturer, and contractor share a common view of the properties of a specified construction material or product. Third, the codes and standards provide a compendium of validated models and criteria for designing to meet the implied performance.

Current building codes have evolved in a way that has not clearly distinguished between these three different purposes, the result being that the performance targets implied by the codes are not apparent through the maze of specified procedures and prescriptive design requirements. This is particularly true for fire and earthquake engineering, where the underlying phenomena and science are so complex that, until quite recently, prescriptive "deemed to comply" provisions provided the only practical way to do routine design. The difficulty is that much like legacy software code, which was originally designed with a simpler purpose in mind, building codes and standards are being challenged to the point that a major overhaul is needed.

The ICC ***Performance Code*** (**ICC** 2001) outlines a new fiamework that articulates the performance intent and design standards through a hierarchical organization of (a) performance objectives, (b) functional statements, and (c) performance requirements. Shown in Table 1 is a conceptual representation of acceptable performance targets, where the performance target (describe in terms of mild, moderate, high or severe damage) is specified **as** a function of building performance group (occupancy and function for a facility) and the magnitude/likelihood of hazard events. The basic concept is to accept more severe damage under less frequent hazard events in less important buildings. This table is **an** adaptation of one originally developed with earthquake hazards in mind (SEAOC Vision 2000), and the representation is not **as** well suited to structural fire engineering – the main reason being that significant fires tend to be binary events **as** opposed to the continuum hazard implied by the vertical column in the table. Nevertheless, this graphic provides a concise way to characterize the basic performance tradeoffs in risk decision-making. Following below are some specific details and discussion of the *ICC* ***Performance Code (200***1) related to structural fire performance.

Table 1 – Maximum level of tolerable damage based on performance group and design hazard event (ICC 2001).

| MAGNITUDE OF DESIGN EVEN (INCREASING MAGNITUDE OF EVENT) | INCREASING LEVEL OF PERFORMANCE → PERFORMANCE GROUPS: Performance Group I | Performance Group II | Performance Group III | Performance Group IV |
|---|---|---|---|---|
| VERY LARGE (Very Rare) | SEVERE | SEVERE | [illegible] | [illegible] |
| LARGE (Rare) | SEVERE | [illegible] | MODERATE | MILD |
| MEDIUM (Less Frequent) | [illegible] | MODERATE | MILD | MILD |
| SMALL (Frequent) | MODERATE | MILD | MILD | MILD |

***ICC -*** General Requirements: The following is a summary of some general performance and risk-acceptance concepts proposed in the ICC ***Performance Code*** approach:

- **Performance Group Risk Factors:** These are factors to articulation the risk to occupants in a facility, taking into account the nature of the hazard, the number of building occupants, the length of time the building is normally occupied, whether or not people sleep in the facility, familiarity of the occupants with the facility layout and means of egress, the vulnerability state of the occupants (particularly with respect to ability to egress). Risk to the occupants, together with the importance of the facility's function **to** the community, are used to establish the performance group of a facility between use group I, II, 111, or IV. Note that the performance group categories are geared toward minimum life safety considerations and, with the possible exception of Category IV (essential facilities), do not consider economic loss issues.

- **Structural Performance:** Structural performance of facilities is distinguished between four levels, which are characterized **as** follows:

  - o ***Mild*** – no structural damage, safe to occupy, comparable to what FEMA **356** (2003) would classify as "immediate occupancy".

  - o ***Moderate*** – moderate but repairable localized structural damage, some delay in re-occupancy, major nonstructural systems operational, low likelihood of life loss, and very low likelihood of multiple life loss. Structure will retain nearly all pre-hazard event strength and stiffness.

  - o ***High*** – Significant structural damage, but no large falling debris. Repair is technically possible, but may not be economical with significant delays in re-occupancy. Significant nonstructural damage, including light debris and disruption to egress. Injuries locally significant with risk to life, but moderate in numbers. This might be considered comparable to what FEMA 356 terms "life safety".

- *Severe* – Substantial structural damage, but no collapse. Significant degradation in strength and stiffness in lateral system, large permanent deformation, and more limited degradation to vertical system. Structure is not safe to re-occupy, and repair may not be technically possible, Significant risk to life may exist, and an additional event (such as an earthquake aftershock) could cause collapse. This state is similar to the FEMA 356 designation of "collapse prevention".

***ICC - Structural Stability:*** On the topic of structural *Stability,* Chapter 5 of the ICC states the *objective,* "To provide a desired level of structural performance when structures are subjected to the loads that are expected during construction or alteration and throughout their intended life. (pg. 19, ICC 2001)." The *functional statements* make additional general statements to the effect that the structural design should limit the threat to life safety, injury protection, and property/amenity protection to levels consistent with Table 1. The *performance requirements* state that structures "shall remain stable and not collapse during construction or alteration and throughout their lives" and "shall be designed to sustain local damage, and that structural system as a who shall remain stable and not be damaged to an extent disproportionate to the original local damage" (the latter point addressing the issue of progressive collapse). Note that these functional statements are very explicit in stating that structures "shall not collapse" and do not make any mention of probabilities or uncertainty. On the other hand, *performance requirements* on functionality provide more latitude through statements such as, structures "shall have a low probability of causing damage or loss of amenity through excessive deformation, vibration or degradation."

Specific reliability levels for "shall not collapse" and "low probability" are left ambiguous, except by specified relations between the expected load magnitudes (small, medium, large, and very large) and anticipated mean return periods. These are summarized in Table 2, along with a conversion fiom mean return period to mean annual probabilities of exceedence. A literal comparison of Tables 1 and 2 (e.g., the expectation of *severe damage* under *very large* loads for Performance Group II) indicates that the implied damage return periods varies dramatically by load type, suggesting need for more explicit thinking about failure probabilities for load effects and their combinations under extreme events. Fire loading is absent from this list of loads and specified return periods in the ICC *Performance Code,* although fire and other extreme loadings (blast, wind borne debris) are cited as considerations for design.

| Load Type | **Mean Return Period of Loads (approx. mean annual probability)** | | | |
|---|---|---|---|---|
| | **Small** | **Medium** | **Large** | **Very Large** |
| **Wind** | **50** *yr (0.02/yr)* | *75yr (0.013/yr)* | *100 yr (0.013/yr)* | *100 yr (0.013/yr)* |
| **Floods** | *100 yr (0.01/yr)* | *500 yr (0.002/yr)* | *case specific* | *case specific* |
| **Snow** | | ***30 yr (0.033/yr)*** | ***50 yr (0.020/yr)*** | ***100 yr (0.033/yr)*** |
| **Earthquake** | *25 yr (0.04/yr)* | *72yr (0.014/yr)* | *475 yr (0.002/yr)* | *2475 yr (0.0004/yr)* |
| | | | | |

***ICC on Fire Performance:*** The users guide to the ICC *Performance Code* acknowledges that the relationships between magnitude of event and level of damage given in Table 1 are not appropriate for fire loads for the reason mentioned previously. The code also expresses the view that the life safety risks from fire should be less than for other loads. Quoting from the *Users Guide*, "Generally, society has a very low tolerance for death or serious injury caused by fires, especially in larger numbers in a single incident." (pg. 131, ICC 2001). Whether or not one agrees with this statement is a topic for discussion. However, the ICC *Performance Code* uses this sentiment as justification to establish a single life-safety performance level of mild impact for all fire events. Referring back to Table 1, this implies performance criteria required for fires equal to that associated with small and frequent events for wind, earthquake and other loads listed in Table 2.

Specific criteria concerning fires and fire safety appear in other chapters of the *ICC Performance Code*. Highlights of those provisions most directly associated with structural fire are summarized below:

- **Limiting Fire Impact and Fire Impact Management (Chapters 6 & 17)**

  *Objective (1701.1):* "To provide an acceptable level of fire safety performance when facilities are subject to fires which could occur... during construction or alteration and throughout the intended life"

  *Functional Statements (I 701.2):* "...design with safeguards against the spread of fire so that no person not directly adjacent to or involved in ignition of a fire shall suffer serious injury or death from a fire and so that the magnitude of property loss is limited as follows:"

  Performance Group I – High Damage
  Performance Group II – Moderate Damage
  Performance Groups II & IV – Mild Damage

  The functional statements also stipulate that, "Buildings and facilities shall be designed and constructed so that the firefighters can appropriately perform rescue operations, protect property, and utilize fire-fighting equipment and controls."

  *Performance Requirements (1701.3):* "Facilities ... shall be designed, constructed, and operated to normally prevent any fire from growing to a stage that would cause life loss or serious injury ... Facilities shall be designed to sustain local fire damage and the facility as a whole will remain intact and not be damage to an extent disproportionate to the original local damage"

  *Structural members* and *assemblies (I701.3.11).* "Structural members and assemblies shall have a fire resistance appropriate to their function, the fire load, the predicted fire intensity and duration, the fire hazard, the height and use of the building, the proximity to other properties or structures, and any fire protection measures"

  *Magnitude of fire event (I701.3.15).* "Design fire events shall realistically reflect the ignition, growth and spread potential of fires and fire effluents that could occur ..."

  *Engineering analyses of potential fire scenarios (I 701.3.15.3).* "Quantification of the magnitudes of design fire events shall be based on engineering analyses of potential fire scenarios that can be expected to impact a building throughout its intended life ..."

*Relationship of design **fire** to* tolerable *damage.* "When determining (assigning) the magnitude of a design fire event, the physical properties of the fire and its effluents shall only be considered in terms of how they impact the levels of tolerable damage."

*Safety Factors.* "Design fires and fire scenarios shall be chosen to provide appropriate factors of safety to provide adequate performance by accommodating for the following factors:
1. Effects of uncertainties arising fiom construction activities
2. Variations in the properties of materials and the characteristics of the site.
3. Accuracy limitations inherent in the methods used to predict the fire safety of the building.
4. Variations in the conditions of facilities, systems, contents and occupants.'

- **Emergency Responder Safety (Chapter 21)**

  *Objective:* "To protect emergency responders from unreasonable risks during emergencies.''

  *Functional Statements: "...* protect against unanticipated structural collapse."

  *Performance Requirements: "* Buildings and structures shall be designed, constructed, loaded and maintained so that the potential for structural collapse is predictable based on the construction method, building condition, and fire size, location and duration."

  Regarding this performance requirement, the ICC User's Guide (pg. 173, ICC 2001) notes, "The committee realizes that it is neither economically feasible nor even realistic to design and build structures and facilities in such a manner that collapse or failure could be eliminated in every instance regardless of the incident circumstances.

***Observations on ICC Fire Provisions:*** The *ICC Performance Code* outlines a reasonably good framework to describe the minimum acceptable performance criteria; however, there is clearly room for discussion and refinement as to what the performance the criteria should target. In particular, one can question that blanket assertion regarding the public's risk tolerance for fire and the requirement that structures be designed for "mild impact" for all fires. Statements made in later sections of the code, such as the discussion of safety factors under fire management and safety of emergency responders, seem more realistic in their performance expectations, given the low probabilities and large uncertainties associated with severe fires. Beyond providing a basic framework to describe minimum acceptable Performance, the current version of the code does not provide much specificity on methods and criteria to assess performance. As such, there is considerable room for research and development to move the code from its present form to the stage of implementation in design practice.

**PERFORMANCE-BASED METHODOLOGY FRAMEWORKS**

In many respects, the challenges faced with performance-based fire engineering are similar to those of performance-based earthquake engineering. Hazards in both cases are low-probability high-consequence events, quantification of which involves complex nonlinear behavior with considerable uncertainties. As such, current design methodologies for both earthquakes and fire rely on prescriptive semi-empirical techniques, which do not offer information to inform risk management decisions and may not provide cost-effective design solutions.

Considerable progress has been made over the past ten years to develop performance-based approaches for earthquake engineering and fire protection engineering; although, for a variety of reasons, these developments have largely occurred separately in the structural (earthquake) engineering and fire protection engineering communities. In spite of this, the development of the performance-base approaches share many features, beginning with a more scientific definition of the hazard and accurate simulations of the structural response to that hazard. One of the persistent challenges in both arenas is to develop strategies for translating descriptions of structural response to meaningful performance measures for risk management and stakeholders.

Since one of the goals of structural fire engineering is to integrate it more into the mainstream of structural engineering, it is proposed to consider structural fire engineering in the context of a performance-based earthquake engineering methodology that is gaining acceptance among structural engineers. The following discussion begins with an overview of a methodology for earthquake engineering that has developed over a number of years, most recently through concerted efforts of the Pacific Earthquake Engineering Research (PEER) Center and the FEMA ATC-58 project. These latest efforts build on concepts that were first envisioned for seismic loss assessment on a regional scale (e.g., HAZUS) and for performance assessment and design of steel buildings (e.g., see Cornell et al. 2002 for the probabilistic underpinnings of the assessment procedure in the FEMA-SAC Guidelines). Following a brief overview of the methodology for earthquakes, a complementary approach for fire engineering is proposed.

***Performance Framework for EARTHQUAKE Engineering:*** **As** outlined in Table **3,** the proposed fiamework for performance-based earthquake engineering characterizes the performance assessment process into four steps, each of which emphasizes a different discipline focus. Data between each step is organized into four generalized variables, defined as *Intensity Measure, Engineering Demand Parameters, Damage Measures, and Decision Variables.* Unambiguous articulation of these variables is key to the framework organization.

TABLE 3: ATTRIBUTES OF PBEE (EARTHQUAKE) METHODOLOGY

| PROCESS | VARIABLE | DISCIPLINE | PARAMETERS | EXAMPLES |
|---|---|---|---|---|
| Seismic Hazard Analysis | IM | seismology & geotechnical engineering | fault location<br>type and length of rupture (magnitude of event)<br>site/soil conditions | • $S_a(T_1)$<br>• PGA, PGV<br>• Aires intensity<br>• ... |
| Structural Analysis | IM→EDP | structural & geotechnical engineering | foundation and structural system<br>dynamic mass & damping<br>... | • story drift<br>• floor accelerations<br>• component forces & deformations<br>• ... |
| Damage Assessment | EDP→DM | structural, mech. & elec. engrg.; construction; architecture; loss modeling | deformation sensitive component fragilities (walls, beams, columns)<br>acceleration sensitive component fragilities (equipment, contents) | • component strength/deformation limits<br>• damage (repair) states<br>• hazards (falling, blocked egress, chemical release, etc.)<br>• collapse |
| Loss & Risk Analysis | DM→DV | construction & cost estimating; loss modeling | occupancy<br>time of earthquake<br>post-eq recovery resources | • fatalities<br>• direct $ losses<br>• repair time/downtime |

The ***Intensity Measure*** (***IM***) describes the seismic hazard at the building site in terms of a seismic hazard determined from a probabilistic seismic hazard analysis considering the seismologic parameters summarized in Table 3. Current practice is to define *IM* in terms of spectral acceleration for the first mode period of the structure, $Sa(T_1)$, which relects important aspects of the ground motion amplitude and frequency content. However, alternative ***IM*'s** are sometimes used, such as peak ground ground velocity (*PGV*). The best IM is one that best reflects the damaging features of earthquake ground motions, i.e., those aspects of the ground motion which correlate best to the resulting building response and damage. Determination of ***IM*** is largely in the discipline of engineering seismology. For routine design, the *IM's* are codified in the form of hazard maps, which are incorporated in building codes and standards; whereas, for unique or important structures, the ***IM's*** would be determined from a site-specific hazard analysis.

Given the ground motion intensity, the next step is to conduct structural analyses (static or dynamic inelastic analyses) to simulate the building response and determine the Engineering Demand Parameters, ***EDPs.*** The ***EDPs*** are response measures that can later be related to Damage Measures (*DMs*), which describe the consequences of the response. Two common ***EDPs*** are peak interstory drift ratios and floor accelerations; other more localized ***EDPs*** include element forces, hinge rotations and generalized strains. The *DMs* quanti@ the damage and consequences of the damage as they affect cost of repairs, safety, and other considerations. For example, *DMs* for architectural wall partitions include relationships between peak inter-story drifts (the ***EDP)*** and damage states ranging from minor (hairline cracking, requiring spackling and painting of walls), moderate (replacement of some wallboards, taping, spackling and painting) to severe (demolition and full wall replacement). ***DMs*** for structural elements may describe similar damage states, in addition to the impact of the damage on the performance of the overall structural frame. ***DMs*** for building contents and equipment may relate to damage and the consequences of damage, such as hazards posed by toppling heavy equipment or hazardous chemical release.

Given a full description of the damage state through the ***DMS,*** the final step is to quantify Decision Variables **(*DVs*),** which express the performance in terms relevant to the owner and other stakeholders. The ***DVs*** include risk of casualties (deaths and serious injuries), direct dollar loss (repair costs and lost inventory), and downtime (duration of repairs). Recognizing the large uncertainties in each step of the performance evaluation, the ***DVs*** are described in a probabilistic sense, as an annual mean rate of exceedence or alternative metric that describes the uncertainties. For example, the direct dollar losses could be described as the mean annual probability that the direct dollar loss exceeds a percentage of the replacement cost of the facility; mathematically, this can be expressed as $\lambda(DV) = \lambda$***(dollar loss > X% replacement cost).*** An alternative would be to express the ***DV*** in terms of a scenario, e.g., given the occurrence of an earthquake of magnitude M on a nearby fault., there is a Y% confidence the direct dollar loss will not exceed X% of the replacement cost.

Underlying the proposed methodology is the recognition of there being significant uncertainties and variability in each stage of the process. Thus, descriptions of each variable and the models relating them should be formulated to include both the characteristic value (e.g., a mean or median response) and the uncertainty associated with each quantity. Based on the total probability theorem, uncertainties in the assessment process are tracked through the following framework equation:

$$\lambda(DV) = \iiint G\langle DV|DM\rangle dG\langle DM|EDP\rangle dG\langle EDP|IM\rangle d\lambda(IM) \qquad (1)$$

where the term ***G[DV |DM]*** represents the conditional probability that ***DV*** exceeds a given value, conditioned on ***DM; dG[DM |EDP]*** is the derivative of the conditional probability for *DM* with respect to ***EDP;*** and similarly for ***dG[EDP|IM].*** The last term on the right, $d\lambda(IM)$, is the derivative of the seismic hazard curve, which defines the mean annual frequency (MAF) of exceeding a specified IM, e.g., a 0.002 *MAF* (or 10% in 50 year chance) of exceeding a specified spectral acceleration level.

The form of Equation (1) implies that the intermediate variables **(*DMs*** and ***EDPs)*** are chosen such that the conditional probabilities are independent of one another and conditioning information need not be carried forward. This implies, for example, that given the structural response described by ***EDP***, the damage measures (DMS) are conditionally independent of **the** ground motion intensity (*IM*), **i.e.,** there are no significant effects of ground motion that influence damage and are not reflected in the calculated ***EDPs.*** The same can be said about the conditional independence of the decision variables **(*DV*)** from ground motion IM or structural ***EDP,*** given ***G(DV|DM).*** Likewise, the intensity measure (*IM*) should be chosen such that the structural response ***(EDP)*** is not also further influenced by, say, magnitude or distance, which have already been integrated into the determination of ***dλ(IM).*** Apart from facilitating the probability calculation, this independence of parameters serves to compartmentalize discipline-specific knowledge necessary to evaluate relationships between the key variables.

***Performance Framework for FIRE Engineering:*** Much like performance-based earthquake engineering, performance-based fire engineering is based on the premise of achieving performance goals set by various interested parties—owners, regulators, code officials, society, etc. As noted by Custer and Meacham (1997), despite the various efforts and huge volume of research world wide, to date there is not a single, generally accepted framework, for performance-based fire engineering. It is therefore proposed, that the aforementioned methodology for earthquake engineering provides a generic framework to model the various aspects and complexities of performance-based fire engineering as well. The overall goals would be the same as in performance-based earthquake engineering, i.e., the ability to relate design decisions to quantifiable risk assessment of life safety and economic factors. Note that the framework itself does not dictate specific target risk levels, rather the focus is only on a methodology to evaluate the risks in a scientifically quantifiable way.

Summarized in Table 4 is a framework for performance-based fire engineering, which is analogous to the earthquake-engineering framework in Table 3. Items listed in the table focus mainly on the structural engineering aspects of fire engineering, but the general framework is envisioned as extendable to the broader concerns of fire protection engineering. A key feature of this fiamework is separation of the performance-assessment into four unique processes, where information between the processes is described unambiguously in terms of the four general variables, *IM*, *EDP*, *DM* and *DV*. As with the earthquake framework, one of the motivations of this approach is to clearly articulate the role of the various professional disciplines and the handoff of information from one discipline to another.

Referring to Table 4, the first step is a probabilistic fire hazard analysis, which culminates in the probabilistic definition of a fire intensity measure, *IM*. For structural fire engineering, the obvious *IM* would be a description of temperatures in the structural members. However, alternative measures such as maximum compartment temperature or normalized heat load are other candidate *IMs*. For the purposes of probabilistically characterizing the uncertainties in *IM*, it is preferable for the primary *IM* hazard variable to be a scalar quantity (e.g., maximum temperature), as opposed to a vector of multiple variables (e.g., maximum temperature plus time to maximum temperature). One might envision that the internal temperatures are described by a probabilistically determined characteristic maximum temperature, supplemented by descriptions of the spatial (and perhaps temporal) temperature gradients throughout the structural members. As summarized by the parameters in Table 4, calculation of the temperature depends on the likelihood of a flashover fire and characterization of the compartment gas temperature (compartment geometry and boundary materials, fuel load, and ventilation) and heat transfer into the structural members (thermal insulation, thermal mass, structural configuration, etc.). An example of the process by which one could develop a probabilistic fire *IM* hazard curve (expressed in terms of material temperature) are presented later. As with *IMs* to characterize earthquake hazards, one could imagine codified ways to determine the structural temperature *IM* in several ways – ranging from tabulated values for certain classes of building occupancies and configurations, to parametric fire curves, or by case-specific assessment by fire scientists and engineers.

**TABLE 4: Attributes of Probabilistic PBFE (fire) Methodology**

| PROCESS | VARIABLE | DISCIPLINE | PARAMETERS | EXAMPLES |
|---|---|---|---|---|
| Fire Hazard 4lysis | *IM* | Fire science and fire protection engineering | - likelihood of structurally significant fire (plume, pre-flashover, & post flashover )<br>compartment geometry and thermal properties<br>- ventilation<br>- **fuel** load & burning rate<br>- fire insulation<br>- structural configuration and fire exposure | • ***maximum steel temperature***<br>• compartmentgas time-temperature curve<br>• normalized heat load ... |
| Structural Analysis | *IM→EDP* | structural engineering | - structural model<br>- fire scenario & steel temperature distribution<br>- steel mechanical and thermal properties<br>- applied gravity loads<br>- ... | • component forces<br>• inelastic deformations<br>• deflections<br>• ... |
| Damage Assessment | *EDP→DM* | Structural and fire prot. engineering; construction; architecture; loss modeling | - damage fragility curves of smoke and thermal barriers<br>- damage fragility curves of structural components<br>- collapse hazard (either local, global, or progressive) | • strengthlimit states<br>• structural damage (repair) states<br>• barrierbreach<br>• local or global collapse |
| L m & Risk Assessment | *DM→DV* | construction & cost estimating; risk assessment; loss modeling | - occupancy<br>- hazardous contents<br>- alarms and egress efficiency<br>- fire duration/endurance<br>- external risk factors (e.g., impact on neighboring buildings) | • casualties (occupants, first responders)<br>• direct $ losses<br>• repair duration & downtime |

Given the maximum steel temperature *(IM)* and guidance on likely fire scenarios (e.g., distributions of the steel temperatures among various compartments, various steel members, and gradients through members), structural engineers can then perform analyses to determine the effects of thermal expansion and degradation of material properties on EDP demand measures, such as induced member/connection forces, deflections, and inelastic deformations. The *EDPs* are next related to *DMs*, such as the impact of structural deformations and induced forces on the structural elements and fire/smoke barriers. Note – it should be emphasized that the present discussion and parameters in Table 4 are limited to structural fire protection - a subset of the broader issues related to fire endurance of the barriers themselves and other fire protection and egress systems in the building.

Finally, information from the *DMs* is next used in loss modeling and risk analyses to determine the *DVs*. In terms of life safety (casualty) risks, this would include the risk to building occupants from (a) smoke/fire, associated with breaches in the fire barriers and blocked egress, and (b) injuries fiom local or global structural collapse. Risks to emergency responders relate more to risks from structural collapse, although sudden breach of major barriers also presents a life safety risk to emergency responders. The two other *DVs* related to economic consequences (repair costs and associated downtime) can likewise be determined from the *DMs*.

An important feature of the comprehensive evaluation, from *EDPs* through to *DVs*, is that it provides generalized performance metrics that feed directly into quantitative risk assessment, thereby avoiding the need for ad-hoc judgments to relate the structural performance to the consequences. For example, current building codes typically differentiate fire insulation requirements for buildings based on the building height and floor area to account for the consequences of a structural collapse. In moving towards performance-based approaches, the goal should be comprehensive approach provides for consistent evaluation through to the final decision metrics, whereby the end result is a direct measure of consequences (e.g., probabilistic measure of fatalities, injuries, or economic losses). One would not want to, for example, apply advanced models and data to evaluate likelihood of collapse, only to then resort to ad-hoc judgments of the consequences of the collapse (e.g., to decide how much more unacceptable is the collapse of a two, ten, or twenty story building).

Implementation of the proposed methodology will require models and data to calculate the necessary parameters. Further, since the intent is to rigorously account for the many uncertainties in the process, the models and data should be formulated so as to provide the conditional probabilities required for Equation (1). These conditional probabilities should account for both intrinsic variabilities in the underlying data and phenomena (aleatory variability) and those associated with lack of data or modeling simplifications (epistemic uncertainties). Although not comprehensive, many of the major parameters that would need to be considered are listed in Table 4.

**Evaluation of Fire Intensity Measure:** To demonstrate the process of evaluating the fire hazard IM in the performance-methodology, the following discussion example is presented to determine the maximum temperature in a steel beam. In terms of Eq. 1 (the total probability equation), the goal is to define λ(IM), i.e., a "fire hazard curve" which describes the mean annual probability of exceeding a specified steel temperature. Calculation of λ(IM) can be broken down into the following equation, which is another application of the total probability equation:

$$\lambda(IM) = \iint dG\langle IM \mid FO\rangle) dG(FO \mid F\rangle \lambda(F) \tag{2}$$

where, λ(F), is the probability of ignition, dG[FO |F] is the conditional probability of flashover, given ignition, and dG[IM |FO] is the conditional probability of the steel reaching a certain temperature, given flashover. The integrations of Eq. 2 imply taking account of all possible fire event scenarios and the uncertainties in all aspects of the problem. Data for the last two terms of Eq. 2 are available from a number of sources (e.g., Buros 1975, Ellingwood 1991, CIB 1983); in this example the following values are assumed **P(FO|F) = 1x10-2** and **P(F) = $8.1\times10^{-4}$.** As ignition and flashover are discrete (binary) events, the integrations involving F and FO turn out to be simple multiplications to give *MAP[FO]* = 8 *x* lo". The remaining discussion treats the conditional probability of the steel temperature, given flashover, i.e., *dG[IM* |FO].

