

**NISTIR 6890**

**Fire Resistance Determination and  
Performance Prediction Research  
Needs Workshop: Proceedings**

William Grosshandler  
Editor

**NIST**

**National Institute of Standards and Technology**  
Technology Administration, U.S. Department of Commerce



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# **Fire Resistance Determination and Performance Prediction Research Needs Workshop: Proceedings**

William Grosshandler  
Editor  
*Building and Fire Research Laboratory*

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**U.S. Department of Commerce**  
*Donald L. Evans, Secretary*

**Technology Administration**  
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## ABSTRACT

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 to put structural fire protection on a stronger scientific footing. The first phase of this program focused on addressing the poor performance of high strength concrete (HSC) in fire, which was not yet reflected in any design codes. The catastrophic collapses of the World Trade Center underscored the need not only to accelerate but also to broaden this effort to include fire safety design of steel construction. A workshop calling upon scientific and engineering experts in materials, fire protection, and structural design was held February 19 and 20, 2002, at NIST to identify the research required to underpin meaningful test and predictive methods for use in evaluating the performance of structures subject to real fires. The specific objectives of the workshop were to review current practices for achieving fire resistance; to explore the promise of fire dynamics simulations and structural behavior predictions at elevated temperatures; to identify new fire resistance options coming from materials science; to identify opportunities and needs in advanced computational methods; and to identify applications and needs for emerging measurement, instrumentation and test methods. Commercial, academic and government experts provided background and suggestions on how best to achieve the objectives, from the perspective of the discipline they represented. This information is summarized in these Proceedings. Key recommendations include the following:

- to develop new experimental methods for measuring high temperature thermal and mechanical properties of structural and insulating materials;
- to develop experimental facilities and capabilities for measuring the behavior of real-scale connections and assemblies under controlled fires that permit extrapolation to total building frame behavior up to the point of failure;
- to improve the physics and speed of sophisticated numerical models, and to expand the use and acceptance of proven, simpler computational design tools;
- to establish as a goal the need to predict the performance of coupled building systems in elevated temperatures to the point of impending failure;
- to develop a strategy to effectively incorporate technological advances in structural fire resistance into engineering tools that support performance-based design alternatives;
- to train and improve communications between the architecture and engineering professions; and
- to appreciate the needs of, and better train, building code officials and regulators.

## **ACKNOWLEDGEMENTS**

The success of any workshop is dependent upon the hard work of the individual speakers and facilitators, and the efforts of participants motivated toward a common goal. These proceedings are an assimilation of the contributions from the workshop participants, with some of the text coming directly from the presentations of the invited panelists from the following organizations:

Arup Fire, UK (Barbara Lane)  
Hughes Associates (Craig Beyler and Philip DiNenno)  
Institute for Research in Construction, NRC-CANADA (Venkatesh Kodur)  
Lehigh University (James Ricles)  
National Institute of Standards and Technology (Howard Baum, Shyam Sunder,  
William Pitts, John Gross, Edward Garboczi, and William Grosshandler)  
University of California, Berkeley (Brady Williamson, Abolhassan Astaneh)  
University of Edinburgh (Asif Usmani)  
University of Liege (Jean-Marc Franssen)  
University of Maryland (James Milke and Fred Mowrer)  
University of Utah (Adel Sarofim and Philip Smith)  
SP Fire Technology (Ulf Wickstrom)  
Stanford University (Greg Deierlein)  
Wiss, Janney, Elstner Associates (Robert H. Iding)

Verbatim copies of the presentations are included in the appendix. In addition, the editor wishes to acknowledge the assistance of Ms. Wanda Duffin of NIST, who helped with the planning, organizing and running of the workshop.

## **DISCLAIMER**

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# **FIRE RESISTANCE DETERMINATION & PERFORMANCE PREDICTION RESEARCH NEEDS**

## **BACKGROUND**

The enormity of the loss of life and the economic impact caused by the destruction on September 11, 2001, has led the scientific and engineering community to recognize its responsibility to understand the technical issues associated with the buildings that collapsed that day. The Twin Towers, as designed, withstood the physical impact of the aircraft but succumbed to the thermal impact of the ensuing fire. WTC 7, with unknown but significantly less structural damage collapsed hours later, apparently due to the fire that burned unchecked, making it the first instance of a building of such a design to ever fail by this method. The relative amount of damage to the Pentagon due to the initial impact and due to the subsequent fire has been investigated, which is important if we are to learn the right lessons from the observed building performance, occupant behavior, and fire fighter response.

Central to all these events is the fire resistance of the structures. No one did a calculation ahead of time to predict how resistant to heat these buildings were in the event of an extreme fire. Why? Consider the following reasons:

- There was no code requirement to include a realistic fire scenario.
- A plane crash into a high-rise building followed by severe fire had never occurred.
- Structural engineers anticipated a possible accidental hit by an aircraft, but the architect responsible for fireproofing did no fire analysis.
- The structural elements were protected with fire resistant coatings and panels following the accepted practice of the day.
- In the late 1960s (when the buildings were designed), the engineering tools available to predict the performance of structural connections and assemblies in an actual large fire setting were primitive.
- The prevailing mindset at the time the Towers were designed was "the engineer designs the structure and the architect specifies the fire protection."

The National Institute of Standards and Technology's (NIST's) Building and Fire Research Laboratory (BFRL), as the national laboratory responsible for research into building fires, initiated a program prior to the events of September 11 to put structural fire protection on a stronger scientific footing. The first phase of this program focused on addressing the poor performance of high strength concrete (HSC) in fire, which was not yet reflected in any design codes. As a result, scientific data and knowledge related to mechanical properties of HSC at high temperature, methods for mitigating explosive spalling in fire-exposed HSC, and recommended code provisions for HSC strength-temperature relationship were developed and published [30-32]. However, the catastrophic collapses of the World Trade Center underscored the need not only to accelerate but also to broaden this effort to include fire safety design of steel construction. A workshop calling upon scientific and engineering experts in materials, fire protection, and structural dynamics was held February 19 and 20, 2002, at NIST in Gaithersburg, MD, to identify the fundamental research required to underpin meaningful test and predictive

methods for use in evaluating the performance of structures subject to actual fires. The agenda with the topics covered, speakers names and affiliations is shown in Appendix I. Appendix II includes a list of those who attended, and Appendix III contains the presentations.

## **WORKSHOP ORGANIZATION AND OBJECTIVES**

The tone of the workshop was set by Sunder (see Appendix III. A) who provided an overview of the NIST strategy for advancing standards, technology and practices leading to cost-effective safety and security of buildings and critical facilities, with explicit reference to the proposed investigation of the World Trade Center disaster. In addition to the 24 month investigation, the strategy calls for sustained research and a developmental effort in structural fire protection; human behavior, emergency response and mobility; building vulnerability reduction; and an industry-led roadmap for construction and infrastructure support. As part of the structural fire protection program, research and development are proposed for methods of fire resistance determination, improved fire resistance coatings and materials, fire safety design and retrofit of structures, and mitigation of progressive collapse.

Grosshandler laid out a vision that extended beyond a direct response to the events of 9/11/01 (see Appendix III. B): ***Vision** Scientifically-based performance predictions for the design and operation of buildings, accepted by regulators and major stakeholders, that enable a rational balance of competing demands for fire safety, function, economy, aesthetics, and environmental stewardship.*

Improvements to current understanding of instrumentation development, computational methods, and measurement techniques are needed to achieve this vision. The need for performance prediction extends to building materials, products, structural elements, and systems up to the point of imminent fire-caused collapse of a significant load-bearing element. Assessment of the uncertainties in the prediction of performance, and convincing the regulators and stakeholders of the validity of the uncertainty established, will be as important as the development of the tools themselves.

The specific objectives of the workshop were laid down by Grosshandler as follows:

- to review current understanding of practices for achieving fire resistance;
- to explore the promise of fire dynamics simulations and structural behavior predictions;
- to identify new fire resistance options coming from materials science;
- to identify opportunities and needs in advanced computational methods; and
- to identify applications and needs for emerging measurement, instrumentation, test methods.

Commercial, academic and government experts provided background and suggestions on how best to achieve the workshop objectives, from the perspective of the discipline they represented. This information is summarized in the following sections, loosely categorized as History and Current Practice, Fire Testing and Simulations, Fire Resistant Materials, and Structural Performance. The final sections provide a summary of the workshop and list specific recommendations.

## HISTORY AND CURRENT PRACTICE

### P. DiNenno and C. Beyler

DiNenno and Beyler (Appendix III. C) provided an overview of designing fire resistance for buildings. The first fire endurance tests in the U.S. were conducted in Denver on floors in 1890. The New York City Building Department adopted a code around 1900, which required floor systems to endure a five hour exposure to a furnace maintained at a temperature of 1100 °C with a mass loading of 211 kg/m<sup>2</sup>, and to subsequently withstand a load four times this for 24 h. A furnace for conducting the test was located at Columbia University. The Baltimore fire in 1904 led to the formation of an ASTM committee to develop an American standard for fire resistance. The first standards were released in 1908, with similar load requirements but the peak furnace temperature decreased from the New York code to 927 °C. Within the next ten years, testing was being conducted at Factory Mutual, the National Board of Fire Underwriters, the National Bureau of Standards and Underwriters Laboratories. Standard fire resistance tests for loaded columns began to be developed at UL around 1917. The year 1918 saw the release of ASTM C19, the first edition of the standard that is now numbered ASTM E119 [1], which contained provisions for floor and wall testing using a standard time-temperature curve and a 25% safety factor with respect to time. Ingberg [2] of the National Bureau of Standards led the efforts in the U.S. during the 1920s, examining different fuel loads and suggesting that integrating the furnace temperature over time was a way to compare performance among various fire scenarios and furnace conditions.

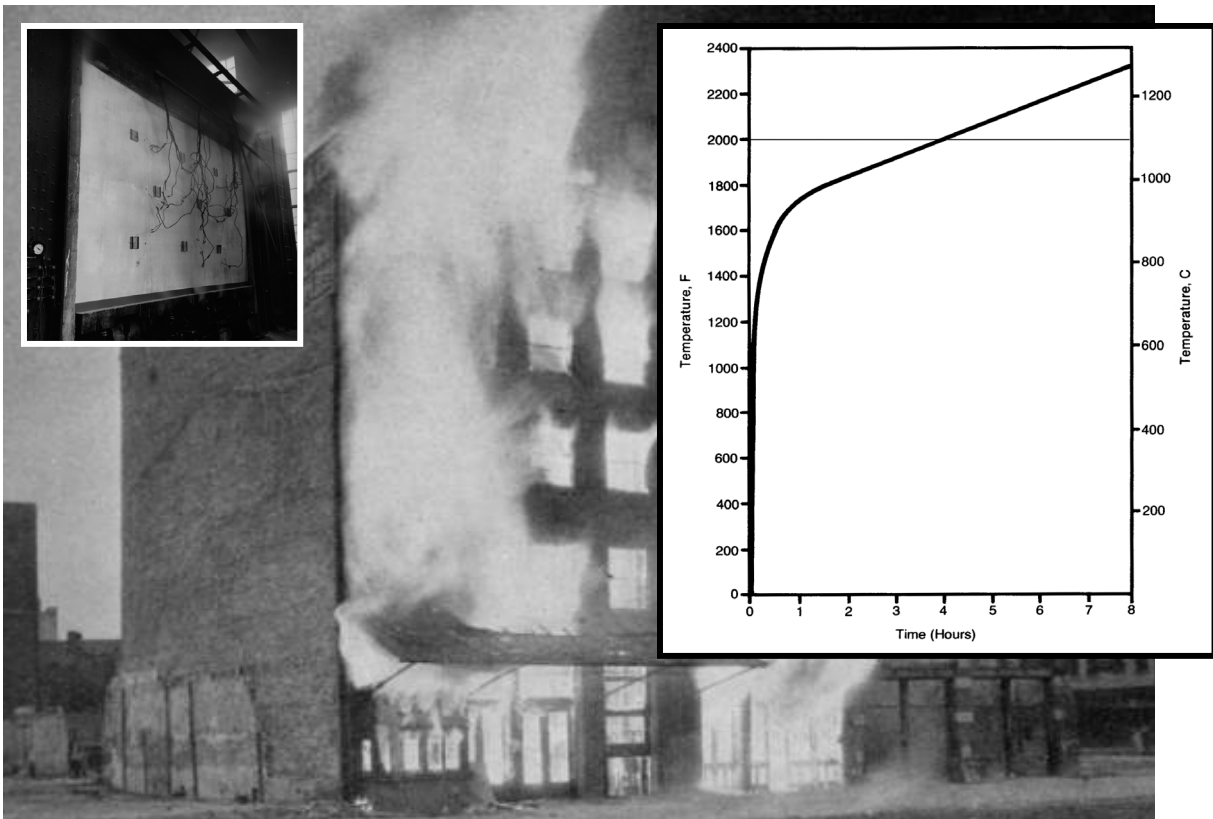


Figure 1. Photograph [3] of building fire as part of a series of tests used to develop time-temperature curve. Inset is a wall assembly ready for testing in the ASTM E119 furnace.

The compelling needs for fire resistance are the following:

- to prevent building collapse;
- to prevent fire spread from building to building;
- to contain the fire from spreading horizontally through wall partitions and vertically through floor assemblies;
- to maintain safe means of egress;
- to control the movement of smoke; and
- to provide for fire fighter safety

Today, fire resistance requirements are established in a purely prescriptive manner by building code and are a function of occupancy, height and area of the space, and whether or not sprinklers are present. Testing is done routinely at many commercial laboratories following the procedures specified in ASTM E119, NFPA 251 [4], ISO 834 [5], or some variant developed by FM or UL. A standard time-temperature curve, based upon the work of Ingberg, is used to challenge the test specimen. Pass/fail criteria are based upon the peak temperature attained at the back of the test article and/or whether or not the test article collapses or distorts in a fashion that allows hot gases to escape (and in the case of E119, whether the wall can withstand the pressure of a hose stream). Many structural elements are tested unloaded; there is no limit on the amount of deflection that a beam can undergo and still pass the test; and connections are not tested at all. Products that are tested with these methods are assigned an equivalent fire endurance time (in hours).

The materials and systems currently used to provide fire resistance to structural members include sprayed fibers, cementitious materials, mastics, intumescent paints, suspended ceilings and drywall assemblies (membranes), concrete encasements, tiles, and plaster/lath. The adhesion and cohesion properties of spray-on fireproofing [6], and gross behavior when exposed to modest deflection and indirect impact loads are measured in standard tests [15, 16], but hardness and resistance to direct impact are not explicitly measured.

While a number of revisions were made to the above standards throughout the twentieth century, the prescriptive nature for these fire resistance test methods remains unaltered, in spite of changing fire loads and significant advances in our knowledge of fire and structural behavior. As early as the 1950s the engineering community was beginning to understand a number of situations that caused the fire exposure curve established by Ingberg [2] to vary significantly from reality, including post-flashover fires, ventilation controlled fires, and different insulation properties of wall linings. More was understood about the thermal response of columns and beams to changes in temperature, with new analytical, numerical, and experimental methods being developed to predict column buckling, beam deflection and truss deflection. Finite element heat transfer models, structural response models (e.g., FASBUS [7]), and models of post flashover fire conditions (e.g., COMPF [8]) were available by 1980. It is suggested by DiNenno and Beyler (Appendix III. C) that all of these tools can be brought to bear on the problem of predicting fire resistance performance of structural systems.

Figure 2 provides a framework for working these issues. Design fire exposure should be dictated by a modern fire load survey, and the knowledge gained from our capability to characterize local heat flux in a way more meaningful than provided by the well-stirred assumption. Data on the

thermal and mechanical response of insulation systems needs to be institutionalized, and standard test methods and performance criteria developed for mechanical response, non-fire impact loading and fire exposure. The performance of fire barriers is needed along with that of load-bearing elements. The relative role for full structural models and detailed local deformation analysis needs to be assessed, especially regarding the performance of connections. A full compliment of test methods are needed to establish engineering properties. Furnace testing should be severe; e.g., ASTM E1529 [9] is a simple bounding fire exposure that provides a harsher (compared to ASTM E119) thermal test of the mechanical properties of fireproofing materials. Test methods should relate more directly to the mechanical and thermal environment likely to be experienced in a real structural fire, and should be used primarily as a validation of engineering methods. Performance criteria must be established depending upon the question being asked.

The greatest difficulty encountered in advancing fire resistance performance prediction, according to DiNenno and Beyler, is translating our increased understanding and technology into codes and standards. It is necessary to develop a broad consensus for the need to change how fire protection engineering is done. Science-based fire protection design practices need to be codified, and building codes must be formulated to accept new practices. Education of engineers, architects and authorities having jurisdiction is essential. Science-based structural fire protection is technically achievable, though it will require a total reexamination of how things are done, from product listing to design to operations (inspection, testing and maintenance). The payoff is known cost-effective performance and assured safety.

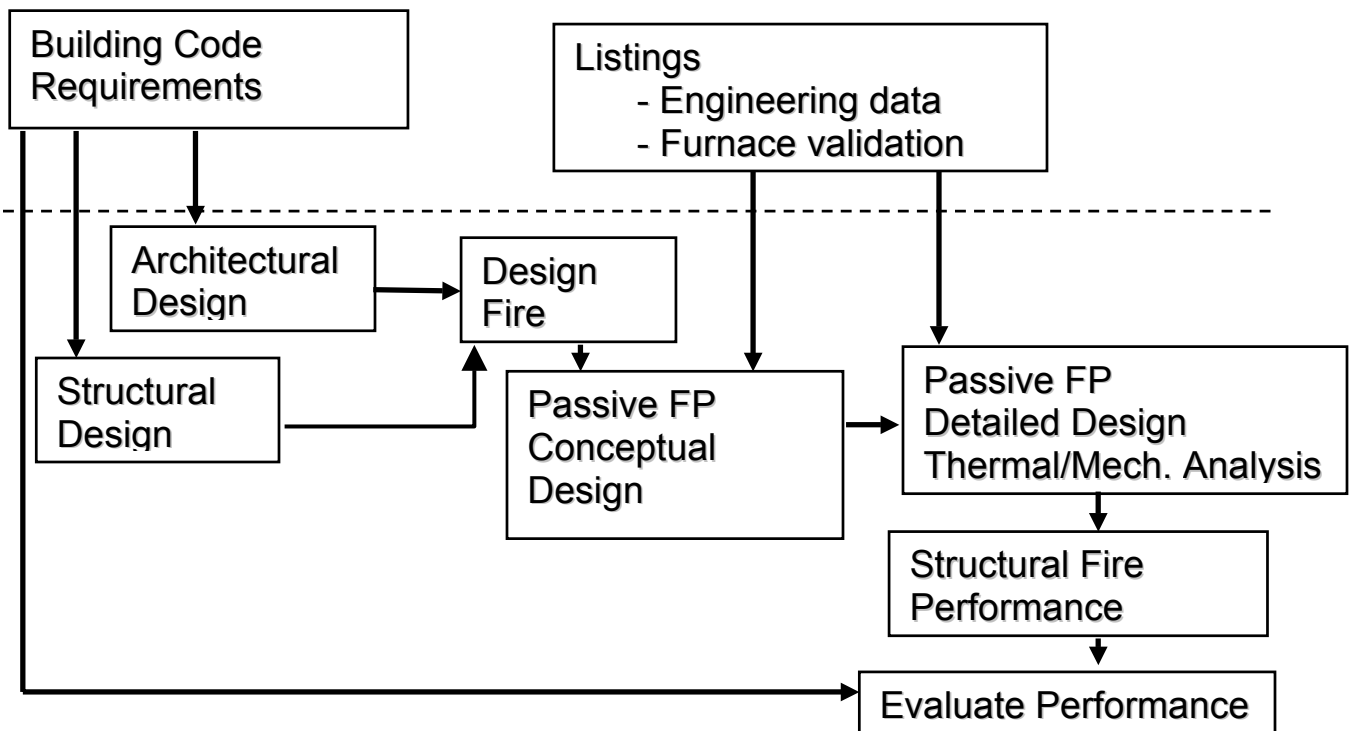


Figure 2. Science-Based Structural Fire Protection Design (DiNenno and Beyler)

### J. Milke

Milke (Appendix III. D) described an effort by the American Society of Civil Engineers (ASCE) and the Society of Fire Protection Engineers (SFPE) to develop a standard on performance-based structural fire protection analyses, motivated by the difficulty in relating the current comparative tests to actual fire performance. The new standard will outline calculation procedures to link the results of tests to structural performance. Other organizations involved in the effort include the American Iron and Steel Institute (AISI), the concrete industry, the Masonry Alliance for Codes and Standards, and the American Forest and Paper Association (AFPA). The analytical framework is shown in Fig. 3. The material properties, thermal response and structural response of concrete, masonry and steel are each handled in their own section of the standard. A role will exist for simple calculations, advanced computations and experiments, all working together to determine the performance of individual structural elements, structural assemblies, and the global response of the building.

The fire exposure will be based upon heat flux (including radiative and convective contributions) as a function of time as well as temperature vs. time. Pool fires, distributed fires, and external fire exposures will be included. The thermal response of the structural elements can be followed using multi-dimensional finite element analysis with the boundary conditions provided by the (experimental and/or numerical) fire exposure. Although some material properties have been tabulated, many more, especially at higher temperature, have to be compiled. The structural response will be determined by a combination of first-order, single element analyses (column stability, moment analysis of a slab/beam, isothermal over a range of temperatures). Computer simulations are needed to account for temperature distributions in space, variable cross-section members, complex loading, and frame analyses. Additional experimental programs are required to develop a complete material properties data base, to better characterize complex material behavior (cracking, adherence, charring and spalling), to calibrate models, and to examine interactions between component building assemblies and adjacent building assemblies within the larger structural frame.

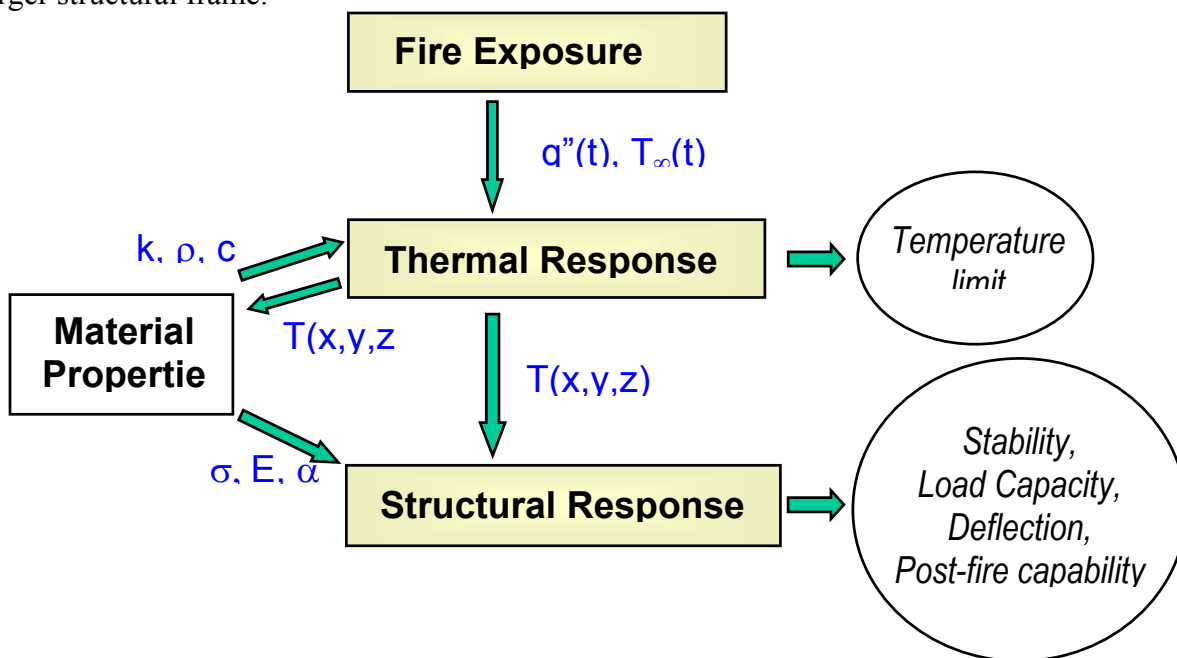


Figure 3. Analytical framework for ASCE/SFPE pre-standard (Milke)

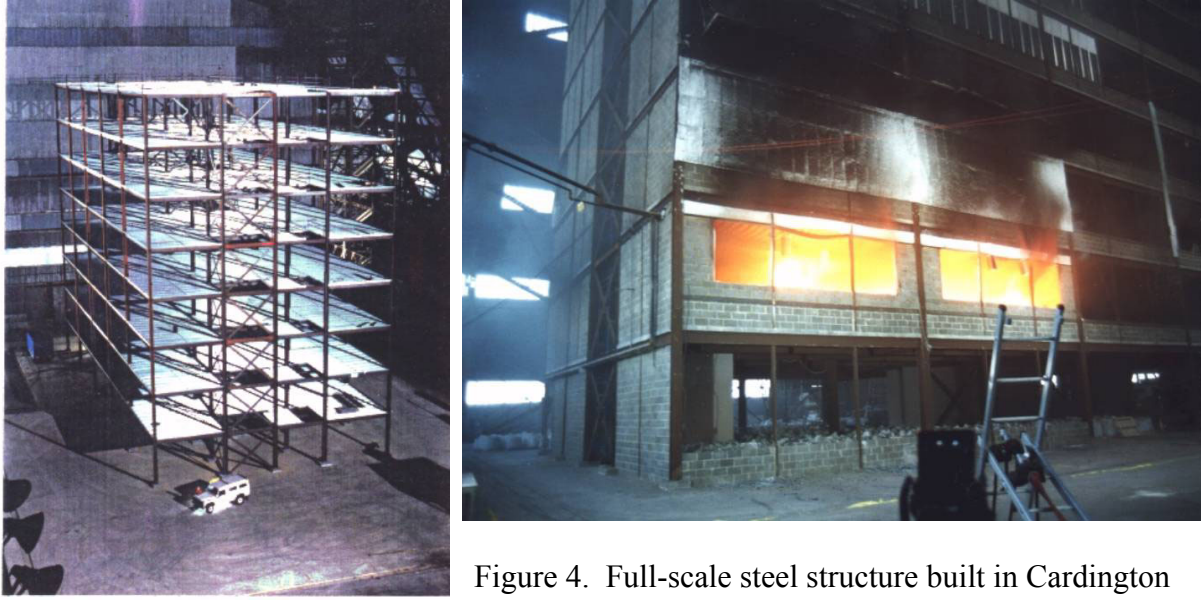


Figure 4. Full-scale steel structure built in Cardington Laboratory (left), and during a test fire (Usmani)

## **FIRE TESTING AND SIMULATION**

### **H. Baum**

The research needs from a fire modeler's perspective were stated succinctly by Baum. The first need is associated with defining the building. While conceptually straightforward, the large amount of data available to describe a modern building and the differing ways that these data are used for design, operations, and maintenance overwhelms the individual interested in predicting fire resistance performance, leading to great inefficiencies in the calculations and limiting their value. An efficient way to generate an electronic database that can be accessed seamlessly for multiple purposes is critical. The detail has to be sufficient to capture the location and operations of the HVAC systems, elevators and stairways. The second need is to develop a better understanding of the burning behavior of the contents of modern buildings, including complex shaped objects (e.g., real furniture), libraries and paper files. Being able to predict the occurrence of fire-induced geometry changes is the third primary need, specifically windows breaking and the warping/penetration of partitions (walls and floors).

### **A. Sarofim and P. Smith**

An overview of the Center for the Simulation of Accidental Fires and Explosions (C-SAFE) located at the University of Utah was given by Sarofim and Smith (Appendix III. E). C-SAFE is allied with the Accelerated Strategic Computing Initiative (ASCI) to develop (unclassified) simulation science in support of the DOE defense program laboratories to safeguard the U.S. nuclear stockpile. C-SAFE is focused on the science-based tools for numerical simulation of accidental fires and explosions, within the context of handling and storing highly flammable material. The accident scenario to be simulated is a conventional high explosive material in a metal container of arbitrary shape, size and location within an arbitrary, sooting hydrocarbon pool fire. Following an assumed ignition of the liquid fuel, the calculations are made of the fire spread, the dynamics of the container, high energy transformations, and conditions that lead to

accidental detonation. An example was provided of a calculation of a 10 m diameter heptane pool fire in a (50 m)<sup>3</sup> domain. With 3.4 million computational cells and 6800 time steps, the calculation took 18 h to complete on the Los Alamos Nirvana computer (500 processors). The challenge for the Center is to make optimum use of the increasing number of processors to allow finer spatial resolution. Problem areas for the integrated calculation exist at the interfaces between the various phases, communication among the multiple scientific disciplines involved and with the ultimate user, and all aspects of data management (transfer, storage, mining). Lessons from Sarofim and Smith that may bear on predicting the fire resistance of structures include the encouragement to consider interdisciplinary approaches on cross-cutting issues, in particular a close collaboration with software engineers and computer scientists. "Amphibians" are needed to bridge disciplinary gaps, and the importance of communication cannot be overstated. The C-SAFE program has advanced the state of computational chemistry to predict properties, mechanisms and kinetics, and more detailed chemistry and fluid mechanics can be included in massively parallel computations. The material point methods show promise for handling large deformations and the break up of structures. Sarofim and Smith concluded by emphasizing the importance of experiments for guiding and validating the computations.

### **A. Usmani**

An eight story steel structure, shown in Figure 4, was built in Cardington, England in the mid 1990s [10] to examine the behavior of individual elements and the structural frame when exposed to various fire environments. The impetus for the full-scale testing was to demonstrate that the requirements for structural design fire safety were overly conservative. The Cardington tests have improved our understanding of structural behavior in fire, produced data for validating computer models. The new understanding of composite framed structure behavior in fire, so generated, may lead eventually to more rational design methods, and could reduce the cost of steel fire protection.

Usmani (Appendix III. G) described the challenge of numerically modeling the response of the Cardington structure to different fire loads. ABAQUS [11, 12] was used to examine a large number of structural arrangements and the details of modeling and subsequent interpretations of behavior are too voluminous to present here. However, interested readers can find many reports and other documentation containing substantial details of this work at

<http://www.civ.ed.ac.uk/research/fire/project/main.html>.

Very briefly, this work revealed the following lessons for whole structure behavior in fire:

- restraint to thermal strain dominates behavior of the composite beam and slab system
- conventional loading contribution to overall behavior is low
- the results show low sensitivity to variations in strength and stiffness properties of steel
- at large deflections tensile membrane action in the spans and compressive membrane action near the perimeter supports of floor slabs were observed
- thermal strains automatically produce a beneficial load-carrying shape in tensile membrane action for slabs without large and damaging mechanical strains
- the load capacity can be further enhanced by thermal pre-stressing
- local buckling of the lower flange always occurred but was not found to be a detrimental mechanism



A simple analysis will reveal that in a member restrained from lateral translation, as the mean temperature increases, compression occurs, but as the through-depth temperature gradient increases, tension occurs. The former scenario is most likely in a slow growing, protracted fire, while the latter results from a rapidly growing, short duration fire. Frames smaller than the Cardington structure may have fewer redundant paths, and the fires could extend over the entire floor. By the same token, large compartments that may be a part of a very large frame may behave quite differently because of the nature of the fire (spreading with local flashover perhaps) leading to significantly different structural response. To enable reliable tensile membrane mechanisms, it is necessary that the floor slab reinforcement is anchored at the compartment perimeter, with interior continuity provided by lapping reinforcement. Edge and corner compartments have discontinuous edges that may or may not have fire protection. Unprotected edges will provide considerably lower anchorage to tensile membrane forces, therefore protecting edge beams seems worthwhile as a means to anchor membrane forces and to protect cladding. Further 3-D modeling using DIANA was conducted to examine the impact of these variables on the structure and the results produced similar conclusions.