Assuming flashover has occurred, calculation of the resulting steel temperature *(IM)* is based on fire duration, fire gas temperature in a compartment, heat flux imposed upon the inside surfaces of a compartment, or enclosure boundary, and heat transfer into the steel member. These in turn are based on the processes of the fuel consumption, the ventilation rate, and the heat transfer process. Fuel consumption and the ventilation rates are based on the type of fuel, amount of fuel, distribution of fuel, geometry of compartment, ventilation area and shape, and the thermal characteristics of the compartment boundaries. Components of heat transfer are geometry of compartment, ventilation area and shape, and the thermal characteristics of the compartment boundaries. Clearly, it is difficult, if not impossible to precisely quantify all of these variables - hence, the motivation to describe the variables and the resulting structural material temperature in a probabilistic sense.

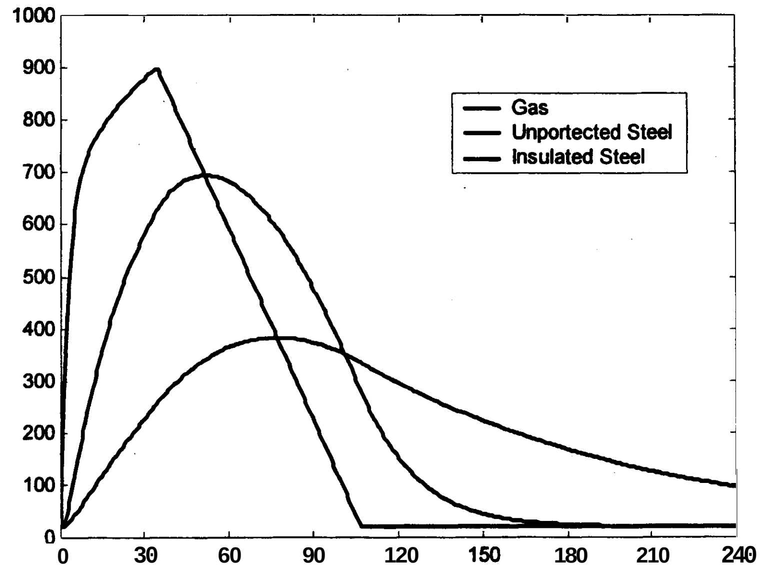


Figure 2 – Time versus temperature relationship for fire compartment gases and steel beam (unprotected and insulated)

As show in Figure 2, a standard way to calculate steel temperature is through a two-step process – the first involving calculation of gas temperature in a compartment, and the second the steel temperature from the gas temperature. Given the time dependency of both processes, the calculations are interconnected. This interconnection is the primary reason for choosing the steel temperature, rather than gas temperature, as the *IM*. Otherwise, had gas temperature been chosen for the scalar *IM*, we would have been faced with the need to estimate the maximum steel temperature with only information about the peak gas temperature (as opposed to the full time versus gas temperature relationship).

The compartment gas temperature can be modeled using a parametric fire equation, such as one from Appendix A of Eurocode 1 (equation A.l, ECS 2001), where the gas temperature is given as a function of a variable that accounts for ventilation, enclosure properties, fuel load, and other parameters related to fire activation and growth (equations A.2 to A.12 of Eurocode 1). Parameters, which have a significant outcome on the results (e.g., ventilation, fuel load, and enclosure properties), are specified as random variables, where the mean values are based on characteristic values for the specific structure, combined with coefficients to describe the variability. In some cases, data are available to describe the random variables, e.g., Eurocode 1 includes data to describe the fire load in terms of a Gumble distribution. However, for most variables probabilistic descriptions are not generally available, which presents **an** important research and development need to apply the probabilistic model with confidence.

Using the compartment gas temperature, the next step is to calculate the steel temperature using **a** standard heat transfer equations, which take into account any insulation on the beam. Key variable parameters in these equations include (a) the ratio of exposed surface area to volume of the steel member, (b) thermal convection and emissivity coefficients, (c) insulation thickness, specific heat, and thermal connectivity of insulation – each of which can be probabilistically described with characteristic (mean) values and variability coefficients. **As** with the **gas** temperature calculations, there is a need for more complete characterization and reporting of statistical properties of key parameters.

Models and random variables for the gas temperature and heat transfer can be combined and evaluated through Monte Carlo simulation or other reliability methods. Shown in Figure 3, is an example of the resulting steel temperature (*IM*) curve that would result fiom the process just described. This specific example shown is of a W24 steel beam in a typical office building (Hamilton et al. 2002). The result of the Monte Carlo analysis is used to determine the conditional probability, $dG[IM|FO]$, which is the probability of reaching a specified maximum steel temperature ($T_{steel} = IM$) given the gas temperature curve associated with flashover, FO. The conditional probabilities are related to the mean annual steel temperature hazard curves for an unprotected and protected beam shown in Fig. 3 by integrating (or in this instance multiplying) $dG[IM|FO]$ with the probabilities of ignition and flashover.

There are a number of interesting observations to note from Figure 3. First, the combined probabilities of ignition and flashover result in a probability of a flashover fire of $5 \times 10^{-5}$, which is in itself quite low relative to other structural hazards mentioned before. Further reduction in probabilities below this point (i.e., the sloping of the temperature hazard curves) reflect the

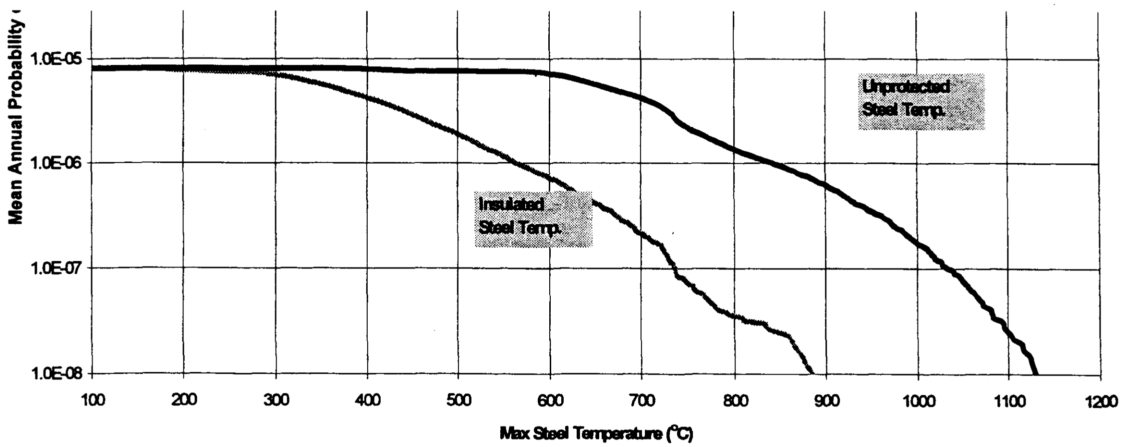


Figure 3 – **Hazard** curve for maximum steel temperature (maximum steel temperature versus mean annual probability of exceedence)

variations of assumed fire load in the Monte Carlo analyses. Second, assuming a "critical design temperature" of about 540°C (when the strength and stiffness of steel drops to about half its original value) we see that the probability of the unprotected beam reaching this temperature is equivalent **to** the probability of flashover, whereas for the protected beam, the insulation reduces the probability of reaching this temperature by about an order of magnitude. Thus, from a risk perspective, the cost of the fireproofing would be judged against the perceived benefit of reducing the probability of reaching the critical temperature fiom about $10^{-5}$ to $10^{-6}$. An additional factor not apparent in these numbers is that the unprotected beam reaches the critical temperature in about **35** minutes versus about 100 minutes for the protected beam.

Finally, certain stakeholders, such **as first** responders, are likely to view risk performance not in terms of the total probability, but rather, from the standpoint that a flashover fire has already occurred. This would imply disaggregating the □*(IM)* hazard into the pre- and post-flashover components, and processing the downstream calculations for ***EDP, DM*** and ***DV*** independently of the ***IM*** probability. Referring back to **Eq.** 2, this can be handled by setting $P(FO|F)P(F) = 1$, which essentially would shift the vertical intercept of the fire hazard curve in Fig. 3 to be 1. Here the role of themal insulation would be to reduce the probability of the beam reaching its critical temperature from 1 to 0.1.

Evaluation ***of*** *EDP-DM-DV:* Given the maximum steel temperature hazard, **as** described by the $\lambda(IM)$ fire hazard curve of the type shown in Fig. 3, the next step would be to calculate the effect of the increased temperature, together with other simultaneous loads, on the structure. This step entails structural analysis, the output of which would be ***EDPs*** (see Table 4), including deflections, forces and inelastic deformations in member and connections, and indices for local and/or global collapse. Following the probabilistic fiamework equation, Equation (1), the analyses should be conducted to describe the demand parameters (response quantities), conditioned on the maximum steel temperature, resulting in the conditional probability relationship $dG(EDP|IM)$. The variability in this step results from assumptions regarding member temperature distributions, structural modeling assumptions, gravity load magnitudes and distributions, and material properties at elevated temperatures. Thus, given the maximum steel temperature (scalar fire *IM*), one must still make choices regarding the distribution of temperatures through the member, the distribution throughout a compartment, and the distributions in adjacent compartments.

Analyses relating *IM* (steel temperature) to ***EDP*** (response), can either be simplified component based analyses or comprehensive nonlinear analyses. The type of analysis will affect the choice of ***EDPs.*** A simplified component analysis would consist of calculating the member forces and deflections (the EDPs) for the specified temperature and mechanical loading. These would then be related to performance criteria, described in terms of discrete damage measures *(DM).* For example, do the imposed member forces exceed the strength calculated at the elevated temperature, thereby suggesting the onset of local collapse? What are the deflections, which may cause damage to adjacent fire barriers? If warranted, a more detailed and in depth nonlinear analysis of the entire structure could be performed, which explicitly models nonlinear temperature effects (thermal strains and degradation of material properties). For comprehensive analyses, emphasis would be to track performance via the deflections and inelastic deformations, e.g., permanent sag, or displacement of beams, local buckling of members, or runaway deflections – the latter signifying the onset of local or global collapse.

Once the EDPs are determined, *DMs* can be calculated, reflecting damage to structural elements and thermal barriers, and the life safety and economic implications of this damage. A significant difference between earthquake and fire damage concerns the relationship of nonstructural to structural damage. In earthquakes, essentially all damage to structural and non-structural components (and building contents) can be related to the structural motion (deformations and accelerations). This is not the case for fires, where most of the nonstructural and content damage is due to heat and other fire load effects, which are related to but distinct from the heat induced structural deformations. Thus, the most important aspects of the structural *DM* evaluation (*DMs* caused by structural *EDPs)* are likely to be those associated with (a) life safety implications of structural forces and deformations imposed on nonstructural heat/smoke barriers from the structural frame, (b) localized failures in a fire affected region that lead to progressive collapse, and thereby impose life safety and economic losses much larger than those caused by the fire itself, and (c) permanent inelastic damage to structural components and systems, which impact post-fire repair costs.

## ISSUES IN CODIFYING PBFE DESIGN PROVISIONS

The methodologyjust described is intended to outline a rigorous assessment method, which is based on detailed simulation of the fire growth, heat transfer, structural performance, and consequences of the performance. Obviously, such a detailed methodology would not be applied routinely in design; but, rigorous methodologies of this sort are important for developing and calibrating simplified methods and criteria for engineering practice. Equally important, the detailed breakdown of the assessment into its constituent parts provides a systematic way to organize research and development necessary to develop the data and technologies necessary to do accurate assessments.

There are a number of ways that the detailed procedures could be simplified for codification in design standards, while preserving important features of a performance-based approach. For example, much in the same way that load and resistance factors are applied to establish limit state checks with a defined probability of exceedence, so too might such methods be applied to target specified limit states or performance points for structural fire engineering. As noted previously, Ellingwood and Tekie (1999) have proposed gravity load combinations for use in conjunction with a fire analysis. They assumed the fire loading and associated limit state as extreme events, and hence they limited their consideration to uncertainties in the gravity load effects. A more complete methodology, would take a account of the statistics and models for fire ignition, growth, and heat transfer to develop temperature intensity hazard information, such as discussed above. Codified procedures could be developed to include load and resistance type factors (partial safety factors) on the fire temperatures and structural resistances to target specified failure probabilities. Such procedures could be modeled after an approach described by Cornel1 et al. (2002), which determines factors of this sort for a simplified probabilistically based assessment for steel structures under earthquakes.

## RESEARCH AND DEVELOPMENT NEEDS

Listed below is a summary of research and development needs to further the development of performance-based assessment and design procedures for structural fire engineering. Many of the needs related to validated models and data, which should be envisioned to determine both characteristic values supplemented by appropriate uncertainty measures and statistics. The modeling needs and format should be clearly formulated ahead of time in terms of input/output variables, so as to fit into the overall performance assessment methodology.

- ***Methodology Development:*** Much work is needed to further develop and refine the methodology framework proposed herein to organize data, models, and criteria into a consistent methodology to' apply for the assessment of fire hazards on structures. The framework should be one that relates to models and approaches common to the structural engineering and fire protection engineering communities. The methodology should establish language and terminologies, with clear definitions to facilitate information sharing between disciplines. One approach would be to adopt the four general terms proposed for performance-based earthquake and fire engineering ***(IM, EDP, DM,*** and ***DV),*** and to describe these in very specific terms within the context of structural fire engineering. Early research on the methodology should investigate significance and sensitivity of the outcome to model parameters, so as to guide research needs on validated models (see next item).

- . ***ValidatedModels:***

  - o Fire Ignition/Flashover: Probabilistic models, statistics and criteria to characterize risk of fire ignition and flashover as a function of occupancy, construction type/quality, fire suppression systems, and other salient features of buildings. Models should be scientifically based, and to the extent possible should reflect clear cause-effect relationships between the input parameters and the fire risk. Mechanisms should be developed and put in place to continually track and update these models as a function of recorded fire events.

  - o Compartment Temperatures: Validated models, statistics and criteria time-temperature compartment temperatures as a function of (a) fire load (combustible materials), (b) ventilation, (c) size and geometry of compartment, (d) thermal properties of the compartment enclosure, (e) fire suppression/fire fighting, and other salient compartment characteristics. Parametric curves in the Eurocodes are a good starting point, but these should be examined and validated based on US construction.
  - o Multi-compartment fire scenarios: Validated models and approaches to quantify multi-compartment fire scenarios, accounting for such factors as (a) risk of simultaneous ignitions due to earthquakes or other outside influence, (b) inter-compartment spread through compartment boundaries by convection, including the statistical probabilities of unanticipated openings in compartment enclosure (c) inter-compartment spread through building facades, and (d) effectiveness and reliability of fire suppression measures.

  - o Heat Transfer: Validated heat transfer models and data to relate compartment temperatures to temperatures in structural members. For steel framed structures, this should include data on common thermal insulation materials and heat transfer in beams cast integrally with concrete slabs or other heat sinks. For structural concrete, the models should describe temperature gradients through concrete and in embedded steel reinforcing, taking into account concrete cracking and the potential for spalling.

  - o Structural Materials & Elements: Validated models to simulate performance of structural materials, members and subassemblies under high temperatures. Primary emphasis should be on materials and systems most common to construction, including structural steel framing, composite steel beam and composite deck floor systems, structural concrete with mild and post-tensioned reinforcement, and other structural construction materials at elevated temperatures.

- Simulation Models: Development and validation of computer modeling techniques for structural systems, taking into account three-dimensional large deformation response under temperature effects (thermal expansion plus material degradation). Validation could be through both comparisons to sophisticated finite element models and to selective large-scale system tests.

- ***Risk Decision-Making:***

  - Articulation of safety and performance metrics. Determine appropriate decision variables (DVs) and metrics to describe fire performance to key decision makers.

  - Risk Communication and Perception: Investigate and implement ways to communicate risk to key stakeholders, with an emphasis on relative risk and cost-benefit decision making.

  - Educational materials and guidelines to help inform building code officials, owners, insurers and other stakeholders about structural fire hazards and the benefits and costs of alternative strategies to manage risk.

- ***Building-Code Implementation:*** Proactively pursue the development and implementation of building code provisions, along the lines that has been done for earthquake engineering. Involve appropriate professional organizations (ASCE, SFPE, SEA, ATC), industry groups (AISC, ACI, fire protection industry), practitioners and researchers involved in structural and fire protection engineers, and key stakeholder groups (building code officials, fire safety officials).

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**White Paper 4**
**Relationship Between Structural Fire Protection Design and Other Elements of Fire Safety Design**

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## INTRODUCTION

Broadly stated, the goals of fire safety design are to limit life loss (both civilian and firefighter), property loss, and enterprise interruption costs. These goals are achieved by limiting the spread of fire and by limiting the extent of smoke and heat spread to people, building contents, and building systems. The general methods for controlling these hazards include passive fire protection, active fire protection, manual firefighting, detection and alarm, egress systems, smoke management systems, and contents/finish control.

Few of these fire protection methods act in only one way. For instance, active fire protection systems, like sprinklers, limit the spread of fire, limit the production (and hence spread) of heat and smoke, as well as detect the fire. Passive fire protection systems like firewalls are designed to limit fire spread, but also serve to limit smoke and heat spread, and facilitate firefighting. Even egress systems, like stair enclosures, function to limit the exposure of people to smoke and heat, while also playing a role in fire department access and safe staging for firefighting. Detection and alarm systems function to alert occupants, as well as the fire department. Smoke management systems provide people and property protection from smoke and heat, while facilitating firefighting. Contents/finish controls limit the initiation and spread of fire within spaces, while lessening the severity of the fire exposure to passive fire protection features and limiting the challenge to active fire protection systems. The multiple roles of individual fire safety systems and the time-dependent interaction of these systems in defining the fire hazard and risk are the sources of the complexity in assessing fire safety performance.

## ELEMENTS OF FIRE SAF'ETY DESIGN

To facilitate further discussions of the interaction of structural fire protection design with the other elements of fire safety design, each element of fire safety design will be reviewed for those less familiar with fire protection engineering practice.

### *Passive Fire Protection*

Passive fire protection includes both the provision of fire resistance to structural elements and systems, as well as building construction features designed to limit fire spread. It is understood that in most buildings, many elements function both structurally and as a barrier to fire spread. The most common examples of this duel function are floor systems and bearing walls.

Building elements are classified as structural fiame, bearing walls, nonbearing walls and partitions, floor construction, and roof construction. Each element classification has its own fire resistance rating requirements. There are many instances when characterizing structural elements is less than straightforward, and the value of making such distinctions is less than clear. Current approaches to structural fire protection call for fire resistance ratings based on these classifications.

In addition to the requirements for fire resistance ratings for structural elements/assemblies, limitations on building height and area, and requirements for horizontal and vertical fire barriers are called for in current regulations. The goal is to prevent the spread of fire beyond defined limits. In order to be effective, these barriers need to prevent the passage of flame, limit heat transfer, and must remain in place. In the latter regard, there is an additional relationship between limiting fire spread and structural fire protection, since excessive deflections in the structure can lead to loss of integrity of fire barriers against flame passage. If a fire barrier is built integrally with a structural beam, the deflection of the beam due to fire exposure can lead to damage to the integrity of the barrier.

***Active Fire Protection***

While in general, active fire protection includes any type of fire suppression system, for most buildings the automatic fire protection is provided by fire sprinkler systems. Most sprinkler systems are designed to control a fire to a limited area. Final extinguishment relies upon the intervention of firefighters. Sprinkler systems are hydraulically designed based upon one or more available water supply sources (e.g., municipal mains, elevated tanks, pumped storage). If the fire grows beyond the design capabilities of the supporting hydraulic system, then fire control is no longer expected.

***Detection and Alarm***

Detection and alarm systems are designed to detect the presence of a fire and communicate with building occupants and emergency services concerning the fire. Modern fire alarm systems should be thought of as a computer-based emergency monitoring and communication system. Smoke and heat detectors, valves, flow switches, fans, and emergency lighting are monitored. In the event of a fire, the system provides information to the emergency services and building occupants. The monitoring functions provide centralized information to emergency responders upon their arrival. Of course, detection and alarm systems do nothing themselves to suppress or mitigate fires.

***Smoke Management Systems***

These systems generally operate upon detection of a fire to control the movement of smoke within the building. These systems support safe evacuation of building occupants, limit heat and smoke damage, and support manual firefighting efforts. Most systems make use of the building HVAC systems, though in single story warehouse and industrial facilities, natural vents that remove smoke through roof vents through the action of buoyancy are often used. In tall buildings, stairway pressurization systems are widely used to maintain smoke-free conditions within the egress paths and additional zoned areas of supply and exhaust are used to further limit smoke spread.

***Egress Systems***

Provisions are made in all buildings for safe means for occupant escape in the event of a fire. The exit pathways are bounded by fire rated construction and are often protected by smoke management systems. Emergency lighting is provided to support evacuation. The alarm system is an integral part of the emergency egress system, notifying occupants and, in some cases, managing the evacuation process. General design practice provides for multiple exit paths in most cases.

*Contents/Finish Control*
Building and fire codes generally limit the contents and use of a facility based upon the occupancy of the building with the goal of limiting building use consistent with the provided fire protection. The use of combustible materials as wall linings is generally regulated. Fuel loads are not limited, but are assumed to be characteristic of the occupancy. These assumed fuel loads underlie the fire resistance ratings required by building regulations.

*Manual Firefighting*
The local fire department provides manual fire suppression and occupant evacuation support for all buildings. Some buildings or facilities provide an in-house fire brigade as the initial first aid firefighting. Support for firefighting operations generally includes hydrants and standpipe systems, with additional support from active, passive, detection and alarm, and smoke management systems for both firefighting and rescue operations. Whether the fire is limited by passive fire protection systems or controlled by automatic systems, the fire department is generally relied upon for the ultimate extinguishment of a fire.

Each of these fire protection systems has a defined capability and finite reliability. Multiple systems work together to achieve fire safety and multiple means provide redundant capabilities to limit fire, heat, and smoke in the building. The recognition of finite reliability and the need for redundant design are the basis for the balanced design approach implicit in most codes. No single system should be relied upon solely to achieve fire protection objectives.

## INTEGRATION OF RATIONAL STRUCTURAL FIRE PROTECTION IN FIRE SAFETY DESIGN

The required structural performance in fire will be determined by occupant egress, firefighting, and property protection considerations. However, the required resistance of the structure to fire to achieve these objectives will also be determined by the other means to limit or control the fire. In the current code requirements, these interactions give rise to what are known as trade-offs. The classic example of a structural fire protection trade-off is the lessening of hourly rating requirements if sprinklers are provided. Currently, such trade-offs are numerous and are introduced on an ad hoc basis with no firm foundation in terms of assuring equivalent or better performance. The performance of the basic requirements is not known and the effect of the trade-off on performance is not determined.

There are two levels at which rational structural fire protection design can be integrated with fire protection design. The first and most ambitious is through the implementation of an overall rational fire safety design method. The second and less ambitious method is to design rational structural fire protection to prevent structural collapse within the current code environment. Both approaches will be discussed here, beginning with the simpler approach. However, it is instructive to review the current basis and methods of assuring structural performance in fires.

*Current Structural Fire Protection Design*
The roots of the current method of protecting structures from fire date back over a century to the era of urban conflagrations and associated building collapses (AISI, 1971). Building components and assemblies (floor assemblies, columns, bearing and nonbearing wall assemblies, penetration protection assemblies, door assemblies) are exposed to a standard fire exposure, assumed to represent the severity of natural fires. The standard test method, ASTM E-119, uses a component or assembly with a length scale of roughly ten feet. Based on ad hoc structural and thermal test

endpoints, a fire resistance rating, in hours, is determined. No engineering data is generated fiom the testing.

The required fire resistance rating is assumed to be determined by the fire load density alone (not ventilation or thermal properties of the boundaries), based on the **1920s** work of Ingberg at NIST (then NBS). Required fire resistance ratings are set based upon the anticipated fuel load for the occupancy, as well **as** the height and area of the building.

The current design method makes no use of modern structural analysis methods, of modem fire dynamics, or of modem heat transfer analysis. It assumes that the performance of a less than real scale component test is representative of real scale structural performance and ignores the central role of ventilation in compartment fire dynamics. Clearly, we can do better with little or no new science. However, there is a need to develop design methods, performance criteria, engineering data, and a code infrastructure to allow rational structural fire protection to be implemented.

***Simple Approach to Integration***

The basic goal of structural fire protection is to prevent extensive building collapse due to a fire in a building. This can be realized if the damage to the structure is limited to that area directly affected by fire. This means that loss of load carrying capability by secondary structural members in the fire is not inherently problematic and loss of primary structural members in the fire area is acceptable as long as load redistribution to the remaining structure is effectively accomplished. If the fire area is well defined, this can in principle be accomplished without the provision of fire resistance and without consideration of the role of fire protection measures. However, even in this simplified approach, fire barriers, active systems, and firefighting will be the means for defining and limiting the fire area, and in fact the structural system must be designed to allow fire barriers to fulfill their intended fbnction.

More typically, structural members will be provided fire resistance through the provision of some form of thermal resistance to fire. Taking credit for the residual strength of the structural members exposed to fire then requires that the thermal exposure to the members be properly characterized and the thermal performance of fireproofing materials/assemblies needs to be known.

Inherent in the balanced design philosophy is the realization that performance must be assured when all systems perform as designed and that defined levels of safety must be achieved even in the event of at least one system failure. For structural fire protection, the current code requirements implicitly require that structural failures need to be prevented in the absence of active fire protection, manual firefighting, or fire barriers. This implicit requirement dates back to the development of fire resistance rating requirements that are linked to occupancy via expected fuel loads and the fire severity linked to the consumption of that fuel load as determined by the work of Ingberg at NIST in the **1920s.** The ability to pass the E-119 test for the required duration is assumed to assure that there will be no structural failure without respect to the physical extent of the fire exposure beyond the structural assembly tested in the furnace. Clearly, in the light of our modem understanding of structural fire protection, this assumption may be exceedingly conservative in some instances and exceedingly non-conservative in other instances.

In determining the system failures appropriate for design, it is worth considering the nature of system failures expected for various systems. For active fire protection systems, it is generally appropriate to consider that when the system is successful, the fire does not grow to become structurally significant. However, when system failures occur, the fire generally will approximate the fire severity expected without the protection system. Thus, for active fire suppression systems, the most significant metric is the success or failure probability, given a fire start. Based upon available studies, the success probability is in the range of 0.9 to 0.95 (Bukowsi, Budnick, and Shemmel, 1999). For manual firefighting, the success probability is a function of the fire size on arrival, manpower, water supply, and passive fire protection system capabilities (Marchant et al., 2001, Sardqvist, 2000). For manual firefighting, it is unlikely that a single success probability can be used to assess performance. For fire barriers, the success probability is a function of the fire severity, the presence and quality of penetrations, and the general quality of the construction. While we speak of the passive fire protection as a system, for the most part the individual fire barriers are largely independent systems, so that passive fire protection also cannot be characterized by a single success probability, even if made appropriately dependent on fire severity and construction. Setting appropriate deterministic design points for structural fire protection design is desirable for simplicity of use, but determination of the design points requires some assessment of the total fire protection system performance and reliability.

In addition to assuring protection from structural collapse, it is important to assure that structural deformations will not cause failures in fire barrier performance. Fire barrier and structural protection are often very much integrated. Deformations of a beam that do not have serious structural consequences may cause failure in the performance of a floor or wall system that acts as a fire barrier. Systems susceptible to this behavior must be avoided or protected to prevent fire barrier failure due to structural deformations.

Fire areas are generally determined by the fire barriers present. The likelihood of various fire areas can be determined using the Building Firesafety Engineering Method (Fitzgerald, 1986). This method assesses the performance of automated, manual firefighting and fire barrier performance through network diagrams. While the method as developed by Fitzgerald uses subjective probabilities, statistical and analytical methods of assessment can be used at any desired level of detail.

In particular, a simplified approach to determining the frequency of a structurally significant fire exposure for a series of compartments separated by fire barriers can be assessed. Here we consider a sprinkler system, fire department operations, and fire barriers as the available means of limiting a fire. We begin with the frequency at which established fires occur, $F_{EB}$. One would expect the frequency of reportable fires to be deduced from fire statistics. A fire will be prevented from becoming a significant threat to the structure if it is extinguished by a sprinkler system with likelihood, $P_{SP}$, or if the fire department is able to control the fire in its early stage of development, $P_{FD}$. This likelihood is, of course, dependent upon the available means to detect a fire and the capabilities of the fire service. Thus the frequency of a structurally significant fire, $F_{SS}$ in the compartment is

$$F_{SS,1} = F_{EB,1} (1-P_{SP,1}) (1-P_{FD,1})$$

The characteristics of the fully developed fire are determined by the fuel load, the ventilation, and the bounding surfaces thermal properties. The fully developed fire environment exposes both the structural elements in contact with this compartment as well as the fire barriers that form the compartment. Spread to an adjacent compartment is largely dependent upon the ability of fire barrier to resist the thermal insult in the first compartment, $P_{B,12}$, augmented by sprinklers, $P_{SP,2}$, and the fire department, $P_{FD,2}$, to defend the fire barrier. This can be expressed as

$$F_{SS,2} = F_{SS,1} (1-P_{B,12}) (1-P_{SP,2}) (1-P_{FD,2})$$

Typically, the probability of success of the sprinkler system in the second compartment would be very low. The probability of the fire department defending the fire barrier will depend upon the barrier performance, the extent of the barrier, and the fire department capabilities. This analysis process can be extended recursively to additional compartments. To a first approximation, time dependent analysis is limited to the submodels for defining the component probabilities. The result of this process is a frequency distribution for the fire area. The structural element temperatures and resulting structural response need to be assessed for fire areas with frequencies above a threshold value. Acceptable consequences would need to be assured, based upon the frequency of the fire area involvement.

***Global Integration of Structural Fire Protection Design with Total Fire Safety Design***

The integration of structural fire protection design with an overall rational fire protection design can be approached through a comprehensive risk assessment methodology, such as CESARE-RISK (Beck, 1997), FIRECAM (Yung et al 1997), FIERA (Hadjisophocleous and Torvi, 2000), or the Carlton University (Hadjisophocleous and Fu, 2003) building risk assessment models. The performance of the suite of fire safety features needs to be understood both individually and together. This means that designers of individual fire protection systems are provided with performance and reliability requirements.

Creating such a methodology requires analytical tools such as CESARE-RISK, which models the performance of the total fire safety system for a set of code provisions. CESARE-RISK was developed to assess expected building performance under existing code provisions and to assess the equivalency of alternate deemed to satisfy requirements. Since there are currently no established research projects in the U.S. to develop such a global fire safety risk model, it is clear that rational structural fire protection design should not wait for the development of the global risk model approach. The elements of the simpler structural fire protection methodology will be able to be integrated into a global fire risk model when such methodologies are developed and validated.

## NEEDED RESEARCH

The primary research need is the development of the overall design methodology framework. This includes the development of the design approach and the methods for determining component probabilities and probability distributions. This effort should be scheduled early in the development process to assure that the outcomes of component development efforts will clearly fulfill the needs of the overall methodology. Additional research required includes the development of validated models for the following:

1. compartment fire time-temperature histories;
2. heat transfer to and through structural and barrier assemblies;
3. mechanical response of structural and barrier assemblies;
4. structural response of the building system;
5. sprinkler reliability and effectiveness model;
6. fire department effectiveness model; and
7. suite of fire test methods to support design method.

## BENEFITS OF A RATIONAL STRUCTURAL FIRE PROTECTION METHODOLOGY

This method of integration with the overall fire safety design is simple and straightforward. It has the benefit that realistic structural fire exposures and realistic structural response methodologies can be applied to enhance the reliability of the design performance with a minimum of interactions with other frre safety systems design. Clearly, the interactions with fire barrier performance cannot be avoided. Since much of the enhanced response methodologies are equally applicable to fire barrier design, it seems efficient and natural to extend structural fire protection design methods to include all fire resistance aspects of building design. The incremental developmental work is incremental and the benefits in extending design reliability are substantial.

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## White Paper 5
## Design Fire Scenarios

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### INTRODUCTION

Fire resistance is typically designed into structures to protect against failure in the event of fire. The design of fire resistance of structures has historically been based on prescriptive requirements that have their basis in research conducted in the early 1900's. These methods typically prescribe minimum fire resistance ratings for individual structural elements based on a number of building characteristics such as occupancy type and building height.

While structures that are designed based on these requirements have a history of excellent performance in fires, by not considering the fire exposures to which structures might be exposed and structural response at elevated temperature, these prescriptive requirements do not provide a true measure of structural performance in fire. Additionally, it is clear from fire experience that structures built according to existing methods do not necessarily perform the same in fires.'

The most effective way to determine true structural performance in fire is through an engineering approach. The first step in engineering structural fire resistance is to determine the fire boundary conditions to which a structure could be exposed. After determining the fire boundary conditions, the thermal response of the structure can be predicted. Finally, with knowledge of the thermal response of the structure, the structural response analysis can be conducted with the use of elevated temperature material properties.

### FIRE SCENARIOS

While the number of possible fire scenarios in a building is essentially limitless, it is typically only necessary to consider fully-developed fires for purposes of structural fire resistance design. There are three types of fire scenarios which may need to be considered: fully-developed, or post-flashover compartment fires, fire plumes and flames from windows which expose exterior structural elements.

Post-flashover fires are fires in compartments where all combustible materials within the compartment are involved in the fire. This scenario would be applicable to enclosures where the fuel load is distributed within the compartment. Window flames are flame projections fi-om windows where there is a post-flashover fire inside the building; this scenario is only of interest if there are exterior structural elements that may be exposed to flame projections from the windows. For cases where fuel is localized, the enclosure is very large, or where there is no enclosure, it may be necessary to consider exposures from fire plumes.

#### Enclosure Fires

The vast majority of design situations will involve the exposure of structural elements in enclosure fires. Fires in enclosures may be characterized in three phases. The first phase is fire growth, when a fire grows in size and heat release rate from a small incipient fire. If there are no actions taken to suppress the fire, it will eventually grow to a maximum size. This maximum size is a function of either the amount of fuel present or the amount of air available through ventilation openings. As all of the fuel is consumed, the fire will decrease in size and the temperature in the compartment will decrease. These stages of fire development can be seen in Figure 1.

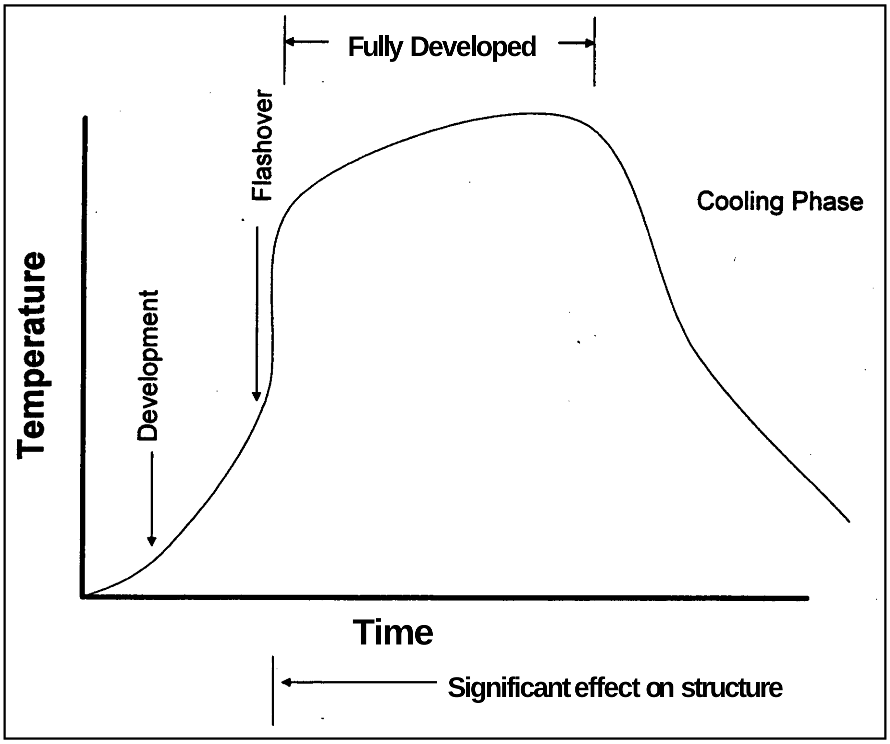


**Figure 1 – Phases of Fire Development**

The size (magnitude) of the fire and the relative importance of these phases (growth, fully developed and decay) are affected by the size and shape of the enclosure, the amount, distribution, form and type of fuel in the enclosure, the amount, distributiop and form of ventilation of the enclosure and the form and type of materials forming the roof (or ceiling), walls and floor of the enclosure.

The significance of each phase of an enclosure fire depends on the fire safety system component under consideration. For components such as detectors or sprinklers, the fire growth stage is likely to be the most significant because these components are typically intended to activate early in the course of the fire. The fire growth stage usually proves no threat to the structure, and is hence typically neglected in designs of structural fire resistance. The threat of fire to the structure is primarily during the duration of the fully-developed fire and the cooling phase? [3]

For enclosure fires, the surface temperature of non-insulated structural materials, including reinforced concrete and timber, can conservatively be approximated as the gas temperature in the compartment, which simplifies the thermal analysis to a conduction problem. The temperature of uninsulated steel will lag the gas temperature in the compartment? Hence, the decay phase can typically be neglected for uninsulated steel, but may need to be considered for design of structural fire resistance of concrete, insulated steel, or timber.

### Window Flames

Exterior structural elements may be exposed by flames which issue from windows. The scenario that is typically considered is a post-flashover fire, which results in flame projections from any windows in the compartment. The shape and temperature distribution of the flame projection is a function of burning rate in the compartment and any air flow through the compartment which is not created by buoyancy of fire gasses.'

### Fire Plumes

In some scenarios, burning will be limited to an object or group of objects with no significant impact from an enclosure. Where discrete objects bum adjacent to or near a structural element, the local fire exposure may be more significant than the hot gas layer that develops in the area of consideration. Some examples are open parking garages, large warehouses, and bridges and overpasses.

## CURRENT METHODS

The methods that are presently available to predict fire boundary can be classified into two categories: computerized fire models and closed-form algebraic equations. Closed-form algebraic equations predict compartment fire temperature based on input data relating to the amount of fuel in the compartment and .compartment characteristics such as compartment geometry, ventilation geometry and thermal characteristics of the construction materials.

With a few exceptions, computer fire models predict the temperature in a compartment as a function of a user-defined fire.[6] Therefore, most computer fire models require the user to predict the burning rate in the enclosure independent of the model. Hence, the quality of predictions made using computer fire models is limited by the ability of the modeler to estimate the heat release rate of the fire. However, NIST's Fire Dynamics Simulator holds some promise here, as it is capable of predicting the burning rate in a compartment fire.

### Enclosure Fires

Historically, the basis for fire resistance in buildings has been the standard time-temperature curve, which specifies temperature as a function of time. A structural element is rated, in hours, where the rating corresponds to the length of time before the element, with any protection, reached prescribed failure criteria based on temperature or ability to support a specified load when subjected to the standard time-temperature curve. Methods are available to calculate the fire resistance of an element without having to expose it to a full scale test.[7] Building codes specify minimum fire ratings as a function of building characteristics such as building use, whether or not sprinklers are provided, and the building height and area.

The current method of designing structural fire resistance based on exposure to the standard time-temperature curve is based on the concept of "equal area" under the standard time-temperature curve. Specifically, two fires with different time-temperature histories would be considered to have equal severity if the areas under their time-temperature curves are equal.[8]

The standard time-temperature curve has two limitations:

- The standard time temperature curve does not consider factors that would influence the temperature and duration of a fire in a compartment, such as ventilation, fuel load, and thermal properties of materials of construction.
- Two identical time-temperatye curves in different furnaces may result in different heat transfer to tested elements? Radiation from furnace walls is believed to be the dominant mode of heat transfer in a test furnace: and furnaces with walls that have a low thermal inertia will result in a more severe exposure than furnaces with walls with a greater thermal inertia, since the walls will heat more quickly. Also, the type of fuel used in furnaces is not specified, so furnaces which use different types of fuel may have different emissive characteristics, resulting in differing radiation heat transfer fiom furnace gasses.

There are several methods available to determine the time in the standard test that would have the same heating effect as a compartment fire.''.[11, 12, 13, 14, 15, 16, 17] These methods overcome, at least to a certain extent, the limitation that the standard time temperature curve does not consider factors that would influence the temperature and duration of a fire in a compartment. However, the other limitation identified above persist. Additionally, long, narrow compartments are not satisfactorily correlated by these methods.[18]

Designing based on the actual fire exposure that could occur in a compartment would overcome both of the limitations identified above. There are several methods available to predict the time-temperature boundary conditions of a fully-developed fire in an enclosure.[16, 19, 20, 21, 22 23, 24, 25, 26, 27, 28] Most of these methods have their basis in fires involving wood cribs. There is one exception,[23, 24] which allows for the consideration of pool fires.

Many hydrocarbon-based materials, such as plastics, have approximately twice the heat of combustion of wood (in other words – burning one kg of a plastic can liberate twice the energy as burning an equal mass of wood). However, use of methods developed based on wood cribs is reasonable for most design scenarios, since more energy is required to cause wood to release flammable vapors than is needed for plastics,[29] which results in longer burning durations. In ventilation limited fires the rate of air flow into the enclosure will govern the heat release rate inside the enclosure, and fuel vapors that cannot bum inside the enclosure will bum outside once they encounter fresh air. Additionally, most compartments of interest contain primarily cellulosic materials.

Each of the methods identified above that can be used to model fully-developed enclosure fires is subject to the following limitations:

- The methods are only applicable to compartments with fuel uniformly distributed over their interior. (Sparse distributions, or concentrated fuel packages should be considered using the methods applicable to fire plumes.)
- The methods are only applicable to compartments having vents in their walls.
- Only natural ventilation is considered as would occur through wall vents such as windows and doors. (The effect of forced ventilations, and wind and stack-effect flows in tall buildings are not addressed.)
- Large fires are considered with heating effects felt uniformly through the compartment.

Concern has been expressed that fires in lon narrow enclosures exhibit different burning behavior than fires in other types of enclosures! Specifically, for ventilation controlled burning in long, narrow enclosures, the burning occurs at the fuel closest to the ventilation opening, and only moves away from the opening as the fuel is depleted. Hence, the assumption of uniform conditions throughout the enclosure does not hold, and predictive methods that were developed based on fires in compartments that are not long and narrow may not accurately predict burning behavior in long, narrow enclosures. However, analysis of data from experiments conducted in a compartment with dimensions of 5.5 m (width) × 23 m (length) × 2.7 m (height)[31] reveals that some methods do satisfactorily predict the temperature and duration of fires in long, narrow enclosures.[4]

With one exception,[23] all of the methods identified above for calculating the time-temperature history for a fire in a compartment are relatively simple, closed form equations, and even the exception has a closed form approximation which provides predictions to within 3-5% of predictions made using the computer program.[24] Simple, closed form equations are possible because of the assumptions made to solve the fundamental conservations equations, e.g., uniform conditions throughout the compartment. Indeed, even the computer model referenced above[23] assumes a uniform temperature in the enclosure.

Many computer models exist that predict fire temperatures for user-defined heat release rates. Use of most computer fire models for predicting post-flashover fire boundary conditions requires the modeler to estimate the burning rate in the compartment using other methods. Given that the heat release rate in a post-flashover compartment fire is a function of the characteristics of the enclosure, it is difficult to apply these models without making additional simplifying assumptions. For example, by assuming that burning in the compartment is stoichiometric or ventilation limited, a burning rate could be estimated as a constant multiplied by the ventilation characteristics of the enclosure. Pool fires could be modeled using burning rate correlations that were developed for open air burning; however, these correlations neglect thermal feedback to the fuel fiom the enclosure.

Field models such as NIST's Fire Dynamics Simulator (FDS) allow abandoning the assumption that compartment gasses are well stirred.[32] Instead of modeling the enclosure as one zone, field models model an enclosure as many rectangular prisms, and assumes the conditions are uniform throughout each of these cells.

FDS contains pyrolysys models for solid and liquid fuels. The pyrolysys rate of the fuel is predicted by FDS as a function of the modeled heat transfer to the fuel, and thermally thick, thermally thin and liquid fuels can be treated. Combustion is modeled by FDS using a mixture fraction model.

While FDS holds promise in calculating heat release rates in fires, it presently must be used with caution, since a number of simplifications are used due to computational, resolution, and knowledge limitations. As stated in the FDS User's Guide, "The various phenomena (associated with modeling combustion) are still subjects of active research, thus the user ought to be aware of the potential errors introduced into the calculation."[33] Any errors that are present with pool-like or slab-like fuels would likely be magnified when considering crib-like fuels such as furniture.

**Window Flames**

The state of the art in modeling fire exposures from window flames is contained in design guide published by the American Iron and Steel Institute (AISI).[34] The AISI guide is a condensed version of work published by Ove Arup & Partners.[35]

The AISI guide provides a multi-step process as follows:

1. Define the room geometry
2. Determine the fire load
3. Determine whether a fire would be fuel or ventilation controlled
4. Determine the burning rate
5. Determine the fire temperature
6. Model the geometry of the window flame
7. Determine the flame temperature at the point nearest to the steel member
8. Calculate the heat transfer to the steel member
9. Determine the temperature of the steel member

The AISI guide provides different methods for cases with and without through draft. If there is no through draft, the burning rate is calculated as the lesser of the burning rates for fuel-controlled and ventilation controlled burning. If there is through draft, the AISI guide assumes that the fire would be fuel-controlled.

For ventilation controlled fires, the AISI guide uses Law's burning rate correlation? For fuel controlled fires, the AISI guide suggests that the fire duration would be approximately 20 minutes, and the fuel controlled burning rate can be determined by dividing the mass of fuel by the duration of burning. The burning rate for fuel controlled fires is a function of the fuel surface area;[22] however, fuel surface area is difficult to estimate for real buildings, and 20 minutes is consistent with Harmathy's finding that the burning duration for fuel controlled fires is typically in the range of 6-25 minutes.[22]

Correlations are provided for flame geometry for cases of through draft and no through draft. The AISI guide contains procedures for calculating the flame temperatures, heat transfer and steel element temperatures for a variety of orientations of steel elements with respect to windows. Maximum temperature criteria are given which are consistent with ASTM E-119; however, the calculated temperatures could be used to determine material properties for purposes of conducting a structural analysis. Similarly, thermal analyses of structural elements that are constructed of materials other than steel would be possible by using the flame heating characteristics in a thermal analysis.

A limitation of the method contained in the AISI guide is that it is predicated on cellulosic fuels. For compartments that contain primarily cellulosic fuels, this may be acceptable. While designing based on cellulosic fuels would be conservative for determining temperatures and burning durations in compartment fires, the opposite is true for window flames. Because cellulosic fuels require more energy to produce volatile vapors than do hydrocarbon-based fuels, the mass loss rate for hydrocarbon-based fuels would be greater less than the mass loss rate for cellulosic fuels. Any fuel that does not burn in the compartment because of ventilation limitations would bum outside of the compartment. The excess volatiles associated with non-cellulosic fuels, which would not be predicted by the AISI method, would burn outside the compartment, providing a more severe exposure to the exterior elements.

Lattimer also provides a method for predicting the heat flux from a window flame to surfaces above the window? In Lattimer's method, the heat flux to surfaces above the window can be estimated from graphs of heat flux vs. heat release rate. No correlation is given, and there is much scatter in the data, although a bounding analysis would be possible.

### Fire Plumes

The state of the art in calculating fire hazards from fire plumes has been summarized by Beyler[37] and by Lattimer.[36] Beyler[37] summarizes available methods for determining the temperature and velocity of fire plumes and ceilingjets as a function of fire heat release rate, height above the plume source, and for ceilingjets, radial distance from the plume centerline. Beyler also summarizes methods of calculating the heat flux from an impinging fire plume on a ceiling. This information could be used in a heat transfer analysis to determine the thermal response of structural elements exposed to fire plumes or ceilingjets.

Lattimer[36] summarizes methods of estimating the heat flux from localized fires, i.e., not flashed-over compartments, to surfaces. Specifically, Lattimer provides methods of estimating heat fluxes from area fires, wall and ceiling fires and the aforementioned window flames to surfaces. Lattimer considers six geometric exposure scenarios, specifically, flat vertical walls, flat ceilings, parallel flat vertical walls, comer walls, comer walls with a ceiling and horizontal I-beams. Predictive methods and comparison with data are provided.

## PROBABILISTIC ISSUES

Although the use of fully-developed fire scenarios eliminates much of the variability in fire scenario development, e.g., first item ignited, fire growth rates, etc., this approach is not without uncertainty. Any of the input variables used in predictive methods could vary. Additionally, manual or automatic intervention would be expected for fires in most buildings. Also, extreme events, such as terrorist attacks, may not be considered since they may introduce additional fuel or ventilation openings.

### Uncertainty in Model Inputs

All predictive methods require as input information about the fuel source, for example, mass of fuel or type of fuel, and information regarding the geometry being modeled. Models involving fully developed enclosure fire scenarios, including flames issuing from windows, require information regarding compartment and window geometry. Many models of fully developed enclosure fires also require thermal properties of the materials that line the enclosure. There may be uncertainty in each of these parameters.

Thermal properties of the enclosure linings generally have the least amount of uncertainty, since the materials of construction are typically selected early in the design of a building and would not be expected to change significantly. Also, predictive methods are typically not highly sensitive to variations in these properties.

Compartment and ventilation geometry could similarly be considered as invariant. However, these factors could change over the life of a building due to remodeling. Also, some serious fire losses have occurred during construction or remodeling.[38, 39]

Fuel characteristics are the property that could be expected to vary the most. Several documents contain information regarding fire loads in different occupancies. Most design guides derive this information from a CIB report,[40] which presents fire loads in $MJ/m^2$ for a variety of occupancies at 80%, 90% an 95% confidence values. These values could be converted to a mass per unit area basis by dividing by an effective heat of combustion. Several researchers have also published surveys of fire loads.[41, 42, 43]

In addition to the total amount of fuel, the surface area also influences burning the rate. For ventilation controlled fires this is typically neglected, although the fuel surface area must be considered for fires which might be fuel controlled. There is limited data available on the surface area of fuel as a function of occupancy, although Harmathy[22] reports that for furniture, the surface area to mass ratio is generally between 0.1 and 0.4 $m^2$/kg, and is most often the range of 0.12 to 0.18 $m^2$/kg.

For deterministic evaluations, it would be prudent to use bounding or reasonably conservative values. One caution that must be considered is that reported surveys generally only consider "normal" occupancy characteristics, and do not include the fire loads that might be present during times of construction or renovation.

Similarly, methods of predicting fire exposures from fire plumes require input values such as heat release rate or dimension from the fire source. When selecting input values for these methods, bounding or reasonably conservative input values would generally be used.

**Intervention**

Intervention, such as sprinkler suppression or fire service response, would be expected in many buildings. If either of these systems functions as intended, the burning duration would be decreased. However, sprinklers are not 100% effective; the actual effectiveness in somewhere in the vicinity of 95%.[44] Similarly, the fire service can't be relied upon to extinguish all fires.

If the sprinkler system were relied upon when designing on a deterministic basis, the design would not be safe approximately 5% of the time. While the fire service could be expected to extinguish some fraction of the remaining 5%, there would still be some fires that would continue until burnout.

To adequately consider both fire resistance and intervention would require designing on a risk basis. For example, acceptance criteria could be stated in a form of $x$ amount of loss per unit time. Designs could then be evaluated on a risk basis as follows:[45]

$$Risk = \sum Risk_i = \sum \left[ F_i \times (Loss_i \times R_k + \overline{Loss_i}(1 - R_k)) \right]$$

| | |
|---|---|
| Where $Risk_i$ = | *Risk associated with scenario i* |
| $Loss_i$ = | *Loss associated with scenario i if the design succeeds* |
| $\overline{Loss_i}$ = | *Loss associated with scenario i if the design fails* |
| $F_i$ = | *Frequency of scenario i occurring* |
| $R_k$ = | *Probability of design succeeding* |

The Eurocode[16] contains an approach for accounting for interventions where the design fire load is reduced by a factor (0.0-1.0). This results in a design fire load that is less than the actual fire load. This is only a quasi risk-based method, as it does not explicitly consider the actual frequency and consequences of fires.

## Extreme Events

Buildings are typically designed based upon the types of fires that might reasonably be expected to occur. However, there are some types of events that may fall outside of the design basis of most buildings; for example, collisions with aircraft or bombings. These types of scenarios might ignite multiple simultaneous fires or a single fire with a large burning area and may change the building characteristics that affect fire performance. Extreme events are, by definition, high consequence/low probability events.

## KNOWLEDGE *GAPS*

There is sufficient information available to predict with reasonable precision the fire boundary conditions to which most structures could be exposed. However, research could be used to reduce the uncertainties in designs or analyses, resulting in more cost effective use of resources without compromising safety. These include the following, which are not listed in any ranked order:

### Fire Load

While some information is available on fire loads in some occupancies, the information displays international differences[40] and is in some cases, dated. Given that the fuel load is a critical input into design fire calculations, reducing the uncertainty would be beneficial. For designs in which fires would be fuel controlled, additional data relevant to the fuel surface area would be beneficial. Additionally, beyond mass or calorific value per unit area, little information is available on fuel characteristics, such as how well they can be approximated as wood cribs or pools.

### Intervention

While there is an accepted approach for considering the impact of active systems on fire resistance in Europe, this approach is not without shortcomings. Development of a true risk-based approach to structural fire resistance would allow an apples to apples comparison of active and passive systems.