The key conclusions from this work are that the structural response to a fire depends upon the rate of heating as well as the temperature of the structure, and that different fires can produce very different stress/strain patterns in composite floor systems. This is because most of the pre-failure response of structural members depends upon the two geometric effects produced by heating, a mean temperature increase and a mean thermal gradient. The material effects of reduction in strength and stiffness begin to dominate just before failure.

Further research was suggested by Usmani to establish the worst case fire scenario on the basis of the maximum structural damage it would inflict on the building (in addition to other life safety issues such as smoke movement and egress, the worst case scenario(s) for these may be quite different). This would require new scientifically based and practical analysis methods for reliable prediction of structural damage against a given heating regime. Research is also required to properly include (in a risk-based framework), extreme fire events as limit states, (which should be the basis of all structural designs). Tall buildings with long evacuation times require special consideration to ensure that localized collapse does not lead to overall progressive collapse. Other questions that need further research are: Are floor slab failures ductile or brittle? Can one generalize that a short and hot fire places a more severe load on the structure than a sustained, less intense fire (or vice versa)? How important is it to model connections, the cooling process, and the integrity of non-load bearing compartment boundaries? A final provocative question posed (but not answered) by Usmani is, How does one define failure?

In terms of the fundamental structural and solid mechanics research required in the context of understanding structural response to extreme events, perhaps the most important research need is as follows. Most failures in large redundant structures have roots in local “seed” events (such as a crack or fracture) that grow without being arrested and cause progressive global collapse. Many local events in a large redundant structure will occur as load redistribution mechanisms and will be self-limiting under the overall equilibrium and compatibility constraints. A thorough understanding of the development of local structural phenomena into events that threaten global structural stability/integrity should be one of the main research objectives.

## **V. Kodur**

The positive attributes of high strength concrete for buildings and columns make it an attractive material, but its high density and low porosity make it susceptible to spalling under fire conditions. Since an intended benefit of concrete is the elimination of additional fire protection, methods are required to ensure the fire safety of high strength concrete. However, there are currently no guidelines for the exposure of high strength concrete to fire. Test methods for evaluating the fire resistance of large-scale structural systems were described by Kodur (Appendix III. H), and used to highlight the differences in performance between high and normal strength concrete.

Columns of both types of concrete were examined, with size, load intensity, fiber reinforcement, fire intensity, and reinforcement configuration the independent variables. The specimens were full-scale and designed according to code, and tested according to the protocol in ASTM E119 (see Figure 5). Column temperatures, deflections and degree of spalling were the dependent variables. The primary observations during the tests were that spalling was not significant in the first 30 minutes, and that using  $135^\circ$  (as opposed to  $90^\circ$ ) column-ties reduces early spalling to a minimum. Within 2 h, hair line cracks appear, widen at corners, and lead to chunks of concrete dropping off for the  $90^\circ$  reinforcing bar ties. Failure occurs when the ties open up and the rebar buckles. The  $135^\circ$  ties remain superior all the way through the test. The normal strength concrete, for comparison, failed only locally, the ties did not open up nor rebar buckle, and less spalling occurred.



Figure 5. Comparison between normal strength concrete (left) and high strength concrete (right) after ASTM E119 column test.



Figure 6. Photograph of modern floor testing furnace (Kodur)

Kodur summarized the factors that influence fire performance of concrete: compressive strength, reinforcement layout, moisture content, concrete density, heating rate, aggregate type, load intensity and type, and fiber reinforcement. The major factors that enhance spalling and decrease fire resistance are higher concrete strength and higher loads; factors that reduce spalling and increase fire resistance are closer tie spacing, 135° ties, use of carbon aggregate, and use of reinforcing fibers. The experimental work conducted at CNRC was complimented by numerical studies of the factors influencing behavior, using thermal and mechanical properties measured at elevated temperatures, to develop design equations for fire resistant structures.

For the future, Kodur emphasized the need for realistic conditions when assessing fire resistance, the need for analytical tools and specified fire scenarios, with validated models, design fires and material properties. To be ready for performance-based codes, the industry must have suitable calculation methods, software packages and design guides. High performing materials must satisfy fire resistance criteria, and practical and cost-effective solutions to overcome current shortcomings are necessary.

#### **U. Wickstrom**

The need for improved fire testing in combination with calculations was the theme stressed by Wickstrom (Appendix III. I). When analyzing the performance of structures exposed to fires,

one needs to consider the fire development (design fire), heat transfer to fire exposed structures, temperature development in the structures, and the resulting mechanical behavior of the structures. To improve fire resistance design, standard methods for measuring thermal and mechanical properties of structural and protective materials must be developed. Techniques for improving furnace testing and for monitoring deformation properties during the test are also required. Two specific techniques put forth by Wickstrom are the transient plane source, heat transmission, thermal diffusivity (TPS) apparatus and the plate thermometer. The former consists of a thin heater that is sandwiched between flat sections of the fire protection material under investigation. By following the temperature as a function of heat input, position, and time, key thermal properties can be generated. The plate thermometer can be used to monitor and control the temperature in the furnace (e.g., ISO 834 or ASTM E119). The benefit of the plate thermometer is that it allows one to calculate the true structural temperature in close agreement with the measured structural temperature (see Figure 7), in contrast to the standard shielded thermocouple. While no techniques were proposed for measuring deflection during the test, Wickstrom emphasized that such data are essential to relate calculated behavior to actual expected behavior.

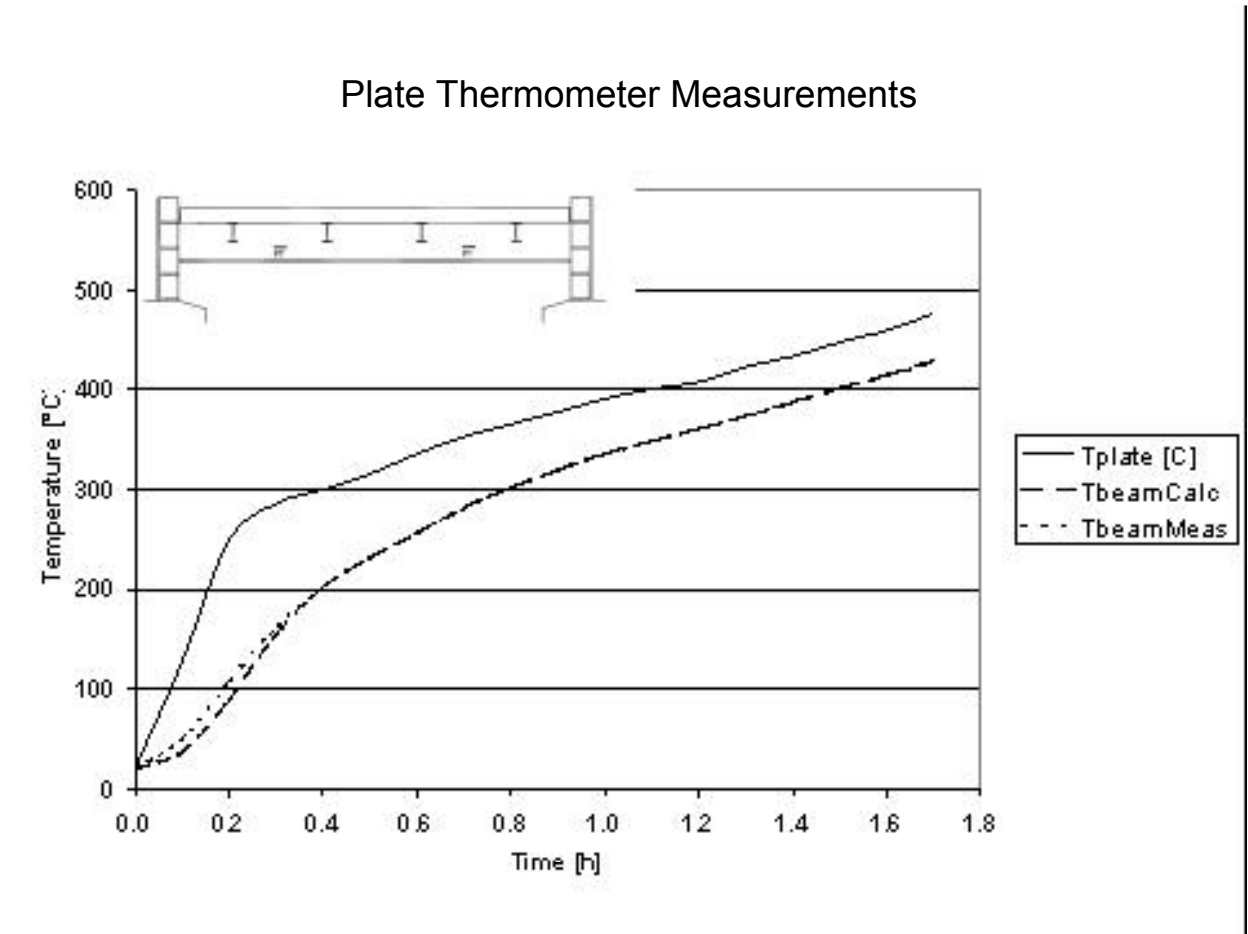


Figure 7. Temperature measurements in floor assembly furnace test, comparing the plate thermometer to the calculated temperature.

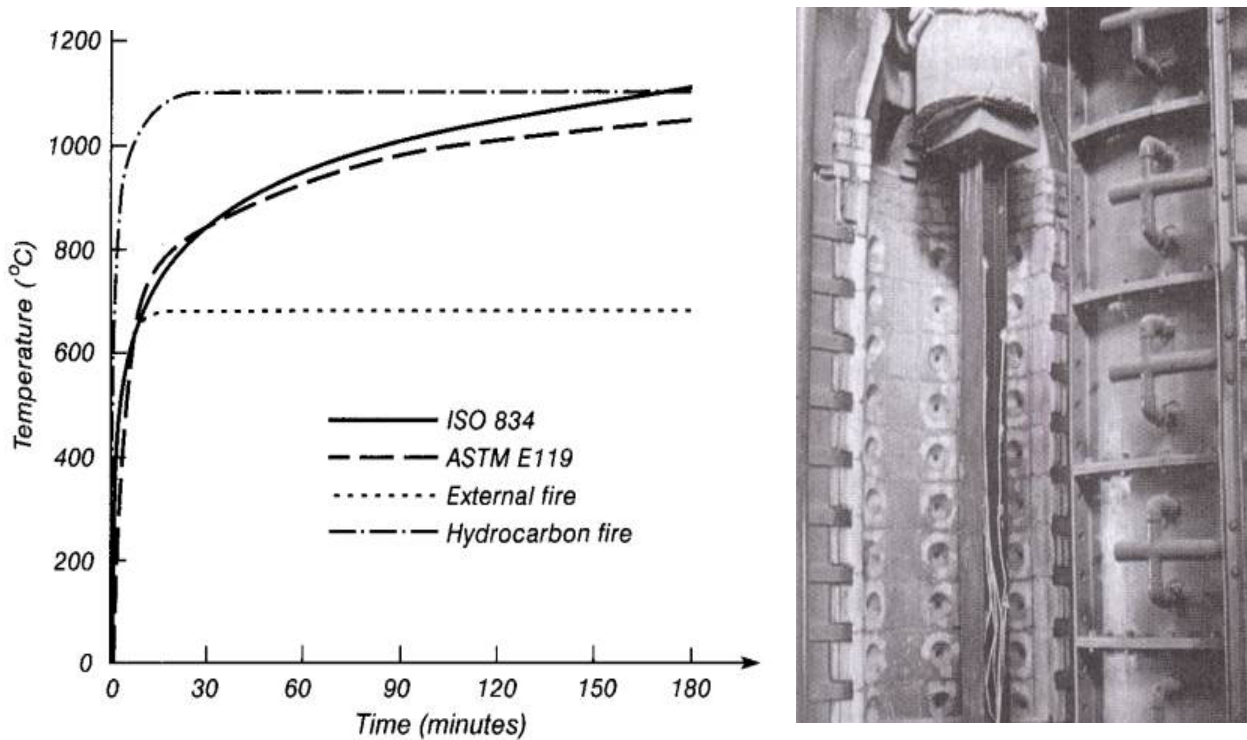


Figure 8. Alternative temperature-time curves for fire resistance tests (left), and a photograph of a steel column ready for testing in the furnace.

## FIRE RESISTANT MATERIALS

### R.B. Williamson

Williamson (Appendix III. K) briefed the participants on the history of fire protection of structural steel and the materials used for that purpose. Dating back to the 1898 Home Life Fire in New York City, a new approach to high rise safety began emerging that required buildings to be constructed of columns, floors, walls and other elements that were fire resistive, defined as the ability of an element to withstand the effects of fire for a specified period of time without loss of its fire separating or load bearing function. This ability was determined by exposure in a furnace to sustained high temperatures. Various temperature-time curves are used today, depending upon the country and application. Figure 8 compares the ISO 834 test, the hydrocarbon fire (ASTM E1529), and external fire exposures to the standard ASTM E119 curve (also shown in Figure 1). A column instrumented for a test is shown on the right.

The first materials used for fire proofing in the early 20th century were traditional construction materials such as masonry or concrete, which led to substantial labor costs and excessive weights. Gypsum-based systems such as wire lath and plaster systems came on the market thereafter, but these also suffered labor and weight penalties. Like concrete, these systems derived



Figure 9. Construction worker applying spray resistive material

much of their effectiveness from water of crystallization, which is immune from normal evaporation. Sprayed fire resistive materials (SFRM) were introduced about 40 years ago as a lower labor cost, lighter weight alternative to concrete and lath/plaster. The SFRM also derived its fire resistive properties from water of hydration contained in the gypsum or portland cement used to bind various fibers and other fillers. A worker is shown applying SFRM at a recent construction site in Figure 9.

Williamson [13] specified four performance requirements of SFRM: performance under actual fire conditions; durability and integrity under normal life of structure; durability and integrity under the construction process; and integrity under extreme conditions (earthquakes, thermo-nuclear attack, severe fire). A number of ASTM tests currently are used (in addition to E119 for fire resistance) to address these requirements:

- ASTM E605 [14], Thickness and Density
- ASTM E736 [6], Test for Cohesive/Adhesive Properties of SFRM
- ASTM E759 [15], Effect of Deflection
- ASTM E760 [16], Effect of Impact on Bonding
- ASTM E761 [17], Compressive Strength
- ASTM E937 [18], Corrosion of Steel by SFRM

A fundamental weakness of all of these tests is that they are not well linked to materials science. According to Williamson (Appendix III. K), there are many different SFRM materials

commercially available today, but the current test methods do not adequately address the most important properties or the range of conditions from ordinary fires to the extremes of a terrorist attack.

The current method for testing the cohesive/adhesive properties of SFRM (ASTM E736) consists of a disk with a hook for hanging a weight that is attached to the sprayed on fire resistive material with a quick setting adhesive. The material must withstand a minimum weight before becoming dislodged. The weakness of this method is that while failure from poor adhesion can be distinguished from failure due to poor cohesion, the method is incapable of providing failure loads for each, just whichever fails first. Williams [19] suggests an alternative approach to evaluate the adhesive properties separately, using what is called a blister test. Williamson (Appendix III. K) suggests adapting this technique to SFRM. A thin plastic bag with a bladder feed hose can be attached to the rigid steel substrate before applying the fire resistant material. The feed hose would extend beyond the fire resistive material layer. A measured pressure could be applied to the feed hose to cause the bag to inflate, and a blister would grow at the interface of the steel and SFRM to a size related to the interfacial properties.

Williamson concluded his remarks by recommending that the fire and non-fire performance of fire resistive materials be reevaluated in terms of current challenges to buildings and other structures. A new approach to testing and approvals is necessary, supported by sound research to characterize the available materials and to establish the micro-structure/property relationships that are central to materials science.

#### **F. Mowrer**

Mowrer (Appendix III. J) listed a series of steps that typically might occur when a building is fireproofed.



Figure 10. Missing spray-on fire proofing around a connection (left ) and missing fireproofing panels on a steel column (Mowrer).

These include the following:

- structure erected
- fireproofing applied
- fireproofing inspected (maybe)
- fireproofing scraped off
- other building services installed
- everything covered with finishes
- fireproofing forgotten

Conditions that are troublesome include connections, attachments, members with extreme W/D ratios, long spans, and end restraints. Since connections are not evaluated in tests, what is the best way to protect them against fire? How much fireproofing do attachments require, and is it a function of the thickness and/or length of the element? Fireproofing thickness requirements are based upon standard geometries; how do those relate to round members and other non-planar arrangements? Four meters is about the maximum span tested; how are the fireproofing requirements extrapolated to spans that are considerably longer? Furnace test articles are often wedged into the frame; how does this arrangement relate to real-world constraint conditions? How can deficiencies in fire proofing be identified during inspections, and how can they be corrected? If fire proofing is damaged or missing, how does that impact the overall performance of the structure? (See Figure 10.) These are all issues that require research solutions.

### **R. Iding**

Iding (Appendix III. L) presented several case studies of performance-based structural analysis to determine fireproofing requirements [20]. There are three key elements in the approach:

- Fire Hazard Analysis - identify all possible fire scenarios and determine gas temperatures achieved adjacent to structural members.
- Thermal and Structural Analysis - calculate temperature history in structural elements and the elements' response (forces and stresses) to the fire with varying levels of fireproofing.
- Risk Mitigation Plan - revise fireproofing scheme, or devise alternative risk reduction schemes, to ensure performance is acceptable for type of building being designed.

A step-by-step methodology was described, with examples given for a transient trash fire in a power plant and fireproofing for an unusual structure for which no prescriptive code applied: the Eiffel Tower II in Las Vegas.

The following specific recommendations were provided by Iding:

- identify material properties at elevated temperatures, particularly those of spray-on fire proofing and intumescent paint
- develop analytical tools for structural connections
- develop peer review protocol for performance-based analysis during transition to new methodology
- incorporate basic capabilities for fire analysis into commercial computer codes that can handle non-linear structural effects



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

### **A. Astaneh**

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

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

## **STRUCTURAL PERFORMANCE**

### **J-M. Franssen**

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

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

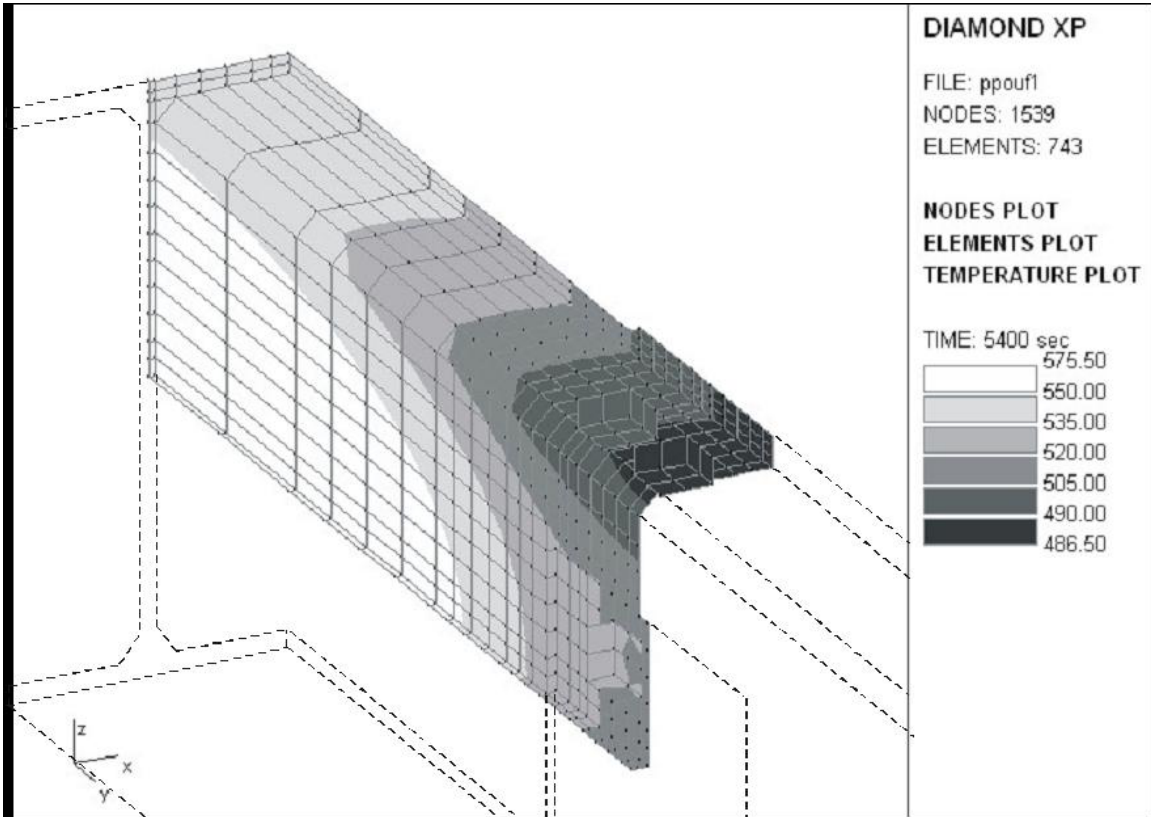


Figure 11. Temperature distribution in two steel beams connected by cover plates (Franssen)

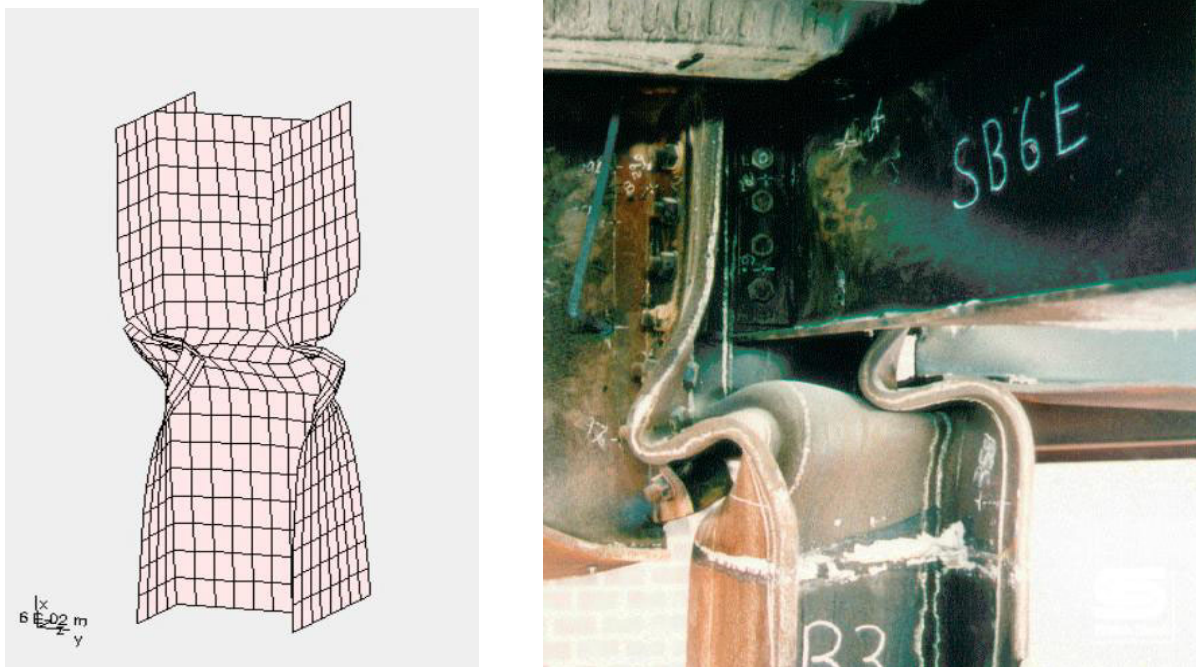


Figure 12. Shell finite element simulation showing severe deformation of a steel column (Franssen)

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

Franssen (Appendix III. N) concludes that

"for understanding and designing structures submitted to fire, numerical modelling offers capabilities that are unique. The frontiers at the moment are

- Spalling in concrete
- Thermal properties
- Local or temporary failures
- Very large structures
- Very large displacements
- Boundary conditions
- Interface with environment in localised fires
- Resources (money, time, people, ... )"

### **J. Ricles**

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

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

Finite element analysis can be applied to building details such as welded connections to examine the impact of cyclic load in the local region around the joints. Non-linear analysis of the

structural system over time can also be performed, with the details of the connections such as panel zone deformations and connector flexibility (i.e., semi-rigid connections) considered.

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

Ricles (Appendix III. O) lists the following research issues and needs:

#### Testing

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

#### Analysis

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

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

#### **G. Deierlein**

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

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

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

Figure 13. ICC 2000 performance matrix [23].

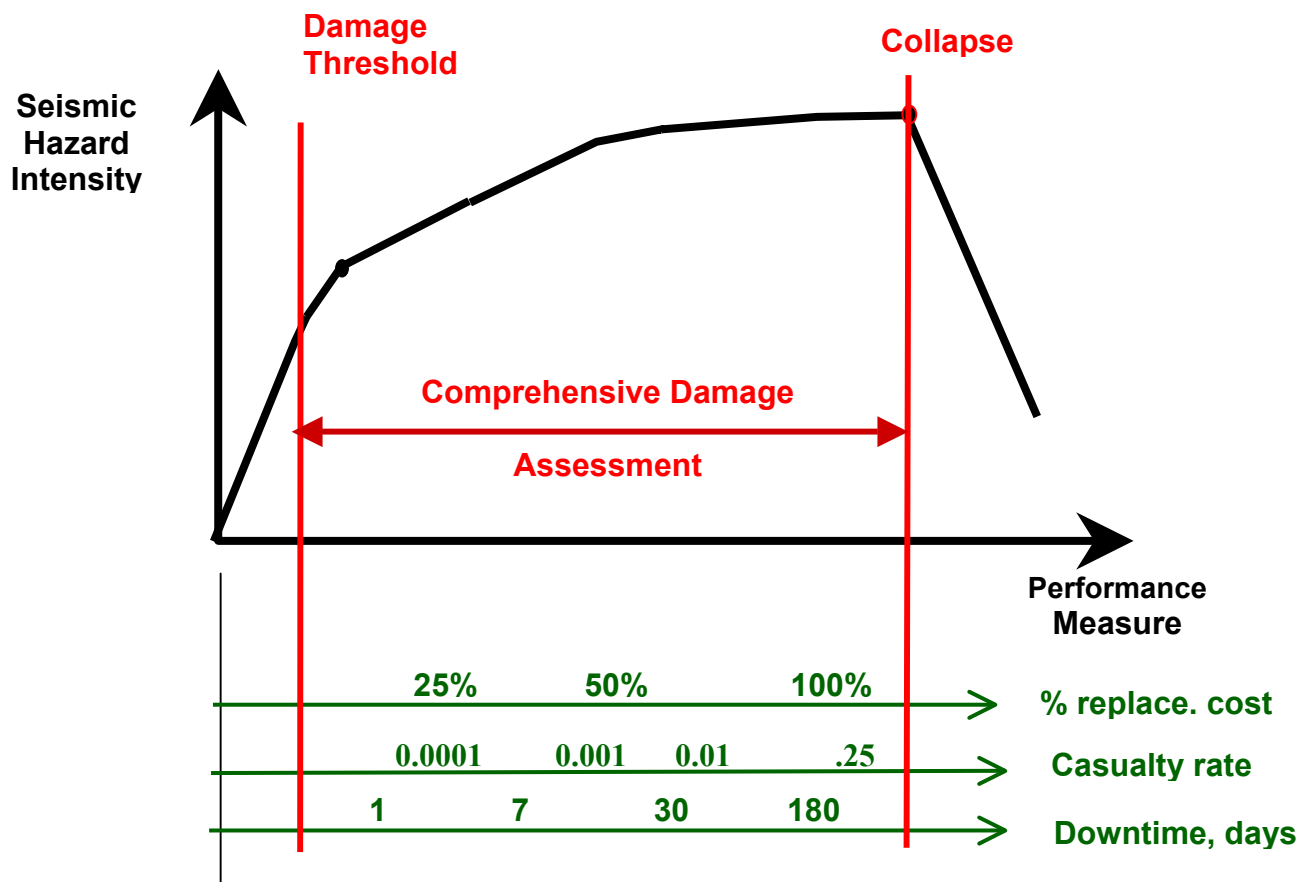


Figure 14. Explicit performance assessment in terms of earthquake intensity [24].