### Long-Narrow Enclosures

Because of the burning phenomena in long-narrow enclosures, the heat transfer boundary conditions are not uniform throughout the enclosure. Although some methods do reasonably predict the temperature and duration of fires in long, narrow enclosures, they do not consider the non-uniform conditions in the enclosure. Additional research is needed to quantitatively understand burning phenomena in ,long, narrow enclosures.

### Window Flames

Much of the work on flames issuing from windows is limited by the types of fuels considered. Research is needed to provide methods that have broader ranges of applicability.

### Predictive Methods

There are a number of relatively simple methods available to predict fire boundary conditions. Some evaluation of these methods has occurred: however, additional evaluation may be needed.

Evaluation is also needed of more complex methods, such as the methods used in NIST's Fire Dynamics Simulator.

While existing methods can be used with confidence in most design or analysis situations, the need for more complex methods should also be explored.

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**White Paper 6**
**Analysis Tools and Design Methods: Current Best Practices**

**J. Milke, P.E., Ph.D.**

## Abstract

A variety of analytical tools are available to assess the thermal and structural response of fire-exposed building assemblies. The available calculations apply to many different types of building assemblies, including floor- and roof-ceiling assemblies, columns, walls and trusses. The building assemblies may be comprised of any of the principal structural materials, *i.e.* steel, concrete, concrete and clay masonry and wood, as well as protection materials and veneers. Significant constraints in the application of such tools include the limited availability of material property data and the limited understanding of these analytical tools by practicing engineers.

## *1. Introduction*

Assessing the response of building assemblies containing structural members consists of evaluating the thermal response and structural response of the assembly. A thermal response analysis considers the heat transfer to the assembly resulting from the heating conditions provided by the defined fire exposure. The structural response analysis determines the effect of the temperature changes induced within the structural assembly as a result of the fire exposure. A variety of analytical tools are available to assist with these evaluations.

This review intends to provide an overview of the analytical tools available to assess the thermal and structural response of structural assemblies. This overview will outline the technical basis, assumptions, limitations and capabilities associated with the variety of analytical tools.

## *2. Thermal Analysis Methods*

The thermal response of a fire-exposed assembly is evaluated by a heat transfer analysis. A thermal response analysis is conducted to determine the temperature distribution throughout the construction assembly or at selected locations. Possible locations of interest can be proposed given the basic objectives of fire resistant assemblies, *e.g.* the unexposed side of the assembly or positions of load-carrying structural members within assemblies. Heat transfer within a solid, non-porous assembly occurs via conduction, with convection and radiation boundary conditions. In assemblies comprised of porous media (wood, concrete, masonry, gypsum board, *etc.*), coupled heat and mass transfer considerations become increasingly important. Consequently, heat transfer within the porous materials is by conduction, convection and radiation.

Several possible approaches are available to solve a conduction heat transfer problem. Exact solutions are often impractical, especially given the non-linear, unsteady boundary conditions typically associated with fire, in addition to the temperature-dependent material properties and complex geometries associated with building assemblies. Consequently, virtually all heat transfer analyses of fire-exposed building assemblies involve approximations, which simplify the governing equations, the geometry, or both. Calculation methods range from applying simple algebraic equations to computer models.

The analytical methods incorporated into design guides are all relatively simple, requiring the application of algebraic equations or graphs. In these analyses, changes in materials caused by decomposition, dehydration or phase changes or changes in geometry are neglected or included implicitly by use of effective values for the thermophysical properties. In contrast, finite element and finite difference models are available that permit temperature-dependent material properties and varying boundary conditions.

## *2.1 Lumped Heat Capacity Analysis*

One of the elementary methods to assess the thermal response of a structural component follows a lumped heat capacity analysis. This approach is based on a simplification of the phenomenon, assuming that any incident heat from the fire causes a uniform temperature increase throughout the exposed object. This assumption is most appropriate for exposed objects with high thermal conductivities, uniform exposure conditions around the entire perimeter and length of the object and relatively thin-walled sections, such as steel columns in the middle of a compartment,. The assumption of uniform temperature is less appropriate for partially exposed steel members such as steel beams in contact with a deck, steel columns partially embedded in a wall, concrete assemblies and timber assemblies.

The lumped heat capacity approach can be applied to steel columns that are unprotected or protected with insulating-type fireproofing materials. The heat flow through the protection material is assumed to be steady-state such that a linear temperature gradient is assumed through the fireproofing material.

With the noted assumption of uniform temperature and constant properties, the lumped heat capacity analysis involves the application of an algebraic equation to determine the temperature rise in the exposed object during a small time step (a maximum time step of **10** sec is stipulated by the Eurocodes **[2001])**. For the case of time-varying exposure conditions or temperature-dependent properties, as typically experienced in fires, the algebraic equation needs to be applied repeatedly, dividing the fire exposure into several small time steps. The lumped heat capacity analysis can be applied to evaluate the temperature rise in unprotected, partially protected or completely protected steel members [Malhotra, **1982]** [Pettersson, ***et al.*, 1976]** [Eurocodes, **200.11.**

The lumped heat capacity approach can be used either to determine the temperature of the steel after a given period of exposure or determine the time for the steel to reach a critical temperature. A spreadsheet routine can be formulated to perform the iterative calculations associated with the lumped heat capacity approach [Gamble, **1989]** [Berger, **19891.**

The lumped heat capacity method is valid for any specified time-temperature relationship. The heating conditions associated with the fire are described in terms of a time-temperature relationship for protected and unprotected columns. For protected columns, the fire exposure conditions are addressed by assuming that the temperature of the outer surface of the protection material is equal to the fire temperature, and the temperature of the inner surface of the insulation is equal to the steel temperature. For unprotected columns, convective and radiative heat transfer parameters need to be specified. The convection heat transfer coefficient is often assumed to be constant throughout the duration of the exposure, typically with a value of **20** to **25** W/m$^2$-°C. A single radiation parameter is often cited, accounting for the emissivity and view factor associated with radiation from flames, smoke, and compartment enclosure surfaces. [Pettersson, ***et al.*,** 1976][ECCS, **19851.**

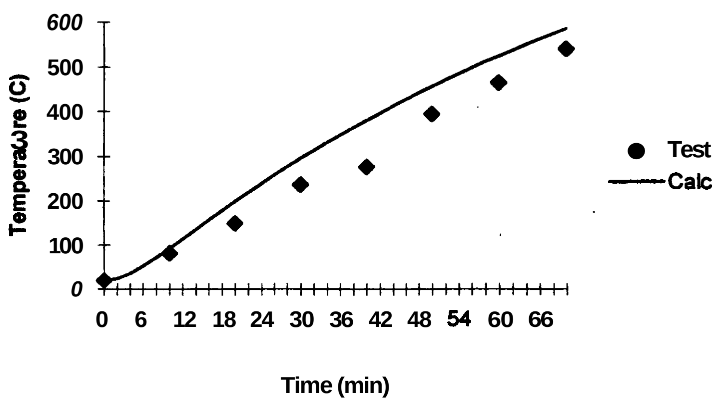
Evaluation of the predictive capability of the lumped heat capacity approach for steel columns protected with a spray-applied cementitious material was conducted by Berger **[19891.** The analysis consisted of comparing predicted versus measured temperatures for steel columns exposed to the standard fire exposure. Comparing the predicted versus measured times for the steel column to reach 538°C is provided in Table **2.1.**

A comparison of the predicted temperature with those measured for one protected steel column assembly is provided in Figure **2.1.** The good agreement is best indicated by the similarity of the slope of the predicted temperatures with the trend in the measured temperature points throughout the exposure. The good agreement of the slope and data trend indicates that for the design evaluated, a proper combination of material properties and exposure conditions were used and the lumped heat capacity analysis was appropriate.

**Table 2.1** Comparison **of** Predicted Time from Lumped Heat Capacity Analysis and Measurements for Protected Steel Column to Reach **538°C**

| Shape | h (cm) | Test (min) | Calc. (min) |
|---|---|---|---|
| W6X16 | 1.9 | 58 | 56 |
| | 3.8 | 112 | 119 |
| | 7.6 | 210 | 251 |
| W8X28 | 3.5 | 122 | 121 |
| | 8.3 | 291 | 298 |
| | 9.5 | 355 | 352 |
| W10X49 | 1.9 | 70 | 62 |
| | 5.6 | 217 | 220 |
| W12X106 | 3.8 | 200 | 203 |
| W14X228 | 1.4 | 123 | 140 |
| W14X233 | 2.9 | 225 | 251 |

Figure **2.1.** Predicted Temperature for **W10X49** Protected Steel Column




Predictions of temperature rise in steel beams by the lumped heat capacity approach are prone **to** be inherently less accurate than those for steel columns [Milke, **19981.** As noted previously, **a** steel **beam** in contact with a slab only has **3** "sides" exposed to a fire and also will lose heat to the slab. Consequently, the temperature of a steel beam exposed to fire is likely to vary appreciably from the bottom flange to the top flange, stretching the validity of the uniform temperature assumption. Nonetheless, for many engineering applications, the lumped heat capacity approach can provide a reasonable estimate of the average temperature rise of a steel beam [Smith and Stirland, **1983]**. Heat losses to the slab may be compensated for by reducing the heat transfer parameters from the fire. However, if the temperature gradient across the beam is important, another analytical approach will need to be applied.

Graphs summarizing the trends in temperature rise of protected columns exposed to natural fires are presented by Pettersson, ***et*** al. **[19761.** Indicated in the graphs is the influence of **two** fire parameters (ventilation and fuel load) and two parameters of the column assembly (steel column shape and protection thickness) on the temperature rise of the steel.

Limitations

Limitations of the lumped heat capacity analysis include the following:

- The heat transfer parameters are "effective" properties, supported by agreement with results obtained in standard tests. The values for these properties may vary appreciably for analyses with natural fires.
- Moisture movement and heat absorption are not addressed [Pettersson, ***et al.*****, 1976]** [Malhotra, 1982]. ECCS [1985] provides a calculation for a time lag to account for moisture loss.
- The steady state assumption of the heat transfer through the insulation is inappropriate for fires with high rates of temperature change.

### *2.2 Steadv-State Heat Balance*

An upper limit of the temperature rise of a structural member can be determined using a steady state heat balance. This approach has been documented for two applications:

1. temperature rise of exterior steel columns and beams exposed to radiant energy **fiom** a compartment fire and flames projecting out of wall openings.
2. temperature rise of fire-exposed, water-filled steel columns.

The temperature of the steel is determined from an energy balance, where the incoming heat fiom the compartment fire is equal to the heat leaving the steel [Law, **1978][AISI, 1979]** [Schleich, 1993][Eurocodes, **200**1]. The incoming heat from the exposing fire is estimated considering radiation heat transfer from the gases inside the compartment and fiom flames projecting fiom compartment openings such **as** windows. Convective heating is also considered for steel sections engulfed in flames projecting **from** the window. The heat leaving from the steel structural member consists of radiative and convective heat losses to the environment. Conduction losses to adjoining building assemblies are neglected. **As** with the lumped heat capacity approach, this method assumes a uniform steel temperature.

In the analysis for water filled columns [Schleich, **19931,** incoming heat from the compartment fire is estimated considering radiation and convection heat transfer fiom the gases inside the compartment. Heat losses include convection to the circulating water.

These methods could be modified to address the temperature rise of the exterior steel or water-filled column as a function of time. This would involve an iterative calculation similar to that in the lumped heat capacity approach. As input, the temperature history of the fire within the compartment needs to be provided along with the time for flames to initially project fiom the compartment opening. The temperature history of the fire is well within the state-of-the-art of compartment fire modeling. However, predicting the time for flames to project fiom the Compartment opening is more difficult. In particular, either the compartment opening needs to be assumed "open" throughout the exposure or breakage of a closed window needs to be assessed.

Limitations

Limitations of the lumped steady-state heat balance analysis include the following:

- the analysis provides an upper limit temperature which may substantially overestimate the temperature expected for the steel, especially where the peak temperature conditions are short-lived.
- predicting window breakage to create the compartment opening involves appreciable uncertainty.

### *2.3 Semi-infmite slab (therm&-thick slab)*

The semi-infinite slab approximation simplifies the heat transfer phenomenon by assuming that the effect of the incident heat on the exposed side dissipates before reaching the unexposed side due to the thickness and thermal properties of the floor, roof or wall slab. As a result, the temperature on the unexposed side of such a slab does not increase appreciably above the initial value. In this situation, the temperature near the exposed surface is dependent solely on the exposure conditions and is independent of conditions on the unexposed side. Even though no actual slab is infinitely thick, a slab can be considered to be ***sufficiently thick*** for engineering purposes to permit the semi-infinite assumption if:

$$\frac{x}{2\sqrt{at}} > 1.0 \qquad (2\text{-}1)$$

For thermally thick walls, simplified expressions are available in the literature for temperatures near the exposed surface if the exposure can be characterized as imposing a constant heat flux on the surface or a constant surface temperature. In the simplified expressions, the material properties of the exposed structural element are assumed constant. The effect of temperature dependent properties can be included in the analysis by evaluating the material properties at an average temperature for the portion of the slab under investigation. The semi-infinite slab approximation has been applied to wood slabs [Schaffer, 1977] for the period before charring is initiated.

Limitations

Limitations of the semi-infinite slab analysis include:

- the fire exposure must provide a steady (or near-steady) heat flux, which is uniform across the entire exposed surface.
- the analysis is not relevant if materials undergo changes in composition, experience significant moisture movement/evaporation or have significant variations in property values between the exposed and unexposed surfaces

As an alternative to the semi-infinite slab approximation involving the exponential function for an exposure consisting of a constant heat flux, a quadratic temperature profile was proposed in Eurocode 5, part 1.2 for timber structures. Janssens and White [1994] found that the quadratic profile provided a reasonable, but conservative fit to experimental data for slabs of eight different wood species exposed to ASTM E119 conditions.

## *2.4 Graphical solutions*

Numerous graphical solutions of the temperature distribution within fire-exposed structural members have been presented in the literature. However, 'most of the graphical solutions are limited to cases involving the standard ASTM El 19 exposure. A limited number of graphical solutions apply to exposures from natural fires, *e.g.* the graphs attributed previously to Pettersson, et *al.* [19761.

Lie [1972] provided a series of graphs for one-dimensional analyses of the temperature distribution in walls or slabs exposed on one or two sides to the ASTM El19 exposure. The graphs can also be used for two-dimensional assemblies such as columns or beams by applying the principle of superposition. Because the material properties are assumed to be constant, average properties need to be identified. In addition, the constant property assumption effectively limits the analysis to slabs and beams composed of relatively inert materials, such as concrete, steel, or wood before charring.

The temperature distribution within concrete slabs is presented graphically based on data from tests with the ASTM E119 exposure [PCI, 19771. Graphs are provided for three aggregates: siliceous, carbonate and sand-lightweight. According to the review by Hosser, et *al.* [1994], the graphical analysis included in the PCI guide provides the best agreement with actual data when compared to predictions from three methods evaluating the thermal response of concrete assemblies using graphs or tables. The other two methods included graphical analyses by ISE [1978] and IBD [1981].

Graphs or tables of the fire resistance of masonry walls as a function of equivalent solid thickness and concrete aggregate type are also available [NCMA, 19961. The fire resistance evaluation is based solely on the temperature rise on the unexposed surface. Consequently, the solutions actually indicate the time required for the average temperature of the unexposed surface of the walls to increase by 250°F when the wall is exposed to the fire environment consistent with ASTM El 19.

Limitations

Limitations of the graphical analyses are:

- most of the graphical methods apply for exposures associated with the standard test
- graphical solutions cannot be readily incorporated into computer-based methods which require temperature of the assembly as input.
- only conduction heat transfer is addressed; mass transport (*i.e.*, effect of moisture evaporation, migration, etc.) is neglected.
- Graphical methods cannot be applied for materials which undergo decomposition or phase change.

## *2.5 Numerical Analvses*

Numerous algorithms are available to evaluate the thermal response of heated objects. These algorithms are based on finite difference or finite element formulations. Finite difference formulations simplify both the geometry and the governing equation. The geometry is approximated by a grid of nodes while the derivatives in the governing equation are replaced by algebraic expressions. Finite element models also approximate the geometry, though utilize the actual governing partial differential equation in the formulation [Minkowycz, ***et al.,*** 19881.

Lie and Harmathy [1972] formulated one of the first finite difference models that analyzed the heating of circular reinforced concrete columns exposed to the standard fire. In addition, finite difference models were applied for concrete floor slabs [Lie, 19781, square reinforced concrete columns [Lie, *et al.*, 19841 and concrete-filled tubular steel columns Lie [1984]. Ahmed and Hurst have applied a one-dimensional, finite difference analysis of the coupled heat and mass transfer **through** carbonate and siliceous aggregate concrete slabs and multi-layered **gypsum** wallboard-and-stud assemblies [1995]. Dehydration and evaporation phenomena and changes in porosity were considered by the model. Mehaffey and Takeda [1995] formulated a finite difference model to analyze the heating of wood stud walls exposed to the standard fire. In Mehaffey and Takeda's model, dehydration and porosity of gypsum wallboard is accounted for through the use of effective properties. Milke and Vizzini developed a finite difference model to investigate the thermal response of fire-exposed anisotropic slabs, such **as** graphite-reinforced epoxy composites [1990] and glass-reinforced thermoplastic composites [1991]. PATHOS-2 is a one-dimensional finite difference model developed principally for the evaluation of fire-exposed structures on off-shore platforms [PCL, 1992]. In a recent review of thermal analysis programs by Sullivan, et ***al.*** [1994], FIRETRANS **[OAP,** 1985] and CEFICOSS [Franssen, 1987] were identified as contemporary finite difference models. FIRETRANS can be used to address one-dimensional problems involving slabs exposed to fire. Heating 7 [Childs, 1999] is a three-dimensional finite difference model which can be applied to address the heat transfer through a wide variety of assemblies. Time-varying boundary conditions and temperature-dependent material properties can be addressed with Heating 7. Several finite difference models have been formulated to assess the heat transfer through light frame walls [Clancy, 1999][Collier and Buchanan, 2002][Cooper, 1997][Sultan, 1996][Sultan, et al., 200 13[Takeda and Kouchleva, 2001].

Several examples can be found where finite element analyses have been applied in recent efforts to analyze the thermal response of fire-exposed building assemblies such **as** steel beams, partially and fully-protected steel columns, wall assemblies, and floor systems [Moss, 20021. Finite element models that have been developed specifically to address the thermal response of fue-exposed building assemblies include FIRES-T3 [Bresler, Iding and Nizamuddin, 19771, TASEF-2 [Sterner and Wickstrom, 19901, SUPER-TEMPCALC [Anderberg, 19881, STABA-F [Rudolph, et *al.*, 1986] and Imperial College's model [Terro, 19911, and SAFIR [Franssen, et al., 20001. Another finite element model, HADAPT [Lamont, et al., 20011 **was** applied for a **two-**dimensional analysis of a composite steel beam and concrete floor slab, though it is not clear whether that model is generally applicable or limited to the situation analyzed in that reference. **SAFIR** is capable of addressing two- and three-dimensional heat transfer **as** the first step of a thermo-mechanical analysis. FIRES-T3, TASEF-2, **SAFIR** and SUPER-TEMPCALC can be used **to** evaluate the thermal response **of** assemblies with voids.

Some of the applications have involved consideration of exposure to the standard fire whereas others have involved exposure to natural fires. Milke [1992) and Sullivan, et ***al.*** [1994] provide reviews of the first five finite element models developed to evaluate thermal response from fire (FIRES-T3, TASEF-2, SUPER-TEMPCALC, STABA-F and Imperial College's model).

Results of predictions by FIRES-T3 are included in Table 2.2. A comparison of the predicted time for a variety of column assemblies to reach 538°C by Milke using FIRES-T3 and that determined in ASTM E1 19 tests are included in Table 4.2.

Being formulated specifically to address heating due to fire exposure, the finite element models include three special features:

- one- or two-dimensional analyses (a three-dimensional analysis may be conducted using FIRES-T3)
- time-varying exposure conditions
- temperature-dependent properties

Approximately 25 years ago when FIRES-T3, TASEF-2, and SUPER-TEMPCALC, these three special features made these models unique. However, several commercially-available algorithms are available with capabilities to address two- and three-dimensional analyses and temperature-dependent properties.

Table 2.2 Comparison of FIRES-T3 Predicted and Measured Times for Protected Steel Columns to Reach 538°C [Milke, 20021.

| Shape | h (cm) | Test (min.) | Model (min.) |
|---|---|---|---|
| W6X16 | 1.9 | 58 | 62 |
| | 3.8 | 112 | 111 |
| | 7.6 | 210 | 232 |
| W8X28 | 3.5 | 122 | 116 |
| | 8.3 | 291 | 283 |
| | 9.5 | 355 | 346 |
| W10X49 | 1.9 | 70 | 77 |
| | 5.6 | 217 | 205 |
| W12X106 | 3.8 | 200 | 199 |
| W14X228 | 1.4 | 123 | 129 |
| W14X233 | 2.9 | 225 | 227 |

There are two drawbacks to the applicability of numerical models to predict the.thermal response of any building assembly to fire. One difficult aspect of applying a numerical model to address the thermal response of fire exposed building assemblies is associated with acquiring the input data. "Boundary conditions" associated with the exposure must be stipulated. Material properties need to be available as a function of temperature.

Another shortcoming of the heat transfer analysis algorithms is that they are applicable primarily to inert materials. Where assemblies experience moisture migration, phase changes, dehydration, decomposition or changes in geometry, specific algorithms will need to be identified or developed to model the thermal response of such assemblies. Results for the available models often deviate appreciably from measured temperatures in the area of 100 to 200°C where concrete, gypsum, wood and other moisture containing materials are included despite the use of effective properties to account for the change in enthalpy [Sullivan, *et al.*, 1994]. Ahmed and Hurst's model has much better predictive capabilities within this range of temperatures [1995].

Limitations

Limitations of the numerical analyses include:

- the material is considered to be homogeneous, with changes permitted only to account for variation in properties due to temperature
- material properties which vary with temperature may not be known, especially for protection materials
- surface movement (recession or expansion) is not addressed, except in PATHOS 2.
- moisture migration and pressure build-up in pores is not addressed, except in the model by Ahmed and Hurst [1995] and in some thermal response models for non-fire purposes [Milke, 1991].
- neither spalling nor cracking is considered.
- heat transfer parameters (convection coefficient and surface radiation properties) are semi-empirically or empirically defined.

### 3. *Structural Analysis Methods*

An analysis of the structural response of fire-exposed building assemblies addresses the consequences of the induced elevated temperatures on the integrity of load-carrying members. The temperature profile resulting from the thermal response analysis is used to determine material property values as well as assess thermally-induced stresses or curvature. The remainder of the input consists of parameters that are needed for typical structural analyses at ambient temperature, *e.g.* load levels (including load combinations), end conditions, and mechanical properties of structural member. Numerous calculation methods are available to analyze the structural response of a heated assembly, ranging from algebraic equations to finite element computer models.

Most of the analysis methods are limited to the response of a single structural member. In these cases, adjoining members are accounted for through the specification of end conditions. However, recently a limited number of calculation methods have been documented which address the response of a structural frame to fire.

#### *3.1 Elementary Mechanics Approaches*

All of the existing design guides for evaluating fire resistance reference algebraic equations developed from elementary mechanics to evaluate the structural response of fire-exposed assemblies. Most of the algebraic equation based methods address buckling and moment capacity analyses of individual components. Buchanan [2001] provides a good overview of the variety of algebraic-equation based methods. A deflection analysis with algebraic equations of a simple frame is outlined by Pettersson, et *al.* [1976]. The principal difference of applying these equations for fire resistance evaluations as compared to ordinary structural calculations is the adjustment of material property values to reflect their dependence on temperature.

Flexural Members

Most of the analyses of the fire resistance of flexural members consist of evaluating a reduction in moment capacity resulting fiom a reduction in strength. The premise of conducting the moment capacity analysis in assessing fire resistance is that the assembly maintains integrity as long as the moment capacity exceeds the applied moment. In some publications, a deflection analysis is described, where a limiting deflection is established, typically expressed **as** a fraction of the span of the beam. Considering a maximum allowable deflection of 1130th of the span, critical temperatures determined fi-om deflection analyses are generally comparable to those determined from moment capacity analyses [ECCS, 19831.

The algebraic equations for moment capacity analyses are similar to those presented for room temperature analyses in elementary mechanics. Algebraic equation-based analyses for moment capacity have been proposed for a variety of flexural assemblies (beams and slabs) comprised of steel, concrete and timber. Evaluation of moment capacity is dependent on the response of the material(s) to fire and whether the assembly is comprised of a homogeneous material or a composite.

**Steel Beams**

In fire resistance calculations, the yield strength of the steel is evaluated at the steel temperature determined from the thermal response analysis. Twilt [1988] proposed the use of an effective yield stress based on 0.5% permanent strain because additional strain is acceptable in fire conditions **as** opposed to ambient temperature conditions.

Plastic analyses are outlined in several publications [Pettersson, et *al.*, 1976] [Malhotra, 1982] [ECCS, 1985] [Buchanan, 20011. In the plastic analysis, the applied moment is changed to account for load redistribution **as** a result of the formation of plastic hinges. In addition, the plastic analysis requires that the elastic section modulus be replaced by the plastic section modulus and the yield strength by the ultimate strength.

Table 3.1 summarizes critical beam temperatures at which the moment capacity is exceeded for steel beams with various end conditions based on **an** elastic or plastic analysis [ECCS, 1985]. The results also indicate the effect of load level and load application on the critical temperature.

**Timber Beams**

The moment capacity analysis for timber members is conducted considering a reduction in the section modulus to account for charring. Variations on the analysis are included in the literature, differing in how they account for the charring. The simplest method assumes that the charring depth is uniform for each exposed side of the timber member. In reality, rounding at the comers (arris rounding) causes a further reduction in the section modulus which should be accounted for in the analysis [Buchanan, 1994]. Consequently, some of the methods using algebraic equations account for the arris rounding through an empirically defined factor [Schaffer, et *al.*, 1986] [Lie, 1977]. Yet another estimates the size of the rounded cross-section and requires that the section modulus be determined for this rounded shape. Another empirical factor may also be included to account for a reduction in material properties.

Table **3.1.** Critical Temperatures of Steel Beams [ECCS, **1985]**

| | | | | Critical Steel Temperature (°C) | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | Load level, proportion of allowable load | | | | |
| type of analysis | statically determinate? | load' | end conditions[2] | **0.3** | **0.4** | **0.5** | **0.6** | **0.7** |
| Plastic | Yes or No | **any** | Any | **585** | **540** | **490** | **430** | **360** |
| Elastic | Yes | **any** | Any | **605** | **565** | **525** | **475** | **425** |
| Elastic | No | distr. | f-f | **640** | **605** | **575** | **545** | **510** |
| Elastic | No | point | f-f | **605** | **565** | **525** | **475** | **425** |
| Elastic | No | distr. | f-p | **650** | **615** | **590** | **560** | **535** |
| Elastic | No | point | f-p | **615** | **580** | **545** | **505** | **465** |
| Elastic | No | distr. | cont/p | **650** | **615** | **590** | **560** | **535** |

1

***An*** essential input for the analysis of timber members is the charring rate. Information on charring rates is available from a variety of **sources** [white, **20021** [Buchanan, **20021,** however virtually all of these rates have been determined empirically based on the exposure of wood specimens to **the** standard time-temperature curve exposure. Several models have been developed over the last **60** years to estimate the pyrolysis of wood for structural **fire** protection purposes [Janssens, **2002].** Janssens has recently developed the model CROW to estimate charring behavior.

**Concrete Beams and Slabs**

Wade reviews the performance of concrete structural members under fire conditions **[1991a, 1991**b]. The moment capacity analysis formulated for reinforced and prestressed concrete flexural members accounts for the composite nature of the assembly. The analysis of concrete slabs and beams is based on methods of analysis used in room temperature concrete design adapted for fire resistance analyses, with support from large-scale test data **from** the Portland Cement Association [Fleischmann **and** Buchanan, **20021.**

When considering the positive moment capacity, the strength of the concrete in a slab is assumed to remain unchanged fiom that at ambient temperature. However, the strength of the steel is reduced commensurate with the temperature at the position of the reinforcement. In addition, thin beams, such as in concrete single or double tee beams, experience an increase in temperature **as** a result of fire exposure. In some analysis methods, any portion of concrete which attains a threshold temperature of at least 650°C for siliceous aggregates or **760°C** for carbonate aggregates is neglected based on a substantial loss in strength occurring at that temperature [PCI, **1977]** [CRSI, **1980].**

Negative moment analyses for continuous and other statically indeterminate sections are appreciably more complex. If the temperature is in excess of the threshold value noted in the previous paragraph, that portion of concrete on the lower edge of the **beam or** slab is neglected to reduce the negative moment **arm** [PCI, **1977** ][CRSI, **19801.** The strength of the concrete and reinforcing steel is reduced given the temperatures at the centroid of the equivalent stress block and reinforcement location. Development lengths of steel reinforcement need to be evaluated, accounting for the redistribution of moments. The thrust due to expansion of the slab is evaluated to determine its effect on adjoining structural members.

Limitations

Limitations of the algebraic equations for flexural members are:

- the analysis for a steel beam assumes a uniform temperature of the beam (as determined from the lumped heat capacity analysis. In reality, a temperature distribution will be present on the beam with the bottom flange being at the greatest temperature and the top flange at the lowest temperature. Because of the temperature gradient in the beam, an additional positive curvature will be induced [Boring, 1979][Eurocodes, 2001]. The moment analysis can be formulated by considering a composite beam comprised of small isothermal sections of the steel beam.
- the analysis for concrete members does not consider failure other than by moment capacity, neglecting shear and anchorage failure [Pettersson, 1986]
- the negative moment analysis for concrete slabs bases the values for slab deflections with varying restraint and location of line of action for thrust force on limited experimental data [CRSI, 19801.
- mass transport phenomena and pore pressure build-up are not considered

Compression Members

The structural response of fire-exposed compression members depends on the anticipated mode of failure, as in the structural analysis of compression members at ordinary temperature. Short columns are expected to fail as a result of the applied stresses exceeding the strength of the heated compression member. In contrast, long, slender columns are expected to fail by loss of stability or buckling, where the applied stress exceeds the critical elastic buckling stress. Generally, columns which are "stout" or "slender" for the purpose of an ordinary temperature structural analysis retain those definitions in elevated temperature analyses.

**Buckling Analyses**

Buckling or stability analyses of steel or timber columns involve the application of the Euler buckling equation, developed from elementary principles of mechanics. The effective length modifies the actual length of the column based on the end conditions. The values of effective length used in design applications are more conservative than the theoretical values.

**Steel Columns**

Using the results of a thermal response analysis to determine the temperature of a fire-exposed steel column, Euler's equation can be applied with the modulus of elasticity decreased as a function of the steel temperature. Euler's equation can only be applied where the column achieves a uniform temperature through the cross-section and along the length. AISC uses a revised form of Euler's equation and defines the slenderness ratio accordingly to permit it to be used for structural steel of any strength [AISC, 19931.

ECCS developed a buckling analysis of fire-exposed steel columns by adapting an empirically-derived set of buckling curves for ambient temperature conditions. Equations were developed via a regression analysis to describe the ambient temperature buckling behavior. The buckling curves for fire-exposed steel columns, presented in Figure 3.1, were determined by multiplying the dimensionless buckling load by the ratio of yield stress at elevated temperature to that at ambient temperature. The advantage of the ECCS equation is that it implicitly accounts for actual steel column behavior including the effect of residual stresses and buckling near the plastic limit.

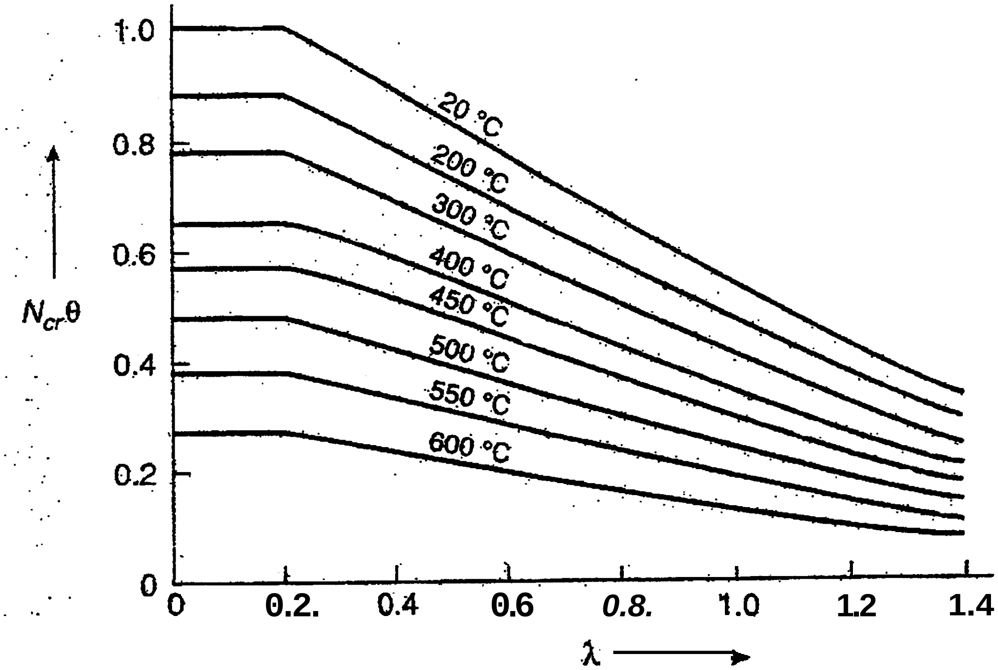



Figure 3.1 Buckling Curves for Steel Columns [Milke, 2002, p. 4-232] (from ECCS, 1985)

**Timber Columns**

As with timber beams, the cross-section of a fire-exposed timber column needs to be reduced to account for charring. A similar analysis is used for the columns as for the beams wherein the buckling load for a charred section is determined accounting for strength reduction and arrises via empirical factors. As with the analyses for beams, the charring rate needs to be known.

**Concrete Columns**

Allen and Lie [1974] evaluated the buckling of reinforced concrete columns by conducting an analysis of the strains through the cross-section at mid-span. Stress resultants were applied to determine the strain distribution through the cross-section and the total strain was related to the curvature in the column. Buckling behavior was concluded when the radius of curvature decreased without limit. The analysis compared favorably with experimental data [Harmathy, 19931. Frannsens and Dotreppe [2003] outline a simplified buckling analysis for reinforced concrete columns exposed to conditions associated with the standard test.

Limitations

Limitations of the algebraic equations for compression members are:

- the analysis for a steel column assumes a uniform cross-section temperature of the column. Partially protected columns will not have uniform temperatures because of the varying exposure conditions around the perimeter.
- the analysis for columns of any material assume that the temperature or degree of charring is uniform along the length of the column.
- all columns are concentrically loaded.

¬ of entary Mechanics Approaches

Hosser, *et al.* [1994] presented a comprehensive comparison of a variety of the elementary mechanics approaches to estimate the fire resistance of assemblies included in design guides fiom North America and Europe, such as those described previously in this section. The comparison was organized according to methods for structural members of a particular material: concrete, steel or wood. The comparison and ranking of methods was based on the following eight factors:

- application: types of members and end conditions addressed
- verification: agreement with experimental data
- precision (referred to as "accuracy" by Hosser, *et al.*): degree of approximation
- physics: extent of theoretical basis of method (versus empirically-derived method).
- completeness: level of documentation to describe basis of method
- input existent: availability of input data
- user friendliness: level of training required to apply method. Algebraic equations receive better ratings than computer models
- approval/standard experience: recognition of method in standard or regulation

Hosser *et al.*, emphasized the verification and application factors by weighting these factors greater than the others. Least important were the physics and user-friendliness factors.

**Concrete**

The following four methods to evaluate the fire resistance of concrete beams or slabs were included in the comparison.

- PCI [PCI, 19771
- ISE [ISE, 1978]
- SWE [Eurocode, 19901
- IBD [Hertz, 1981]

All four methods can be applied to analyze the integrity of fire-exposed beams or slabs. In addition, ISE and SWE can be applied for combined slab-beam cross-sections. All four methods address the moment capacity of the member, though fiom varying perspectives. All methods except SWE can be used to evaluate reinforced or prestressed concrete members. According to the ranking developed by Hosser, *et al.*, the PCI method received the best rating (with IBD being a close second), while the ISE method was worst.

**Steel**

The following seven methods evaluating the fire resistance of steel columns and **beams** were included in the review.

- ECCS [1983]
- SIA [1985]
- Combined ECCS and SIA
- DTU [1982]
- NORDTEST [1985]
- Bongard [1974]
- Lie and Stanzak [1974]

Lie and Stanzak's method evaluates fire resistance by comparing the temperature rise of a steel section fiom a thermal response analysis to a predetermined critical temperature. The NORDTEST method involves a means of interpolating standard test results. The approach by Bongard was considered to be outdated by Hosser, *et d.*, though the basis for that opinion was not provided.

The ECCS method is the basis for the approach included in Eurocode Part 3. Of the other four methods which account for temperature rise, load levels and structural performance, the ECCS and SIA methods were highly rated, with the combination ECCS and SIA method being the highest rated (obtaining almost a perfect. score). However, in a comparative analysis of the predicted fire resistance by the methods, the ECCS method was observed to overestimate the fire resistance for stout columns.

**wood**

A detailed review was conducted of the following seven methods which evaluate the fire resistance of wood columns and beams.

- Seekamp/Stanke [1969]
- Klement/Rudolphi/Stanke [1972]
- Meyer-Wns [1976]
- Meyer-Ottens/Haksever [1979]
- Scheer/Schatz [1985]
- White [2002]
- Stiller [1983]

All of the methods address the fire resistance of wood members given the fire exposure associated with the standard test. The latter three methods are applicable *to* beams or columns, although the methods by Klement, *et d.*, and Meyer-Ottens and Haksever are only applicable to columns and those by Seekamp and Stanke and Meyer-Ottens apply only to beams. Methods are applicable to solid wood sections, laminated wood sections or a combination thereof. All of the methods consider the amount of charring resulting fiom the fire exposure, although methods by Klement, *et d.*, and Meyer-Ottens and Haksever consider rounding of the comers. A reduction in material properties in heated, uncharred regions is considered by Klement, *et al.*, and Meyer-Wns and Haksever.

The method by Stiller was rated best, with the method by Klement, *et al.* being second. Hosser, *et al.*, indicate that Stiller's method is the more recently developed method and improves on the other methods. Its principle strength is the timedependent predictions of charring and stresses. The methods by Scheer and Schatz and White received the lowest ratings due to over-simplification of the equations.

## *3.2 Numerical Analvses*

Most contemporary studies of the structural analysis of fire-exposed structural members or frames have been conducted by finite element models. Sullivan, ***et*** al., [19941 indicate that most of the existing finite element models used for structural fire protection analyses were developed originally for research applications. Considering the fourteen papers presented in the area of structural fire protection at the Fourth IAFSS Symposium [Kashiwagi, 1994] and the International Conference on Fire Research and Engineering [Lund, 19951, the majority of papers involved either the development or application of finite element models. Few recent structural analyses have been conducted with a finite difference model.

FASBUS-II is one of the early finite element model developed in the U.S. to evaluate the structural response of complex building assemblies such as floor assemblies consisting of a two-way concrete slab, steel deck and steel beam [Jeanes, 19821. Input for FASBUS-II includes the temperature distribution, temperature-dependent mechanical properties, geometry, end conditions and loading. The output of FASBUS-II includes deflections, rotations and stresses in the components of the assembly which then need to be compared to performance limits. Use of FASBUS-II has not been indicated in the literature for over 10 years.

Sullivan, ***et al.*** [1994] and Franssen, ***et*** al. [1994] provide extensive reviews and comparisons of existing finite element models for structural fire protection applications. According to Sullivan, ***et*** al., all of the models make the following assumptions:

- Navier-Bernoulli hypothesis: plane sections remain plane
- Perfect composite action is assumed for steel-concrete assemblies, neglecting **any** slippage between the steel and concrete
- torsion is neglected
- moisture effects are neglected

Sullivan, ***et al.*** [1994] reviewed the following eight finite element models:

- FASBUS-II [Jeanes, 1982]
- FIRES-RCII [Iding, ***et*** al., 1977]
- CONFIRE [Forsen, 1982]
- STEELFIRE [Forsen, 1983]
- CEFICOSS [Franssen, 1987]
- LUSAS [1988]
- Sheffield/Nethercott [1988]
- BRE [Yong, 19901

The review of the models was conducted by a literature survey, comparing the formulation and basis of each of the models. The capabilities of each of the models is reviewed in terms of the maximum number of nodes or elements, **types** of elements, materials and types of assemblies which can be modeled. The following comments were provided Sullivan, et *al.* based on the review:

- the predictive capability of the structural models is less than that for the thermal finite element models due to:
  - inadequate material models
  - uncertain material property values at elevated temperature
  - sensitivity of the structural analysis, given the accumulating error from material models and thermal response analysis
- stress history is ignored
- transient thermal creep in concrete is ignored, having its greatest impact on concrete columns
- the effect of creep in steel appears to be of second order importance. Creep is generally compensated for by defining other mechanical properties as "effective" properties.
- programs are limited to two-dimensional analyses
- programs are based on Navier-Bernoulli assumption of small displacements. Hence, large displacements are not accurately modeled.
- Weaknesses in the programs included:
  - poor documentation
  - poor user-friendliness

Comparisons of predictions and measurements have been included in the literature. Examples of such comparisons for steel columns, beams and frames are provided in Figures 3.2 and 3.3.

Franssen, *et* al. [1994] reviewed five models, of which only one, CEFICOSS, was also reviewed by Sullivan, *et* al. The other four models reviewed by Franssen, *et* al., include DIANA, LENAS-MT, **SAFIR** and SISMEF. In addition to a literature survey of the formulation and limitations of each model, eight numerical tests were conducted to compare the output from each model. The tests included simulation of Lee's frame [Lee, *et* al., **19681,** a uniformly loaded column and **an** eccentricity loaded column. Heating conditions were varied in the eight tests ranging from the standard exposure to one which uniformly heats the structural member. In general, the agreement between the models is reasonable. The output, in terms of maximum load or failure temperature varies for any two models by less than 6% for any of the tests. Greater disagreement **was** noted in the predicted displacements by the models. These differences are attributed to different methods of addressing residual stresses.

While not finite element formulations, other computer-based structural models which can be coupled to finite element thermal analyses do exist. All of the following methods were included in the review by Sullivan, ***et al.***, except SAWTEF:

- STABA-F [Rudolph, *et* al., **19861**
- ISFED [Towler, *et* al., **19891**
- BFIRE [Sullivan, *et* al. **,**1994]
- FIRESTRUCT **[OAP,** 1985]
- SOSMEF [Virdi, **19881**
- **SAWTEF** [Cramer **and** Shrestha, **19931**

These methods accept temperature input to evaluate material properties and thermal **strain.** A moment or curvature analysis is conducted to evaluate the performance of the fire-exposed member.

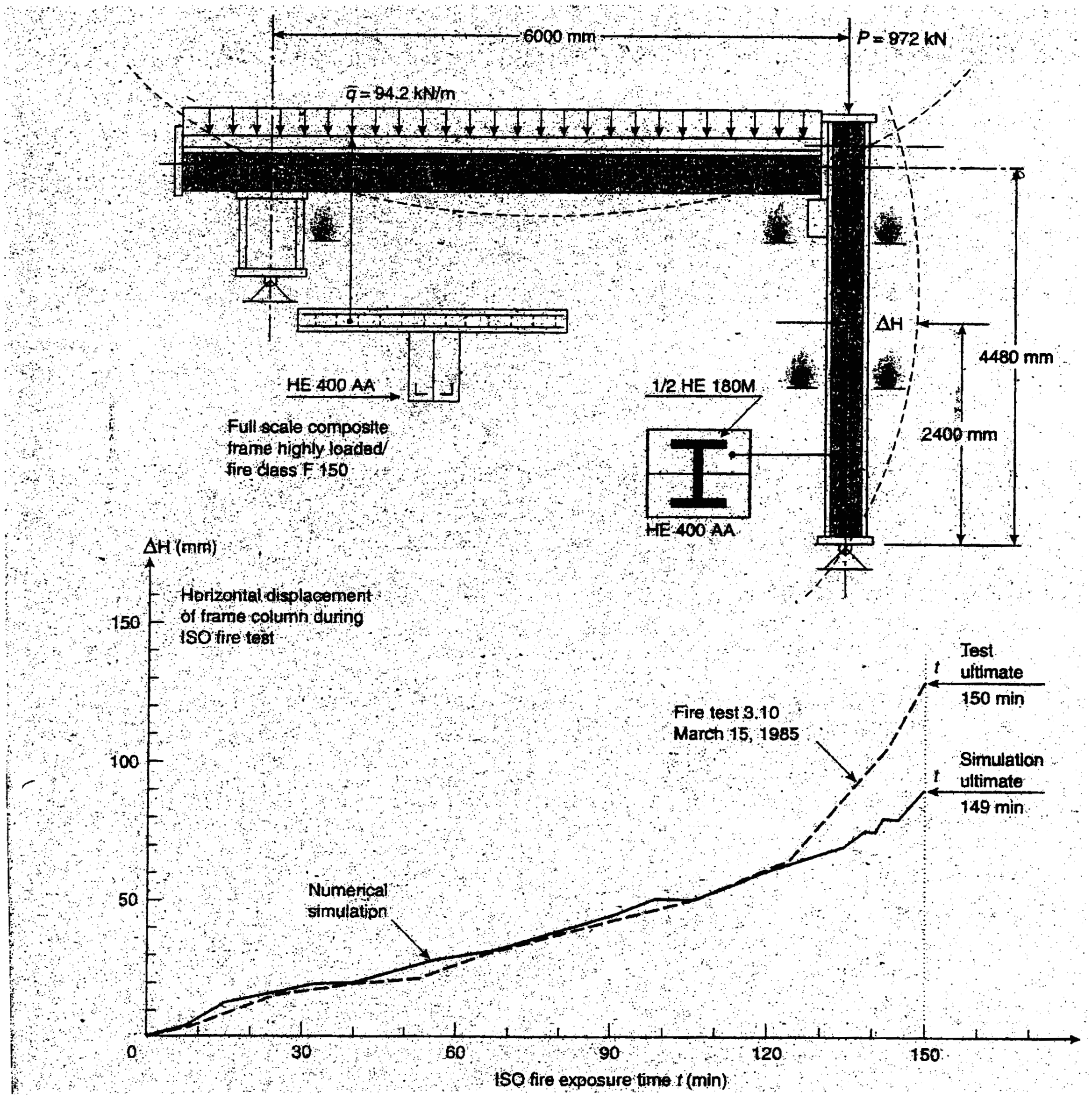



**Figure 3.2 Predicted Deformations of Structural Frame [Schleich, 1993, p. 60]**

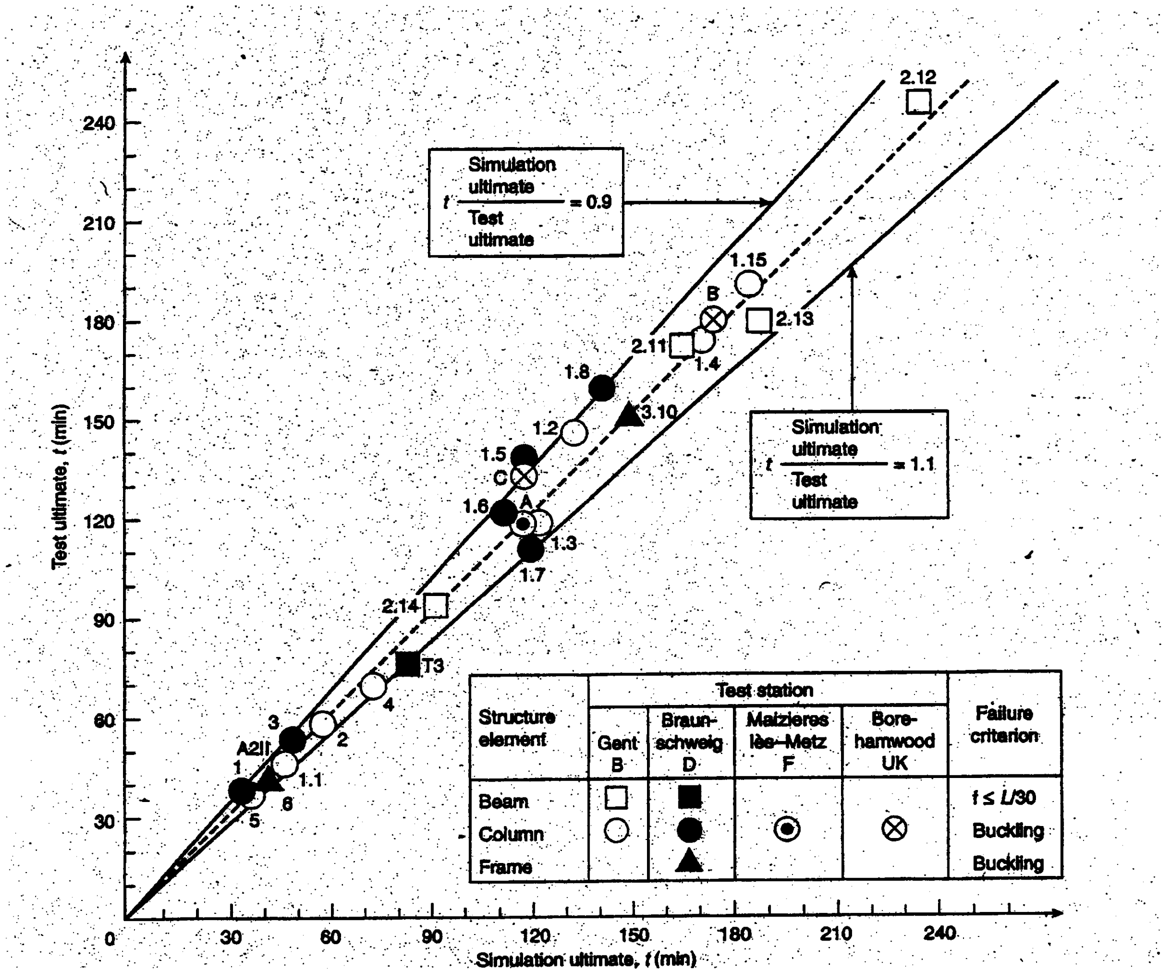



Figure **3.3** Comparison Predicted and Measured Fire Resistance of Steel Structural Members [Schleich, **1993,** p. 60]

SAWTEF is applied to analyze the integrity of fire-exposed wood trusses. SAWTEF accounts for material property changes with temperature, both for the wood and metal connecting plates. **Stress** resultants **are** determined for the wood members and connector plates and displacements are determined for each connection point.

**SAFIR** is one of the few models that ***can*** conduct a thermo-mechanical analysis, where the results of the heat transfer analysis **are** provided for the structural analysis. This does not mean that the analysis is fully coupled, **as** the geometry is not redefined, etc., however, this is a promising first ***step*** toward that end.

Since the mid-90's reviews, development and application of finite element models have **been** described in several papers. As an example, VULCAN has been applied to model the structural response of the floor assemblies in the Cardington test **[Huang,** et al., 20021. Existing models ABAQUS and ***ANSYS*** have also been applied for structural fire protection analyses [Spyrou, et al., 20021 [Gillie, et al., 20021 [Cameron and Usmani, 20021 [Zhao and Kruppa, 20021.

## *3.3 Frame Analvses*

Recently, methods to analyze the effect of fire exposure on a building fiame have been developed. The frame analyses range from algebraic-equation based methods to finite element analyses, As indicated in the review of finite element models by Franssen, *et* al., [19941, Lee's fiame is used extensively as a test case in the documentation for several models.

Pettersson, *et al.* [1976] include a frame analysis via algebraic equations used to determine displacement. The frames consist of beams supported by one or two columns at mid-span. The analysis assumes that each beam or column has a uniform temperature (though the temperature of the beam is not required to be that of a column). A pinned connection between the structural members is assumed. The analysis considers the compatibility'ofthe deformation of each member by requiring that the change in length of the column is equal to the beam deflection at the point of contact.

Schleich, et *al.*, [1986] describe the application of CEFICOSS [Franssen, 1987] for a fi-ame analysis. The fiame consists of a single beam and column, where one end of the column is connected to an end of the beam. Reasonable agreement is indicated between predicted and measured results.

El-Rimavi, *et* al., [1994] describe the application of another finite element model, NARR2, for the evaluation of a large building fiame involving numerous beams and columns. The large fiame is divided into several subfi-ames for computational ease. Good agreement is noted between predictions of deflections and force resultants obtained involving simulations of the full building frame and subframes. Slightly greater failure temperatures were determined for semi-rigid connections as compared to rigid connections.

Liew and Ma [2002] apply the model FAHTS to assess the response of a steel frame with concrete floor slabs to fire exposure. The principal intent of their analysis is to assess the response of the frame to varying levels of fireproofing provided to the steel columns and beams.

One of the current areas of research activity and modeling involves the analysis of connections. Many of the previous efforts involving frames assumed that the integrity of the connection was maintained throughout the duration of the exposure. Papers by Franssen and Brauwers [2002] **(see** Figure **3.4)** and Spyrou, et al., [2002] recently analyzed the performance of connections in steel frame buildings.

Limitations

The principal limitation associated with frame analyses are related to the rigidity of the connection.

- Limited information is available concerning the effect of elevated temperature on the rigidity of the connection.
- Other than the Cardington tests, no other data is available on the performance of fire-exposed frames with which to compare results from models.