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

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

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

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

### **B. Lane**

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

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

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

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

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

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

Lane's wish list consists of the following:

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

## **SUMMARY**

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

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

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

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



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

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

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

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

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

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

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

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

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

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

## **RECOMMENDATIONS**

The stated objectives of the workshop were to review current practices for achieving fire resistance; to explore the promise of fire dynamics simulations and structural behavior predictions; to identify new fire resistance options coming from materials science; to identify

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

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

### **Communication/Education/Training**

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

### **Thermal and Mechanical Properties of Materials**

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

### **Measured Behavior of Connections and Assemblies**

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

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

### **Computational Models**

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

### **Standard Test Methods and Codes**

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

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

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## APPENDIX I. Workshop Agenda

# RESEARCH NEEDS FOR FIRE RESISTANCE DETERMINATION & PERFORMANCE PREDICTION

National Institute of Standards and Technology  
Gaithersburg, Maryland, USA  
Building 101, Lecture Room B  
February 19 and 20, 2002

### WORKSHOP AGENDA

#### Tuesday

8:45 Introductory Session (Chair: **William Grosshandler**, Chief, Fire Research Division, NIST)

*Welcome to NIST*, **Jack Snell**, Director, Building and Fire Research Laboratory

*NIST Response to Sept. 11*, **Shyam Sunder**, Chief, Structures Division, NIST

*Goals of Workshop*, **William Grosshandler**

9:20 Session I (Chair: **William Grosshandler**)

*Overview of Designing Buildings for Fire Resistance*, **Craig Beyler** and **Philip DiNunno**,  
Hughes Associates, Baltimore, USA

*ASCE/SFPE Standard on Performance-based Structural Fire Protection Analyses*, **James Milke**,  
Department of Fire Protection Engineering, University of Maryland, USA

10:00 Break

10:20 Session II (Chair: **William Pitts**, Fire Research Division, NIST)

*Simulation of Accidental Fires and Explosion*, **Adel Sarofim** and **Philip Smith**, Department of  
Chemical Engineering, University of Utah, USA

*Research Needs for Building Fire Models*, **Howard Baum**, Fire Research Division, NIST, USA

*Simulation of the Cardington Fire Tests*, **Asif Usmani**, University of Edinburgh, UK

*Fire Resistance Evaluation of Large-scale Structural Systems*, **Venkatesh Kodur**, Institute for  
Research in Construction, NRC-CANADA

*Improved Fire Testing in Combination with Calculation*, **Ulf Wickstrom**, SP Fire Technology,  
Borås, SWEDEN

Discussion and short presentations from participants on fire modeling

12:20 Lunch, NIST cafeteria

1:15 Session III (Chair: **Edward Garboczi**, Building Materials Division, NIST)

*Degradation in Performance of Installed Fire Resistance Materials*, **Frederick Mowrer**,  
Department of Fire Protection Engineering, University of Maryland, USA

*Performance-Based Analytical Prediction of Fireproofing Requirements in Complex Buildings*,  
**Robert H. Iding**, Wiss, Janney, Elstner Associates, San Francisco, USA

*Materials for the Fire Protection of Structural Steel*, **Brady Williamson**, Department of Civil  
and Environmental Engineering, University of California, Berkeley, USA

*Protection of Steel Structures Against Blast, Impact and Ensuing Fires*, **Abolhassan Astaneh**,  
Department of Civil and Environmental Engineering, University of California, Berkeley, USA

Discussion and short presentations from participants on fire resistant materials

3:20 Session IV (Chair: **John Gross**, Structures Division, NIST)

*Structural Fire Modeling: Where is the Frontier Nowadays?* **Jean-Marc Franssen**, Institute de  
Mécanique et Génie Civil, University of Liege, BELGIUM

*Fire Resistance and Performance Prediction: Structural Analysis Issues and Research Needs*,  
**James Ricles**, Department of Civil and Environmental Engineering, Lehigh University, USA

*Parallels Between Performance-Based Engineering for Fire and Earthquake Hazards*, **Greg  
Deierlein**, Department of Civil and Environmental Engineering, Stanford University, USA

*A Consultant's Wish List for a Numerical Model of Structural Response to Fire Conditions*,  
**Barbara Lane**, Arup Fire, London, UK

Discussion and short presentations from participants on structural modeling

5:00 Break-out sessions to identify research needs (**W. Pitts** [LR-B], **J. Gross** [B111], and  
**E. Garboczi** [B113], facilitators)

6:30 Dinner and informal discussion at local restaurant

### Wednesday

8:30 Reconvene breakout sessions (**W. Pitts** [LR-D], **J. Gross** [B111], and **E. Garboczi** [B113])

10:45 Summary of breakout session discussions (spokespersons from parallel sessions), LR-D

12:15 Lunch, NIST cafeteria

1:15 Open discussion, LR-D (Chair: **W. Grosshandler**)  
Workshop Recommendations and Assignments

4:00 Adjourn





**APPENDIX II. Workshop Attendance List**

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# APPENDIX III. Presentations

## A. NIST Response to Sept. 11 Shyam Sunder, Chief, Structures Division Building and Fire Research Laboratory, NIST

**Standards, Technology, and Practices for:  
Cost-Effective Safety and Security of  
Buildings and Critical Facilities**

Jack Snell, S. Shyam Sunder  
Building and Fire Research Laboratory, NIST  
301-675-6713; sunder@nist.gov  
February 19, 2002

South tower: Hit at 9:03 AM  
Collapsed after 56 minutes

North tower: Hit at 8:45 AM  
Collapsed after 1 hour, 43 minutes

**INITIAL NIST RESPONSE**

- Code comparison study for FEMA
- 36-day Pentagon repair and rebuilding study

John Dross examines steel connection failures from WTC

WTC Field Observations: Ground Zero looking east

AGCS Team investigated damage to Pentagon

Analytically simulate containment dispersion in East Senate Building

Long Chen, an ASCE Consultant Team

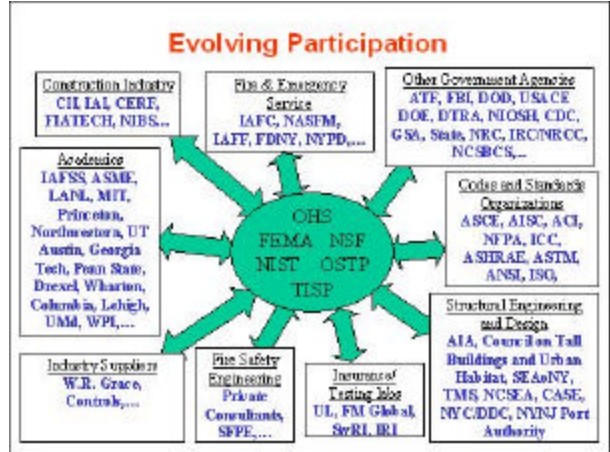
**I. National Building and Fire Safety Investigation of the World Trade Center Disaster (\$15.4 M)**

**Goal:**  
To investigate the building construction, the integrity of the materials used, and the technical conditions that contributed to cause the disaster.

**Objectives:**

- Determine the quality of work on the buildings, WTC 1 and 2, and possibly WTC 2, collapsed.
- Determine the impact and initial cause of the disaster, including all technical aspects of the problem, fire, explosion, structural, and occupant behavior and emergency response.
- Determine whether WTC construction procedures and standards were used in the design, construction, operation, and maintenance of the WTC buildings as the factors related to the collapse of the buildings and associated injuries and fatalities.
- Determine whether there are new technologies/procedures emerging that could be used or adopted in the future to reduce the potential risk on structures and associated injuries and fatalities.

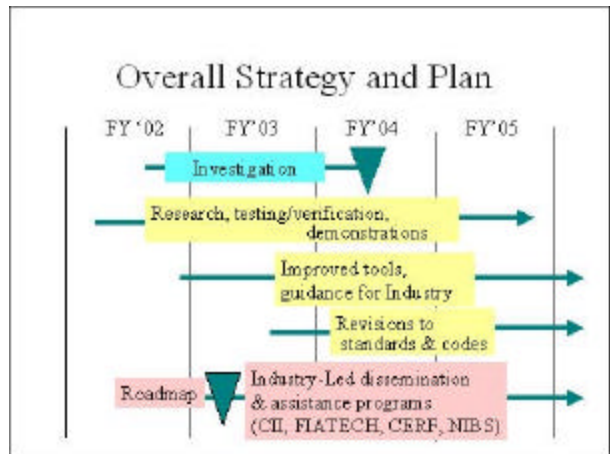
**What/When:**  
NIST Technical Report, to be released within...



**Response Plan - Overview**

- I. National Building and Fire Safety Investigation of the World Trade Center Disaster
- II. Structural Fire Protection
- III. Human Behavior, Emergency response & Mobility
- IV. Building Vulnerability Reduction
- V. National Construction and Infrastructure Roadmap and Support

National Construction Safety Board









### IV. Building Vulnerability Reduction \$7.8 M

- Standard information models
- Guidelines, advanced technology for Chem, Bio, Rad. attacks
- Cost-effective risk management tools

**Partners:** IN, FIATTECH, ASHRAE, GSA, DOD, State Department, GSA, Wharton, NSF, CII, NOBSCS,...

### V. National Construction and Infrastructure Roadmap and Support \$6.0 M

**Concept:**

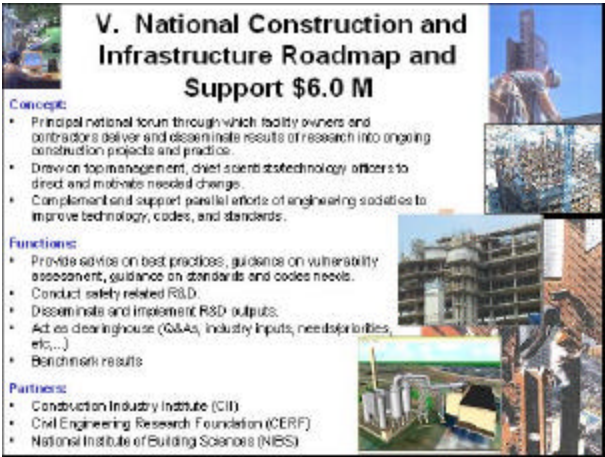
- Principal national forum through which facility owners and contractors deliver and disseminate results of research into ongoing construction projects and practices.
- Drive on top management, chief scientist/technology officers to direct and motivate needed change.
- Complement and support parallel efforts of engineering societies to improve technology, codes, and standards.

**Functions:**

- Provide advice on best practices, guidance on vulnerability assessment, guidance on standards and codes needs.
- Conduct safety related R&D.
- Disseminate and implement R&D outputs.
- Act as clearinghouse (Q&As, industry inputs, needs/priorities, etc...)
- Benchmark results

**Partners:**

- Construction Industry Institute (CII)
- Civil Engineering Research Foundation (CERF)
- National Institute of Building Sciences (NBS)



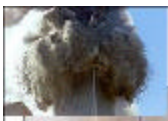

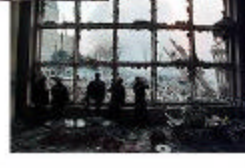

### Outputs and Impacts

**Outputs:**

- Authoritative answers
- Practical/best practices guidance in near term
- Applications of cost-effective state-of-the-art and advanced technologies in mid term
- Revisions to standards and codes

**Impacts:**

- Reduced vulnerability - saved lives & costs
- Speedier economic recovery and renewed growth

B. Goals of Workshop  
 William Grosshandler, Chief, Fire Research Division  
 Building and Fire Research Laboratory, NIST

**FIRE RESISTANCE DETERMINATION & PERFORMANCE PREDICTION**

**Vision:** A rational balance of competing demands for function, aesthetics, fire safety and economy in tall buildings

- enabled by scientifically-based performance predictions, and
- endorsed by all major stakeholders.

**Time Horizon:** Ten years

**FIRE RESISTANCE DETERMINATION & PERFORMANCE PREDICTION**

**Developments needed to achieve vision:**

- Validated tools (*instrumentation, computational methods, measurement techniques*) necessary to predict performance of *building materials, products, structural elements, and systems* up to the point of imminent fire-caused collapse of tall buildings

**FIRE RESISTANCE DETERMINATION & PERFORMANCE PREDICTION**

**Objectives of Workshop:**

- Review current practices for achieving fire resistance.
- Explore promise of fire dynamics simulations and structural behavior predictions.
- Identify opportunities in materials science.
- Identify opportunities/needs in advanced computational methods; and for new measurement, instrumentation, and test methods.

**WHAT IS WITHIN OUR CHARTER?**

**WHAT IS OUTSIDE OUR CHARTER?**

- Buildings less than ten stories tall
- Industrial facilities
- Impact damage
- Blast protection
- Progressive collapse not initiated by fire
- Incremental improvements to current codes and standards

## WORKSHOP PRODUCTS

- Report summarizing objectives and general consensus on priority, approach, funding options and associated timelines, and required follow-on actions
- Roadmap to streamline implementation of research results into international product standards, fire codes, and construction practices



## WORKSHOP MECHANICS (1/2)

Invited presentations, with comments and discussion throughout (Tuesday morning and afternoon)

- overview of fire protection designs
- fire modeling
- fire resistant materials
- structural modeling

Lunch breaks: NIST cafeteria

Concur on vision and begin parallel break-out sessions (Tuesday, late afternoon) (Bill Pitts, LR-B; John Gross, B111; Ed Garboczi, B113)



## WORKSHOP MECHANICS (2/2)

Dinner, informal discussion (7 pm):  
Mrs. O'Leary's, 555 Quince Orchard Rd.

Parallel break-out sessions (Wednesday morning)  
(Bill Pitts, LR-D; John Gross, B111; Ed Garboczi, B113)

Report out (spokepersons)

Discussion among all participants, leading to recommendations and assignments

Adjourn (4 pm Wednesday)



C. Overview of Designing Buildings for Fire Resistance  
 Craig Beyler and Philip DiNenno  
 Hughes Associates, Baltimore, MD

## Overview of Designing Building for Fire Resistance

Philip DiNenno  
 Craig Beyler  
 Hughes Associates, Inc.  
 Presented at NIST Workshop  
 Research Needs for Fire Resistance Determination  
 And Performance Prediction  
 February 19, 2002

## Overview

- Brief History
- Current Status
- Current Role in Fire Safety
- Current Status
- Status Circa 1965-1970
- Needs for Science Based Structural F.P.

## History

- 1890 ■ Denver – 1st fire endurance tests (floors)
- 1896 ■ NYC Bldg. Dept Floor system
  - 2000° F (1093°C), 5 hours
  - 150 lb/ft<sup>2</sup> → 600 lb/ft<sup>2</sup> (24 hrs)
  - Led to requirements in NYC BC
- 1902 ■ Columbia U Furnace

## History

- 1906 ■ ASTM — Committee after Balt. fire
  - 1700°F, 150 lb/ft<sup>2</sup> — 600 lb/ft<sup>2</sup>
- 1908-1909 ■ 1<sup>st</sup> ASTM Standards
- 1910 ■ FM, NBFU, NIST > furnaces At UL
- 1917 ■ Column Test

## History

- 1918 ■ ASTM C-5
  - Floor and Wall
  - Time related end points (temp and mech)
  - Test for 25% Safety Factor wrt. time
  - Standard TTC
- 1922 ■ NBS/INGBERG – Fuel Load & Fire Resistance Time equivalency
  - Fuel Load- Fire resistance time “Equivalence”

## Role of Fire Resistance in Fire Safety

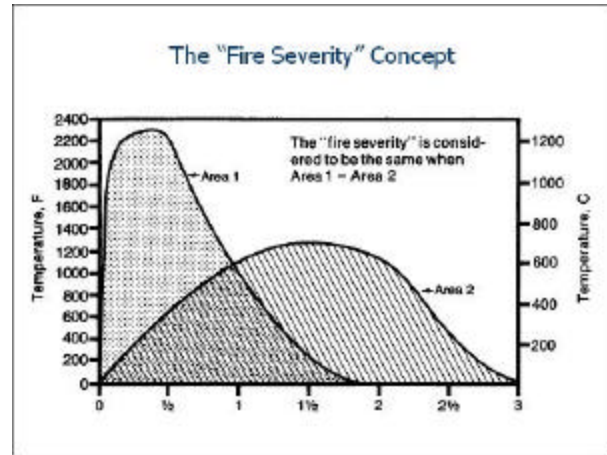
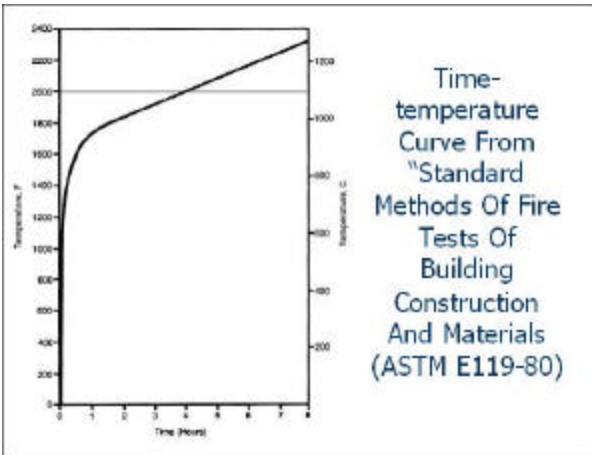
- Prevent Building Collapse
- Prevent External Spread
- Vertical/Horizontal Fire Spread
- Means of Egress
- Smoke Control
- Firefighter Safety

## Current Status

- Fire Resistance Requirement
- Established by building code – function of
  - Occupancy
  - Height/area
  - Sprinkler protection
- Testing per UL, NFPA, ASTM
- Listing by UL, FM et al
- Find requirement in hours
- Look it up in a listing book
- Spec it
- Maybe Inspect it

## Current

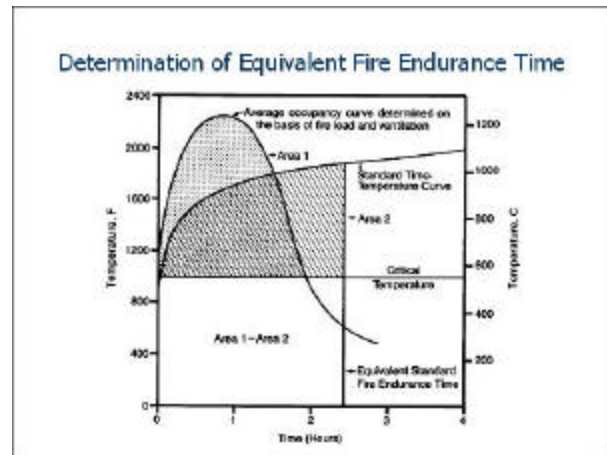
- Fire Exposure
  - Standard Time Temp Curve (since 1910) in force
- Thermal Response
  - Temperature Measured from Sample
- Mechanical
  - If loaded, don't open or collapse
  - No cracks, lint or delamination
  - No connections
- Physical Properties
  - Adhesion, cohesion
  - No delamination, spalling, chipping, cracking, etc. testing
- Reliability
  - Unknown and variable
  - Implicitly treated through listing approval
- In-situ Testing
  - Done in small % of cases
  - Usually where problem is obvious

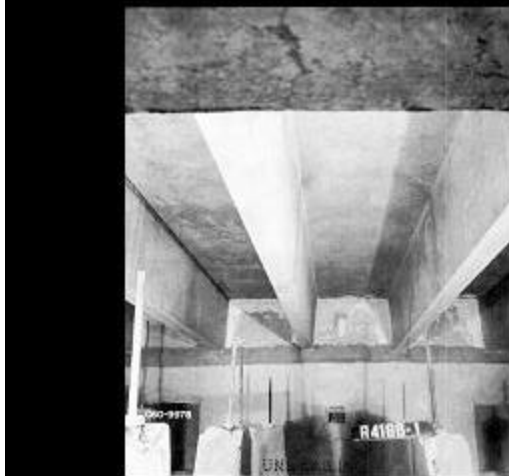


### Relationship Between Fire Load and Fire Endurance

Average Fire Load psf <sup>a</sup>	kg/m <sup>2</sup>	Equivalent Fire Endurance (hours)
5	24.4	1/2
7 1/2	36.6	3/4
10	48.8	1
15	73.2	1 1/2
20	97.6	2
30	146.5	3
40	195.3	4 1/2
50	244.1	6
60	292.9	7 1/2

<sup>a</sup> Determined on the basis of a potential heat of approximately 8000 Btu/s per pound

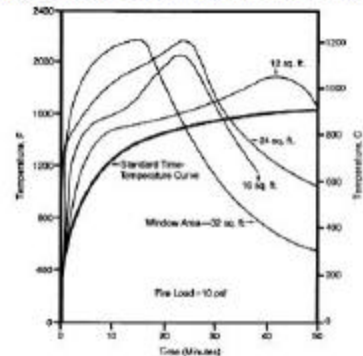




## Materials/Systems Currently Used

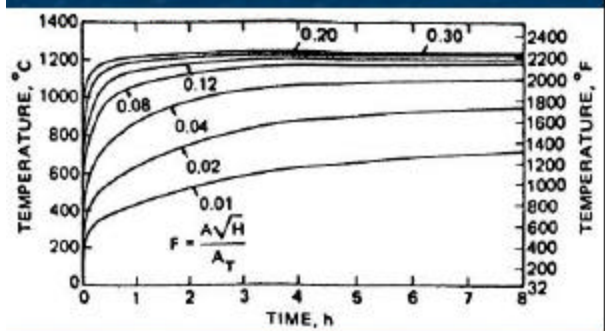
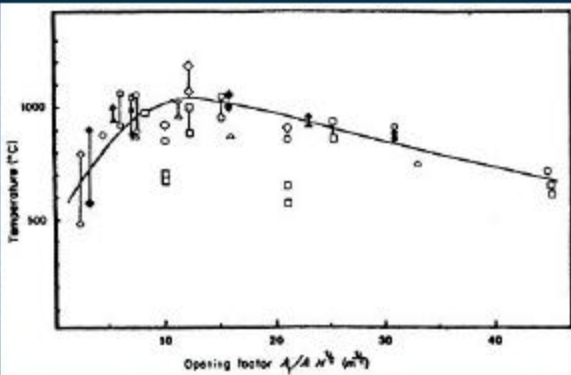
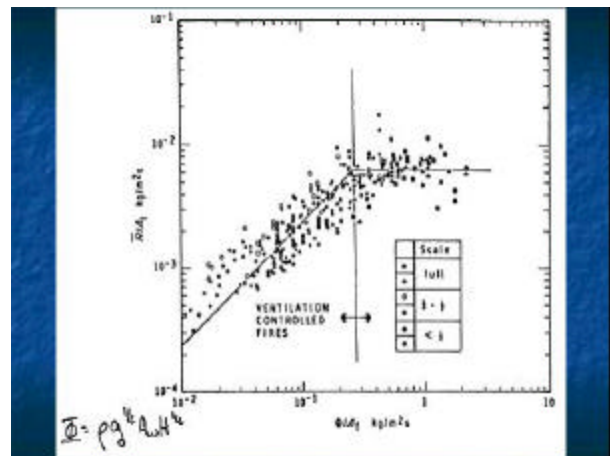
- Sprayed Fiber
- Cementitious
- Mastic
- Intumescent Paint
- Membrane
  - Suspended ceilings
  - Drywall assemblies
- Concrete encasement
- Tile
- Plaster/loft

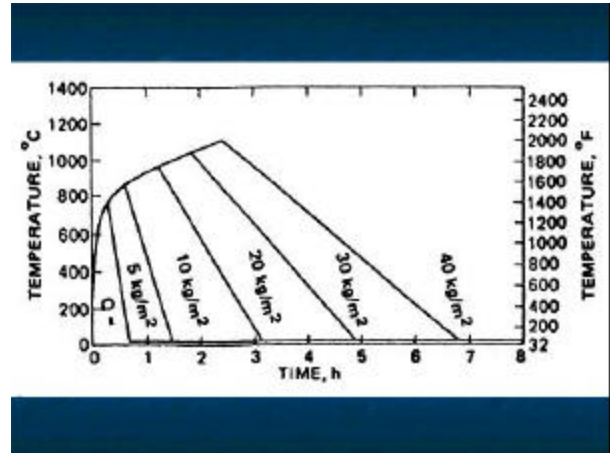
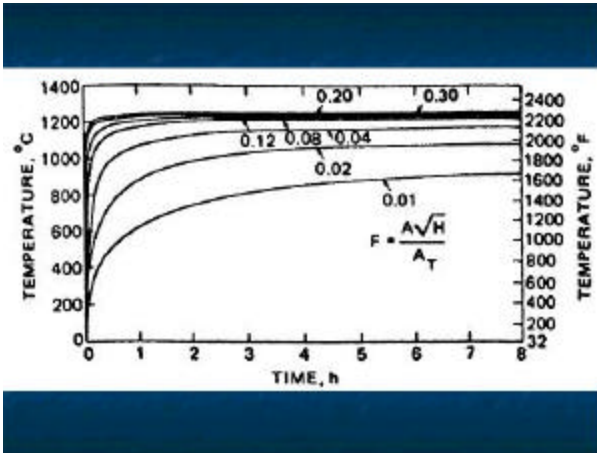
## Effect of Window Area on Fire Temperatures During Burnout Tests with Natural Ventilation



## State of Art (circa 1965–1975)

- Fire Exposure
  - Design exposure curves
  - Post-flashover
  - Ventilation controlled
  - Insulation properties of wall linings
- Thermal Response
  - Critical temperature
    - Columns, beams
    - 1-D analytical
    - 2-D finite differences schemes





## State of Art (circa 1965–1975)

- Mechanical Response
  - Column buckling
  - Beam deflection
  - Truss deflection
- Physical properties
  - Transport & Mechanical properties as a f(T)

Question: Capability for 30-35 years... Integrated into design guides and never utilized in US regulations

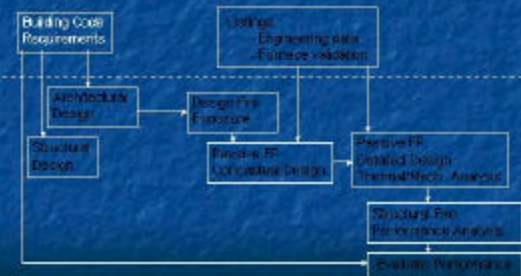
## 1975-1980

- 3-D Finite Element Heat Transfer Model
- Structural Response Model (FASBUS)
- Model of Post Flashover Fires (COMPFF)

## Needs for Science-Based Structural Fire Protection Design

- Design fire exposure
- Thermal/Mechanical Response of Insulation Systems
- Structural Performance in Fire
- Test methods
- Performance Criteria
- Technology Transfer

## Science-Based Structural Fire Protection Design





## Design Fire Exposure

- Modern fire load survey data
- Combined local/global fire exposure characterization, i.e. beyond well stirred

## Thermal/Mechanical Response of Insulation Systems

- Institutionalized thermal properties test methods
- Test methods and performance criteria for mechanical response; non-fire, impact loading, fire exposure
- Fire barrier performance- must address along with structural frame performance

## Structural Performance in Fire

- Assess needs for full structural frame analysis vs more detailed local deformation analysis
- Assessment of connection performance

## Test Methods

- Need full compliment of test methods for engineering properties
- Revisit furnace testing methods:
  - exposure should be severe (1709)
  - test should be a validation of engineering methods
  - revisit the relationship between the test and real structural frames

## Performance Criteria

- What are we trying to achieve?
- Acceptable local performance
- Acceptable global performance
- Risk, reliability, and relationship to the total fire protection design
- Inspection, Testing, and Maintenance (ITM)

## Technology Transfer "The Real Problem"

- Develop a broad consensus for the need to change how we do SFP
- Codify SFP design practice
- Formulate building code requirements
- Educate engineers, architects, AHJ's

## Needs for Science-Based Structural Fire Protection Design

- Design fire exposure
- Thermal/Mechanical Response of Insulation Systems
- Structural Performance in Fire
- Test methods
- Performance Criteria
- Technology Transfer

## Summary

- Science-based structural fire protection is clearly technically achievable
- It will require a total reexamination of the SFP process from listing, to design, to ITM
- The payoff? - known, cost effective performance and safety

D. ASCE/SFPE Standard on Performance-based Structural Fire Protection Analyses  
 James Milke, Department of Fire Protection Engineering  
 University of Maryland, College Park, MD


**ASCE/SFPE STANDARD ON PERFORMANCE-BASED STRUCTURAL FIRE PROTECTION ANALYSES**  
*RESEARCH NEEDS FOR FIRE RESISTANCE DETERMINATION AND PERFORMANCE PREDICTION*

Jim Milke, Ph.D., P.E.  
 Department of Fire Protection Engineering



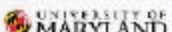
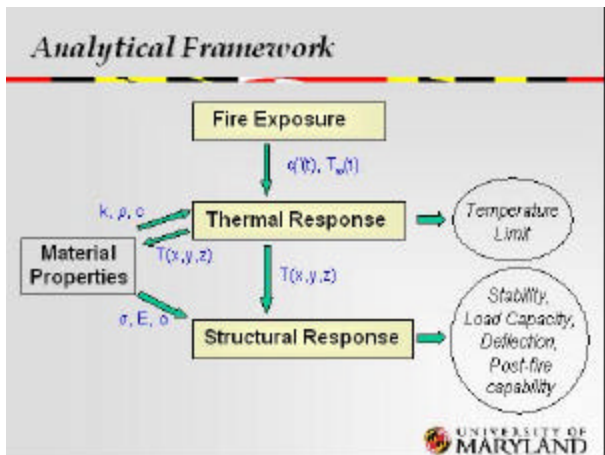
**Scope and Motivation**

- ❖ **Motivation**
  - The current test procedure is a comparative test and is not easily related to actual fire performance
- ❖ **Scope**
  - Develop standard outlining calculation procedures to assess performance of structures to actual fires



**Status**

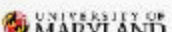
- ❖ **Status: Pre-standard developed:**
  - ASCE/Structural Engineering Institute
  - SFPE
  - AISI
  - Several industries within the concrete sector
  - Masonry Alliance for Codes and Standards
  - AFPA
- ❖ **Pre-standard distributed to committee in summer 2001**

**Organization of Pre-Standard**


- ❖ Fire Exposure
- ❖ Concrete
- ❖ Masonry
- ❖ Steel

Material properties  
 Thermal response  
 Structural response



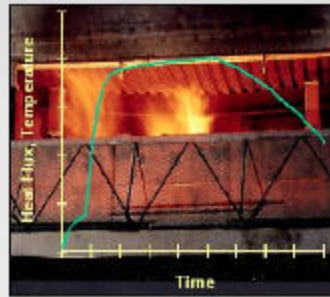
**Structural Analysis Approaches**

	Individual Members	Portions of the Structure	Global
Simple Computations	+		
Advanced Computations	+	+	+
Experiments	+	+	+

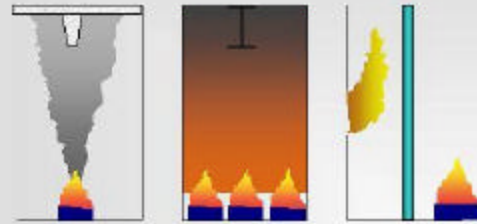


## Fire Exposure

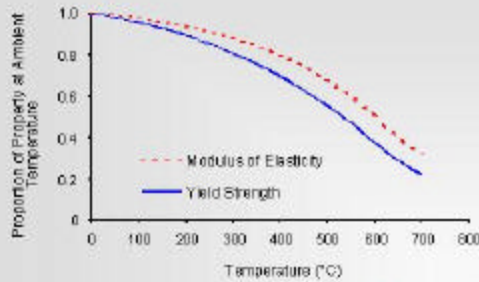
- ❖ Describe heating conditions
  - Heat flux vs. time
  - Temperature with radiative and convective parameters vs. time
- ❖ Methods: algebraic equations, computer models



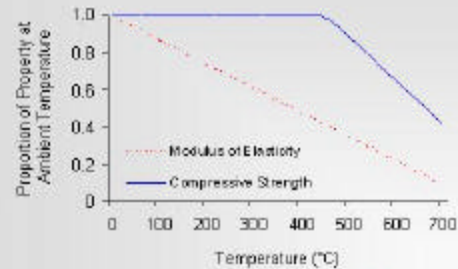
## Fire Scenarios



## Mechanical Properties - Steel

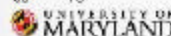
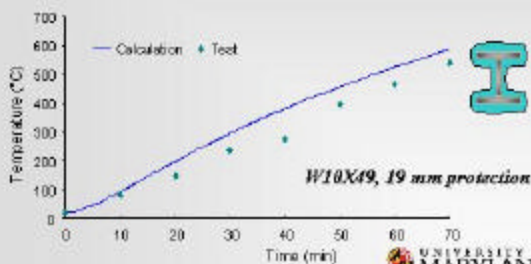


## Mechanical Properties - Concrete



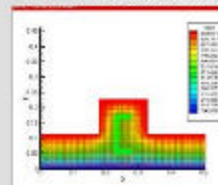
## Thermal Response

- ❖ Algebraic equations: *uniform temperature of steel member exposed to any fire*



## Thermal Response

- ❖ Computer analyses: 1-, 2-, or 3-D Temp. Distribution
  - Variable exposure
  - Complex geometry
    - composite floor assembly
    - wall with voids
    - asymmetric or partially protected members

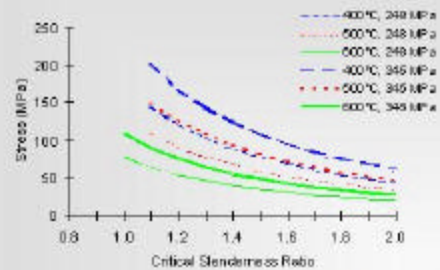


## Structural Response

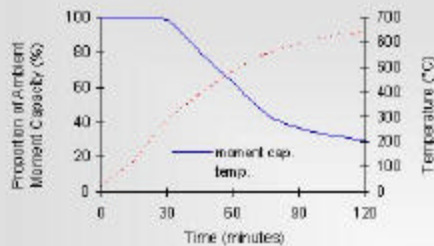
- ❖ 1<sup>st</sup> order analysis; single member analysis using elementary equations
  - Column stability of isothermal element
  - Moment analysis of slab/beam
  - Apply temperature-dependent material properties
- ❖ Computer models
  - Temperature distribution
  - Variable cross-section
  - Complex loading
  - Frame analyses



## Steel Column Stability



## Moment Capacity Analysis



150 mm Siliceous Concrete Slab with cover=25 mm,  
Standard fire exposure



## Structural FEM

- ❖ CEFICOSS (SAFIR)
  - ❖ CONFIRE
  - ❖ DIANA
  - ❖ FASBUS-II
  - ❖ LENAS-MT
  - ❖ LUSAS
  - ❖ SISMEF
  - ❖ VULCAN
- ❖ Input
    - Temp. distribution
    - Strength, modulus, coefficient of thermal expansion, creep
    - Load
    - End conditions
  - ❖ Output: stresses, strains, deflections



## Summary

- ❖ A framework and analytical methods are available to predict the effect of fire on structural components
- ❖ Methods are applicable to
  - beams, columns, slabs, walls
  - assemblies comprised of concrete, steel, timber, advanced composites, gypsum, protective materials...



## Summary

- ❖ **Experimental data is required to:**
  - Determine material properties at elevated temperatures (via standard test methods?)
  - Characterize material behavior: cracking, adherence, charring and spalling
  - Calibrate models
  - Examine interactions between
    - Components of building assemblies
    - Adjacent building assemblies (as part of structural frame)



E. Simulation of Accidental Fires and Explosions  
 Adel Sarofim and Philip Smith, Department of Chemical Engineering  
 University of Utah, Salt Lake City, UT

**Center for the Simulation of  
 Accidental Fires and Explosions**

Adel F. Sarofim and Philip J. Smith  
 Department of Chemical and Fuels Engineering  
 University of Utah

Workshop on  
**RESEARCH NEEDS FOR FIRE RESISTANCE  
 DETERMINATION AND PERFORMANCE  
 PREDICTION**

NIST Gaithersburg  
 February 19, 2002



**OUTLINE**

- Background on C-SAFE
  - What is C-SAFE?
  - Relevance to Workshop
    - Interdisciplinary
    - Large Scale Simulations
    - Multi-phase, Multi-scale
- Vignettes
  - Computational Chemistry
  - Fire Spread
  - Material Point Methods
- Lessons Learned
  - Keys to success
  - Problem areas
- Conclusions



**ASCI & C-SAFE**

The Accelerated Strategic Computing Initiative (ASCI) Alliances have been set up to develop unclassified simulation codes in support of the DCE Defense Program Laboratory mission to safeguard the U.S. nuclear stockpile. Five universities have been funded as part of the ASCI alliance:

- Stanford University*: development of technology suitable for the design of gas turbine engines
- California Institute of Technology*: shock waves induced by high explosives on various materials in different phases
- University of Chicago*: long-standing problem of astrophysical thermonuclear flashes
- University of Utah*: science-based tools for numerical simulation of accidental fires and explosions, within the context of handling and storing highly flammable material (C-SAFE's project)
- University of Illinois*: whole-system simulation of solid propellant rockets under both normal and abnormal operating conditions



**Specific Focus**



**Hydrocarbon Fire**

- Arbitrary Size
- Includes soot

**Container**

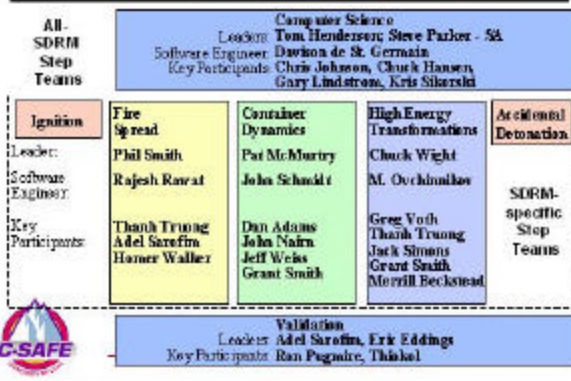
- Metal construction
- Arbitrary size/shape
- Arbitrary location

**HF Material**

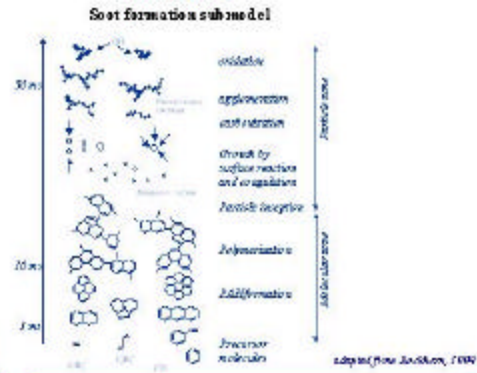
- PBX 9501



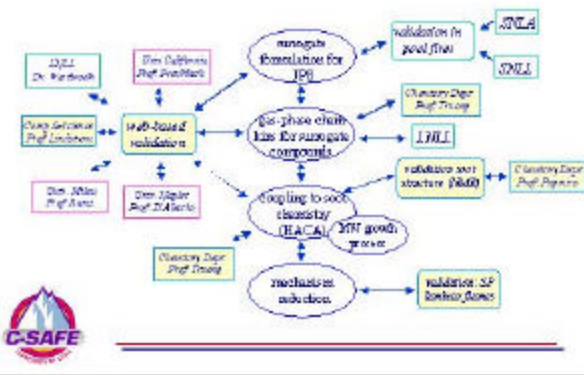
**C-SAFE Team Structure**



**Firespread**

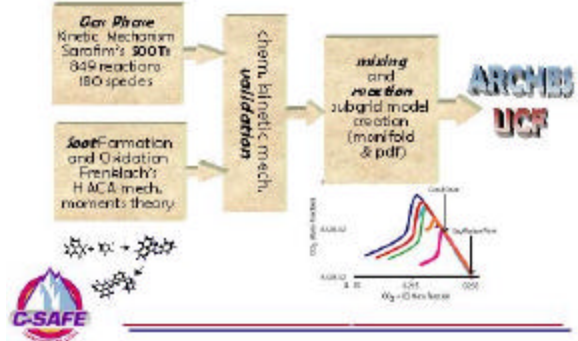


### Present Collaborations and Linkages



### Chemistry / Mixing & Fire

bridging micro to macro scales in fire simulations



### Example: buoyancy driven flames (10m heptane pool fire)

- resolutions 150<sup>3</sup>
- domain: (50m)<sup>3</sup>
- 500 processors
- 18 hrs on Nirvana (LANL)
- 6B2B time steps

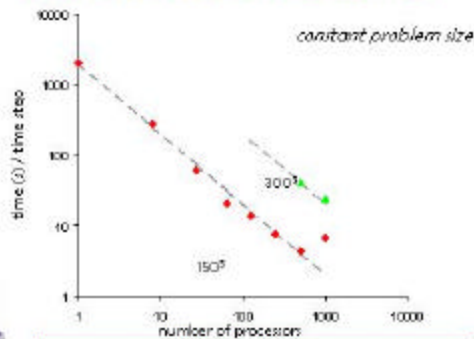


### Jet-Fuel Pool Fire Testing



Jet-Fuel pool fire experiments are conducted for comparison with detailed computer models being developed in the Center for Simulation of Industrial Fires and Explosions at the University of Utah

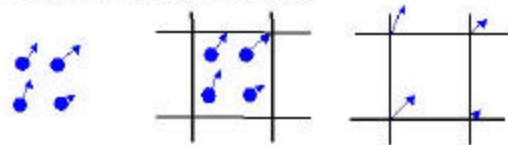
### Multiprocessor Scalability



### Container Dynamics

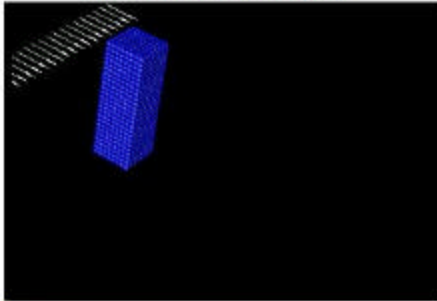
The Material Point Method (MPM)

Explicit Algorithm (Sulsky et al., 1994)



## MPM Demonstration

Flexible beam in a crossflow



## HIGH ENERGY MATERIALS

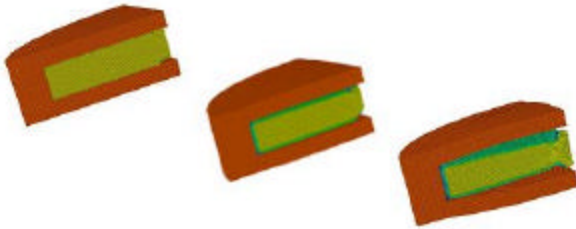
Container/PBX Heating Response Simulation

Container: Steel  
 bulk modulus: 200e9 Pa  
 shear modulus: 77.8e9 Pa  
 yield stress: 250e6 Pa  
 hardening modulus: 77e7 Pa  
 OD: 0.03136 m  
 ID: 0.02498 m  
 Thickness: 0.0016 m  
 Contents: PBX – ViscoScram  
 Center hole: 0.0032 m  
 Burn Model: HE Team, rate =  $Akp^n$   
 Initial Temperature: PBX, 300K  
 Specified heat flux at container surface

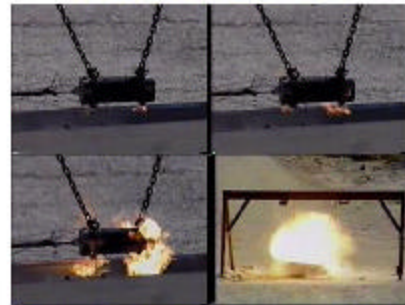


## Container/PBX Heating Response Simulation

Mass evolution:



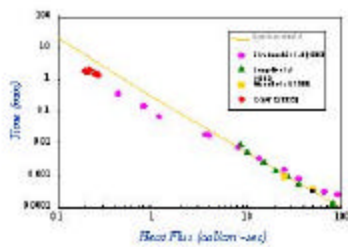
## Images from Propane-Fired Fast-Cook Off Test



(a), (b) and (c) Release of pyrolysis gases, (d) Explosion



Time to Explosion Correlates with Heat Flux  
 (Inferred from T-t using Duhammel Superposition)



## Container Remnants

Electrical Input:

110 V - 19  $\text{kW/m}^2$

Time to Explosion:

26 min

Electrical Input:

220 V - 83  $\text{kW/m}^2$

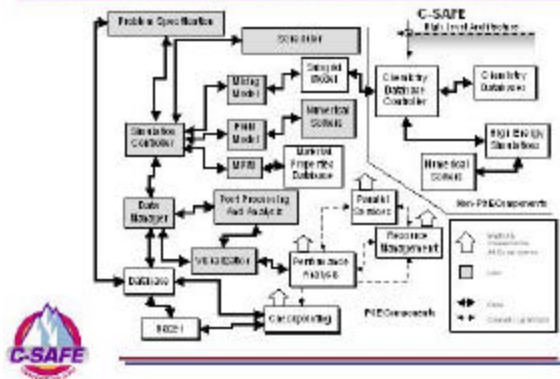
Time to Explosion:

3 min





## Uintah Computational Framework



## Keys to Success

- Well defined goals
- Management Committee chaired by Dave Pershing to provide
  - priorities,
  - timetable,
  - resource allocation,
  - conflict resolution
- Designation of software engineer for each step to work with the computer scientists on
  - Algorithms development
  - Common computer architecture
  - Problem solving environment
  - Parallelization, Visualization
- Networking with the DOE laboratories and with national and other discipline experts
- Tie in with experimental programs for validation



## Problem Areas

- Interfaces
  - Between phases
- Communication
  - Between disciplines
  - With ultimate user
- Data
  - Communication
  - Storage
  - Mining



## Conclusions

- Crosscutting Issues need Interdisciplinary Approaches
  - C-SAFE experience underlines importance of close collaboration between software engineers and computer scientists
  - 'Amphibians' needed to bridge gaps between disciplines
  - Importance of communication cannot be overstated (GBS: "The greatest myth about communication is the mistaken belief that it has taken place.")
- Major Advances in Simulation Science
  - Computational chemistry for properties, mechanisms, kinetics
  - More detailed kinetic and fluid mechanics models can be included in massively parallel computations
  - Material point methods show promise for handling large deformations and break up of structures
  - Experimental validation and guidance is crucial



?? Defining the building

- Generating electronic databases
- HVAC systems, stairways, and elevators

?? Burning the office environment


- Furniture and other non-planar items
- Libraries and paper files

?? Fire induced geometry changes

- Window breaking
- Warping of partitions

# G. Simulation of Cardington Fire Tests


Asif Usmani,  
University of Edinburgh, UK



School of Civil & Environmental Engineering  
**STRUCTURES AND FIRE RESEARCH INSTITUTE**  
111 Rankine Rd Drysdale, BP Sials, J Torrie, AS Usmani, Paulraj, M Gillie

## Computational Modelling of the Cardington fire tests

AS Usmani  
coworkers: S Lamont, M Gillie, AM Sanad, M O' Connor, JM Rotter, DD Drysdale, B Lane  
University of Edinburgh, Scotland, UK  
Corus Plc, Ove-Arup & Partners




DEPARTMENT OF STRUCTURAL ENGINEERING, 200  
111 Rankine Road, Drysdale, BP Sials, J Torrie, AS Usmani, Paulraj, M Gillie

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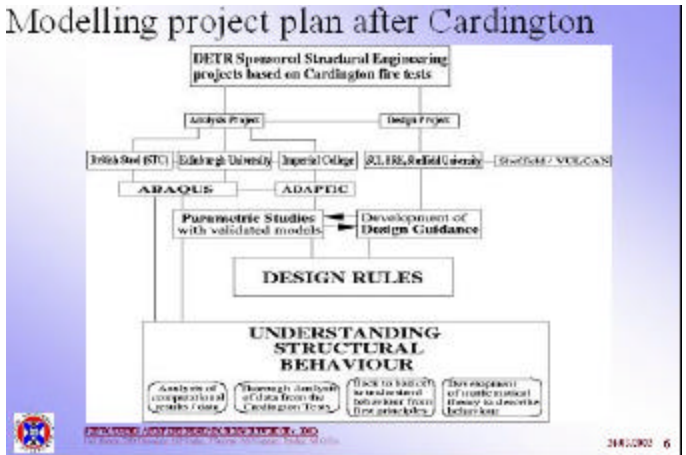
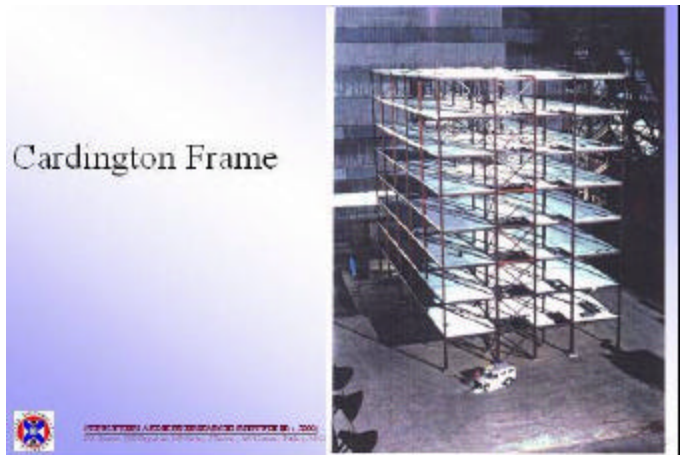
## Background

- ◆ Events showed structural design for fire as overly conservative
- ◆ Cardington tests carried out to address primarily this, and to
  - ◆ improve understanding of structural behaviour
  - ◆ produce data for validating computer models
  - ◆ eventually help develop more rational design methods
  - ◆ reduce cost of steel fire protection and sell more steel!
- ◆ Move on from the entrenched poor practice! standard fire test



DEPARTMENT OF STRUCTURAL ENGINEERING, 200  
111 Rankine Road, Drysdale, BP Sials, J Torrie, AS Usmani, Paulraj, M Gillie

23-01-2002 2



## Key equation

$$\epsilon_{\text{total}} = \epsilon_{\text{thermal}} + \epsilon_{\text{mechanical}}$$

$\epsilon_{\text{total}} \Rightarrow$  Displacements

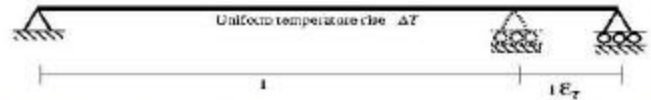
$\epsilon_{\text{mechanical}} \Rightarrow$  Stresses



## Thermal expansion

$$\epsilon_{\text{thermal}} \Rightarrow \epsilon_T = \alpha \Delta T$$

### Unrestrained thermal expansion



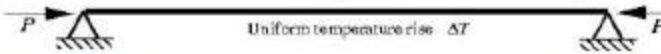
$$\epsilon_{\text{total}} = \epsilon_T = \epsilon_T = \alpha \Delta T$$

$$\epsilon_{\text{mechanical}} = \epsilon_m = 0$$



## Thermal expansion

### Restrained thermal expansion: Pre-buckling



$$\epsilon_t = \epsilon_T + \epsilon_m = 0$$

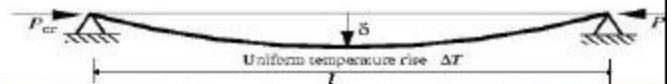
$$\epsilon_m = -\epsilon_T$$

$$P = EA \epsilon_m = -EA \epsilon_T = -EA \alpha \Delta T$$



## Thermal expansion

### Buckling due to restrained thermal expansion



$$P_{cr} = \frac{\pi^2 EI}{l^2}$$

$$EA \alpha \Delta T = \frac{\pi^2 EI}{l^2}$$

$$\Delta T_{cr} = \frac{\pi^2}{\alpha l^2}$$



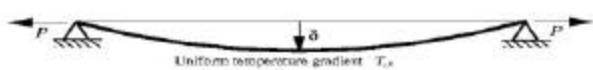
## Thermal bowing

Curvature  $\Rightarrow$   $??T_y$

### Thermal Bowing with ends restrained against rotation



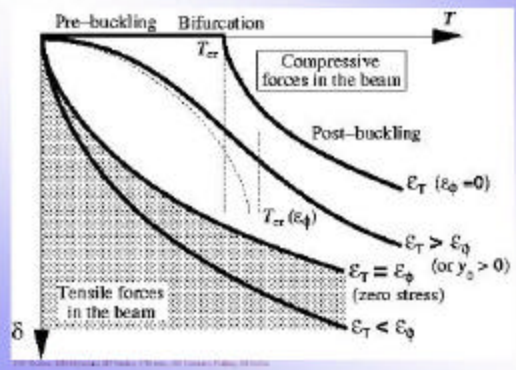
### Thermal Bowing with ends restrained against translation



$$?? ? 1? \frac{\sin \frac{l?}{2}}{\frac{l?}{2}}$$



## Various temperature-deflection responses



## Main principles to interpret model output

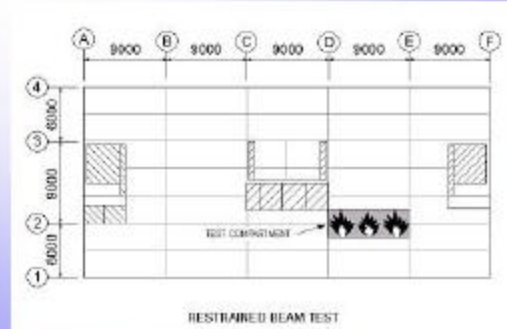
- Fire effect on beams and slabs can adequately be described in terms of mean temperature increment  $\Delta T$  & through depth thermal gradient  $T_z$
- Restraint to lateral translation produces compression (small restraint enough)
- Thermal gradients impose curvature in unrestrained pin ended members
- Gradients induce moment in members with rotationally restrained ends
- Gradients induce tension in pin-ended translationally restrained members
- Combinations of thermal expansion and bowing with various restraint conditions produce a large range of deflection and internal force patterns
- In slabs and other 2D members compatibility of displacements in the two directions may govern internal forces and displacements



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## British Steel Test 1 (Restrained beam test)



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Tel: +44 (0)151 709 2222 Fax: +44 (0)151 709 2223

24/02/2002 24

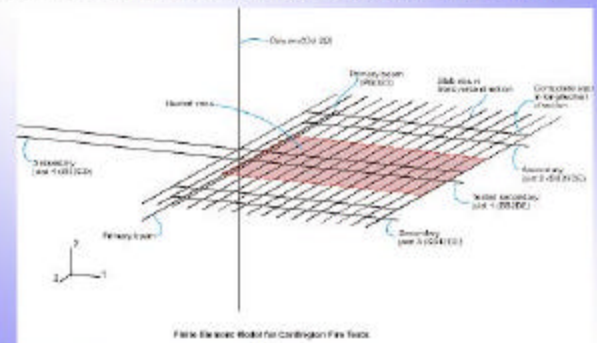
## British Steel Test 1 (Restrained beam test)



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100 Brook Street, Liverpool, L69 3GB, UK  
Tel: +44 (0)151 709 2222 Fax: +44 (0)151 709 2223

24/02/2002 25

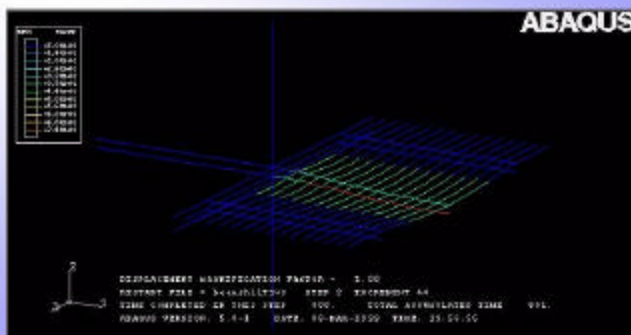
## Grillage model for Restrained beam test



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24/02/2002 26

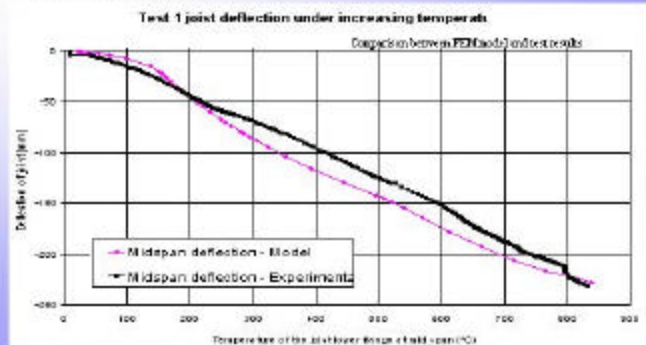
## Deflected model



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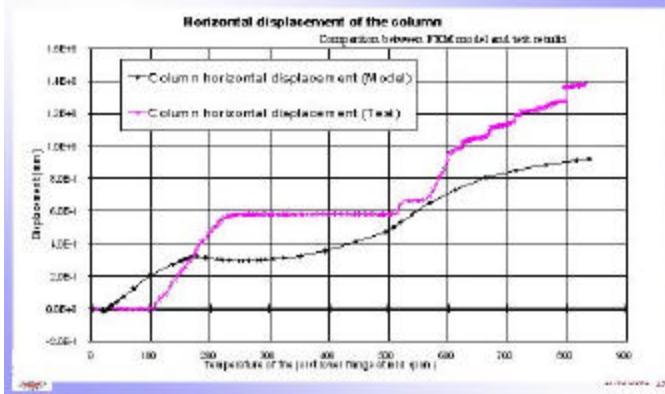
## Deflections



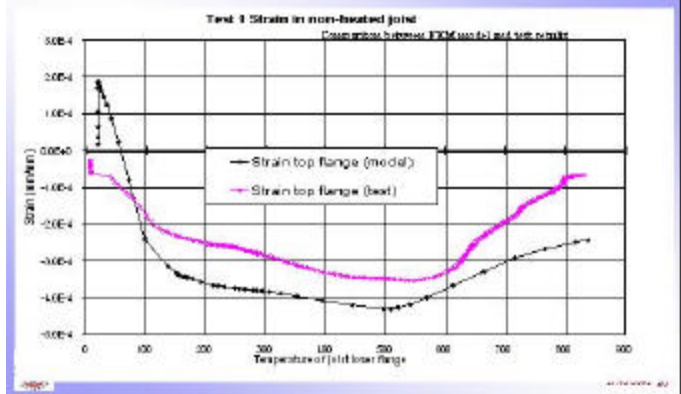
UNIVERSITY OF LIVERPOOL  
100 Brook Street, Liverpool, L69 3GB, UK  
Tel: +44 (0)151 709 2222 Fax: +44 (0)151 709 2223

24/02/2002 28

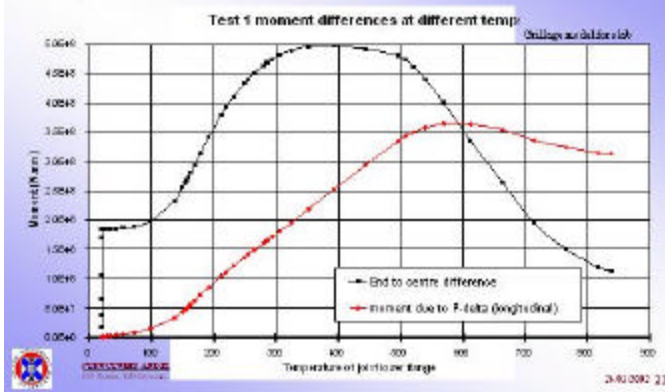
## Column lateral displacement at floor level



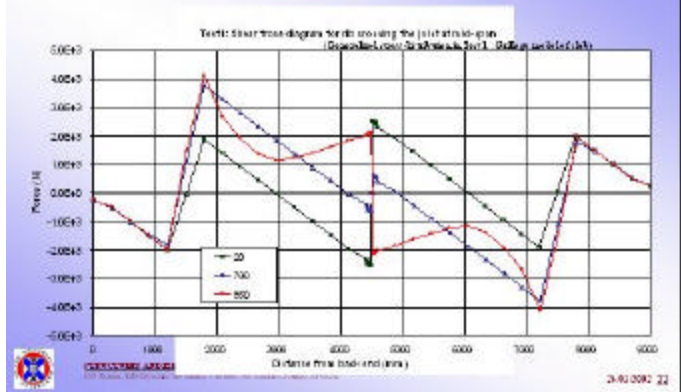
## Strain in the top flange of adjacent beam



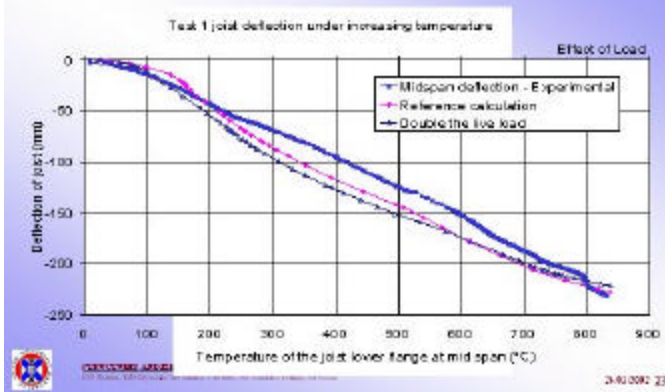
## Composite beam moments during fire



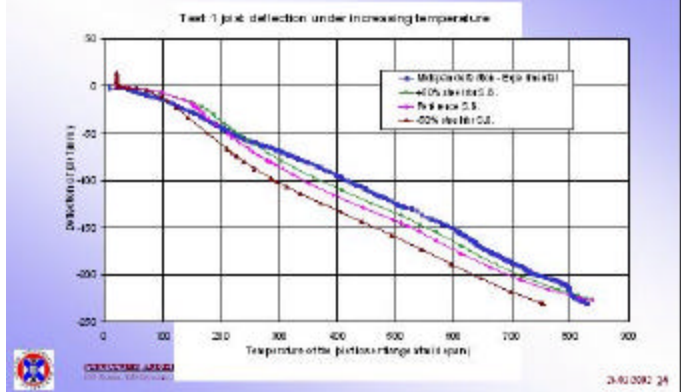
## Slab rib shears during fire



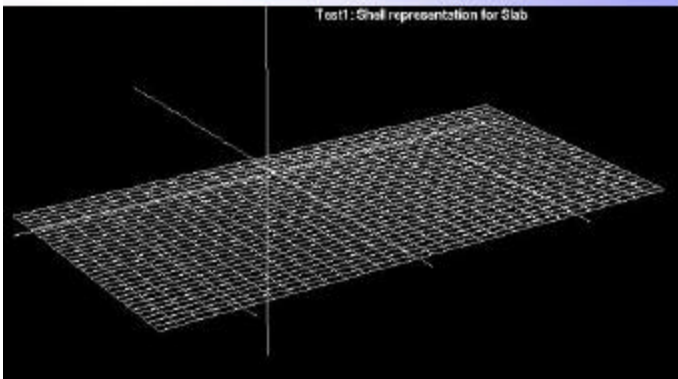
## Effect of live load



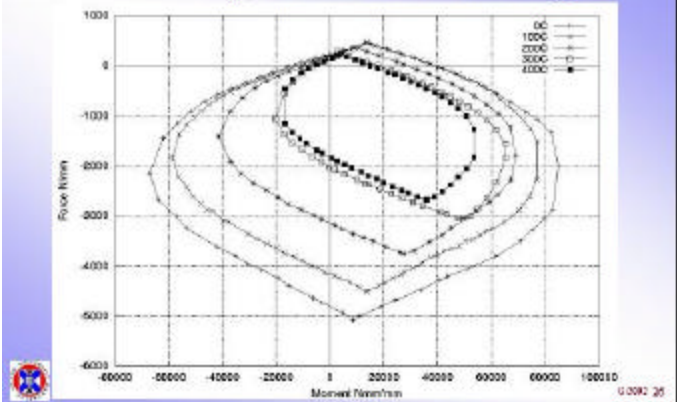
## Effect of steel section size



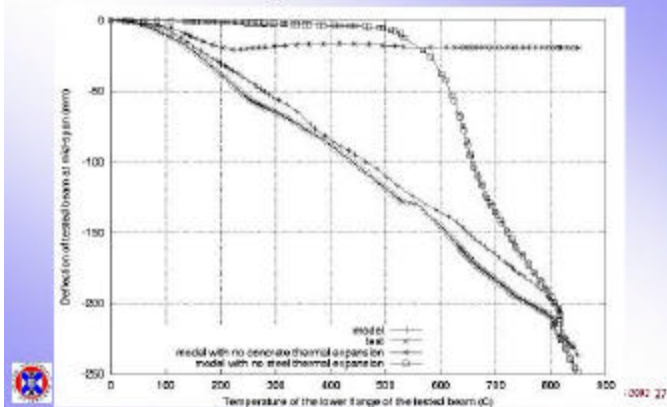
### Gen. stress shell elements for slab (Test1)



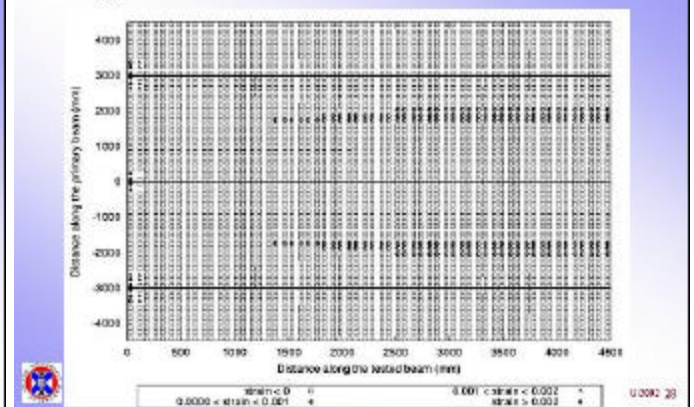
### Model of Cardington concrete deck strength