## *4. Summary and Research Needs*

A wide variety of calculation methods for structural fire protection have been reviewed in the previous sections. The available calculations apply to many different types of building assemblies, including floor- and roof-ceiling assemblies, columns, walls and trusses. The building assemblies may be comprised of any of the principal structural materials, *i.e.* steel, concrete, concrete and clay masonry and wood, as well as protection materials and veneers. In fact, in a previous survey of experts in structural fire protection conducted almost 20 years ago, a strong majority indicated that techniques were available at that time to assess the fire resistance for engineering purposes of any type of structural member [Milke, 1985].

Several published evaluations of the predictive capabilities of the methods have been conducted. In general, the predictive capability of the methods is acceptable for engineering purposes. However, all calculations from a particular method should not be expected to agree perfectly with measured parameters. For example, calculated stresses may be in good agreement with measurements while agreement of displacements is disappointing. Even so, many of the tools do appear to adequately capture the first-order effects of fire resistance assessments to qualify as candidates for use in design applications. The adequacy of the engineering tools for fire resistance assessments is indicated by the incorporation of analysis procedures into the Eurocodes documents.

Significant constraints in the application of such tools include the limited availability of material property data and the limited understanding of these analytical tools by practicing engineers. However, as in virtually any area of engineering, numerous "unknowns" or gaps in the state of knowledge remain. These gaps have been identified in the previous sections, often as limitations of a particular calculation method. Some of the gaps indicate a lack of understanding, while others relate primarily to a lack of data. The impact of the unknowns varies, though many of them relate to issues of second order importance. One principal effect of the unknowns is to limit the applicability of the calculation methods to selected types of building assemblies. Even though many of the unknowns are individually of second order importance, together they may have significant impact in certain applications. Thus, if the gaps can be addressed, "anomalies" in the predictions may be resolved and broaden the applicability of the calculation methods. The gaps are summarized in the following sections.

### *4.1 Material Effects*

Material response to fire is a principal area of weakness in evaluating the response of building assemblies to fire exposure and serves as a major constraint to the application of analytical methods for fire resistance assessments. Except for the principal structural materials and a limited number of protection materials, material property data at elevated temperature are sparse. Part of the problem concerning material property data is the shortage of standard test methods for conducting such analyses for a wide variety of materials for the wide range in temperatures relevant to fire resistance analyses.

Other issues include the inability to predict crack initiation and development, adherence of protection materials to structural members and ablation and intumescence of protection materials, though attempts have been made at assessing such behavior [Butler, et al., 19951. Aspects of heat absorption and moisture migration are often neglected or are incorporated implicitly into other material properties. A model for spalling behavior of concrete is not available. Char rates typically cited for wood members are independent of the stress state and are only valid for the standard fire exposure.

In some cases, the deficiencies simply restrict the ability of calculation methods to be applied for that material, such as intumescent materials. In other cases, the gaps may be of second order significance, given the recognition given to existing design guides that ignore the gaps and the presence of some of these same gaps in structural engineering calculations for ambient temperature conditions.

Two approaches can be proposed to narrow these gaps in material effects. One approach is to conduct fundamental research to narrow or eliminate the gap. Such research could result in improved material models. The second approach is to continue conducting large-scale tests involving fire exposure to develop "effective" properties and implicitly address complex issues such as adherence of protection materials or cracks.

### *4.2 Thermal Response*

A principal limitation in heat transfer analyses is the lack of coupling to mechanical analyses. While output from some heat transfer models is easily provided as input, geometric changes are neglected. Further, assemblies are treated from an idealistic perspective, i.e. crack formation is neglected as is the loss of adherence of fireproofing materials. A model for intumescent protection materials is lacking. While models have been developed for research applications that couple heat and mass transfer for moisture containing materials, such has not been applied for structural fire protection. An improved basis for heat transfer parameters, especially convection, is needed. As indicated in the previous section, the dearth of material property data, especially at elevated temperature for protection materials is a significant barrier.

While some of the shortcomings can be improved via model development, most of the shortcomings are due to the lack of experimental data. The majority of the experimental data needed relates to material behavior and can be conducted via small-scale tests. However, developing an improved understanding of heat transfer in fully-developed fires requires large-scale experiments.

### *4.3 Structural Response*

As with the shortcomings for thermal response analysis, the shortcomings for structural response can be divided into the need for additional data and the need for improved models. The principal issue relating to modeling again addresses the need for a coupled thermo-mechanical model. Data needs again involve material property values at elevated temperature, improved understanding of the role of stress on spalling and charring, creep, and the performance of connections in frames exposed to fires.

As noted for thermal response analyses, the data needs involve conducting small- and large-scale experiments. Much of the material behavior aspects can be explored via small-scale tests, while understanding the performance of connections involves a larger-scale experiment.

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## White Paper 7

# Thermal and structural analysis methods and tools – gaps in knowledge and priority area for research from a practice perspective

**Barbara Lane, Ph.D., Arup Fire**

## Introduction

This NIST workshop is being held to create a detailed research and development roadmap for Fire Safety Design and Retrofit of Structures.
This paper addresses thermal and structural analysis methods and tools only. Specifically this paper aims to create a list of knowledge gaps in this field, which are priority areas for research, from an Engineering Practitioners perspective.
The information presented in this paper is based on expertise within Arup Fire from related design projects and research, which also form part of existing commissioned surveys such as that carried out for the American Institute of Steel Construction 2003.

The paper has been written as a discussion point only and therefore does not contain a literature review of this field as a preamble to the gaps identified.

The following is a list of gaps in the current ability of practitioners to successfully carry out fire safety design of structures.

## Regulatory Guidance and Control

In order to ensure the success of structural fire engineering design methods – from complex finite element analysis to single element analytical methods, the acceptance by the regulatory authorities is essential. As well as a general understanding and acknowledgement of the rigorous validation behind such analyses, an ability to review proposed solutions is required.
Currently there exists no good practice guide for structural fire engineering design methods. It seems key that authorities should have accepted codes of practice that provide a step by step guide to evaluating proposed design methods. For example minimum levels of input and corresponding output, key structural items and materials to be considered, peer reviewed data sources and design methods, basic test scenarios – specific fires that amply evaluate the structural response, etc.
Initial reviews of the current state of the US building regulatory system indicate that it is not yet ready to support widespread application of performance-based structural fire protection. This is largely due to the individualized nature of performance-based projects. The performance-based design concept requires that building projects be analyzed individually and that their specific details be considered in the development of fire protection strategies. It is difficult for a regulatory system based largely on standard test methods and fire ratings to evaluate buildings that have been designed to meet unique performance criteria. Also however there is no back up information for authorities even if they did decide to approach such a problem.

Similarly for designers, a good practice guide is essential to limit abuse of analytical and numerical methods for passive fire protection designs.

### *Possible Ways Forward*

The following is a list of possible changes or additions to building codes that may be necessary to support engineered structural fire protection.

1. **Regulatory support for defining project goals, objectives, and performance criteria.** In order to evaluate the adequacy of a given design, both the building designers and the regulatory officials must understand the goals, objectives, and performance criteria of the project and must compare these to the expected performance of the design. If a standardized method of defining this information is not available then regulatory control of projects will be very difficult and regulatory bodies will be reluctant to allow performance-based fire protection approaches.

2. **Regulatory Support for Defining Design Fire Scenarios.** Along with a system of defining goals, criteria, and objectives, codified design fire data may be necessary. Structural engineers will require guidance in choosing appropriate thermal environment data for structural fire analyses, and regulatory officials will need a way of ensuring that appropriate design fires have been utilized for a given project.

3. **Regulatory Support and Approval for Analytical Methods.** In order to allow nationwide application of performance-based techniques, a system of identification of approved and appropriate analysis methods must be developed. This will inform and instruct structural engineers in the correct use of appropriate tools for given situations and will help authorities to ensure that appropriate methods have been utilized correctly. This may be accomplished by code references to existing or future design guides.

### Approved Simple Analysis Methods

While advanced, non-linear analysis methods are available and may be the most accurate ways to evaluate theoretical structural behavior at fire temperatures, their complexity and the level of knowledge required to apply them correctly require a great deal of knowledge on the part of the engineer. They are also still relatively rare for real structural assessments.

Because of this, these tools are a long way from being widely accepted for structural design projects. However, if a performance-based approach to structural design for fire conditions is to be widely accepted, methods to accomplish the required analysis must be evaluated, approved, and made available to engineers. Application of simple methods, developed from complex assessments of structures in fire, is a logical and reasonable approach to this issue.

Various simple analysis methods exist that could be used to determine certain aspects of structural fire behavior. These include spreadsheet applications, parametric and linear equations, and graphical approaches. Topics such as the strength and deformation of horizontal members at elevated temperatures are relatively well covered in the range of existing simple approaches, and some research exists validating or disputing these approaches. However, numerous specific topics exist for which simple analysis methods do not accurately represent real behavior, or simply do not exist.

### *Possible Wavs Forward*

A specific list of topics for which future research regarding simple analytical methods is required should be developed. A full understanding of simple approaches to analyzing structural response to fire temperatures requires research into each of these topics. However, the most important work in this area will be the validation and justification of the use of simplified methods to represent the highly complicated, nonlinear structural behavior associated with fires in buildings.

As mentioned previously, approval and acceptance of complex nonlinear analysis tools by the regulatory bodies and the practicing engineers for general structural design projects will be very difficult to attain. Such goals for simplified methods are more reasonable, initially. However, widespread acceptance of simplified analytical methods will require the completion of several tasks:

1. Validation of different simple analytical methods for specific design purposes (for example, validation of a tool for the analysis of ribbed concrete slabs, etc.).
2. Regulatory acceptance of the validation of various models.
3. Regulatory dissemination of approved simple analytical methods.
4. Availability of regulatory and industry guidance on the proper use of available simplified analytical methods for the benefit of authorities having jurisdiction and engineers alike.

If the above four tasks can be accomplished, great strides will have been taken towards the accomplishment of widespread acceptance of engineered structural fire safety approaches.

## Information Availability

A large amount of data exists worldwide regarding various aspects of the behavior of structural components under fire conditions. However, this data is not organized or linked together in a way that provides structural engineers with easy access to appropriate answers for specific questions that arise during the design and analysis of structures exposed to real fire temperatures. Also, many research efforts do not get published for public use, so an engineer may not be able to use the information they contain. Thus, an engineer may not have access to state-of-the-art information regarding the specific functions the engineer needs to perform, such as those that make up the performance-based structural engineering process.

### *Possible Ways Forward*

The engineering world in general has long been devoted to the dissemination of knowledge amongst its members. The current lack of access to pertinent data is due largely to the separation that has long existed between structural and fire protection engineers. This gap has prevented or discouraged the efficient trade of information between these fields. However, the performance-based approach to structural fire protection requires that structural engineers have access to the knowledge of the fire protection engineering community, and that this and structural engineering information be easily and efficiently accessed.

To this end, the following are general recommendations for advances that may help bring needed information to engineers designing structures for fire safety:

1. **Information Management.** Develop and make widely available a database system dedicated to the dissemination of structural fire engineering information. This database should provide access to information covering all aspects of the process of designing and analyzing structures at fire temperatures, and should provide the engineer with guidance in choosing appropriate methods, data, and other critical information.

2. **Research Support and Publication.** Encourage global contribution to the body of knowledge regarding structural fire safety issues by identifying gaps in that knowledge, making these gaps known to researchers and engineers, and sponsoring research efforts, and also by providing a forum for dissemination of new knowledge (such as a database system as discussed above).

3. **Availability of Existing Research.** Collect information regarding existing research, both published and unpublished, and make this information available to engineers.

4. **Author Submission of Past Research.** Encourage the availability of past research efforts by providing an easy and efficient way for authors to submit information regarding their existing work to a forum such as that discussed above.

## Compartment Fire Models

Computer Fire Models have been traditionally divided in two groups, Zone Models (ZM) and Computational Fluid Dynamics (CFD) or Field Models.

Zone models treat compartments as a control volume sub-divided into two smaller control volumes. All heat transfer related quantities within these codes are established in an empirical manner.

The main aspect that differentiates CFD codes is the way by which turbulence is modeled. Thus, CFD codes can be divided into three groups, Reynolds Averaged Navier-Stokes (RANS) models, Large Eddy Simulation (LES) models and Direct Numerical Simulation (DNS) models.

Specific limitations of these models relating to structural design follow.

Characteristic time scales for the heating of solids are in general considered much larger than the time scales for fire growth. Thus it has been an accepted approach to ignore the fire growth period and conduct all structural analysis under conditions corresponding to a post-flash over or fully developed fire. Within a fire scenario it is possible that flashover might be attained within the compartment of origin before any structural element has undergone significant heating, nevertheless none of the adjacent compartments will be expected to have reached fully developed conditions. Furthermore, growth beyond the compartment of origin will generally be within the same time scales as the heating of structural elements. If the objective is to integrate CFM's with structural analysis, significant effort is necessary to establish realistic timescales and characteristic conditions of fire growth beyond the compartment of origin. Experimental validation should follow because little or no useful data exists.

It is of importance to note that extensive experimental data has been gathered on the evolution of the temperatures within a compartment but very little information exists on the evolution of the heat fluxes imposed on a compartment surface. This data is of immediate need if any validated integration of Fire and Structural Engineering is to be achieved.

Time scales more relevant to structural behavior imply in most cases fully developed fires. None of the existing CFD codes has been properly validated under these conditions. The data available for post-flashover, fully developed fires is generally in the form of average punctual measurements of temperature, which is more suited for the validation of Zone Models than of CFD codes. Combustion and soot models are greatly sensitive to the burning conditions therefore the capability of existing model to provide reasonable predictions under fully-developed fire conditions remains untested.

Independent of the model used all numerical tools are severely limited by an improper definition of the fundamental properties of materials controlling fire growth. An analysis of the input variables for all flammable materials shows a systematic dependence of simple and very approximate databases. The errors that can be induced by an improper or incomplete selection of material properties can be more important than those generated by an improper use of the parameters of the turbulence model.

## *Possible Wavs Forward*

The following is a list of specific research areas regarding compartment fire models for which future effort is required:

1. Establish realistic timescales and characteristic conditions of fire growth beyond the compartment of origin plus experimental validation so as useful data exists for modelers.
2. Validate existing CFD codes for time scales more relevant to structural behavior (fully developed fires).
3. Validations of combustion and soot models to provide reasonable predictions under fully-developed fire conditions.
4. Further validation of empirical constants with detailed and quantitative measurements is required for zone models, specifically entrainment rates and their validation under conditions other than free axis-symmetric or line fires.
5. For zone models, of the constant properties in each zone, complicated geometries would be treated in the same way as less complicated ones. The absence of velocity fields and lack of turbulence modeling implies that the convective heat transfer will not be affected by complicated geometries. The use of zone model for very complicated geometries requires validation.
6. Establish sensitivity of heat fluxes to the different numerical parameters and physical models.
7. Validation of wall functions and heat transfer models with detailed quantitative measurements.
8. Validation of turbulence models for transitional flows, re-circulation areas and regions close to walls.
9. Evaluation of the effect of fire retardants on soot production.
10. Effect of soot deposition on soot concentrations in fire related environments.
11. Extension of soot models to flames generated by materials typical of fires.
12. Quantitative evaluation of the effect or roughness on existing turbulence models and convective heat transfer.
13. Development of more efficient numerical schemes to speed computations and allow modeling of more complex environments.
14. Establish sensitivity of heat fluxes to the different numerical parameters and physical models.

## Thermal and Mechanical Properties of Structural Materials

While numerous sources for thermal and mechanical material properties exist, some gaps are evident in the body of data. This conclusion is based on the following observations:

1. Information is greatly limited regarding values and temperature dependence of numerous specific steel properties. Those observed here are:

   Temperature-dependent tensile strength of steel

   Temperature-dependent shear modulus of steel

   Temperature-dependent density of steel

   Temperature-dependent Poisson's Ratio of steel

2. Information is greatly limited regarding values and temperature dependence of numerous specific concrete properties necessary for analysis of composite construction. Those observed here are:

   Temperature-dependent compressive strength and elastic modulus for concrete

   Temperature-dependent shear modulus of concrete

   Temperature-dependent density of concrete

   Temperature-dependent Poisson's Ratio of concrete

   Mass loss rate at elevated temperatures

3. Information is greatly limited regarding the temperature dependence of passive protection material properties. Specifically, no resources reviewed here included mathematical expressions to describe the temperature-dependence of protective material properties. Parameters which require further research and would benefit from correlation to mathematical expressions are:

   Temperature-dependent protection material thermal conductivity.

   Temperature-dependent protection material specific heat.

   Temperature-dependent protection material density.

   Temperature-dependent protection material rate of thermal expansion.

   Additionally, material property data for intumescent coatings is difficult to obtain, and the information that is available is greatly limited and frequently proprietary.

4. Available property information is largely limited to traditional materials. Recent tendencies toward performance-based building design have increased the use of more novel, high performance materials such as high-strength steels, concretes, and composite materials, as well as both common and novel insulation materials. The availability of thermal and mechanical properties are, in general, lacking for these materials.

5. Advanced research on material properties is often not readily available. In order to analyze a complex structural assembly or a novel material, the engineer needs access to sources of appropriate and accurate information regarding a wide range of material properties.

***Possible Ways Forward***

Based on the observations presented above, the following are recommendations for future research efforts in regard to structural material thermal and material properties:

1) **Steel Properties.** Several steel properties require exploration to accurately determine temperature dependence. These are:

Tensile Strength
Shear Modulus
Density
Poisson's Ratio

In addition to simply understanding the temperature dependence of the above steel properties, the industry would greatly benefit from the correlation of mathematical expressions describing this temperature dependence.

2) **Concrete Properties.** Several concrete properties require exploration to determine temperature dependence for use in the analysis of composite elements. These are:

Shear Modulus
Poisson's Ratio
Density
Mass Loss Rate

Mathematical expressions for the above would prove very beneficial to the field. Also, mathematical expressions describing the temperature dependence of the modulus of elasticity of concrete and the strength and modulus of elasticity of reinforcing steel are required.

3) **Protection Material Properties.** Several protection material properties require exploration to determine temperature dependence. These are:

Thermal Conductivity
Density
Specific Heat
Coefficient of Thermal Expansion

Formal mathematical representations of these temperature dependent properties could serve to increase the accuracy with which the performance of protective materials under fire conditions is predicted in structural analysis. The ability to model intumescent paints are of particular interest.

4) **Development of Tests for Material Properties.** Where accepted tests do not exist for determining specific thermal or mechanical properties identified as necessary for analysis and not currently available (see above), new test methods will need to be developed or existing test methods adapted.

5) **Novel Materials.** Additional research is necessary to define the high-temperature behavior of novel and high-performance materials. These may include but are not limited to the numerous high strength steels and alternative metals that are emerging, high-strength concretes, composite materials, and insulation materials.

6) **Availability of Material Property Information.** Compilation of the full range of available research, either into comprehensive overview sources or a network or database of specific sources, is necessary to ensure that those practicing performance-based structural analysis and design have access to inputs that the analysis requires.

7) **Material Property Model Validation.** Existing and future research efforts must continue to be confirmed and refined through comparison to actual structural fire behavior. This can be accomplished through parametric studies of large- and small-

scale fire tests, as well as through analysis of real structure fires. Such research can help refine the general understanding of material behavior and can lead to more accurate prediction of actual structural fire performance.

## Heat Transfer Analvsis Methods

Heat transfer to unprotected structural steel can generally be calculated by hand or spreadsheet because its high conductivity and homogeneity make simple calculations accurate.

Input to any calculation or computer program always requires an estimate of the emissivity and the convective heat transfer coefficients. These are both areas that still need investigating.

Unprotected steel acts as a large heat sink and the effect of this on fire temperatures is not well understood. It is known that in a standard furnace a lot more fuel is pumped into the furnace to maintain the fire temperature when testing unprotected steel.

Moisture migration is essentially a concrete problem and the nuclear industry has spent a huge effort in understanding pore pressures and migration of water. This level of accuracy is probably not required for fire calculations although it is critical in helping to determine spalling of concrete, which is not well currently understood.

Heat transfer through thin film intumescents is not well understood and needs to be quantified.

Various tools are available for predicting heating conditions in sophisticated projects where the design fire is not a relatively simple post-flashover fire involving the whole Compartment. A common example of such a tool is FDS (Fire Dynamics Simulator, developed by NIST), a computational fluid dynamics code that has become an industry standard in predicting compartment fire behavior. Unlike simpler zone models, FDS can be beneficial in compartments with large floor plates and when fire spreads from one compartment to another. Also, FDS and similar models are useful for predicting temperature distributions throughout a compartment, information which is necessary for the prediction of localized heating effects and performance under uneven heating conditions.

The current method of utilizing FDS or other computational fluid dynamics models in structural analyses is to record time-temperature relationships for specific points in a structure (i.e. air temperatures near structural members) and then input them into the structural analysis, at which point a heat transfer analysis must be included to calculate material temperatures. In order to accomplish this, the output of the FDS model needs to be coupled with the heat transfer model, or the mesh used in both the FDS model and the structural analysis model need to be very similar if not exactly the same. The boundary condition between the fire temperature and the steel surface is difficult to model accurately and assumptions must be made about convection at this boundary. Additional work is required to refine this process.

### *Possible Wavs Forward*

1. **Coupling of Computational Fluid Dynamics, Thermal and Mechanical Analyses.** Possibly the most important needed development is the streamlining of the interaction of fire models, heat transfer models, and structural analysis models. The industry will benefit greatly if a link can be developed between fire behavior prediction and structural analysis such that an engineer can efficiently move from nodal time-temperature curve predictions to material temperatures and the resulting structural response. This is challenged by numerous issues, not the least of which is the difficulty inherent in modeling thermal boundary conditions close to physical objects (e.g. structural members). However the immediate urgency of this seems

remote as currently there remains so much that is not understood fiom uncoupled thermal-structural modeling.

2. **Material Thermal Properties.** Additional research regarding thermal properties of construction materials is needed, as discussed above. Specifically, thin film intumescents require significant further work.

3. **Heat Sink Behavior.** The effects of heat sink behavior on fire temperatures must be better understood and quantified through physical testing and parametric studies.

## Non-Linear Analvsis Methods

Simple analytical methods are generally favorable in the everyday design environment due to their relative ease of use and their time and cost efficiency. However, such methods are generally incapable of considering numerous complex structural behavior issues. Advanced analysis methods, specifically finite element models, are available for complicated situations or when increased detail and accuracy is required in an analysis.

In general, commercially available finite element codes have all the capabilities necessary to perform any non-linear analysis; structural response to fire is just one of these. The software packages developed in universities and research institutes are frequently less functional but are generally designed specifically for modeling some aspect of structural fire behavior.

Commercial software packages are readily available and have the advantage of being tested on a number of highly non-linear and sophisticated problems by the writers and users around the world. Upgrades and improvements are released on a regular basis. One disadvantage is the computing power necessary to run such models. With the advent of very powerful personal computers this is becoming less of an issue. The initial investment in buying the FE program and the computer to run it may be considerable.

Several research institutions have developed special-purpose non-linear structural mechanics codes to model structural behavior in fire. Vulcan at the University of Sheffield and SAFIR at the University of Liege are probably two of the most advanced. However, research codes are generally designed to deal with the structural fire problem specifically. Therefore, such codes may be improved and modified much more readily for a specific problem than commercial codes. However commercial codes are by their broader use subject to constant scrutiny and improvement.

While significant capabilities exist in available finite element codes, the accuracy of their analyses depends on their appropriate application. A good deal of effort has gone towards validation of models and analysis techniques, especially with the availability of significant data sources, such as the Cardington tests, but many situations and details exist for which modeling techniques or capabilities are lacking or have not been validated. Some of these details are discussed below.

One of the main drawbacks to advanced analysis methods is the difficulty inherent in their regulation. Advanced knowledge is required to utilize these models, and likewise to understand their use and the results they produce. Most regulatory officials are not intimately familiar with the methodologies implemented in advanced models, and thus may be uncomfortable in allowing their application to projects or in assessing their predictions.

### *Possible Wavs Forward*

While advanced finite element models are currently the most accurate way to simulate complex material and structural behaviors, such as those experienced during a building fire, several aspects of the use of these models require additional work. The following is a list of future work efforts designed to fill various gaps noted in the current knowledge regarding the use of finite element models in analyzing structures at fire temperatures.

1) **Regulatory Guidance and Approval.** The structural design community, traditionally dedicated to prescriptive guidance and support, will require that regulatory bodies indicate approved advanced analysis methods. Also, regulatory guidance on applying these methods appropriately will most likely be required.

2) **Coupling Thermal and Mechanical Analyses. As** noted, the coupling of thermal and mechanical analyses would be a very significant step forward in performance-based structural fire engineering, and could greatly streamline the process of moving from a prediction of fire compartment temperatures to a prediction of mechanical structural response. This is seen as a long term objective.

3) **Model Validation.** Significant available research (the Cardington tests, for example) is available for use in validating advanced structural analysis methodologies, and this is a critical goal. However, additional aspects of structural fire behavior may not be evident from currently available test data, and thus additional testing is required in order to fully validate advanced models and approaches. Aspects that require future investigation include:

   - Mathematical representations of thermal and mechanical material properties.
   - Brittle rupture of steel members.
   - Representation of mechanical behaviors of concrete slabs.
   - Cracking and fracture of concrete members and slabs.
   - Fracture of concrete reinforcement.
   - Accurate modeling of connections.

## Failure Criteria / Performance Criteria

A significant obstacle hindering the development and acceptance of performance-based design in the US is the availability of information for use in establishing performance criteria for structural fire design. Regardless of the availability of validated and approved analysis methodologies and material property data sources, structural analysis cannot be carried out without defined performance (or failure) criteria definitions. An understanding of the performance of a structure during a given fire is only half of the performance-based structural fire engineering approach. The necessary other half involves defining acceptable performance and comparing actual performance with this, thus determining if the structure performs adequately in the fire.

Some guidance is currently available for the basic process of defining general failure criteria. However, most of this guidance simply suggests that building performance should be adequate in terms of prevention of collapse and aiding of life safety. There are currently no defined failure criteria for structural fire engineering assessments. In the UK, common practice is to use one of the following to demonstrate stability and maintenance of compartmentation throughout the design fire duration:

- Beam deflections do not exceed the rates stated in the standard furnace test BS 476 (one example is beam span/20).
- Rapid increases in beam deflections do not occur during the design fire duration.
- Column instability does not occur during the design fire period.

However, the above criteria are not standardized, and thus a method of justifying their application is not currently in place. Such an approach could provide a model for the definition of performance criteria in the US, however.

### *Possible Ways Forward*

In order to provide engineers and regulatory officials with guidance in determining appropriate performance criteria for performance-based structural design, the following achievements are viewed as necessary:

1. Experimental study (particularly full-scale tests) into appropriate definitions regarding failure modes and limiting values of material parameters for determination of structural failure under fire conditions.
2. Consensus regarding the definition of structural failure during fire.
3. Codification (and thus widespread availability) of either numerical values for parameter limit states or approaches to defining specific and appropriate performance criteria for use by engineers and regulatory officials.
4. Given the lack of current knowledge regarding this subject, a forum of international experts may be in order for the review of the topic. Note that such conversations have already occurred in the UK with no measurable results.