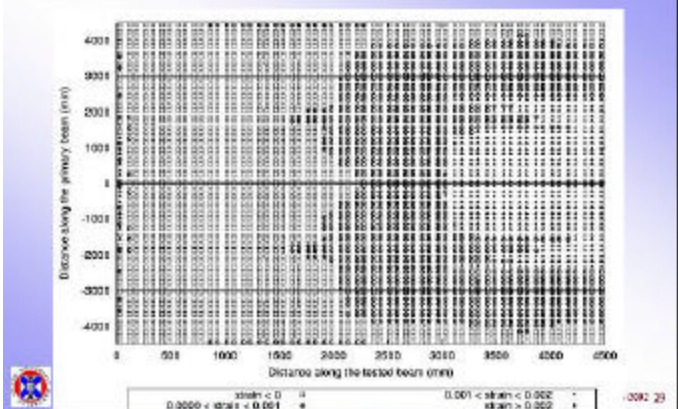
### Deflections from generalised stress shell



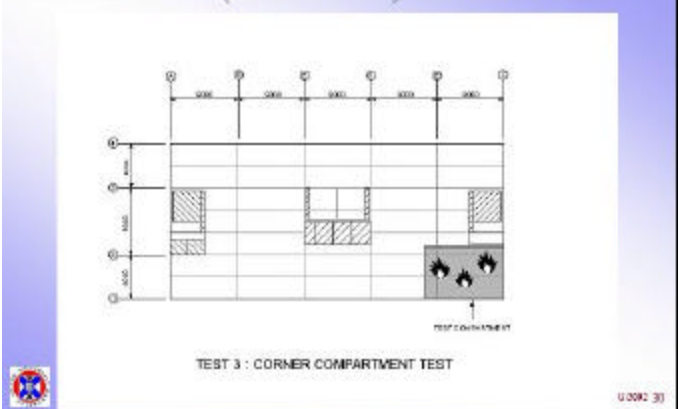
### Longitudinal strains at reinf. level



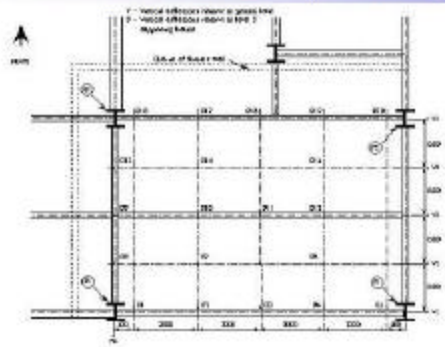
### Transverse strains at reinf. level



### British Steel (now Corus) Corner Test



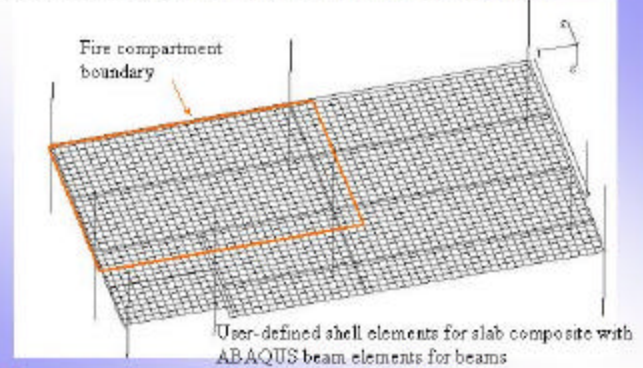
### British Steel Corner Test (structure)



Det 3 - Transverse Position for Measuring Vertical Deflection

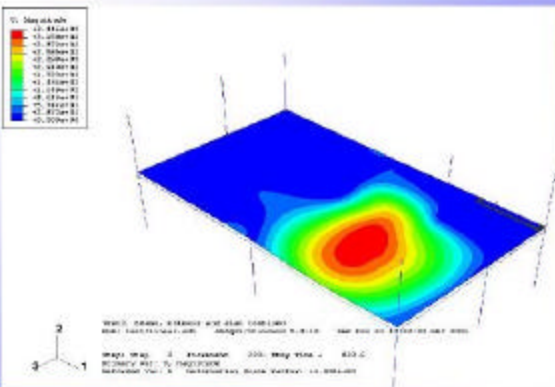
2/31

### British Steel Corner Test - Finite element mesh



CREATING ANALYSIS MODEL FOR B.S. 200

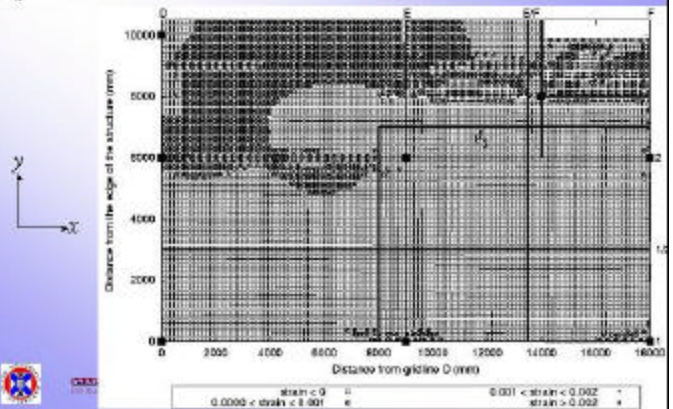
2/4/2002 32



CREATING ANALYSIS MODEL FOR B.S. 200

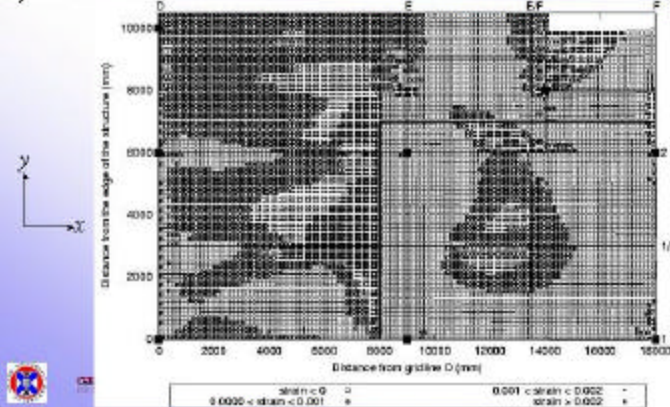
2/4/2002 33

### $\epsilon_x$ distribution at reinforcement level



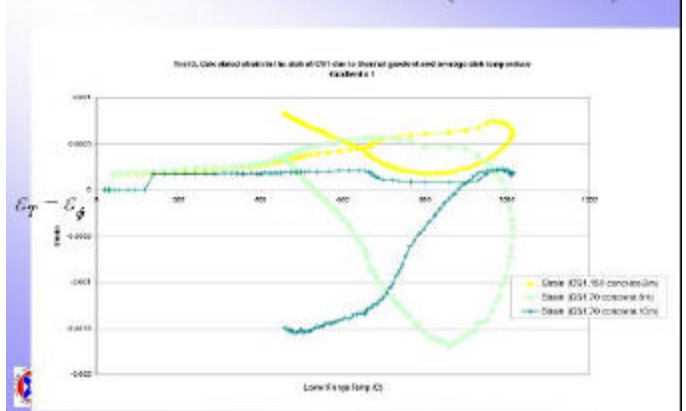
CREATING ANALYSIS MODEL FOR B.S. 200

### $\epsilon_x$ distribution at reinforcement level



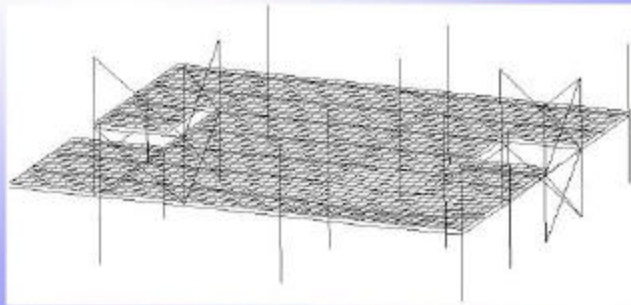
CREATING ANALYSIS MODEL FOR B.S. 200

### Estimated strains in concrete (corner test)





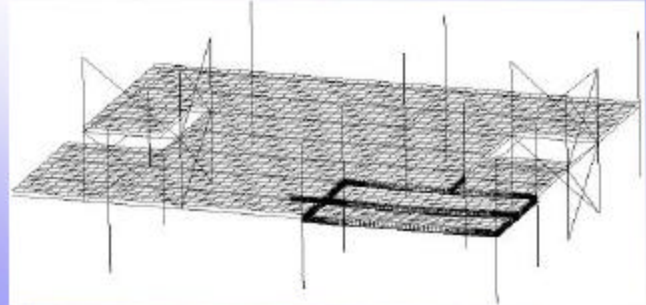
### Elastic shell model



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2/17/02, 00:00 (local) 2/17/02, 0:00 (local) 2/17/02, 0:00 (local)

2/17/02 37

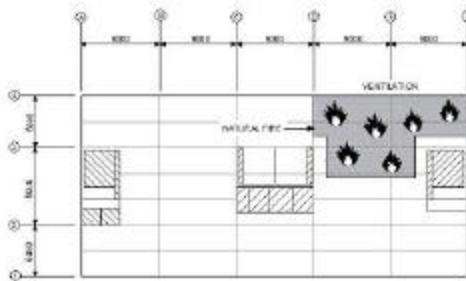
### Elastic shell model with detailed beam modelling



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2/17/02, 00:00 (local) 2/17/02, 0:00 (local) 2/17/02, 0:00 (local)

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### British Steel “Office” Test

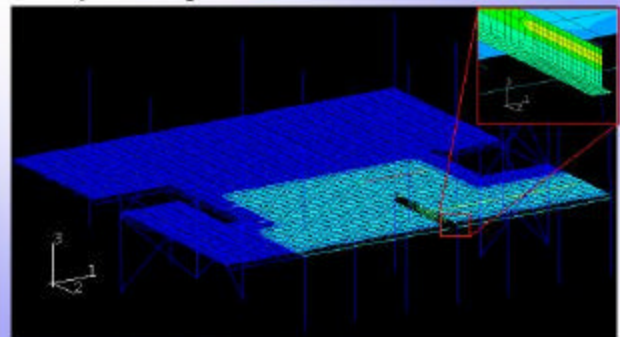


TEST 4 : DEMONSTRATION TEST FIGURE 1



0/2 39

### ABAQUS-Explicit model of “Office Test”



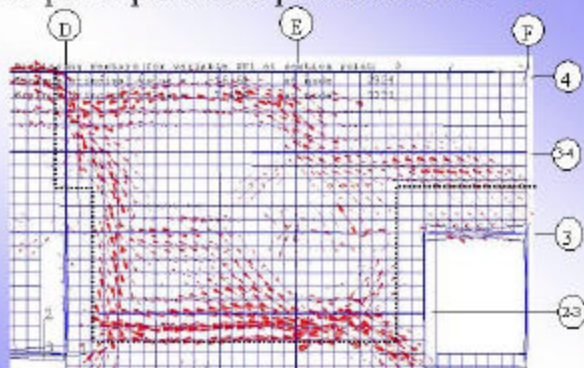
Shown inverted ABAQUS Concrete cracking model using

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Courtesy Corus (STC)

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### Shell principal stress pattern at 1100 °C



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Courtesy Corus (STC)

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### LESSONS

- ◆ Restraint to thermal strains dominates response
- ◆ Conventional loading much less important when restraint is high
- ◆ Response sensitivity to steel strength is low
- ◆ The above will change near failure or collapse, failure not observed in tests of modelling, how far is it?
- ◆ Tensile membrane action (TMA) in the spans and compressive membrane action (CMA) near perimeter observed
- ◆ This load carrying mechanism more reliable in fire, thermal strains help produce the “right shape”
- ◆ Capacity further enhanced by thermal pre-stressing (CMA)

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## FURTHER MODELLING

### ◆ The two key thermal effects governing structural behaviour

- ◆ mean temperature increase  $\Rightarrow$  compression  $\Rightarrow$  long cool fires
- ◆ through depth thermal gradients  $\Rightarrow$  tension  $\Rightarrow$  short hot fires

### ◆ Cardington was a medium size braced frame (high redundancy)

- ◆ What about small frames (low redundancy) and whole floor fires
- ◆ What about very large frames (with large compartments)

### ◆ Tensile membrane force need anchoring at compartment perimeter

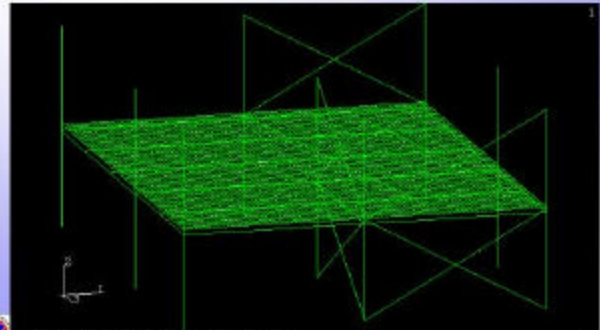
- ◆ Interior continuity can be provided by lapping reinforcement
- ◆ Edge and corner compartments have discontinuous edges



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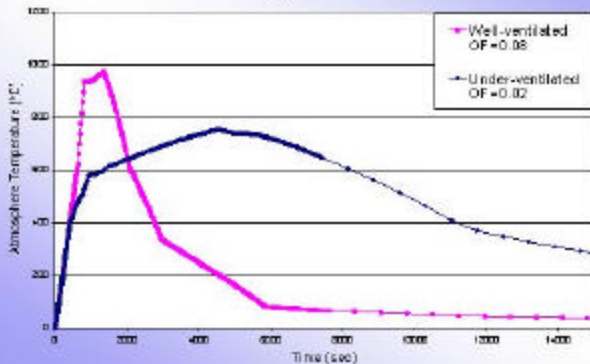
## The 2x2 generic frame mesh



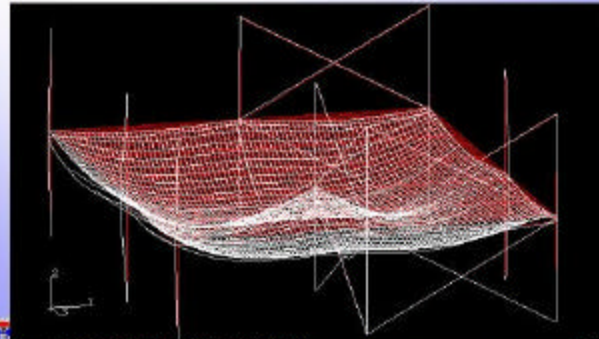
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## Pettersson design fires



## The 2x2 generic frame mesh



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## Studies with different fire scenarios

Long-Cool fires  
Short-Hot fires



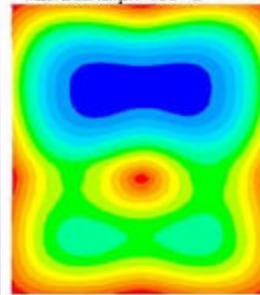
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## Deflection Contours - 2x2 generic frame

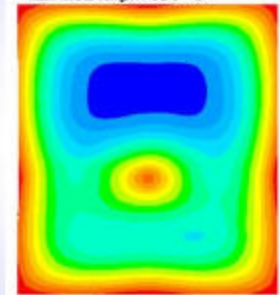
(protected edge beams)

max. defl = 310 mm @ 28 mm/s  
max. steel temp = 750 °C



OF=0.02

max. defl = 705 mm @ 23 mm/s  
max. steel temp = 930 °C

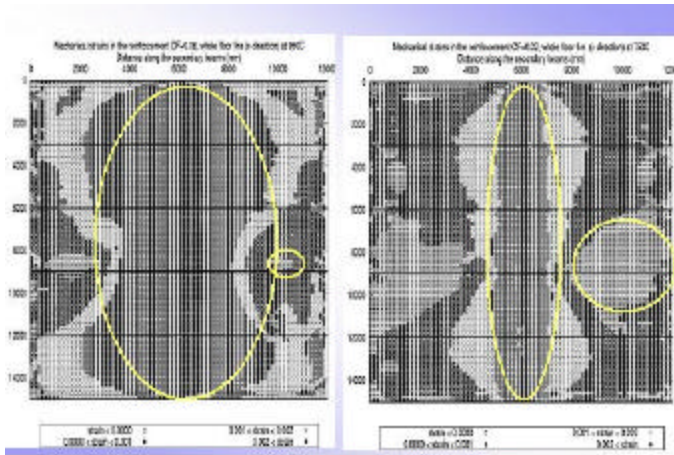


OF=0.08



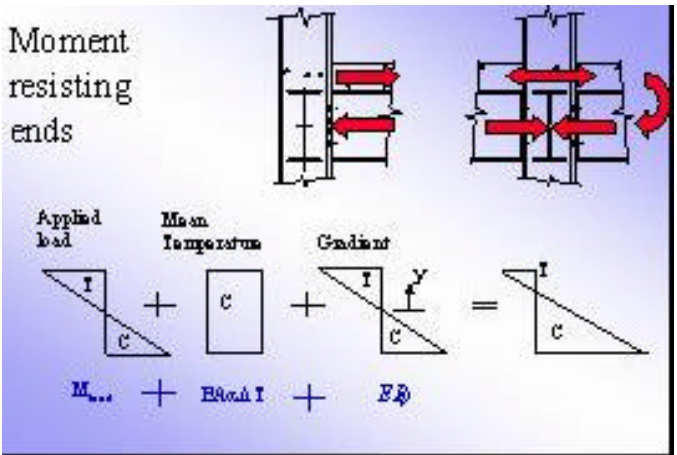
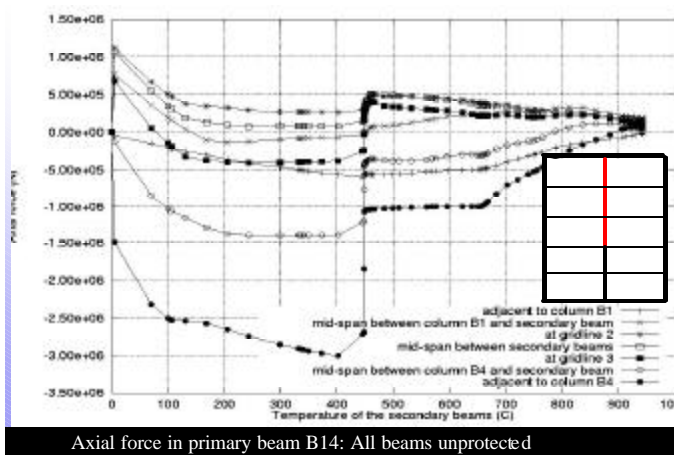
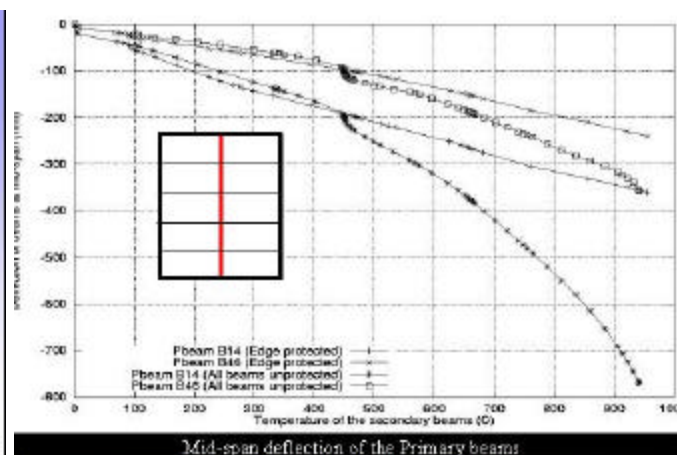
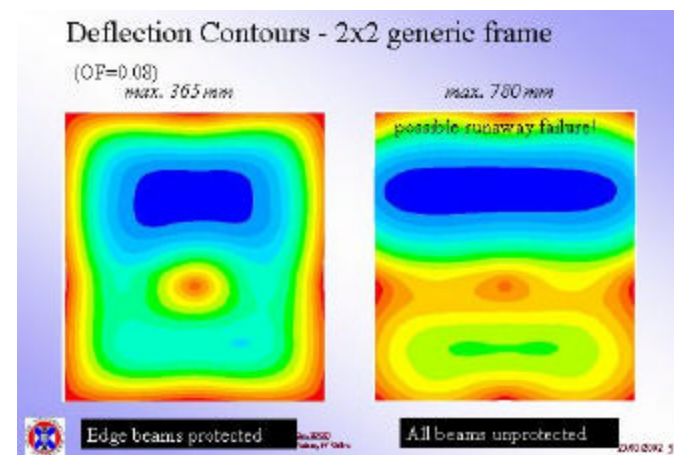
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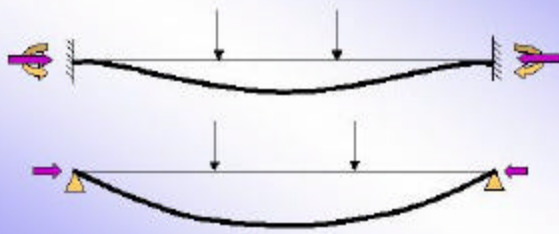
## Studies with different edge beam protection

Edge beams protected  
Edge beams unprotected



# Primary beam instability

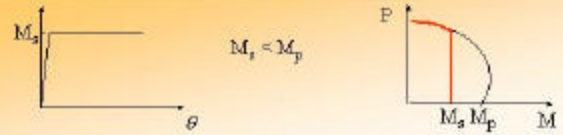
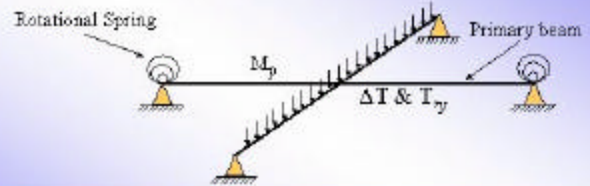
Point loads from Secondary beams



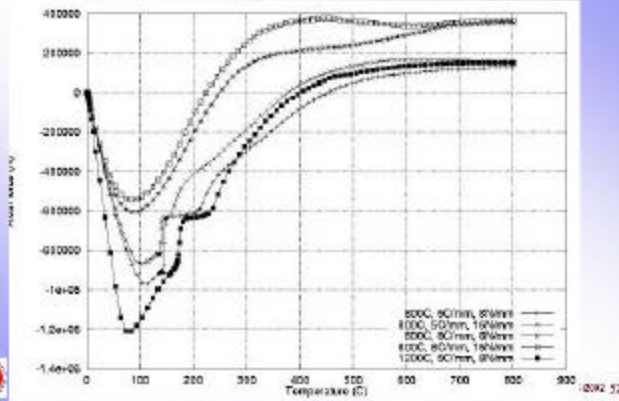
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# Simple ABAQUS beam model

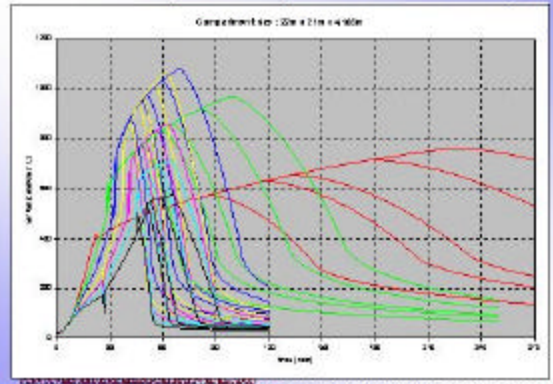


# Instability occurring in the simple model



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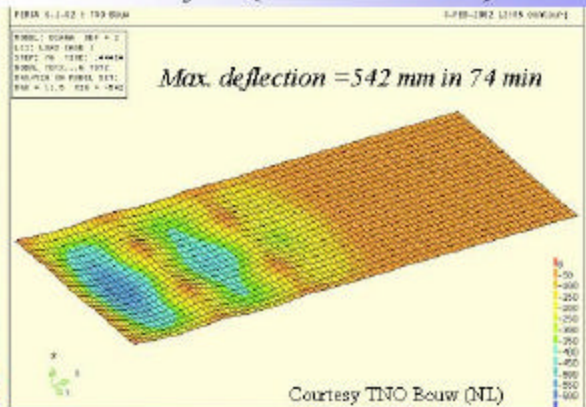
# Fire scenarios (air temperature vs time)



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Courtesy PROFIL-ARBED R&D 2002-092 59

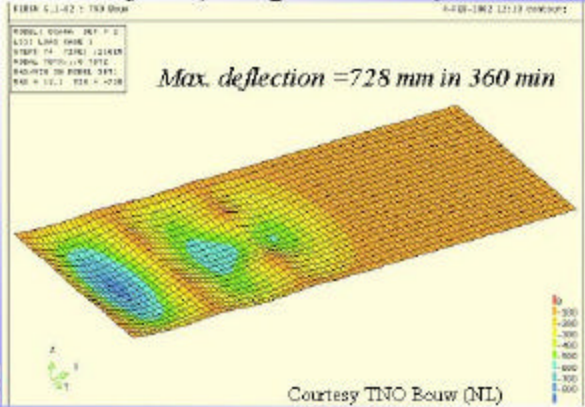
# DIANA analysis ("short hot" fire)



Courtesy TNO Bouw (NL)

2 59

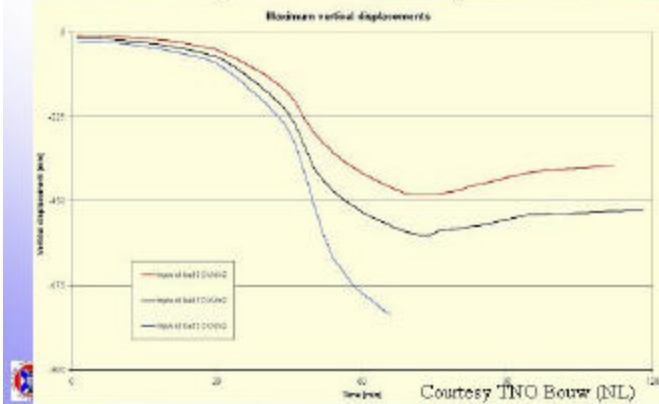
# DIANA analysis ("long cool" fire)



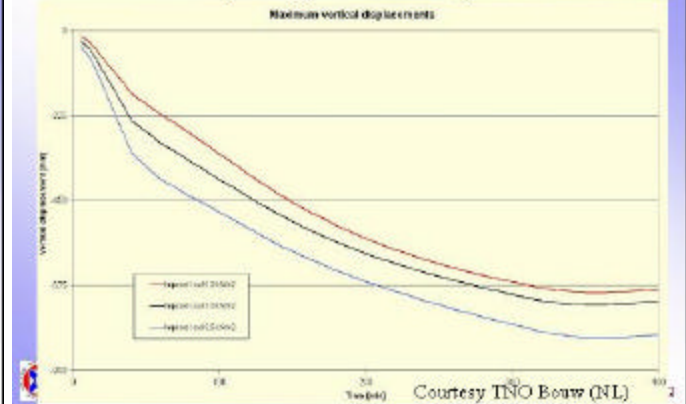
Courtesy TNO Bouw (NL)

32 60

## Deflections ("short hot" fire)



## Deflections ("long cool" fire)



## Conclusions

- ◆ Fire design is based on time - Structural response depends on temperature and rate of heating
  - ◆ Implications of this on current design?
- ◆ Different fires can produce very different varied different times & train patterns in composite floor systems
- ◆ The benefit of protecting g. beams seems worthwhile (to enable anchorage of membrane forces and "tying" effect - also cladding protection)
- ◆ A new (and possibly dynamic) phenomenon identified which needs confirmation and assessment of its potential for damage



CONCRETE AND COMPOSITE STRUCTURES IN FIRE  
 Dr Paul Girdlestone, Dr Colin Frith, Dr Graham Taylor, Dr John

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## Further research: Strategic

- ◆ Worst case fire scenario can only be based on its potential for structural damage (only for structural integrity considerations)
- ◆ Limit state design scenarios must be the basis of all structural design
- ◆ Limit states resulting from extreme fire events should be included
- ◆ Localised collapse should not cause over all progressive collapse
- ◆ Tall buildings (where suppression/evacuation time is large), will require special consideration (no collapse)



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## Further research: issues of detail

- ◆ Floor slab failures, are they ductile (runaway) or brittle (fracture)
- ◆ Short hot v Long cool fires: which is worse?
- ◆ What happens on cooling?
- ◆ Detailed modelling of connections
- ◆ What kind of fire loading in large compartments
- ◆ Integrity of non-loadbearing compartment boundaries
- ◆ Development of a rational restrained test
- ◆ HOW TO DEFINE FAILURE?



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<http://www.civ.ed.ac.uk/research/fire/project/main.html>



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H. Fire Resistance Evaluation of Large-scale Structural Systems  
Venkatesh Kodur, Institute for Research in Construction  
NRC-CANADA

NRC · CNRC  
**Fire Resistance Evaluation of Large-scale Structural Systems**  
V.K.R. Kodur  
Institute for Research in Construction  
Canada

**Outline**

- Background
- Current Research Projects
- Fire Performance of HSC
- Experimental Studies
- Factors Influencing Fire Performance
- Design Guidelines
- Trends, Needs, Directions


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**Fire Safety**

- Buildings - Design requirements
  - Fire - Severe conditions
  - Fire safety
    - loss of life and property
- Fire resistance - structural elements
  - safe evacuation of occupants & fire personnel
  - minimize property damage
  - control spread of fire
- Modern buildings

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**Figor Assembly after FR Test in Floor Furnace**



NRC · CNRC

**Steel Stud Wall Assembly in Wall Furnace**



NRC · CNRC

**Steel Stud Wall Assembly in Wall Furnace**



NRC · CNRC

### Intermediate Scale Furnace - Walls & Floors



ARC-CARC

### High Strength Concrete

- Superior Performance
  - High strength
  - Durability
- Applications
  - Bridges, Infrastructure Projects
  - Buildings - Columns

ARC-CARC

### HSC Exposed to Fire

- NSC - good fire resistance
- HSC - behaviour of different from NSC
- Spalling
  - low porosity, high density
  - pore pressure
- No guidelines on HSC exposed to fire
  - NBCC, ACI 318/216, CSA-A23.3
- Eliminate fire protection

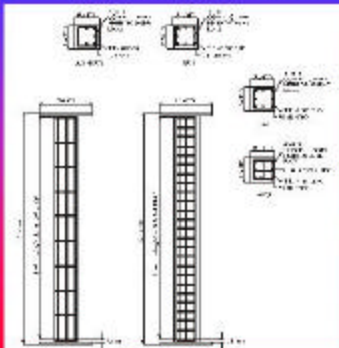
ARC-CARC

### Experimental Studies

- RC columns - HSC, NSC
- Test variables
  - 28-day compressive strength
  - siliceous, carbonate aggregate
  - reinforcement configuration - ties
  - size
  - load intensity
  - fibre reinforcement
  - fire intensity

ARC-CARC

### Elevation & C.S. Details of HSC Columns



ARC-CARC

### Fire Resistance Experiments

- full-scale specimens
- designed to code specifications
- loads, ends conditions
- std. time-temperature (ASTM-E119/E1529)
- temperatures, deflections, fire resistance
- spalling

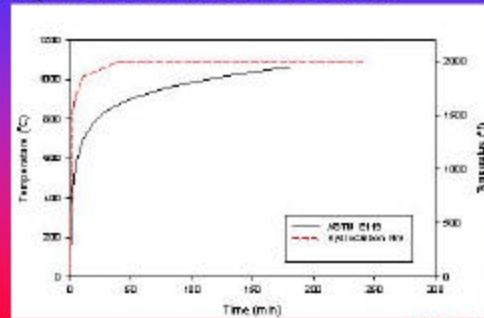
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## Column Furnace



ARC-CARC

## ASTM E119 and E1529 (Hydrocarbon Fire) Exposure for Fire Resistance Tests



ARC-CARC

## HSC Column after Fire Resistance Test



ARC-CARC

## Spalling in HSC

- Not significant in early stages (30 min)
  - very minimal in columns with 135° ties
- Spalling progression (1-2 hrs)
  - hair line cracks, widen at corners
  - chunks fall off (ties not at 135°)
- Significant towards end of test (failure)
  - ties open up, buckling in rebars
  - Much higher in columns with ties 90°

ARC-CARC

## Post-failure Observations

### □ NSC Column

- ties did not open up
- less buckling of rebars
- less spalling
- failure confined to locally

### □ HSC Column

- ties opened up
- buckling of rebars
- significant spalling - cross-section loss
- failure over length of column

ARC-CARC

## View of HSC2 after Fire Test



ARC-CARC

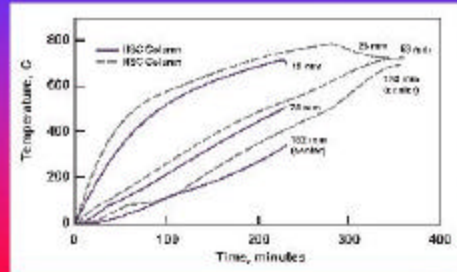


### View of HSC6 after Fire Test



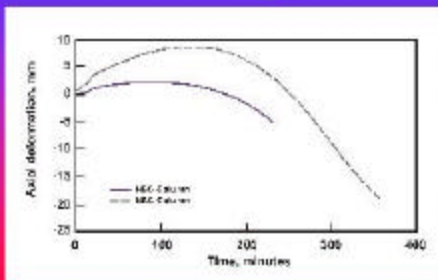
ARC-CIRC

### Variation of Temperature with Time in NSC and HSC Columns Exposed to Fire



ARC-CIRC

### Variation of Deflection with Time in NSC and HSC Columns Exposed to Fire



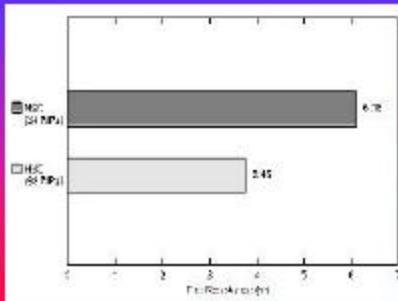
ARC-CIRC

### Factors Influencing Fire Performance

- Compressive strength
- Reinforcement layout
- Moisture content (RH)
- Concrete density
- Heating rate (fire intensity)
- Aggregate type
- Load Intensity, Type
- Fibre reinforcement

ARC-CIRC

### Effect of Strength



Higher Concrete Strength

- Decreases Fire Resistance
- Enhances Spalling

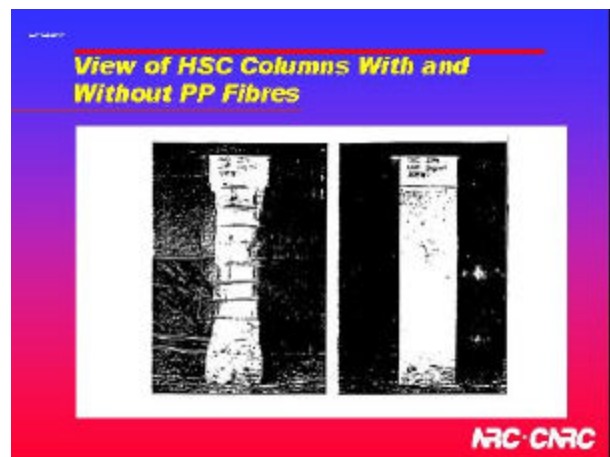
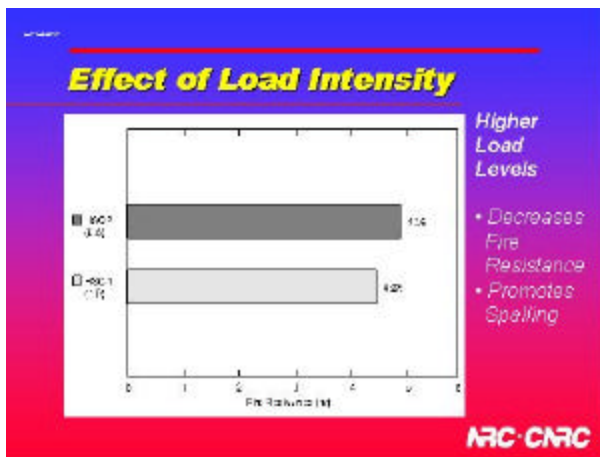
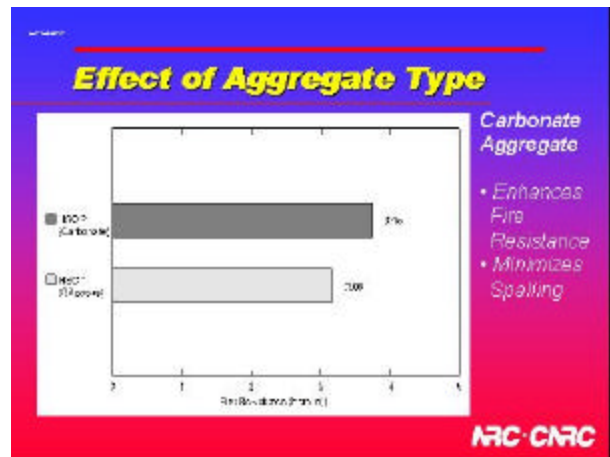
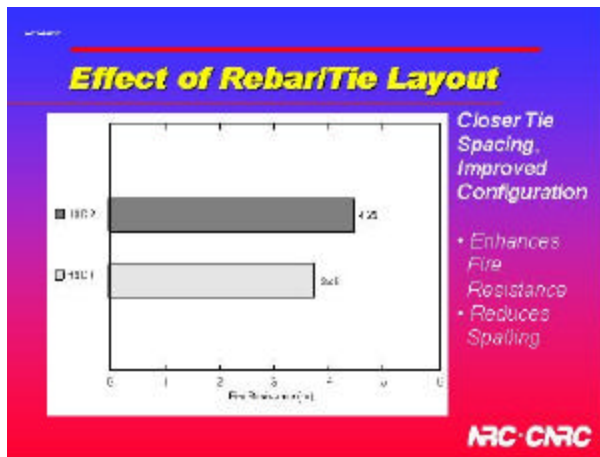
ARC-CIRC

### View of NSC and HSC Columns after Fire Resistance Tests



(a) Normal strength concrete column (b) High strength concrete column

ARC-CIRC



### Design Solutions

- HSC columns
- Reinf. detailing
  - tie configuration
  - bending ties @ 135°
  - tie spacing - closer
  - cross ties
- minimizes spalling
- enhances FR

ARC-CSRC

## Cures (Solutions) – Spalling

- Carbonate aggregate (limestone)
- Normal density aggregate
- Sufficient concrete cover
- Lower load intensity; eccentricity

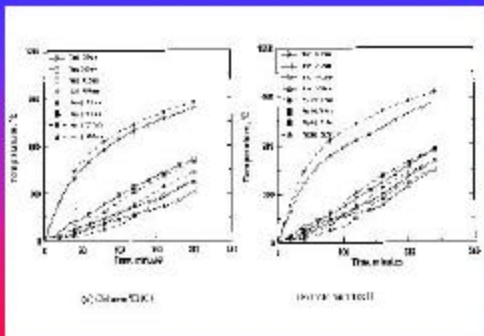
ARC-CIRC

## Numerical Studies

- Material properties at elevated temp.
  - Thermal and mechanical properties
- Computer program
  - Predicting the behaviour of HSC columns
- Parametric studies
  - Factors influencing the behaviour
  - Design equations for fire resistance
  - Integration with structural design

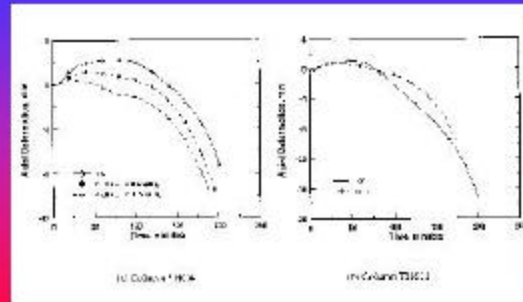
ARC-CIRC

## Temperatures from model & test



ARC-CIRC

## Axial deformation from model & test



ARC-CIRC

## Collaborations

- Concrete Canada
- CCA
- PCA
- CANMET
- MOBIL R and D Corp. Tech. Inc
- NCTU, Taiwan

ARC-CIRC

## Future Trends, Industry Needs, Research Directions

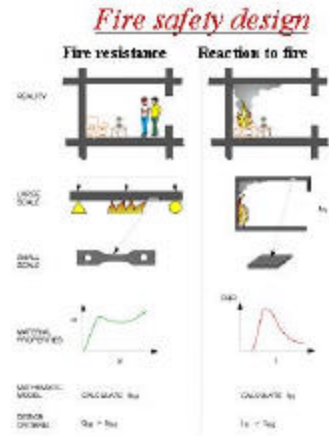
- Fire Resistance - Realistic Considerations
  - tools for analysis, fire scenarios
  - validated models, design fires, properties
- Performance-based Codes
  - calculation methods
  - design guides, software packages
- High Performing Materials
  - satisfy fire resistance - governing factor
  - Practical & cost-effective solutions

ARC-CIRC

I. Improved Fire Testing in Combination with Calculation  
 Ulf Wickstrom, SP Fire Technology  
 Borås, SWEDEN

"Improved fire testing in combination with calculations".

- Ulf Wickström
- SP
- Borås, Sweden



Analysis of fire exposed structures

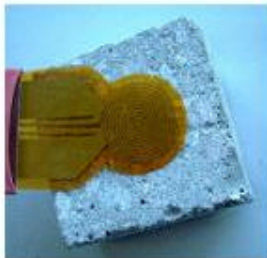
- Fire development – design fires
- Heat transfer to fire exposed structures
- Temperature development in structures
- Mechanical behaviour of structures

Proposals for improvements in fire resistance design

- Develop methods for measuring **thermal** properties of structural and protective materials at elevated temperature
- Develop methods for measuring **mechanical** properties of structural materials at elevated temperature
- Improve furnace testing and develop techniques for monitoring deformation properties of structural elements

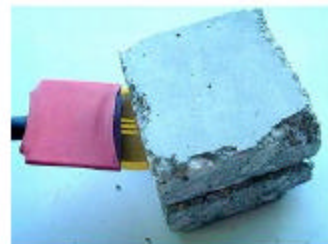
TPS apparatus for measuring thermal properties

TPS = transient plane source, heat transmission, thermal diffusivity



TPS apparatus for measuring thermal properties

TPS = transient plane source, heat transmission, thermal diffusivity



## TPS apparatus for measuring thermal properties

TPS = transient plane source, heat transmission, thermal diffusivity



## Proposals for improvements in fire furnace testing

- Use **Plate Thermometers** to monitor and control temperature in furnaces
- Measure the deformation properties of structural elements during fire test exposure

## Temperature control of furnaces



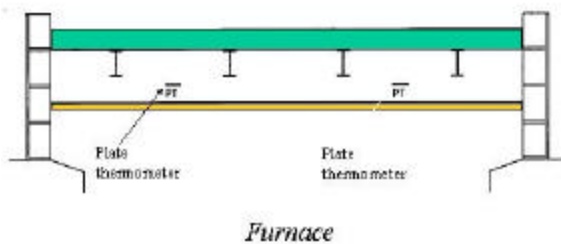
ASTM

## The Plate Thermometer yields better temperature control of furnaces

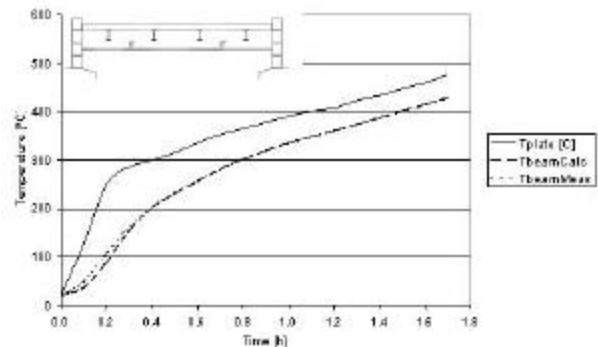


CEN and ISO

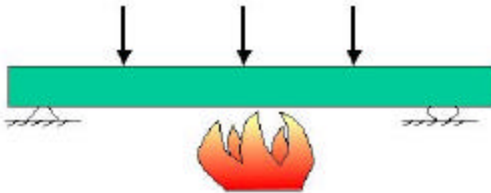
## Plate thermometer measurements



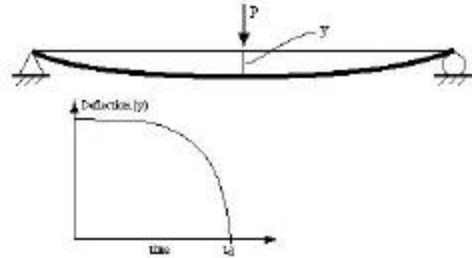
## Plate thermometer measurements



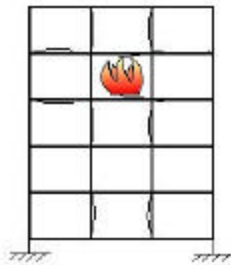
Test model in standard test



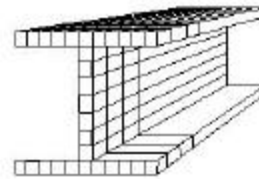
Standard testing of a loadbearing beam yields only the fire endurance time



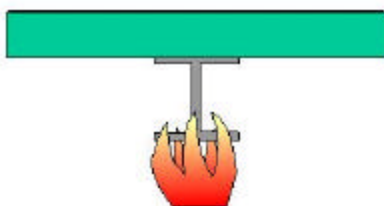
A global analysis requires member deformation properties



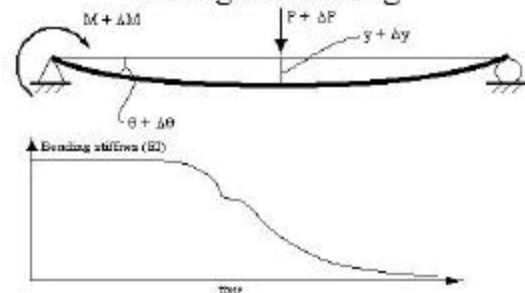
Finite element modelling



Composite structure



Get the deformation properties during fire testing



J. Degradation in Performance of Installed Fire Resistance Materials  
Frederick Mowrer, Department of Fire Protection Engineering  
University of Maryland, College Park, MD

### Performance of Installed Fire Resistance Materials



**Frederick W. Mowrer**  
Dept. of Fire Prot. Eng.  
University of Maryland



### Process

- Erect structure
- Apply fireproofing
- Inspect fireproofing (maybe)
- Scrape off fireproofing
- Install other building services
- Cover everything up with finishes
- Forget about it

### Some issues

- Connections
- Attachments
- Long spans
- End restraint
- Condition of fireproofing
- W/D ratios



### Connections

- Connections not evaluated in tests
- How should they be protected?



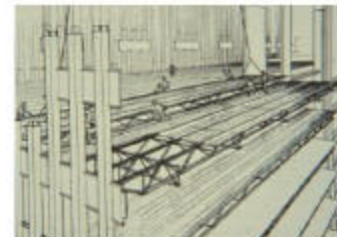
### Attachments

- How much fireproofing do attachments require? Thickness? Length?



### Long spans

- Spans of approximately 12-15 feet tested
- Actual spans can be much longer





## End restraint

- Test specimens wedged into frame
- How does this relate to real-world restraint?



## Condition of fireproofing

- How can deficiencies in fireproofing be recognized? How can they be analyzed?



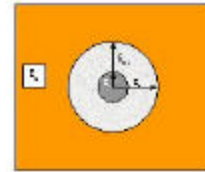
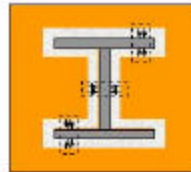
## Missing fireproofing

- What is the effect on overall performance?
- What tools are needed / available to analyze?



## W/D ratios

- W/D ratios used for different geometries
- Theory based on Cartesian 1-D analysis
- Not applicable to cylindrical coordinates



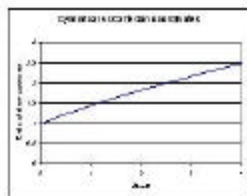
## Time constants ~ W/D ratios

- Cartesian

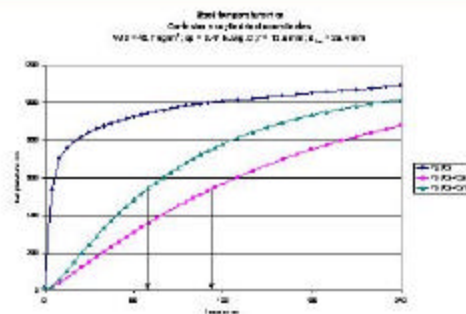
$$\tau = \frac{\rho_s c_{ps} \delta_{ins} \delta_s}{2k_{ins}}$$

- Cylindrical

$$\tau = \frac{\rho_s c_{ps} r_o^2 \ln(r_o/r_i)}{2k_{ins}}$$



## Example







## Summary

---

- There are a number of significant issues related to predicting field performance of structural fire protection
- Some issues are widely recognized
  - Missing fireproofing / attachments / restraint
- Some issues not as widely recognized
  - Connections / spans / W/D ratios
- All issues require research to improve predictive capabilities

K. Materials for the Fire Protection of Structural Steel  
 R. Brady Williamson, Department of Civil and Environmental Engineering  
 University of California, Berkeley CA

UCB Fire Safety Engineering Science

## Materials for Fire Protection of Structural Steel

**Robert Brady Williamson**  
 Interdisciplinary Graduate Program in Fire Safety Engineering Science  
 Department of Civil & Environmental Engineering & Forest Products Laboratory  
 University of California, Berkeley

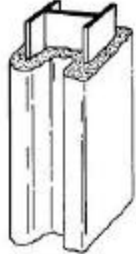
**WORKSHOP**  
 Research Needs for Fire Resistance Determination  
 & Performance Prediction  
 National Institute of Standards and Technology  
 Gaithersburg, Maryland, USA.

February 19 & 20, 2002

UCB Fire Safety Engineering Science

## Overview

*Historical Background*  
**Fire Resistance**  
*It's Origins*  
*Focus on Building Elements*  
*More Advanced Approaches*  
**Survey of "Fire Proofing" Materials**  
**Sprayed Fire-Resistive Materials**  
*Performance Requirements*  
*Tests for Cohesion &/or Adhesion*  
**Conclusions & Recommendations**



UCB Fire Safety Engineering Science

## Background



Fires like the NYC Home Life Fire in 1898 helped shape the 20<sup>th</sup> century approach to "High Rise" fire safety. The new approach was to make columns, walls, floors & other "elements" *Fire Resistive*.

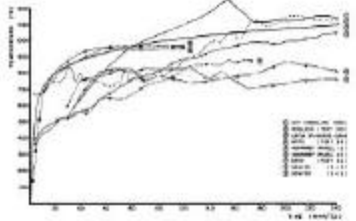



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## Fire Resistance & It's Origins

*"Fire-Resistive Construction"* is defined as "the ability of an **element** of building construction to withstand the effects of fire for a specified period of time without loss of its fire separating or load bearing function".

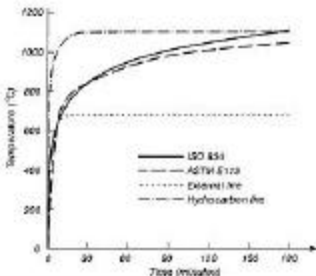

The standard ASTM E-119 Temperature v. Time curve evolved from many fire tests; fuel was continually added to the fire. The Columbia University test hut is shown here.

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## Fire Resistance in the Late 20<sup>th</sup> Century

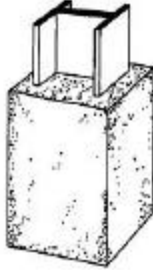
Building elements (columns, beams, walls, floors, etc) are exposed to the Standard Time v. Temperature Curve. They need to hold the load and/or prevent the fire from spreading to the next space. Here are 4 of the standard curves of the left. A column is ready for test at the right.

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## The First Materials Used for "Fire Proofing"

The 1<sup>st</sup> materials used in the early 20<sup>th</sup> century were traditional construction materials such as masonry or concrete. These required substantial labor costs & high densities.



### In the Middle Decades of the 20<sup>th</sup> Century Gypsum Plaster Came into Use

The first gypsum-based systems, such as the wire lath & plaster system at the right, also required substantial labor, & they were not very light.

They shared the basic protection mechanism with concrete of hydrated water.

This water of crystallization was immune from "drying out" & was very effective in achieving good fire performance.



### In the Last Half of the 20<sup>th</sup> Century "Sprayed Fire-Resistive Materials" Became Important

There was a general change from the traditional fire proofing systems to "Sprayed Fire-Resistive Materials" (SFRM) which used hydrated gypsum or portland cement as a binder with various fibers & other fillers.

These required lower labor costs & imposed weight penalties than the materials that had been previously used.



### Sprayed Fire-Resistive Materials

SFRM being applied to Soda Hall at UCB.

They have become the standard.



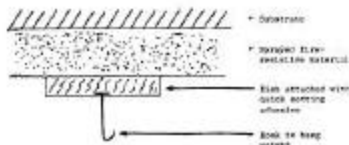
### Performance Requirements for SFRM

In 1972 Williamson gave 4 requirements for SFRM<sup>\*</sup>:

- A. Performance under actual fire conditions,
- B. Durability & integrity under normal life of the structure,
- C. Durability & integrity under the construction process, &
- D. Integrity &/or general condition under special conditions such as earthquakes, thermo-nuclear attack, or the relative ease of repair following a fire exposure.

<sup>\*</sup> Williamson, R.B., Report to Sprayon International, 1972.

### A Test for Cohesive/Adhesive Properties of SFRM



The test method schematically shown above is described in [ASTM 736](#) which was originally published in 1980.

The fundamental problem with this test is that failure can occur in two ways as captured in the title: it is either a *cohesive* or an *adhesive* failure.

### Other Tests for SFRM

There are a number of tests currently used to evaluate the non-fire performance of SFRM:

- ASTM E 605 Thickness & Density
- ASTM 759 Effect of Deflection (of a deck)
- ASTM 760 Effect of Impact on Bonding
- ASTM 761 Compressive Strength
- ASTM 937 Corrosion of Steel by SFRM

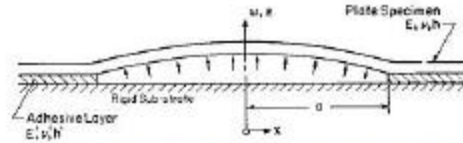
Like ASTM 736 These tests are not necessarily well linked to Materials Science.

### Research Needs for SFRM

There are many different SFRM materials commercially available today, but the current test methods do not adequately address the most important properties or the range of conditions represented by the WTC attack.

For instance, the cohesive/adhesive test (ASTM 736) needs to be supplemented by a test which evaluates the bonding of the SFRM to the substrate.

### A Possible Test for Adhesion of SFRM

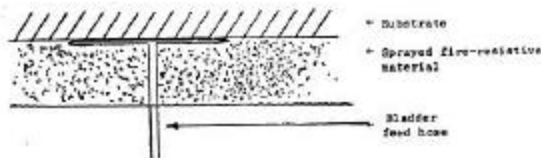


The schematic diagram above shows the geometry of the *blister test* to evaluate the adhesion of a deformable material adhered to a rigid substrate (Williams<sup>1</sup>).

There will always be an "adhesive layer" for any material, & it is important understand its structure.

<sup>1</sup>Williams, M.L., J. Appl Poly Sci, 14, (1970), p 735-745.

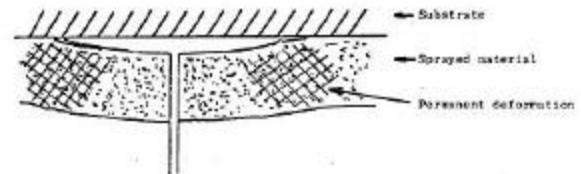
### A Blister Test for SFRM



A thin plastic "bag" can be attached to the substrate before the SFRM is applied.

Then a measured pressure can be applied to the feed hose to cause the bag to inflate.

### A Blister Test for SFRM



The application of pressure to the "blister" can cause the SFRM to deform &/or a crack to grow at the interfaced of the substrate & the SFRM.

### A Blister Test for SFRM



The substrate on the left was oily & the SFRM had poor adherence

The SFRM was well bonded to the steel.

### Conclusions & Recommendations

The fire and non-fire performance of Fire-Resistive Materials should be reevaluated in terms of the current challenges to buildings & other structures.

A new approach to testing & approval of these materials should be started.


There should be generalized "Materials Science-Based" research to characterize the available materials & to establish the "micro-structure/property" relationships that are central to Materials Science.

L. Performance-Based Analytical Prediction of Fireproofing Requirements in Complex Buildings, Robert H. Iding, Wiss, Janney, Elstner Associates, San Francisco  
(See file App III L.pdf)

M. Protection of Steel Structures Against Blast, Impact and Ensuing Fires  
 Abolhassan Astaneh, Department of Civil and Environmental Engineering  
 University of California, Berkeley CA

**Protection of Steel Structures Against Impact, Explosion and Ensuing Fire**

By  
 Abolhassan Astaneh-Asl  
 University of California, Berkeley



A Presentation at the  
 RESEARCH NEEDS FOR FIRE RESISTANCE DETERMINATION AND PERFORMANCE PREDICTION  
 National Institute of Standards and Technology  
 Organized by William Gosthaus, Chief, Fire Research Division, NIST  
 February 13-21, 2002, Washington, D.C.

Types of Impact, Explosives and Ensuing Fires on Tall Buildings

- Impact** of airborne or ground attacks such as jetliners, smaller planes, rockets and cars
- Explosions** inside or outside the building as a result of above attacks
- Ensuing Fires** due to fuel delivered by attackers or fuel present inside the building.



Effects of **Impact** on the Buildings

1. Applies concentrated dynamic force to the building.
2. Depending on dynamic interaction of the building with impacting object, dynamic forces will be generated throughout the building and its structure.
3. Such dynamic forces can cause serious damage at local and global level to structural, non-structural and **fire protection system**.



In case of "extreme event" attacks and fires, the main goal of protection is life safety by preserving egress routes and preventing Collapse.

A building can collapse due to:

- a. Initial damage to its structure,

Deterioration caused by **ensuing fire**.

**Effects of Impact and Ensuing Fire on the Structure**

1. Local and Global Damage to Structure
2. Initial Damage to **Fire Protection Systems**
3. Progressive Collapse Due to Deterioration in Strength or Stability of Gravity Load Carrying System Caused by **Ensuing Fire**.

**Tests of Floors Catenary Action to Prevent Progressive Collapse**

Abolhassan Astaneh-Asl, Ph.D., P.E.  
 Erik Madsen and Roger Jung

Department of Civil and Environmental Engineering  
 University of California, Berkeley  
 2000-2001

Sponsored by  
 General Services Administration and  
 Skilling, Ward Magnusson Barkshire

## Specimen

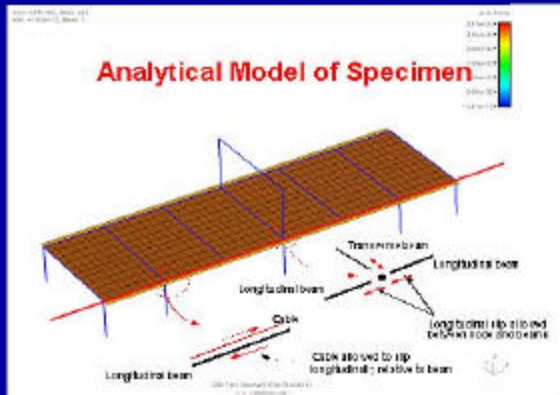


## Floor Deformation, Test-1



Column had 110 kips, dropped 20 inches and was supported by Catenary action of the cables and floor.

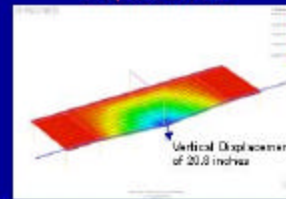
## Analytical Model of Specimen



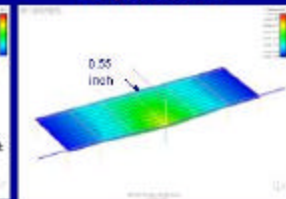
## Finite element Analyses

The main challenge was to model composite floor realistically.

### Vertical Displacements



### Horizontal Displacements



Challenges and Research Needs in Realistic Modeling of Behavior of Steel and Composite Structures Under Intense and Sustained Fires

## Research Needs

### Material:

Research Data on Fire-Resistance of Light Weight and High Strength Concrete is Needed

## Steel Structures: Connections

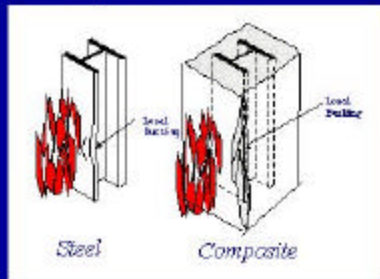
Research Funded by NSF

**Steel Structures:**  
Research data and more realistic models of:

1. Local Buckling
2. Overall Buckling and
3. Connections

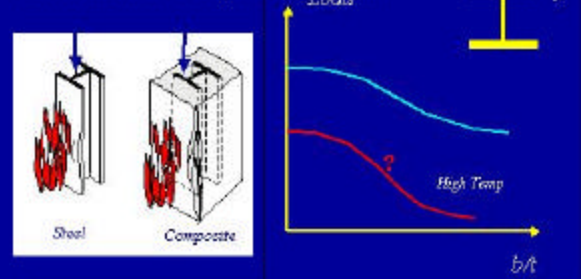
can be very useful.

## Local Buckling in Steel and Composite Structures at Elevated Temperatures:



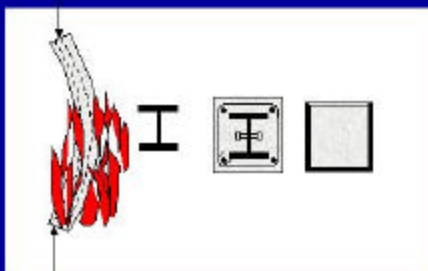
More reliable data and better prediction models are needed

## Local Buckling in Steel and Composite Structures at Elevated Temperatures:



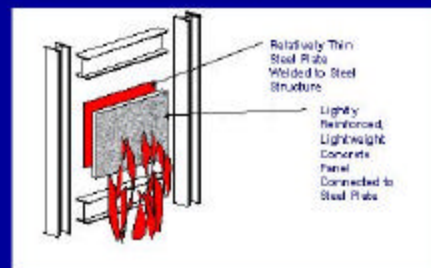
More reliable data and better prediction models are needed

## Overall Buckling in Steel and Composite Structures at Elevated Temperatures:



More reliable data and better prediction models are needed

## Composite Shear Walls at Elevated Temperatures:



More reliable data and better prediction models are needed



### Seismic Studies of an Innovative and Traditional Composite Shear Walls

by Q. Zhao and A. Astaneh-Asl

The diagram illustrates the components of a composite shear wall: Steel Columns and Beams, Steel Plate, Pre-cast Concrete Wall, and Bolts. It compares two wall types: an Innovative Composite Wall with a 'Gap' between the steel plate and concrete wall, and Traditional Composite Walls with 'No Gap'.