### Connection Analysis and Design

The specific effects of connection performance on the fire performance of structures are not well understood. Additionally, practical tools do not yet exist to guide designers in their choice of connection detailing. Traditionally, connection performance has not been analyzed implicitly, and overall frame behavior has been assumed to be indicated by the performance of individual members. However, depending on connection details, factors such as load and moment redistribution can play a very significant role in building fire performance by transferring loads away from components that are nearing or have reached failure. Thus, a true representation of real structural fire performance might not be obtained unless the behavior and performance of the associated connections is specifically considered.

Most connection analysis is accomplished through advanced fmite element modeling, since this approach can take into account the highly nonlinear nature of connection behavior at high temperatures. However normally gross simplifications are made to reduce computational time so these response tends not to be modeled explicitly. Some recent work has led to relatively simple methods that can be used to approximate beam-column connection performance. Validation of this work for different connection details is required.

There is currently little code advice in regard to the fire protection of connections. Generally, codes specify that connections must be protected to the same degree as the surrounding structural elements. Some research aimed at understanding the fire performance of connections has been undertaken, especially given the apparent importance of connection performance in WTC Towers 1 and 2 and in the Cardington tests. However, a great deal of additional research will be required to fully understand the behavior of the various connection types commonly used.

### *Possible Ways Forward*

Further research is needed to increase the understanding of how real structures perform in fire. Although testing of components greatly increases the understanding of their behavior in fire, many component tests do not model the complex structural interactions that are found in normal building structures and are greatly impacted by connection conditions. Topics regarding connection design for which future research is needed include:

1) Simple analytical methods for considering the effects of elevated temperatures on structural connections.

2) Performance of fin plates/shear plates in fire, for beam column and beam to beam joints. A review of minimum edge distances is required.

3) Forces and strains generated within connections in the cooling cycle.

4) Minimum slab reinforcement and connectivity needed to satisfy fire conditions.

5) Shear stud performance and shear force distribution during the fire cycle.

6) Development of realistic 3-dimensional finite element models of connections subjected to series of loads and restraints in simulated real fire conditions.

7) Review of the need for column stiffener plates, where the bottom flange is connected to the column.

### Conclusions

This paper summarizes specific items, which require research and development, to ensure robust fire safety design of structures. This ranges from simple analytical methods to complex finite element analysis of structures in fire.

This list is from a practitioner's point of view, such that design methods, which are robustly validated, can be presented to authorities having jurisdiction for careful review and consideration. The overall aim being, the improved design of structures for fire.


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## White Paper 8
## Evaluation And Retrofit Of Existing Buildings For Structural Fire Safety

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### Introduction

This white paper addresses structural fire safety in existing buildings. In many respects, the analysis of structural fire safety in existing buildings is no different **fiom** the analysis of new buildings. The same basic principles apply to both. But evaluation of structural fire safety in existing buildings is generally more complicated than in new buildings for a number of reasons, including one or more of the following:

- Undocumented design basis;
- Presence of archaic building systems and materials with unknown structural and thermal performance characteristics;
- Concealment of design details;
- Unknown condition of concealed structural elements and fireproofing systems.

Assuming these issues can be addressed in a satisfactory manner, retrofit options must be considered. In this respect, the analysis of existing buildings may also be more complicated than for new buildings because the designer must identify retrofit options that **are** compatible with the existing design **as** well **as** cost effective.

In this paper, design approaches to the evaluation and retrofit of buildings for structural fire safety are addressed. ***An*** analogy is made to the seismic retrofit of structures. Issues related to the evaluation and retrofit ***of*** structures for improved fire performance are addressed. Recommendations are made for the research and development that is necessary to implement a code of practice for the retrofit of structures for improved fire performance.

### Design approaches

There are three general **aspects** to the analysis of structural fire safety in both new and existing buildings. These include:

- Evaluation of the thermal conditions resulting fiom design basis fires, commonly expressed in terms of time-temperature histories;
- Evaluation of the thermal response of structural elements and assemblies, including effects of fire resistance treatments, to the imposed fire conditions;
- Evaluation of the structural response of structural elements, assemblies and frames resulting fiom their thermal response.

There are two general approaches to the analysis of structural fire safety in both new and existing buildings, These include:

- Prescriptive approach
- Performance-based design

In the prescriptive approach that has traditionally been applied to structural fire safety, the relationship between thermal performance and structural response is evaluated by subjecting representative building elements and assemblies to standardized exposure conditions and obtaining a standard fire resistance rating for the element or assembly. In the prescriptive approach, structural design for fire is basically just a matter of specifying and selecting structural elements and assemblies that have been tested and meet the standard fire resistance rating requirements mandated by prevailing building regulations.

The prescriptive approach assumes that there is an implicit relationship between the mandated fire resistance requirements, the fire resistance test performance of rated elements and assemblies, and the expected performance of these elements and assemblies under actual fire conditions in the field. Unfortunately, the exact nature of this relationship is not known, in large part because only isolated elements and assemblies are tested, without consideration of the impact on the entire structural frame. Consequently, applying this prescriptive code approach to retrofitting an existing structure would not be very useful and would amount to little more than searching for and correcting code violations.

In performance-based structural design for fire, the relationship between fire-induced thermal exposure conditions and structural response to these exposure conditions is addressed explicitly. The performance-based design process generally includes the following steps:

- Identify possible fire scenarios;
- Calculate fire temperatures and durations for these scenarios;
- Calculate temperatures of structural elements;
- Calculate the structural response of each member;
- Calculate the structural response of the building as a whole.

In the design process, several trial design concepts are evaluated until a final configuration is chosen which gives the desired fire response. In the retrofit process, the existing building is evaluated structurally and several retrofit concepts are also evaluated until one meeting requirements of practicality and desired fire response is found. The performance-based design approach can be used to evaluate existing buildings and serve as a basis for analysis and design of retrofit options. The general methodology of the performance-based approach is the same for designing new buildings or for evaluating existing buildings.

**The seismic retrofit analogy**

There is a well-established code of practice for seismic retrofit of existing buildings that has evolved over the last 50 years [1]. Some of this methodology may be useful for developing a similar code of practice for retrofitting buildings for improved fire performance. Some cost savings would probably be realized if seismic and fire retrofit options were considered together. It should be recognized, however, that there are significant differences between the hazards and risks of fires and earthquakes that will prevent the wholesale adoption of the seismic retrofit methodology for fire. Of most significance, earthquakes are an extrinsic hazard, while fires are an intrinsic hazard. In seismic design, designers have no control over the magnitudes or frequencies of earthquakes; they rely on statistical data for these parameters. In fire design, both the frequency and the magnitude of fires are influenced by human interactions and design decisions. They have both random and intentional aspects. In this respect, fire design is more analogous to blast design than to seismic design. Despite these important differences, the seismic retrofit code of practice can serve as a useful starting point for a fire retrofit code of practice.

Under the seismic retrofit code of practice, seismic retrofit design can follow either a performance-based or a prescriptive code approach. Using the newer performance-based approach, risk analysis is used to establish an earthquake return period, from which acceleration history and lateral forces are determined. The structure is then modified to resist these lateral forces without collapsing. Often the structure is also required to withstand a smaller earthquake with a shorter return period without suffering serious structural damage. Additional requirements of ductility and connection detailing may be imposed. The actual design of a seismic retrofit is primarily a matter of common sense, general design experience and intuition, and good engineering judgment, backed by calculations to test and evaluate trial retrofit configurations. However, attempts to establish a code of practice have been made by FEMA [1] and others. There are also publications suggesting standard details for reinforcing connections and other aspects of seismic retrofit design.

Establishing a methodology for retrofit for improved structural performance in fire could follow a similar pattern:

1. Develop criteria for determining when retrofit is required or desirable.
2. Codify fire loadings. Two levels of design fire intensity and duration may be useful: one with a higher probability of occurrence for which structural damage would be minor, and another with a more remote possibility for which only avoidance of structural collapse is desired. Much of the work needed to establish these fire loadings has already been done [2].
3. Calculate thermal and structural response for proposed retrofit schemes and verify that the structure performs in an acceptable manner. There is an extensive literature on analysis techniques suitable for this purpose [3].
4. Develop additional requirements that would improve a building's survivability when subjected to extreme initiating events, such as fire coupled with earthquake, explosion or impact. Among these would be flexibility or ductility requirements, toughness requirements, and improved redundancy, as discussed later in this paper.

Most of this fire retrofit methodology is the same for design of new buildings. However, retrofit gives rise to many special difficulties since the designer must work around and with existing structure. As with seismic design, good solutions are based on common sense and good engineering judgment. Many of the methods developed for seismic retrofit would not be useful because they deal with dynamic properties of buildings, energy absorption, horizontal diaphragms, and other properties not related to fire performance. Furthermore, some seismic retrofit techniques, such as wrapping columns with fiber-reinforced plastics, may increase fire hazards without providing any structural benefits under fire conditions. However, some of the techniques used to improve connections and to tie together all parts of the buildings to better resist non-gravity loading could find application to fire retrofit. For example, the FEMA code of practice [13 presents details for the following:

- Cover plates, gusset plates, knee braces, and boxing members to increase connection strength;
- Supplemental frames and braces to add redundant load paths for lateral loads;
- Lateral bracing methods for unsupported flanges of long-span trusses or beams;
- Encasing steel members in concrete to create stronger composite members;
- Increasing strength and toughness of slabs and diaphragms with overlays;
- Methods for anchor bolts and other improved connection of trusses and beams at their supports.

Seismic retrofit often does not give consideration to how effective these methods would be if exposed to fire. However, many of the methods are only intended to give additional strength for a seismic lateral load which would not be on the structure at the time a fire occurs, so lack of fire resistance is not always a problem. Fire retrofit must always consider performance of the retrofit under elevated temperatures, the magnitude of which will be coupled with the materials and methods used to insulate structural elements **fiom** the fire conditions.

**Evaluation of existing conditions**

After the potential need to retrofit a structure for fire is recognized, the next step is to evaluate the existing conditions. This includes evaluation of both the existing structural design as well **as** the thermal protection and fire endurance of the existing structural elements and assemblies.

The retrofit evaluation process requires identification of the design basis for the existing building. To the extent such documentation is available, structural design drawings, calculations, specifications and test data can be used to evaluate the expected structural performance of the existing building. Such documentation should be verified by visual inspections and surveys to determine if the as-built condition is the same **as** the design documentation indicates.

**A** significant issue with respect to verification of the existing conditions is accessibility. In many existing buildings, structural elements and assemblies have been encapsulated or covered by other materials. In some cases, these materials serve only an aesthetic function, while in other cases, these materials may also serve a fireproofing or thermal insulation function. Regardless of their purpose, the presence of such materials may prevent the direct visual inspection of some or all of the structural elements and connections in an existing building. Depending on the importance associated with verification of existing conditions, removal and replacement of materials covering structural elements may be necessary. Ironically, if the covering materials are serving a fireproofing function, the removal and replacement of such materials for visual inspection may have a negative impact on post-inspection fire performance.

Because the basic structure as well as the thermal insulation materials may be concealed from view, it would be desirable to develop nonvisual, nondestructive methods to evaluate the existing condition of a structure as well as of the fireproofing materials protecting the structural elements and assemblies. It may be possible to adapt ultrasonic, magnetic or other nondestructive evaluation methods for this purpose. This issue should be explored further.

**Evaluation of expected performance of existing buildings and structural elements**

Analysis of the fire performance of an existing building ultimately depends on calculation of its fire response. In this respect, evaluation of existing buildings may be easier than evaluation of new buildings because the structural design and construction of an existing building is already established while the design of a new building may not be. While both new and existing buildings may require analysis of a multitude of fire scenarios, the basic design of an existing structure is established, at least before retrofit options are evaluated. Once structural retrofit options are considered, the picture once again becomes more complicated in terms of the number of variables that need to be considered.

Evaluation of the expected fire performance of existing buildings will generally follow the performance-based design process outlined above. As a first step, the effects of losing one or more structural elements to fire-induced failures can be considered without actually calculating the fire conditions leading to such failures. This would permit identification of those elements that are critical to the overall stability of a structure or, expressed differently, those elements that would cause disproportionate damage or collapse if they were to fail. Such identification of the critical structural elements may influence the selection of retrofit options and focus retrofit activities on the most critical structural elements.

Once the critical structural elements are identified and prioritized, the performance of these elements under different fire conditions can be evaluated. In a performance-based analysis, the postulated fire conditions should bear some relationship with the actual fire conditions expected under different fire scenarios. Evaluation of the expected fire conditions would be the same as for new buildings.

**Retrofit / repair alternatives**

Retrofitting buildings to improve their structural fire safety can generally take one of two forms, or in some cases a combination of both. The options generally include:

- Enhance the structural performance of the structural elements and assemblies;
- Enhance the thermal performance of the fire resistant materials and assemblies protecting the structural elements.

Retrofitting buildings to improve their structural performance in fire is a relatively new field. Cases in which the actual structure of a building has been modified solely for the purpose of improving its fire performance have been very rare. However, the same methodology used in the performance-based design of new buildings for structural fire safety is directly applicable. In applying this methodology, the following principles should be useful:

1. Build in more redundancy if it is lacking. Add members to give alternate load paths or strengthen connections to mobilize other portions of the building to increase redundancy.
2. Move or isolate particularly bad fire scenarios so important members are not impacted.
3. Strengthen connections to give better flexibility and ductility to the building so that it may accommodate the large distortions that are caused by fire. The structural system should be well tied together and tough. Unlike seismic retrofit, energy absorption is not important - just the ability to move without breaking joints and to permit redistribution of loads away from areas of local failure. Moment-resistant joints are preferred and can add considerable redundancy to the structure. Add thermal protection to connections if they can be exposed to fire.
4. Add bracing where necessary to prevent local collapse of floor assemblies or other structural members from leading to instability in primary structural members. *An* example of this would be a light truss floor system that braces walls or columns.
5. Repair damaged or improperly designed elements that affect fire resistance. Examples would be reinforcing bars that have become exposed due to spalling, walls or other load-bearing elements that have been removed, or areas of defective fireproofing.

In many cases, the basic structure will not require retrofitting, but the level of thermal insulation will need to be increased to meet current structural fire safety goals and objectives related to fire endurance. In evaluating the current level of fire resistance and the alternatives available for upgrading this level, the fundamental question will be whether to add additional layers of thermal insulation to the existing installation or to remove the existing thermal insulation and replace it with new materials. In either case, environmental impacts need to be considered, particularly for fibrous materials that may contain asbestos or other fibers with potential health or environmental consequences.

For the addition of new thermal insulation to an existing installation, a number of issues need to be considered, including:

1. Is it better to use contour or membrane protection? In many existing installations, contour protection has been adhered to the structural elements, then the insulated assembly has been enclosed in finish materials, which may impart additional fire resistance. In some cases, the simplest and most cost-effective upgrade may be to simply add additional membrane protection to the existing assembly. This is analogous to the component additive method [4] used to evaluate the fire resistance of timber structures. In other cases, adding additional contour protection may be the simplest and most cost-effective alternative.
2. Are there adhesion or cohesion issues related to the application of new contour protection to old? Contour protection materials are typically adhered to steel or concrete substrates. If these materials are applied to similar existing contour protection materials, the adhesion of the new material to the old must be considered along with the continued adhesion of the old material to the substrate as well as the continued cohesion of the old material as it is subjected to new stresses imposed by the addition of the new material. The quality of the upgrade will depend on all of these issues.

3. What are the performance evaluation issues for the composite assembly? Large-scale testing is still generally used to evaluate the fire resistance of insulated building assemblies. This is true at least in part because it is still difficult to predict or calculate all of the factors that can cause the delamination or differential movement of components in a fire resistive assembly. Consequently, the option to add additional thermal insulation to an existing installation may require extensive and expensive fire testing to evaluate the expected performance of such composite assemblies until correlations can be established similar to those used in the component additive method.

For the replacement of an existing installation with a new one, issues that need to be considered include:

1. What issues are associated with the removal and disposal of existing;fireproofing materials? In many existing buildings, the fireproofing systems may contain asbestos or other fibers that may have health or environmental consequences. The removal and disposal of these materials must be handled properly, which may incur high costs and make this option less cost effective than alternative methods. Encapsulation of existing fireproofing may be a more cost-effective and environmentally-friendly solution.
2. What issues are associated with adhesion of new material to the existing;substrate? If the existing fireproofing material is removed fiom its substrate for replacement by new material, the substrate may require reconditioning in order for the new material to properly adhere.

**Some guidance for retrofit designers**

It is generally recognized by structural fire designers that certain features of a structure can cause problems during a fire. These features should be carefully scrutinized in order to focus the design or retrofit effort on the most critical elements. Among these are the following:

1. Look for lack of redundancy. A structure that will perform well in a severe fire will permit gravity loads that must be supported during the fire to be carried to the foundations using several load paths. That is, if one large member is removed, the weight it supported will redistribute to other nearby members and collapse will not occur. Identify critical, irreplaceable members, which if softened or buckled in a fire would cause more than a local failure, **i.e.** lead to progressive collapse of the entire building. The types of members to look for include nonrepetitive long-span trusses and beams, columns with large tributary areas, cantilevers, and members necessary for lateral stability of trusses or buckling stability of columns. Structural assemblies that tend to have a high degree of redundancy are composite floor slabs and moment frames. When conducting calculations keep in mind that the live load on the structure at the time of a fire is almost always less than the full design load and this reduction contributes to redundancy.
2. Look for weak connections. Connections are very important and are critical in holding a building together during the large movements that occur in a fire. They must be ductile or flexible **so** they do not break due to these large distortions in the building. This quality in a structural component is called toughness. In addition, strong connections give continuity to mult-span beams and other flexural members, reducing bending moments and therefore increasing fire resistance. Strong and flexible connections also permit these flexural members **to** develop into a catenary when they fail in bending and sag, increasing the fire endurance even more. The types of connections that often perform poorly in a

fire are simple bearing connections and shear tabs. Best are moment-resistant framing connections in steel or welldetailed, ductile moment connections in concrete.

3. Beware of very large, very stiff structural elements. When such elements are exposed to fire, they may expand against weaker restraining members surrounding them, breaking connections and perhaps causing other types of failure.. Earthquake retrofitting often introduces these types of elements (diaphragms, braces, etc.) and it is important to make sure restraining elements have sufficient flexibility, ductility and stability to accommodate the expansion if the stiff elements can be exposed to fire. When conducting calculations keep in mind that braces under elevated temperature will eventually buckle but not actually fail, since the thermal force is self-limiting and often leads to a stable post-bucking reaction, limiting the force on adjacent structure. In fire, buckling of a brace is sometimes a good thing since it limits the damage its expansion can cause to the rest of the structure.

4. Pay particular attention to light members. These members have notoriously low fire resistance. Determine how these members would fail and be sure the failure will be strictly local and not spread to other parts of the structure. For example, the collapse of a floor assembly in a single bay probably would remain local. Light trusses are particularly problematical since they are difficult to fireproof and have very little fire resistance without fire protection.

5. Check that important braces will not fail in fire. Such failures can undermine the stability of primary structural members, even ones that are cool and not involved in the fire. Fireproofing'of these braces may be necessary. Examples of such braces are those that give lateral stability to trusses and beams.

6. Pay special attention to prestressed concrete members. Prestressed concrete members are particularly vulnerable to fire because prestressing steel loses strength quickly at elevated temperatures. Check for adequate cover.

7. Watch for high risk or high temperature fire sources located close to particularly critical members, such as fuel tanks or fuel lines near large trusses or nonredundant columns.

**Recommendations for further research and development**

Based on the foregoing discussion of issues, the following recommendations are made for research that is needed to develop a code or standard of practice for the evaluation and retrofit of existing buildings for structural fire safety:

- A survey should be conducted of nondestructive evaluation technologies that might be adapted for evaluating the existing conditions of inaccessible structural elements and thermal protection in buildings. The more promising of these technologies should be evaluated for adaptation €or this purpose.
- An engineering guide should be developed that describes the general retrofit options that could be applied to buildings designed with different structural systems. Research should be performed to address the relative costs and benefits of these different retrofit options.
- Research should be performed to evaluate how retrofit design for fire can be coordinated with seismic retrofit design to cost-effectively address both issues together.

The following recommendations are made to advance the practice of structural fire safety design for both new and existing buildings:

- Methods should be developed for building codes for structural design to give more consideration to fire loads. Ultimately, fire should be a design load condition, just as gravity, wind, earthquake and other thermal loads are.
- Computer software for structural analysis and design for fire should be developed and distributed to structural fire safety designers. Research should be conducted to determine how fire loading can be incorporated into widely used commercial structural design programs.
- Workshops and training courses should be developed to introduce practicing engineers and building officials to structural design for fire, particularly the newer performance-based methods.
- Design for structural fire safety should be incorporated into structural engineering curricula and given the same emphasis as design for other extreme events is currently given.
- Research funding should be provided to support graduate students interested in developing expertise in structural fire safety design. Research performed by such graduate students would advance the state of knowledge while the graduate students would become the educators of future structural fire safety designers as well as leaders in the field of structural fire safety design.

**Summary and conclusions**

Evaluation of structural fire safety in existing buildings presents many of the same challenges as in new buildings. These challenges include:

- Identification of the relevant fire scenarios to be analyzed;
- Uncertainties in the calculation of expected fire conditions and structural response, including both parameter and modeling uncertainties;
- Lack of information on the high-temperature properties of building materials, particularly those materials used to insulate structural steel from fire temperatures;
- A general lack of design practices, educational opportunities and designers educated and experienced in the field of structural fire design.

Evaluation of structural fire safety in existing buildings also presents many challenges different from those associated with new buildings. These challenges include:

- Identification of existing structural and thermal conditions, including adaptation of nondestructive evaluation technologies and methods for this purpose;
- Lack of design information on different retrofit options including the relative costs and benefits of the different options;
- Lack of a code of practice specifically for retrofitting for structural fire performance analogous to the code of practice that has been developed for seismic retrofit.

It is recommended that methods for evaluation and retrofit of existing buildings for structural fire safety be developed in concert with the development of retrofit methodologies for other hazards, such as wind and earthquake. In this way, the relative costs associated with fire retrofits would be minimized, while the relative benefits could be maximized. It is also recommended that structural fire safety design be incorporated into structural engineering curricula.

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**White Paper 9**

# International Status Of Design Standards For Structural Fire Safety

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## ABSTRACT

This paper describes international design standards for structural fire safety. These standards range **fiom** very simple prescriptive documents to sophisticated codes which allow advanced methods of analysis under a wide range of realistic conditions. The paper focuses on the Structural Eurocodes which are the most comprehensive suite of documents for structural fire design at the present time.

## INTRODUCTION

The purpose of this paper is to benchmark the international status of development and adoption of design standards for structural fire safety, and the overall codes and standards context. Some of this paper is based on the author's book, Structural Design for Fire Safety (Buchanan, 2001).

## LEGISLATIVE ENVIRONMENT

The legislative environment is very different in different countries. Many countries are moving at various speeds to adopt performance based codes, or to move from a prescriptive code environment to a more performance based environment.

### Performance based codes

Until recently, most structural design for fire safety has been based on *prescriptive* building codes, with little or no opportunity for designers to take a rational engineering approach to the provision of fire safety. Many countries have recently adopted performance bused building codes which allow designers to use any fire safety strategy they wish, provided that adequate safety can be demonstrated. In general terms, a prescriptive code states "how a building is to be constructed" whereas a performance based code states "how a building is to perform" (Buchanan, 2001).

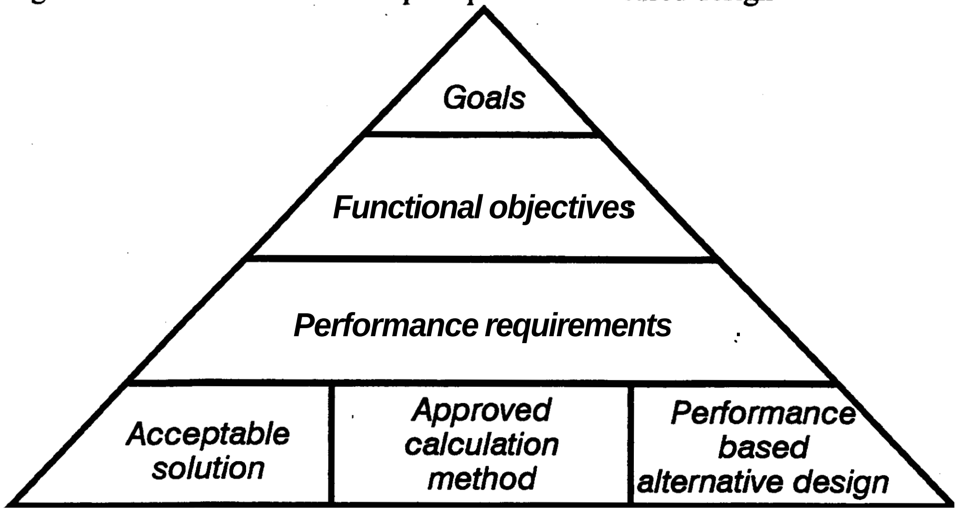
Performance based design is not totally new. Even within prescriptive codes, there is the opportunity for performance based selection of structural assemblies. For example, if a code specifies a floor with a fire resistance rating of 2 hours, the designer has the freedom to select from a wide range of listed systems which have sufficient fire resistance.

In the development of new codes, many countries have adopted a multi-level code format as shown in Figure 1. At the highest levels, there is legislation specifying the overall goals, functional objectives and required performance which must be achieved in all buildings. At a lower level, there is a selection of alternative means of achieving those goals. The three most common options are either to comply with a prescriptive "acceptable solution", to comply with an "approved calculation method", or to carry out a "performance based alternative design" from. first principles, using all the information available.

Standard calculation methods have not yet been developed for widespread use, so compliance with performance based codes in most countries is usually achieved by simply meeting the requirements of "acceptable solutions" ("deemed-to-satisfy" solution), or alternatively carrying out a "performance based alternative design" based on fire engineering principles. Alternative designs can often be used to justify variations from the Acceptable Solution in order to provide cost savings or other benefits.

The code environment in England, Australia and some Scandinavian countries, is similar to that in New Zealand (described by Buchanan, 1994,2000). Moves towards performance based codes are being taken in the United States (IFCI 2000). Codes are different around the world, but the objectives are similar; that is to protect life and property from the effects of fire.

Figure 1.1 Heirachical relationship for performance based design




**Eurocodes**
For more than twenty five years, European countries have been working on a new coordinated set of structural design standards known as the Structural Eurocodes. These are comprehensive documents which bring together diverse European views on all aspects of structural design, for all main structural materials. The Eurocodes are being prepared by the European Committee for Standardization (CEN) under an agreement with Commission of the European Community. The Eurocodes recognize the need for member countries to set national safety standards which may vary fiom country to country, so each country's national standard will comprise the full text of the Eurocode, with local modifications in a supporting document. More details are given later in this paper.