Sponsor: National Science Foundation

### Ongoing Cyclic Tests of Composite Shear Walls

- Two 1/2-scale specimens tested.
- Cyclic shear displacements applied to the top of specimen.
- Drifts of up to 4.5% reached.

The diagram shows a test setup with a 750-ton actuator applying displacement to a 6.2 m high test specimen, which is supported on a 2.1 m wide R/C reaction block.

Seismic Studies of an Innovative and Traditional Composite Shear Walls, by Q. Zhao and A. Astaneh-Asl

### Specimen 2 Prior to the Test

A photograph showing the physical specimen 2 in the laboratory before testing.

Seismic Studies of an Innovative and Traditional Composite Shear Walls, by Q. Zhao and A. Astaneh-Asl

### Views of Specimen

Three photographs showing different views of the specimen in the test rig.

Seismic Studies of an Innovative and Traditional Composite Shear Walls, by Q. Zhao and A. Astaneh-Asl

### Composite Shear Walls Can Be Used Around Stairwells to Protect Egress Routes

The image shows a photograph of specimen 2 and a diagram illustrating how composite shear walls can be used around stairwells to protect egress routes.

Research Data on Fire Resistance Can be Useful

Seismic Studies of an Innovative and Traditional Composite Shear Walls, by Q. Zhao and A. Astaneh-Asl

### Global Performance of Various Structural Systems at Elevated Temperatures:

The diagram compares the global performance of Steel and Composite structural systems at elevated temperatures. It shows a Plan View with Cladding and Interior Walls, and a vertical view showing a Braced Frame and Moment Frame for both systems, with a Shear Wall in the composite system.

More reliable data on Progressive Collapse are needed

*Some Research Needs on Steel and  
Composite Structures Subjected to High  
Temperature*

- ❖ *Light Weight Concrete*
- ❖ *Local Buckling*
- ❖ *Overall Buckling*
- ❖ *Performance of Various Systems*

N. Structural Fire Modeling: Where is the Frontier Nowadays?  
 Jean-Marc Franssen, Institute de Mecanique et Genie Civil  
 University of Liege, BELGIUM

**Structural Fire Modelling.**  
**Where is the frontier nowadays?**

Jean-Marc FRANSSSEN  
 jmf.franssen@ulg.ac.be



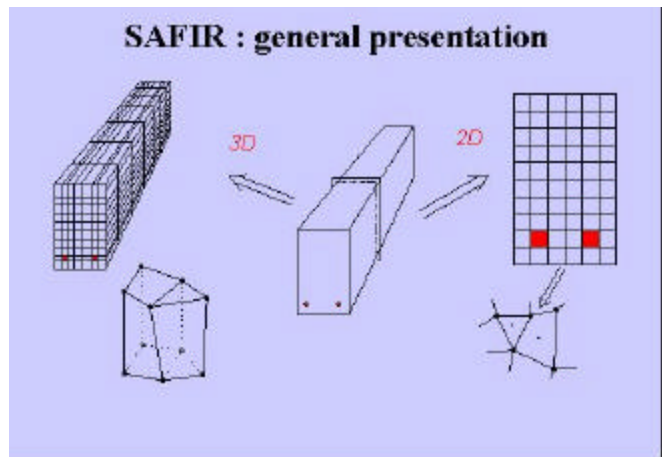

**Numerical modelling**  
**of building structures under fire**

1 – Temperatures in the compartment => OZone  
 2 – Temperatures in the structure  
 3 – Mechanical behaviour } => SAFIR

**SAFIR : non linear finite element software**

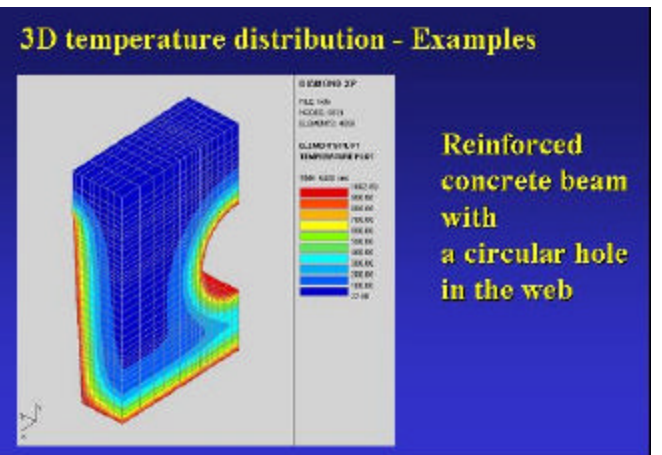
**Determination**

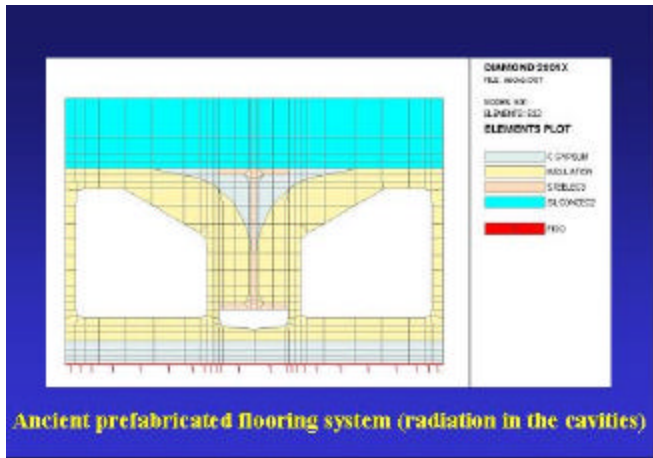
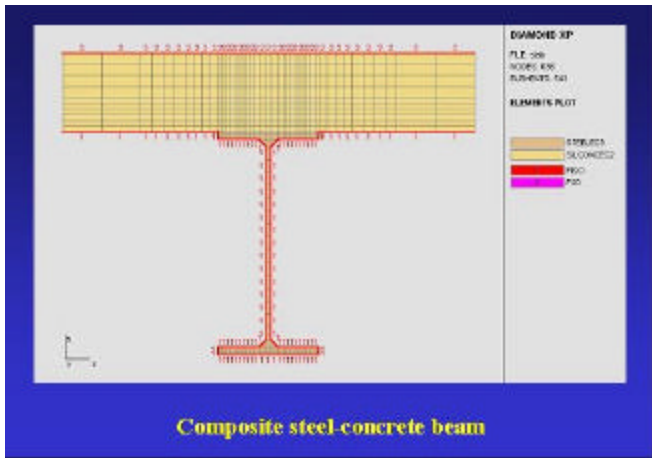
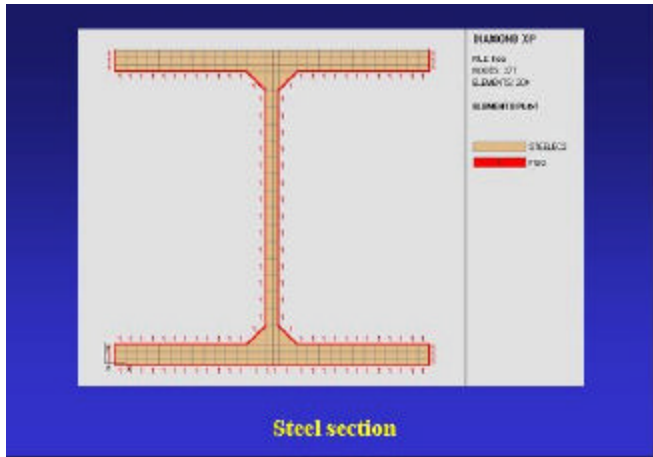
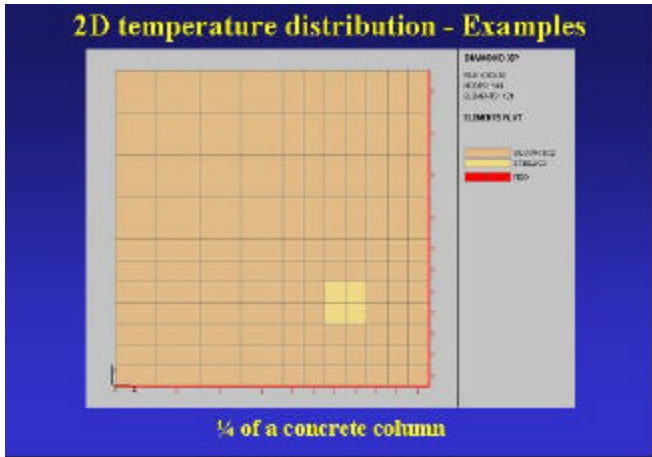
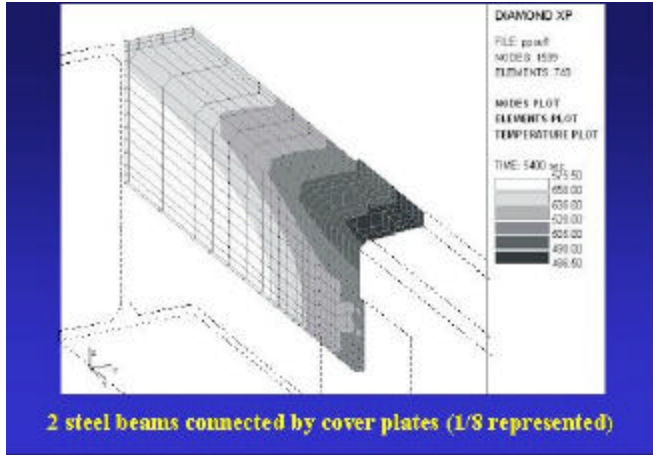
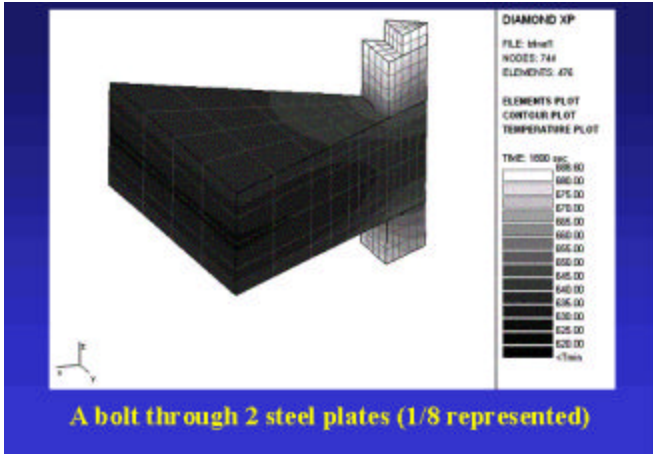
- of the temperature in the structure;  $T_s = f(x, y, z, T_g)$
- of the mechanical response;  $u = f(x, y, z, \text{loads}, T_s)$

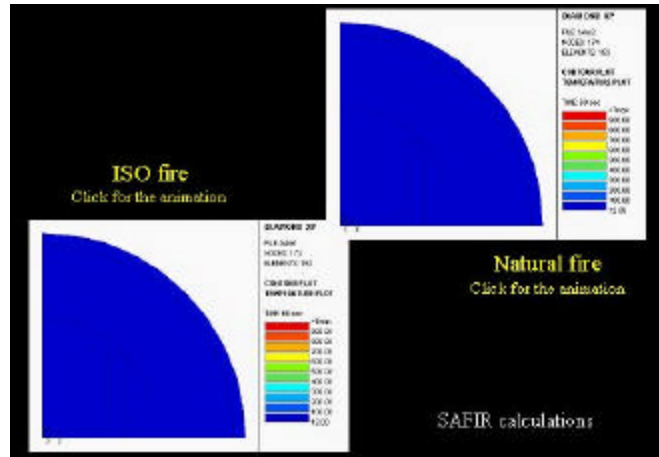
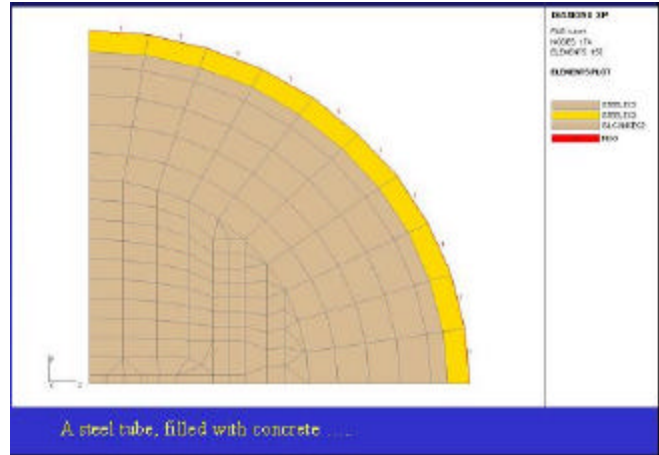
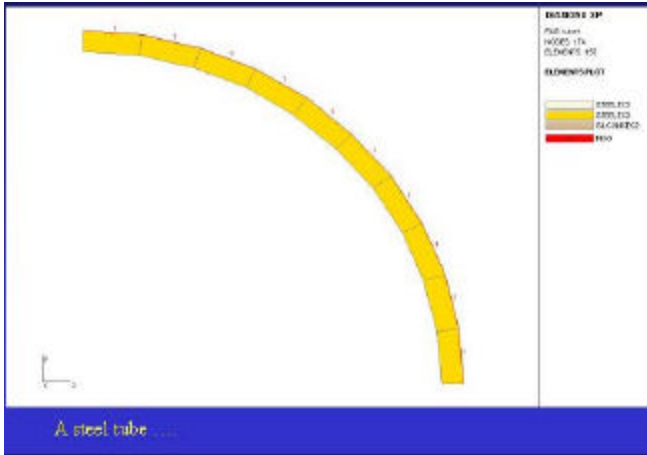


**SAFIR : general presentation**

Temperature field	Mechanical model
3D F.E.	=> Simple calculation model
2D F.E.	=> Beam F.E. (2D or 3D)
1D F.E.	=> Shell F.E. (3D)
Simple calculation model	=> Truss F.E. (2D or 3D)

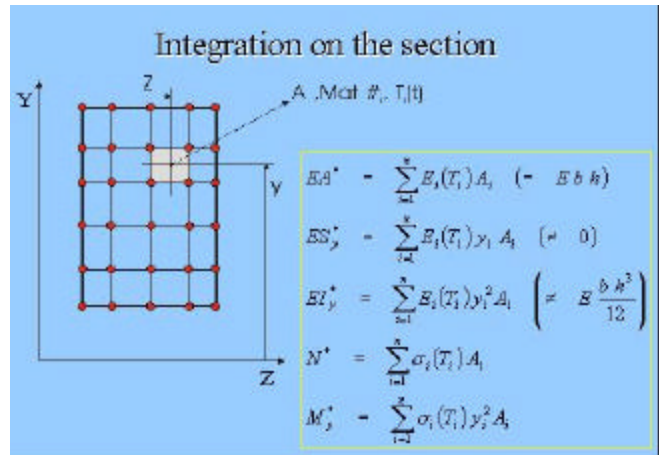




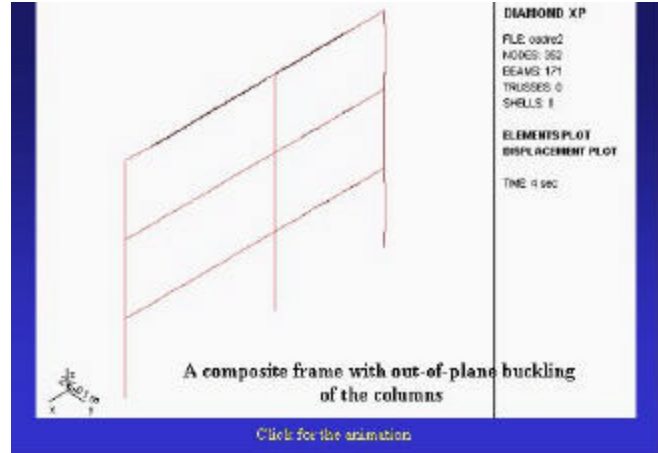


**Beam finite element**

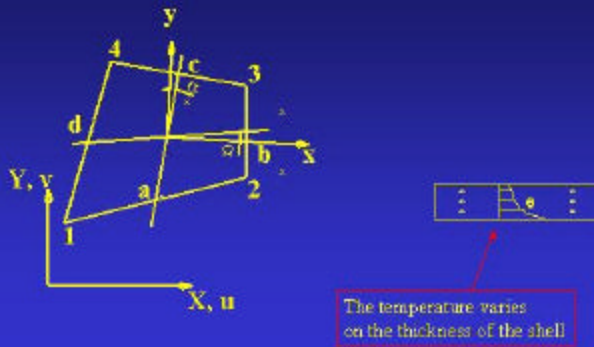
**Link between the thermal and the mechanical analysis**



## Beam finite element Example

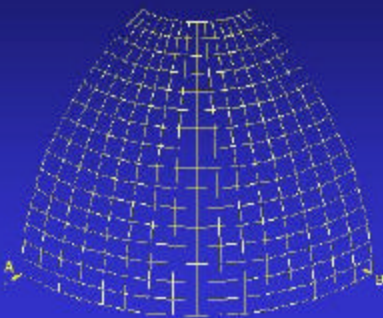


## The shell finite element



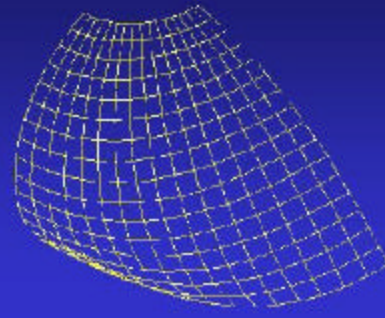
## Shell finite element Examples

### Benchmark test : hemispheric dome (1/4 modelled)

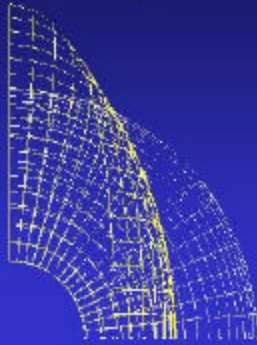


### The same after deformation

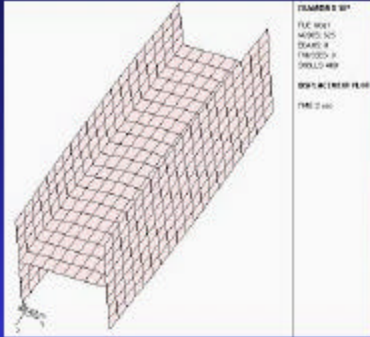
(elastic calculation at 20°C)



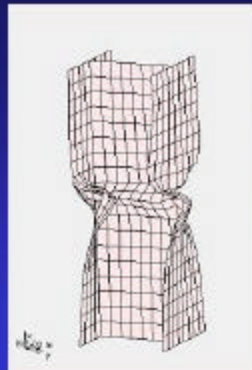
**Comparison between deformed et initial shape**  
 (No amplification of the displacements in the drawing)



**U section in bending**  
 elastic at 20°C  
 Displacements x 1



Imposed shortening and heating : 1°C/sec  
 No amplification of the displacements in the drawing  
 Click for the animation



**Structural Fire Modelling**  
 What are the limits we are facing today?

**Structural Fire Modelling**  
 What are the limits we are facing today?

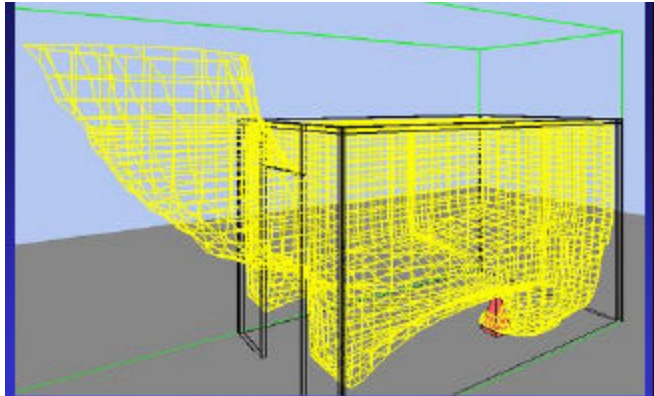
1. Thermal properties of materials
  1. Thermal conductivity of concrete
  2. Shadow effect around H steel sections

N.B. This is a *European* problem

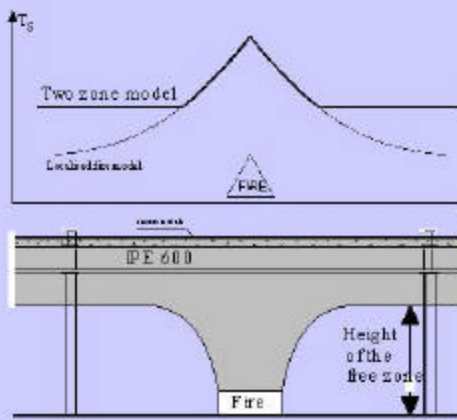
## Structural Fire Modelling

### What are the limits we are facing today?

1. Thermal properties of materials
2. Interaction between the gas and the structure in case of localised fires
  1. In case of C.F.D. modelling
  2. Also for zone models



Example of result from a field model (SOFIE)  
How to transfer the results to the structure?



## Structural Fire Modelling

### What are the limits we are facing today?

1. Thermal properties of materials
2. Interaction between the gas and the structure in case of localised fires
3. Spalling in concrete

More a producer's problem than a modeller's problem.  
Research can help in explaining the phenomena and identifying the parameters, but not give a deterministic answer (even if it could, at what price in terms of required data?).

## Structural Fire Modelling

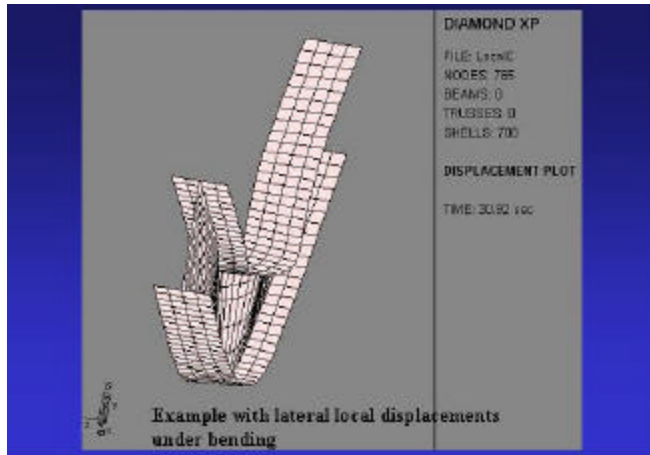
### What are the limits we are facing today?

1. Thermal properties of materials
2. Interaction between the gas and the structure in case of localised fires
3. Spalling in concrete
4. Consequences of Bernoulli hypothesis in the beam F.E.
  1. Rotation capacity
  2. Local buckling
  3. Shear failure
  4. Debonding

All sections are seen by a Bernoulli beam F.E. as Class 1 sections

- Class 1 => no problem
- Class 2 => normally, no hyperstatic structure
- Class 3 => use modified properties
- Class 4 => ?????

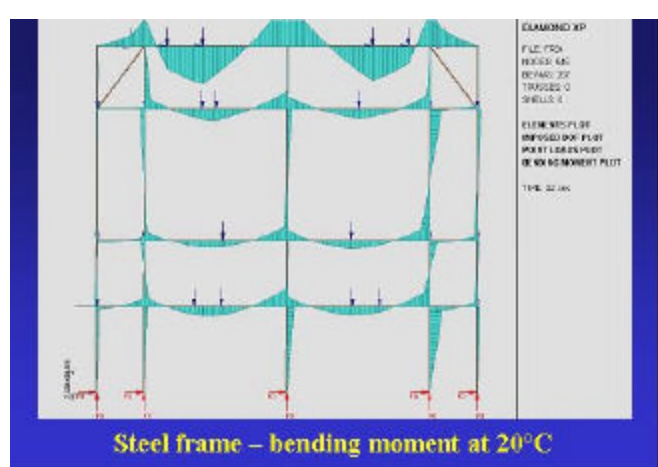
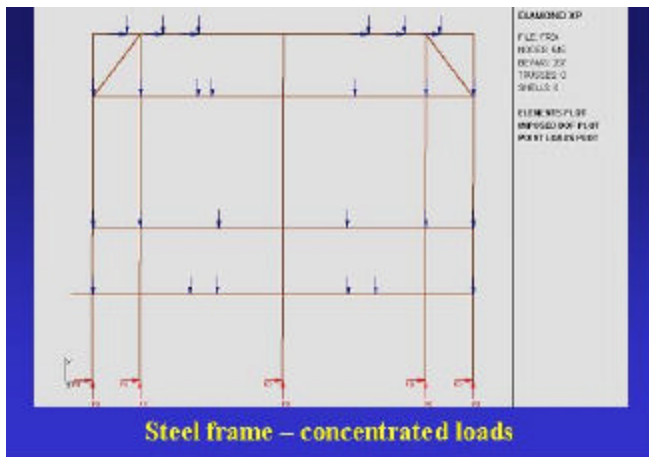
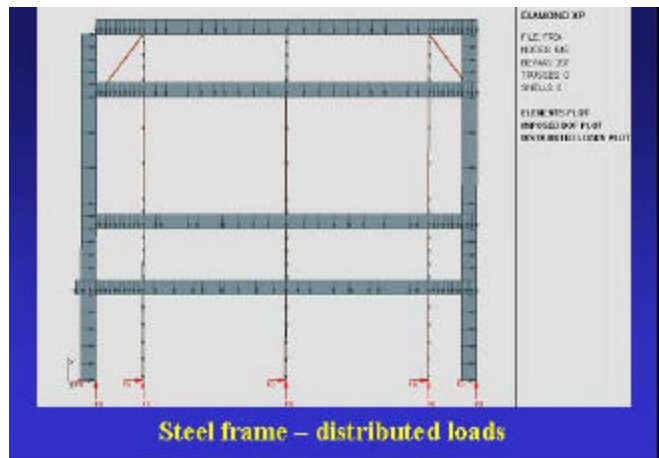
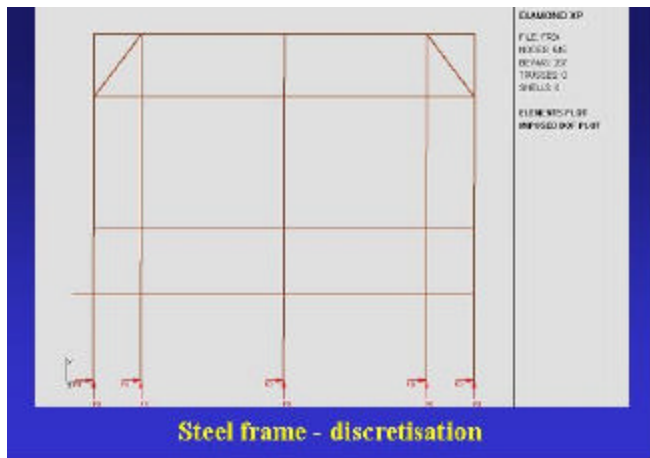


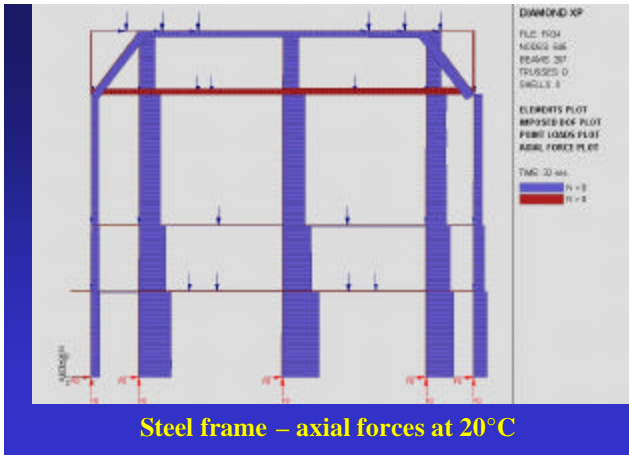


### Structural Fire Modelling

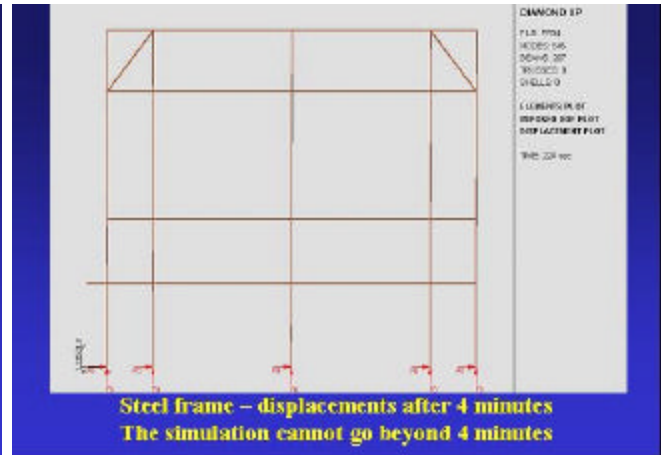
#### What are the limits we are facing today?

1. Thermal properties of materials
2. Interaction between the gas and the structure in case of localised fires
3. Spalling in concrete
4. Consequences of Bernoulli hypotheses in the beam F.E.
5. Local and/or temporary negative stiffness





Steel frame – axial forces at 20°C



Steel frame – displacements after 4 minutes  
 The simulation cannot go beyond 4 minutes

DIAMOND XP  
 FILE: F504  
 MODEL: 146  
 BEAMS: 207  
 TRUSSES: 0  
 SHELLS: 1  
 ELEMENTS PLOT  
 IMPOSED DOW PLOT  
 TIME: 10 sec  
 N > 0  
 N < 0

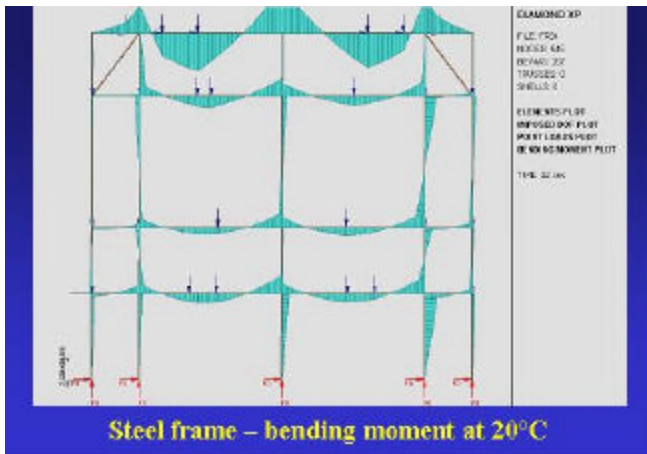
**$N = f(t)$**   
 Click for the animation.