## Structural Design for Fire Conditions

**Design objectives**
Fire safety objectives must be established before making any design. The overall design needs to set objectives for property protection and safety of occupants and fire fighters. Design for fire safety is often split into active and *passive* fire protection. A major component of passive fire protection is *fire* resistance, which is only one component of the overall fire safety strategy. Structural design for fire safety is a subset of fire resistance.

Structural elements can be provided with fire resistance for either *controlling* the *spread of fire* or *preventing structural collapse*, or both, depending on the functional requirements for the particular building. This paper concentrates on the latter.

**Design process**
Structural design for fire conditions is conceptually similar to structural design for normal temperature conditions. Before making any design it is essential to establish clear objectives, and determine the severity of the design fire. The design can be carried out using either working stress

or ultimate strength (LRFD) format. The main differences of fire design compared with normal temperature design are that, at the time of a fire:

- the applied loads are less
- internal forces may be induced by thermal expansion
- strengths of materials may be reduced by elevated temperatures
- cross section areas may be reduced by charring or spalling
- smaller safety factors can be used, because of the low likelihood of the event
- deflections are not important (unless they affect strength)
- different failure mechanisms need to be considered

The above factors may be different for different materials.

**Design equation**

The fundamental step in designing structures for fire safety is to verify that the fire resistance of the structure (or each part of the structure) is greater than the severity of the fire to which the structure is exposed. This verification requires that:

$$\text{fire resistance} \geq \text{fire severity}$$

where ***fire resistance*** is a measure of the ability of the structure to resist collapse, fire spread or other failure during exposure to a fire of specified severity, and

***fire severity*** is a measure of the destructive impact of a fire, or a measure of the forces or temperatures which could cause collapse or other failure as a result of the fire.

As shown in Table 1, there are three alternative methods of comparing fire severity with fire resistance. The verification may be in the ***time*** domain, the ***temperature*** domain or the ***strength*** domain, using different units, which can be confusing if not understood clearly.

Table 1. Three alternative methods of comparing fire severity with fire resistance

| Domain | Units | FIRE RESISTANCE | ≥ | FIRE SEVERITY |
|---|---|---|---|---|
| ***Time*** | minutes or hours | Time to failure | ≥ | Fire duration, as calculated or specified by code |
| ***Temperature*** | °C | Temperature to cause failure | ≥ | Maximum temperature reached during the fire |
| ***Strength*** | kN or kN.m | Load capacity at elevated temperature | ≥ | Applied load during the fire |

**Loads for structural fire design**

The most likely loads at the time of a fire are much lower than the maximum design loads specified for normal temperature conditions. For this reason, different design loads and load combinations are used. Most codes refer to an "arbitrary point-in-time load" to be used for the fire design condition. Loads and load combinations are given, for example, by ASCE (1995) and the Eurocode (EC1,2002).

## Fire Severity

### Fire Severity For Design

The fire severity to be used for design depends on the legislative environment and on the design philosophy. In a *prescriptive* code, the design fire severity is usually prescribed by the code with little or no room for discussion. In a *performance* based code, the design fire is usually recommended to be a complete burnout, or in some cases a shorter time of fire exposure which only allows for escape, rescue, or firefighting. The equivalent time of a complete burnout is the time of exposure to the standard test fire that would result in an equivalent impact on the structure.

### Standard fire exposure

Most countries around the world rely on full size fire resistance tests to assess the fire performance of building materials and structural elements. The time temperature curve used in fire resistance tests is called the *standard fire*. Full size tests are preferred over small scale tests because they allow the method of construction to be assessed, including the effects of thermal expansion, shrinkage, local damage and deformation under load.

The most widely used standard test specifications are ASTM El 19 (ASTM 1995) and ISO 834 (ISO 1975). Other national standards include British Standard BS 476 Parts 20-23 (BSI 1987), Canadian Standard CAN/ULC-S 101-M89 (ULC 1989) and Australian Standard AS 1530 Part 4 (SAA 1990). The standard time temperature curves from ASTM El 19 and ISO 834 are compared in Figure 2. They are seen to be rather similar. All other international fire resistance test standards specify similar time temperature curves.

The ASTM El 19 curve is defined by a number of discrete points The ISO 834 specification (ISO 1975) defines the temperature T (“C) by the following equation:

$$T = 345 \log_{10} (8t + 1) + T_0$$

where t is the time (minutes) and
$T_0$ is the ambient temperature (“C)

Figure 2 also shows two alternative design fires from the Eurocode (EC1 2002). The upper curve is the hydrocarbon fire curve, intended for use where a structural member is engulfed in flames from a large pool fire. The temperature T (°C) is given by

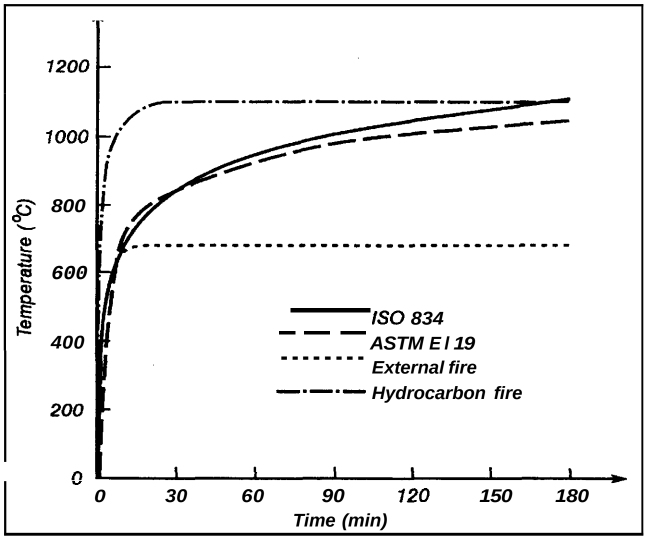
$$T = 1080 (1 - 0.325e^{-0.167t} - 0.675e^{-2.5t}) + T_0$$

where t is the time (minutes)
$T_0$ is the ambient temperature (“C)

The lower curve is intended for design of structural members located outside a burning compartment. Unless they are engulfed in flames, exterior structural members will be exposed to lower temperatures than members inside a compartment. The temperature for external members is given by

$$T = 660 (1 - 0.687e^{-0.32t} - 0.313e^{-3.8t}) + T_0$$

Figure 2. Standard time temperature curves




**Realistic fire exposure**
If a fire in a typical room is allowed to grow without intervention, assuming sufficient fuel and ventilation, temperatures will increase with increasing radiant heat flux to all objects in the room. At a critical level of heat flux, all exposed combustible items in the room will begin to burn, leading to a rapid increase in both heat release rate and temperature. This transition is *flashover*, after which the fire is often referred to as a "post flashover fire", "fully developed fire" or "full room involvement".

The most widely referenced time temperature curves for post-flashover fire exposure are those of Magnusson and Thelandersson (1970) shown in Figure 3, often referred to as the "Swedish" fire curves. They are derived from heat balance calculations for the burning rate of ventilation controlled fires. A group of curves, such as the one shown, is provided for different ventilation factors, with fuel load as marked. Note that the units of fuel load are MJ per $m^2$ of total internal surface area (not MJ per $m^2$ of floor area which is more often used in design calculations). In a similar approach, Lie (1995) performed heat balance calculations for post flashover fires with a range of ventilation factors and different wall lining materials. Computer programs for calculating temperatures in post flashover room fires include COMPF2 (Babrauskas, 1979), Ozone (Franssen et al 1999). FASTLite (Buchanan 1997) and CFIRE (Yii, 2003).

The Eurocode (EC 1,2002) gives an equation for "parametric" fires, allowing a time- temperature relationship to be produced for any combination of fuel load, ventilation openings and wall lining materials, to give an approximation to the Swedish curves shown above. The Eurocode equation for temperature T (°C) is

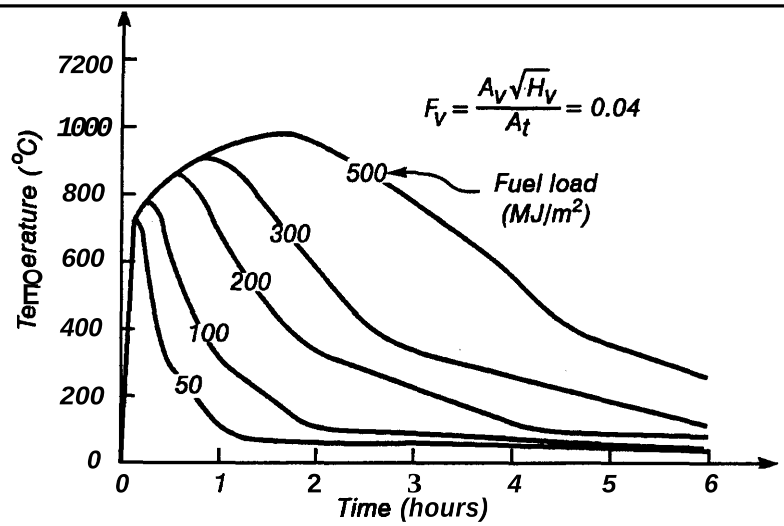



**Figure 3. Time temperature curves for given ventilation factor and different fuel loads (MJ/m² of total surface area) (Magnusson and Thelandersson 1970)**

$$T = 1325\,(1 - 0.324e^{-0.2\,t^*} - 0.204e^{-1.7\,t^*} - 0.472e^{-19\,t^*}) \qquad [1]$$

where $t^*$ is a fictitious time (hours) given by $t^* = \Gamma\, t$
t is the time (hours) and

$$\Gamma = \frac{(F_v / 0.04)^2}{(b / 1160)^2}$$

where b is dthermal inertia = $\sqrt{(k \rho c_p)}$ $(Ws^{0.5}/m^2K)$
$F_v$ is the ventilation factor $F_v = A_v \sqrt{H_v} / A_t$ $(\sqrt{m})$
$A_v$ is the area of the window opening (m)
$A_t$ is the total internal surface area of the room $(m^2)$
$H_v$ is the height of the window opening (m)

Equation 1 is a good approximation to the ISO 834 standard fire curve for temperatures up to about 1300°C, so the Eurocode parametric fire curve is close to the ISO 834 curve for the special case where $\Gamma = 1$.

The duration of the burning period $t_d$ (hours) in the Eurocode has been increased by 50% in the latest version (2002) simplified as:

$$t_d = 0.0002\, e_t / F_v$$
$$= 0.0002\, E / (A_v \sqrt{H_v})$$

where $e_t$ is the fuel load (MJ / m² total surface area)
or E is the total energy content of the fuel (MJ)

The Eurocode uses a basic decay rate of 625°C per hour for fires with a burning period less than half an hour, decreasing to 250°C per hour for fires with a burning period greater than two hours, all modified by the $\Gamma$ factor. Recent research using the COMPF2 program and many test fire results has shown that the temperatures in the Eurocode formula are often too low and the rate of decay is often inappropriate, leading to proposals for empirical modifications (Feasey and Buchanan 2000).

**Time equivalence**

The concept of *equivalent fire* severity is used to relate the severity of an expected real fire to the standard test fire. This is important when designers want to use published fire resistance ratings from standard tests with estimates of real fire exposure. There are several methods of comparing real fires to the standard test fire, the most common being the time equivalence formula given in Eurocode 1 (EC1, 2002), which gives the equivalent time $t_e$ (min) as

$$t_e = k_b \, w \, e_f$$

where $e_f$ is the fuel load (MJ/m$^2$ of floor area)

$k_b$ is a parameter to account for different compartment linings

w is the ventilation factor, given by

$$w = \left(\frac{6.0}{H_r}\right)^{0.3} \left[ 0.62 + \frac{90(0.4 - \alpha_v)^4}{1 + b_v \alpha_h} \right] > 0.5$$

$H_r$ is the compartment height (m)

$\alpha_v = A_v / A_f$ $\quad 0.05 \leq \alpha_v \leq 0.25$

$\alpha_h = A_h / A_f$ $\quad \alpha_h \leq 0.20$

$b_v = 12.5 (1 + 10\alpha_v - \alpha_v^2)$

$A_f$ is the floor area of the compartment (m$^2$)

$A_v$ is the area of vertical openings in the walls (m$^2$)

$A_h$ is the area of horizontal openings in the roof (m$^2$)

The equivalent fire severity is very useful where the details of the compartment are known, and where the designer wishes to use published fire resistance ratings for selection of construction elements.

## FIRE RESISTANCE

Fire resistance is a measure of the ability of a building element to resist a fire, usually the time for which the element can meet certain criteria during exposure to a standard fire resistance test. Individual materials do not possess fire resistance. Fire resistance is a property assigned to building; elements which are constructed from a single material or a mixture of materials. A *fire* resistance rating is the fire resistance assigned to a building element on the basis of a test or some other approval system. Some countries use the terms *fire* rating, fire endurance rating or *fire* resistance *level* which are usually interchangeable.

## Failure criteria

The three failure criteria for fire resistance are ***stability, integrity*** and ***insulation.*** To meet the ***stability*** criterion in a standard fire resistance test, a structural element must **perform** its load bearing function and carry the applied loads for the duration of the test, without structural collapse. The integrity and insulation criteria are intended to test the ability of a barrier to contain a fire, to prevent fire spreading from the room of origin. **To** meet the ***integrity*** criterion, the test specimen must not develop any cracks or fissures which allow smoke or hot gases to pass through the assembly. To meet the ***insulation*** criterion, the temperature of the cold side of the test specimen must not exceed a specified limit, usually an average increase of 140°C and a maximum increase of 180°C at a single point.

***An*** increasing international trend is for fire codes to specify the required fire resistance separately for stability, integrity and insulation. For example a typical load bearing wall may have a specified fire resistance rating of 60/60/60, which means that a one hour rating is required for stability, integrity and insulation, respectively. If the wall was non load-bearing, the specified fire resistance rating would be -/60/60. A fire door with a glazed panel may have a specified rating of **-**/30/**-** **,** which means that this assembly requires an integrity rating of 30 minutes, with no requirement for stability or insulation.

## Approvals

**Most** countries require that fire resistance tests be certified by a recognized testing laboratory or approvals agency. In North America, independent testing organizations such as Underwriters Laboratories (UL 1996) and Southwest Research Institute (SWRI 1996) maintain registers of fire resistance ratings. **Most** of these ratings are based on standard tests. Ratings based on these approvals *are* listed in some national building codes (eg NBCC 1995, UBC 1997). Small countries may need to use approvals from other countries, **so** that in New Zealand for example, a register of approved listings is maintained by the national standards organization (SNZ 1991). Some trade organizations (eg. ASFPCM 1988, Gypsum Association 1994) maintain industry listings of approvals for products manufactured or used by their members. Listings generally fall into three categories; ***generic ratings, proprietary ratings,*** or ***calculation methods.***

***Generic*** fire resistance ratings, or "tabular ratings" are listings which assign fire resistance to typical materials such **as** concrete or steel. Generic ratings are derived from full-scale fire resistance tests carried out over many years, and are widely used because they can be applied to commonly available materials in any country. However, generic ratings make **no** allowance for the size and shape of the fire exposed member or the level of load.

***Proprietary*** fire resistance ratings apply to proprietary products made by specific manufacturers, so they may be more accurate than generic ratings, but cannot be applied to similar products **from** other manufacturers.

As fire engineering develops, it is becoming feasible to assess fire resistance of structural members and some assemblies by ***calculation.*** Some listing agencies and national design codes now include approved calculation methods for assessing fire resistance. Calculation methods must be based on full scale fire resistance test results of similar assemblies. Calculations can be used for predicting insulation and load-bearing response, but not integrity.

An increasing number of listed fire resistance ratings are based on ***expert opinion.*** The opinion will state whether the assembly would be considered likely to pass a test, based on observations of similar successful tests, calculations, and the considered experience of the testing and approving personnel.

## MATERIALS STANDARDS

In most countries the materials standards for structural design provide methods of assessing or calculating fire resistance.

### Europe

By far the most comprehensive international documents for structural design of buildings and structures in fire conditions are the Structural Eurocodes. The main codes are listed below, with details in the list of references:

| | |
|---|---|
| EN 1991 Eurocode 1 | Basis of design and actions on structures; |
| EN 1992 Eurocode 2 | Design of concrete structures; |
| EN 1993 Eurocode 3 | Design of steel structures; |
| EN 1994 Eurocode 4 | Design of composite steel and concrete structures; |
| EN 1995 Eurocode 5 | Design of timber structures; |
| EN 1996 Eurocode 6 | Design of masonry structures; |
| EN 1997 Eurocode 7 | Geotechnical design; |
| EN 1998 Eurocode 8 | Design provisions for earthquake resistance of structures; |
| EN 1999 Eurocode 9 | Design of aluminum alloy structures. |

All of these have substantial fire sections, (100 pages or more). Most are nearing completion, published in final draft form, and will go to a formal vote this year after final editing and translation into French and German. Most of the structural Eurocodes include the following statement:

> "A full analytical procedure for structural fire design would take into account the behaviour of the structural system at elevated temperatures, the potential heat exposure and the beneficial effects of active and passive fire protection systems, together with the uncertainties associated with these three features and the importance of the structure (consequences of failure).
>
> At the present time it is possible to undertake a procedure for determining adequate performance which incorporates some, if not all, of these parameters and to demonstrate that the structure, or its components, will give adequate performance in a real building fire. However, where the procedure is based on a nominal (standard) fire the classification system, which call for specific periods of fire resistance, takes into account (though not explicitly), the features and uncertainties described above."

Design can then be at various levels in a hierarchy, as shown in Figure 4. which identifies the prescriptive approach and the performance-based approach. In general terms, the most simple designs will be at the far left hand side of Figure 4 (using tabulated data for single members in a prescriptive environment), with the most sophisticated designs being at the right hand side of Figure 4 (using advanced calculation models for entire structures).

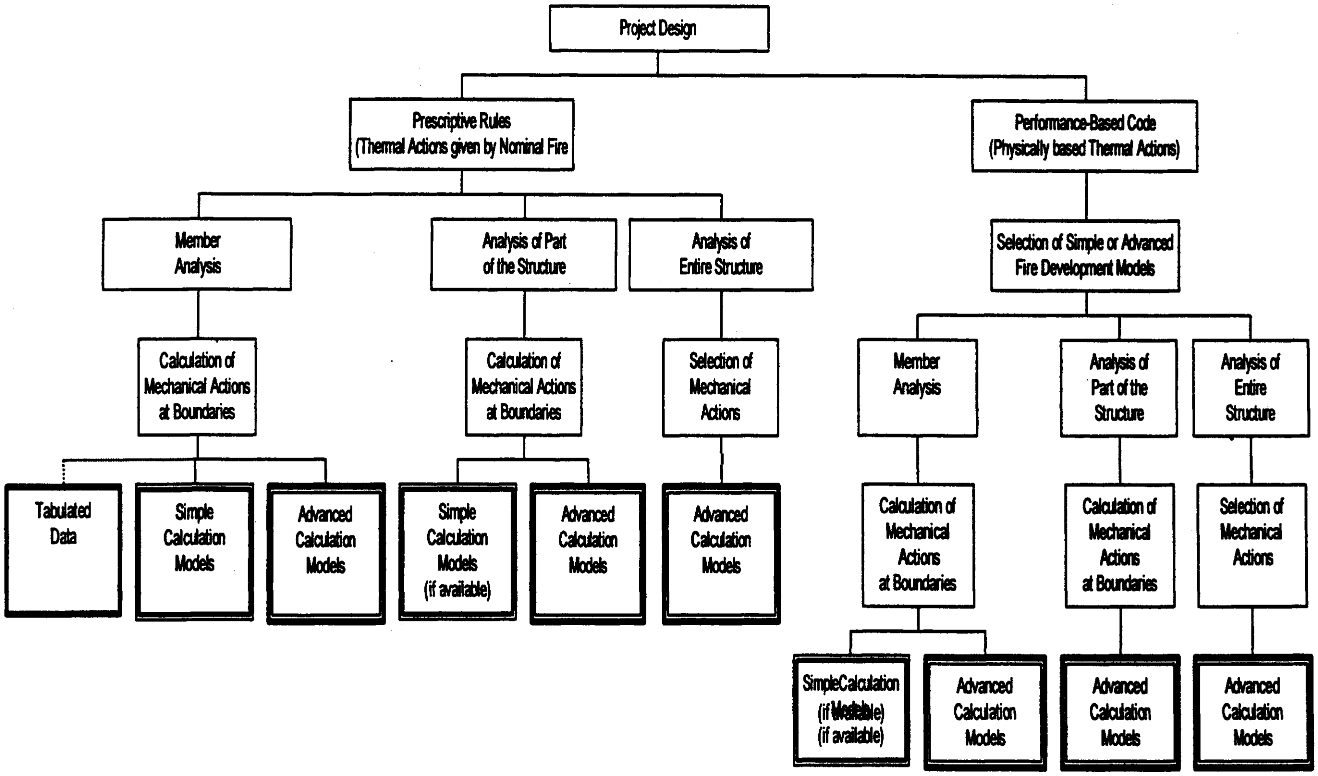



Figure **4.** Alternative design procedures in the Structural Eurocodes (EC2, 2002)

Table 2 (abbreviated from EC2, 2002) further illustrates the applicability of alternative methods of verifying fire resistance.

Table 2. Summary table showing alternative methods of verification for fire resistance.

| | **Tabulated data** | **Simplified calculation methods** | **Advanced calculation models** |
|---|---|---|---|
| **Member analysis** | **YES**<br>Standard fire only | **YES**<br>Standard fire and parametric fire | YES<br>Only the principles are given |
| **Analysis of parts of the structure** | NO | YES<br>Standard fire and parametric fire | YES<br>Only the principles are given |
| **Global structural analysis** | **NO** | **NO** | YES<br>Only the principles are given |

All the structural Eurocodes include the following sections:

- Basis of design
    - o Fire exposure
    - o Verification methods
    - o Methods of structural analysis
- Material properties
    - o Mechanical properties
    - o Thermal properties
- Design procedures
    - o Tabulated data
    - o Simple calculation methods
    - o Advanced calculation methods
- Construction details

The fire exposure allows for standard or realistic fire design curves to be used. The ***simple calculation methods*** are for predicting the behavior of single members based on simple assumptions. The ***advanced calculation methods*** provide the principles for computer analyses based on fundamental physical behavior, for both thermal analysis and mechanical behavior. These analyses need to take into account factors such as transient temperature gradients, variation of thermal properties with temperature, axial and flexural restraint, thermally induced forces, and thermally induced deformations, throughout the duration of the expected fire. The effects of creep are not explicitly included in the advanced calculation methods, but the stress-strain relationships have been modified to include creep in an indirect way.

The Eurocodes include information which does not generally appear in other fire codes, such as comprehensive expressions for thermal and mechanical properties at elevated temperatures, and stress-strain relationships at elevated temperatures. This is very useful for any analytical modeling of fire behavior of structures. The tabulated listings in the Eurocodes are far more extensive than most other codes, the particular benefit to designers being that the tables include the improved fire resistance for members which are loaded below their design capacity at the time of a fire.

**European countries**

All of the major European countries have been involved in development of the Eurocodes, but they have also been maintaining parallel development of national codes which are used for everyday design. The transition to design office use of the Eurocodes is expected to be slow in most countries, depending on the rate at which the existing national codes are phased out.

In the United Kingdom, a comprehensive recent publication is ***Structural Response and Fire Spread Beyond the Enclosure of Origin*** (BSI ***2003)*** which is a "Published Document" in support of BS 7974 ***Application of Fire Safety Engineering Principles to the Design of Buildings*** **(BSI,** 2001). BS 7974 is currently the most comprehensive code of practice for specific fire engineering design in any country.

The Published Document (150 pages) is complementary to the Structural Eurocodes, and provides data and guidance for calculating the fire exposure and fire resistance (structural and non-structural) for a wide range of materials and assemblies. The document recognizes that detailed structural analysis of complex load-bearing structural frames is beyond the scope of such a guidance document.

**North America**

Structural design for fire safety in the United States has not moved **as** quickly as in Europe. Existing building codes include prescriptive requirements for fire resistance which have not changed greatly in recent years. The current movement **fiom** regional to national building codes (IBC, NFPA codes) has not been accompanied by significant changes in design for fire resistance. However the need for change has been recognized and several background documents have recently been published (ASCE/SFPE ***1999,*** SFPE 2003a, SFPE 2003b) which will eventually lead to code changes. The collapse of the World Trade Center towers in 2001 has obviously given new impetus for change (FEMA, 2002).

Industry groups for particular materials (steel, concrete and timber industries) are also developing standards and guidance documents for structural fire resistance.

**Canada**

Most design standards (concrete, wood and steel) in Canada refer to the National Building Code of Canada (NBCC, ***1995)*** for fire resistance specifications. The **2004** edition of the NBCC will include a few changes with respect to fire resistance. New design equations are proposed for fire resistance of concrete filled steel columns with **bar** reinforced concrete and steel fiber reinforced concrete filling. The prescriptive fire resistance ratings tables for walls and floors are being expanded with some additional assemblies, based on recent fire tests. A new standard for fiber reinforced plastics (FRP) is CSA-S806 which was published in 2002, including design charts for the fire resistance design of FRP-reinforced concrete slabs.

**Australia and New Zealand**

The Australian and New Zealand fire codes permit specific fire engineering design in a similar performance based environment. However, the minimum fire ratings specified by the Australian prescriptive documents are much higher than in New Zealand. The fire requirements in the structural design codes are rather simplistic; using tabulated values for reinforced concrete, for example, or specifying that standard tests should be used for establishing fire resistance ratings. All fire resistance values are based on standard fire exposure, with little or no mention of realistic fires. Alternative calculations are permitted but, unlike Europe, very little guidance is given (Buchanan, 2000). As in many other countries, the structural timber standards include a calculation method based on a constant rate of charring under standard fire exposure. A useful ***Guidefor the Design of Fire Resistant Barriers and Structures*** has recently been published in Australia (England et al. 2000).

## CONCLUSIONS

- Structural design is only part of the overall provision of fire safety. Structural fire safety must be provided as part of a comprehensive fire safety strategy.
- It is possible to use simple methods for specifying the required fire resistance, and to use tabulated data for compliance. The more simple the method, the more conservative the underlying assumptions need to be, and the less the accuracy of predicted behaviour.
- For large or prestigious buildings where the consequences of failure are most serious, the need for advanced structural design for fire safety becomes very important.
- Structural design for fire conditions must consider many different fire scenarios, with realistic; assessment of possible fire conditions.
- Maturing analytical tools for advanced structural analysis, combined with developing knowledge of material properties under elevated temperatures, are allowing the development of sophisticated methods for structural design for fire safety.
- Structural analysis **and** design of buildings in fire conditions is far more complex than for normal temperature conditions. It is necessary for design to be restricted to those with advanced knowledge of structural engineering, suitable analytical tools, and knowledge of thermal and mechanical material properties.
- The Structural Eurocodes provide the best current source of peer-reviewed information on principles and details for structural fire resistance.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