DIAMOND XP  
 FILE: F504  
 MODEL: 146  
 BEAMS: 207  
 TRUSSES: 0  
 SHELLS: 1  
 ELEMENTS PLOT  
 BENDING MOMENT PLOT  
 TIME: 10 sec  
 M > 0  
 M < 0

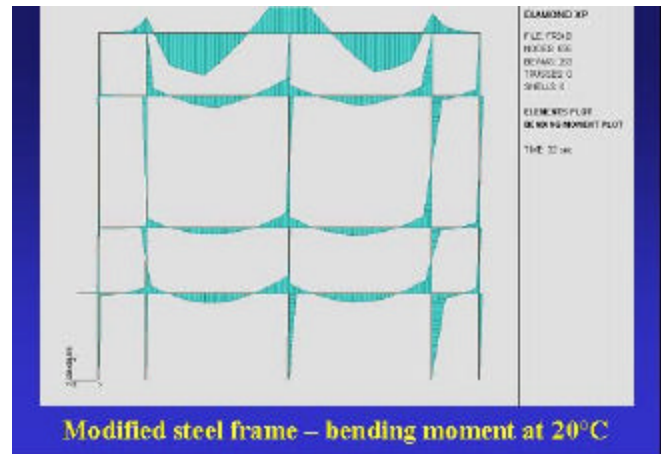
**$M = f(t)$**   
 Click for the animation.



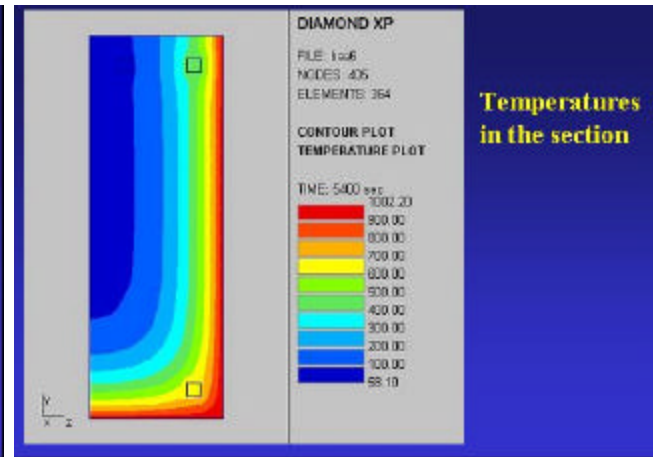
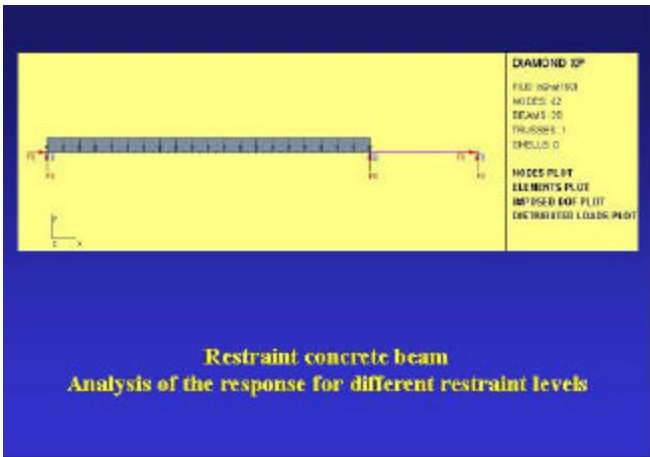
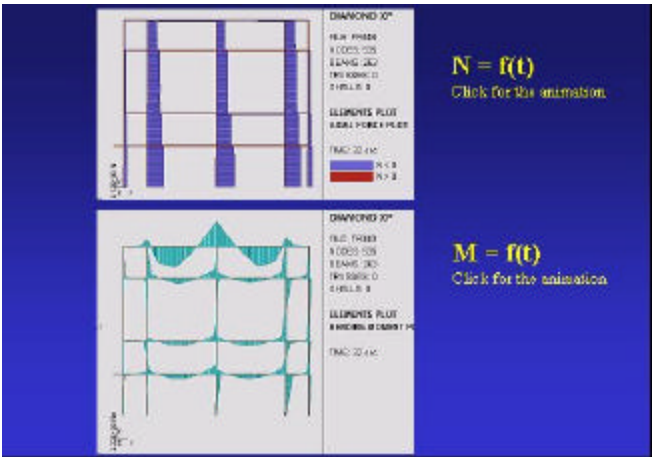
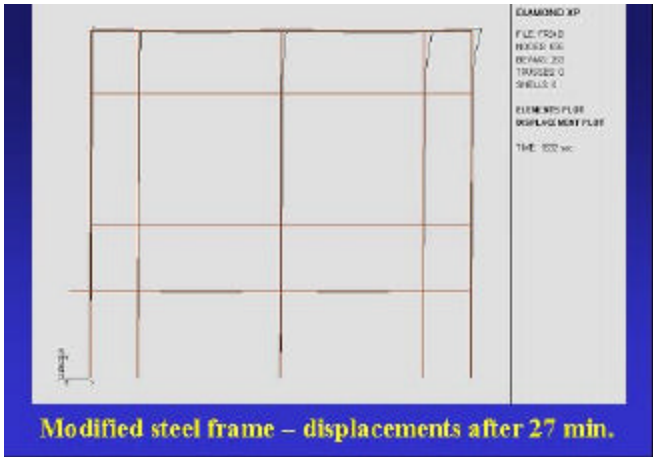
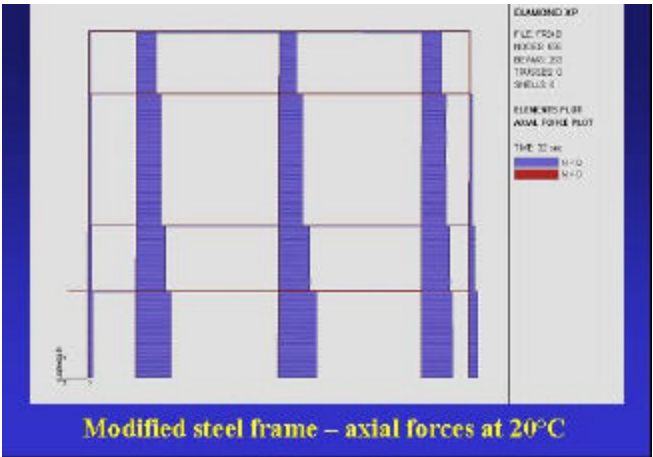
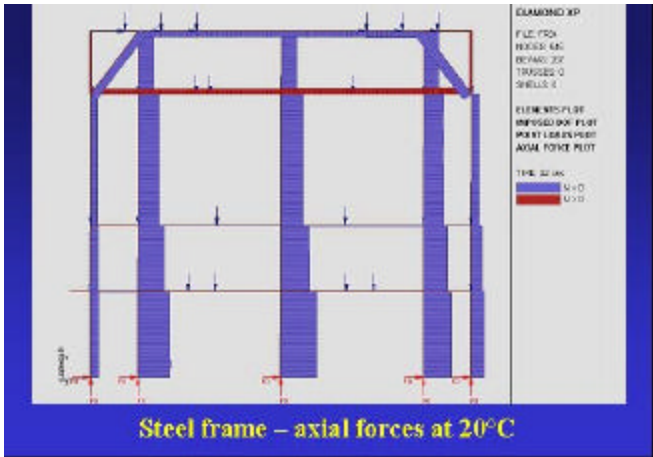
Modified steel frame (no diagonal) - discretisation

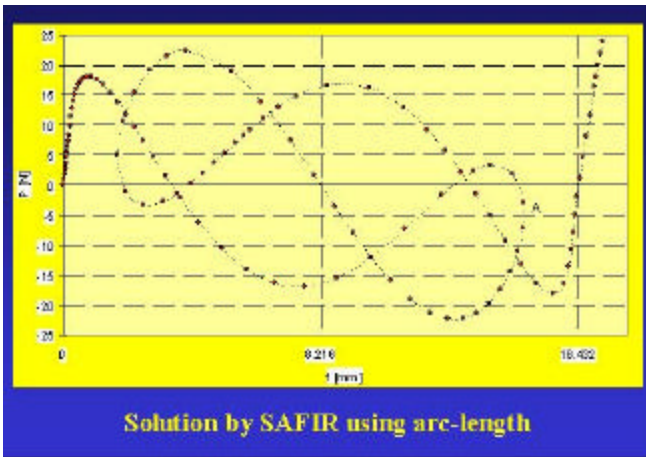
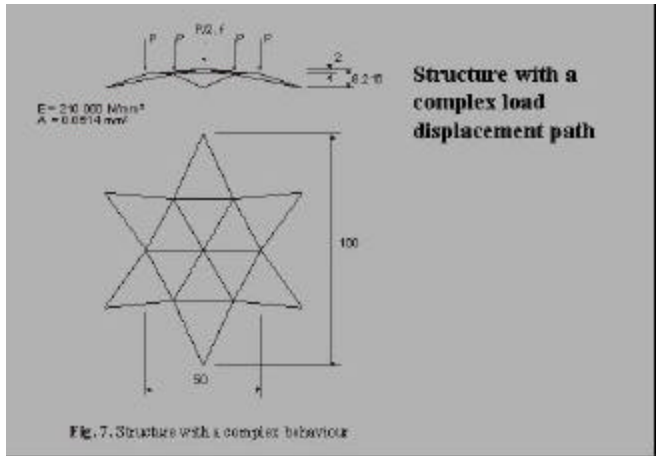
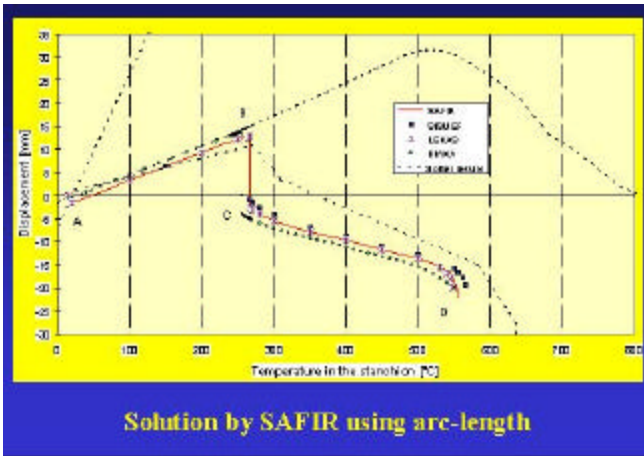
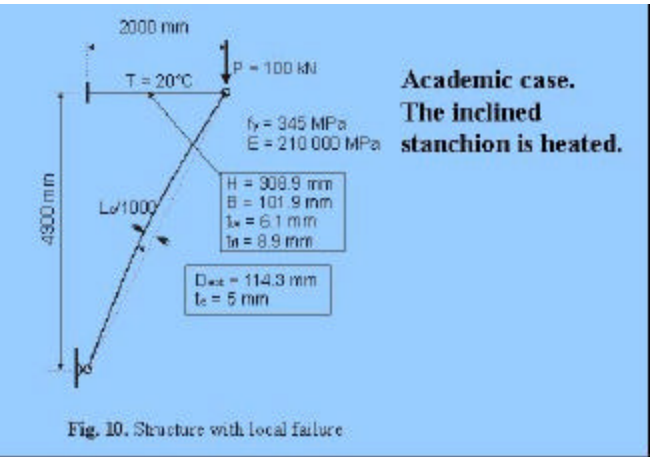
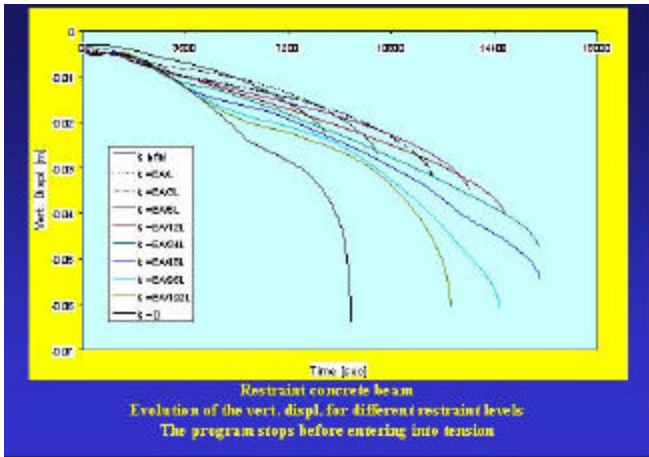


Steel frame – bending moment at 20°C



Modified steel frame – bending moment at 20°C





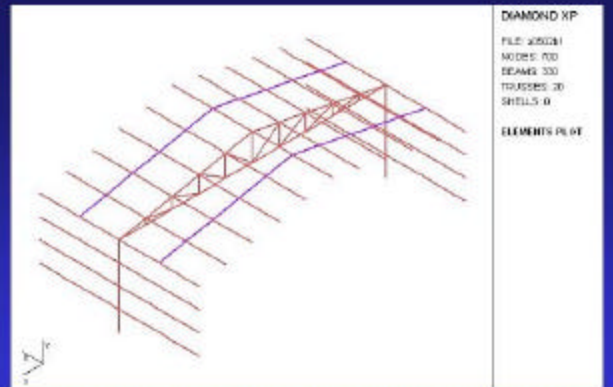
Unfortunately, arc length

- does not work in all cases
- involves an unloading that is not physically correct

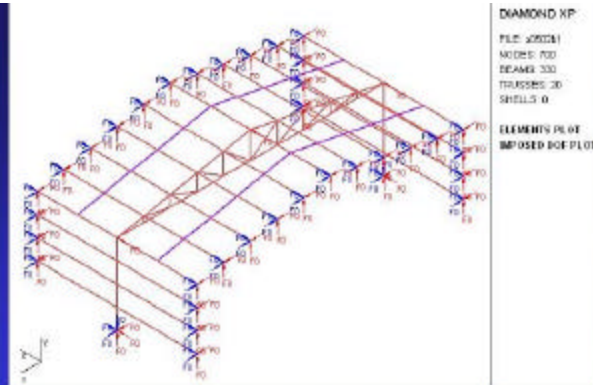
## Structural Fire Modelling

### What are the limits we are facing today?

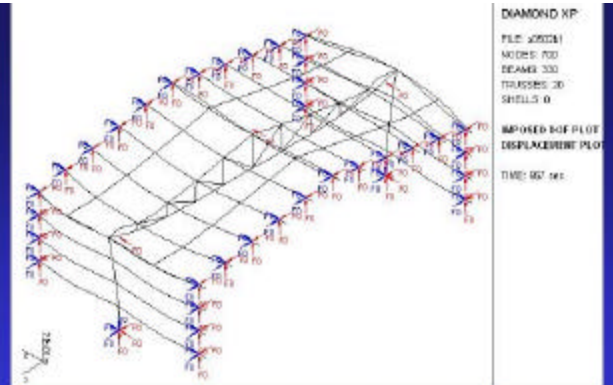
1. Thermal properties of materials
2. Interaction between the gas and the structure in case of localised fires
3. Spalling in concrete
4. Consequences of Bernoulli hypotheses in the beam F.E.
5. Local and/or temporary negative stiffness
6. Boundary conditions in substructures



Industrial building: one frame + purlins represented



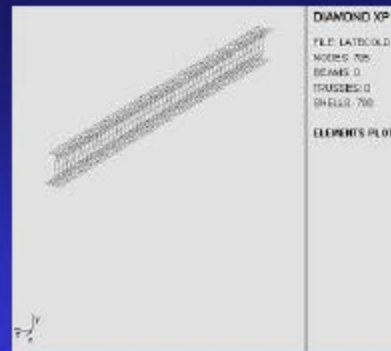
Elongation of the purlins: free or fixed?



## Structural Fire Modelling

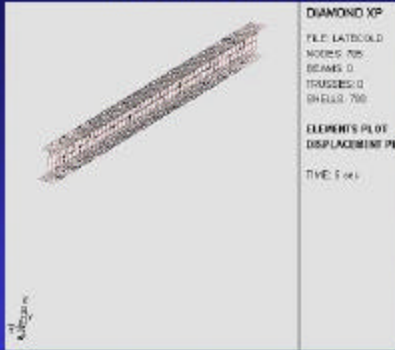
### What are the limits we are facing today?

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3. Spalling in concrete
4. Consequences of Bernoulli hypotheses in the beam F.E.
5. Local and/or temporary negative stiffness
6. Boundary conditions in substructures
7. Definition of failure in case of very large displacements



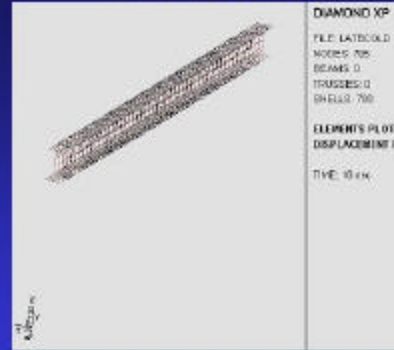
Simply supported beam (displacements x 1)

Is this failure or not?



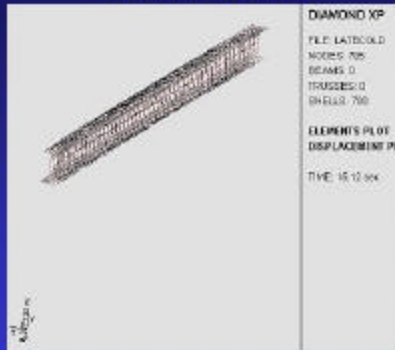
Simply supported beam (displacements x 1)

Is this failure or not?



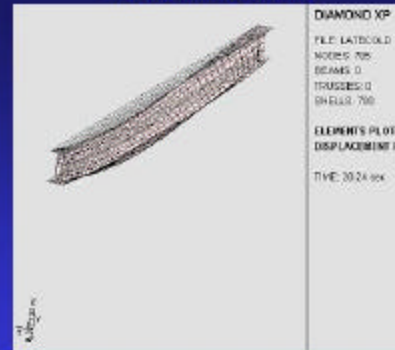
Simply supported beam (displacements x 1)

Is this failure or not?



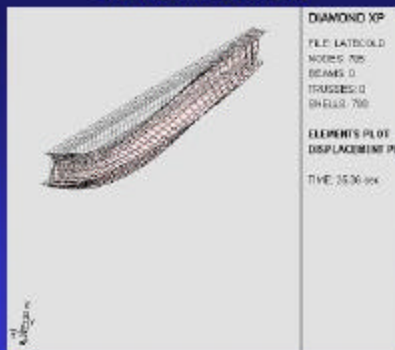
Simply supported beam (displacements x 1)

Is this failure or not?



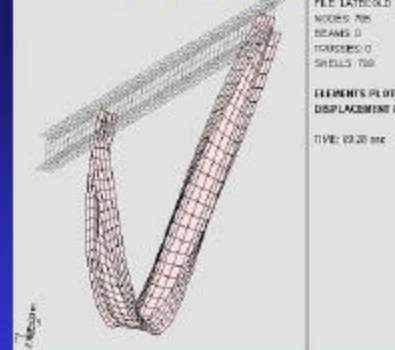
Simply supported beam (displacements x 1)

Is this failure or not?



Simply supported beam (displacements x 1)

Is this failure or not?

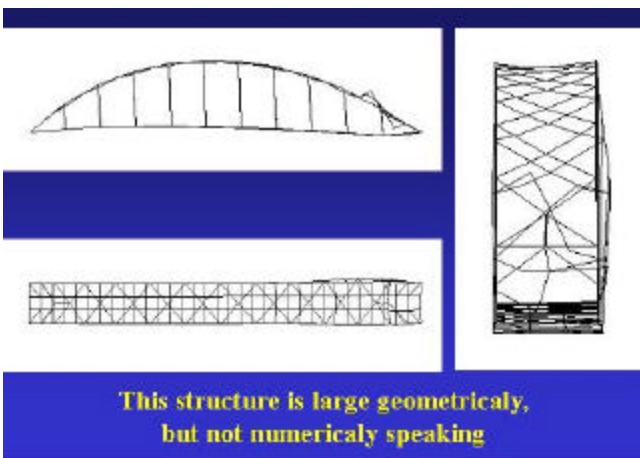
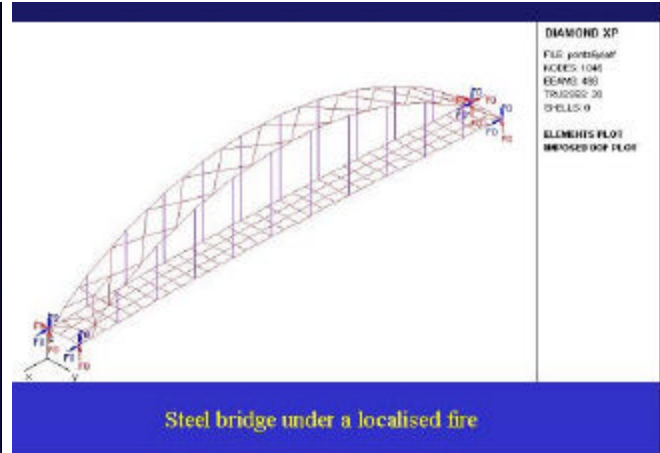


Simply supported beam (displacements x 1)

## Structural Fire Modelling

### What are the limits we are facing today?

1. Thermal properties of materials
2. Interaction between the gas and the structure in case of localised fires
3. Spalling in concrete
4. Consequences of Bernoulli hypotheses in the beam F.E.
5. Local and/or temporary negative stiffness
6. Boundary conditions in substructures
7. Definition of failure in case of very large displacements
8. Problems for solving very large structures



### Conclusions

For understanding and designing structures submitted to fire, numerical modelling offers capabilities that are unique.

### Conclusions

The frontiers are:

- Spalling in concrete
- Concrete properties
- Local or temporary failures
- Very large structures
- Very large displacements
- Boundary conditions
- Interface with environment in localised fires
- Ressources (money, time, people, ... )

O. Fire Resistance and Performance Prediction: Structural Analysis Issues and Research  
Needs  
James Ricles, Department of Civil and Environmental Engineering  
Lehigh University, Bethlehem PA  
(see file App III O.pdf)



P. Parallels Between Performance-based Engineering for Fire and Earthquake Hazards  
 Greg Deierlein, Department of Civil and Environmental Engineering  
 Stanford University, Stanford CA

Parallels Between Performance-Based Engineering for Fire and Earthquake Hazards

Greg Deierlein  
 Stanford University & PEER

NIST – Research Needs for Fire Resistance Determination and Performance Prediction  
 Feb. 19-20, 2002

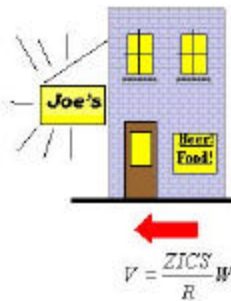


Final Draft ICC Performance Code (ICC 2000).

Objective: To limit the impact of a fire event on the building, its occupants, processes and use, and to limit the impact of an exposing fire on buildings, adjacent properties and processes.

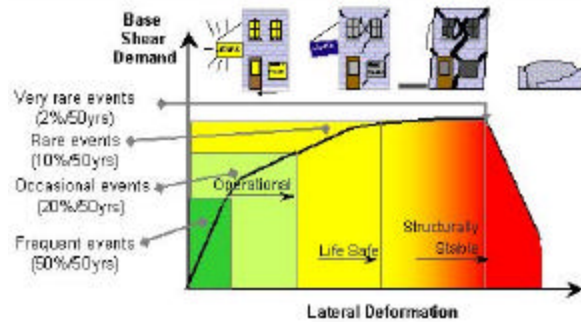
	PERFORMANCE OBJECTIVES			
	I	II	III	IV
Very Large (Key Area)	SEVERE	SEVERE	HIGH	MODERATE
Large (Box)	SEVERE	HIGH	MODERATE	MILD
Medium (Less Program)	HIGH	MODERATE	MILD	MILD
Small (Bayside)	MODERATE	MILD	MILD	MILD

Traditional Earthquake Engrg. Approach



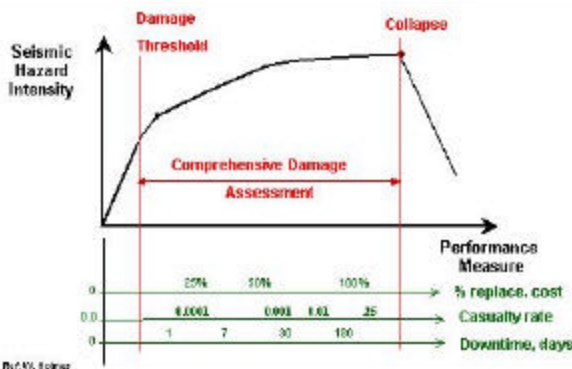
- Linear analysis model
- Simplified design base shear
- Prescriptive details
- Uncertain outcomes
- Owners informed of code conformance, but not building performance

FEMA 273/356 Performance Assessment



Ref. R.O. Hamburger

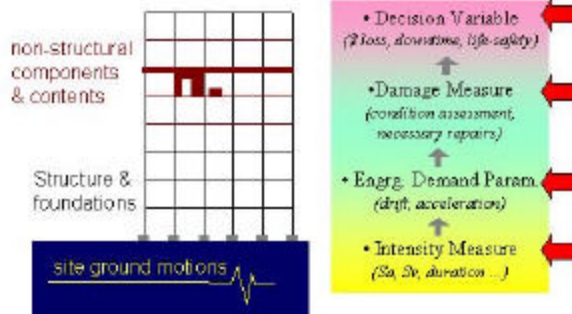
More Explicit Performance Assessment



Key Attributes of Performance Based Approaches

- More Scientific & Transparent
- Address Stakeholder Decision Needs
  - multi-level decision-oriented performance objectives
- Consistent treatment of risk and uncertainties

## PBEE Methodology Components



## PBEE – Probability Framework Equation

$$v(DV) = \iiint G(DV|DM) |dG(DM|EDP)| |dG(EDP|IM)| d\lambda(IM)$$

Impact Performance (Loss) Models and Simulation Hazard

IM – Intensity Measure  
EDP – Engineering Demand Parameter  
DM – Damage Measure  
DV – Decision Variable

**Implementation Through LRFD-like Format:**

$$v(DV) = \text{Prob.} \left( \gamma_{DIS} \cdot \hat{D}_{S_a} \leq \phi_c \cdot \hat{C} \right)$$

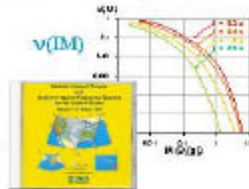
(e.g., Mean Annual Loss, Mean Annual Repair Cost, etc.)

## Hazard Intensity Measure (IM)

Current Practice: Spectral Acceleration  $S_a(T_1)$

### USGS Hazard Curves

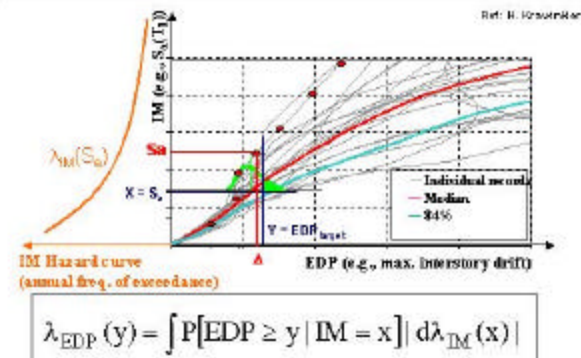
Map of Peak Location  
Likelihood of Peak Exceeds program (see end location)  
Probabilistic Magnitude Prediction (PM)  
Database (Data File)  
Attenuation Relationship:  $S_v(T) = f_m(MCL, T, r, LL, \dots)$



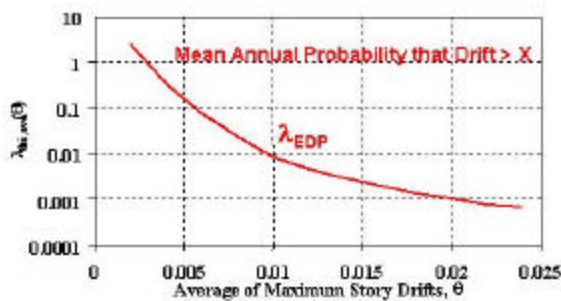
Static Analysis:  $V \propto S_o(T_1)$

Dynamic Analysis: scale records to  $S_o(T_1)^p$

## IM to EDP via “Incremented Dynamic Analysis”



## EDP Hazard Curve (Interstory Drift)

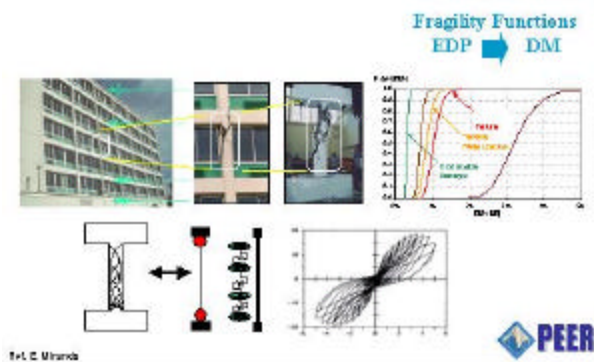


Ref: H. Kraussner

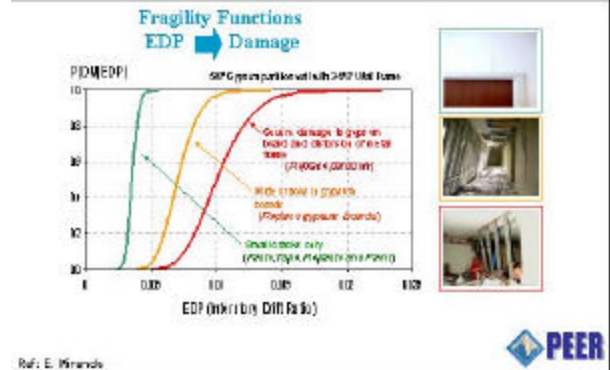
## Damage Measures

- EDP  $\Rightarrow$  Physical Condition  $\Rightarrow$  Consequences
- Physical Condition**
  - cracking spalling, rebar buckling, ...
  - component failure, tipping, ...
- Consequences**
  - repair measures (minor to major replacement)
  - life safety issues (e.g., chemical release, falling hazards, etc.)
  - functionality (e.g., bridge alignment)

## Damage Measure of Structural Components



## DM of Nonstructural Components



## Performance Assessment & Decision Making

### Damage to Decision Variables:

Casualty Rates (Risk of Injury)

Direct Loss (Repairs & Content Loss)

Schedule → Downtime → Indirect Loss



### Decision Process:

Economic Modeling (e.g., Benefit-Cost Analysis)

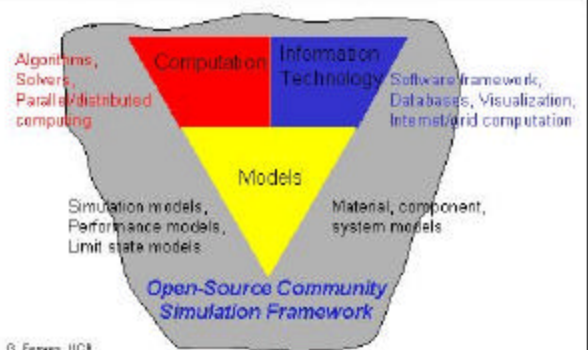
Societal - Political Expectations and Constraints

Risk Management (risk aversion, insurance vs. mitigation, ...)

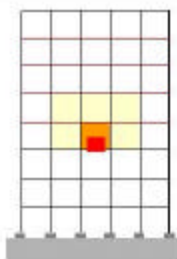
Decision Arena (single facility, multiple facilities, large inventory)



## OpenSees – Integrated Simulation Platform



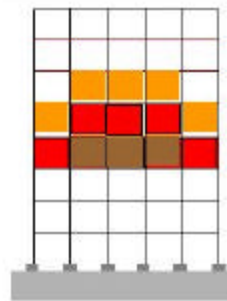
## PBFE Methodology Components



- Decision Variable (Loss, downtime, life-safety)
- Damage Measure (condition assessment, necessary repairs)
- Engrg. Demand Param. (temperature?, deflections?)
- Intensity Measure (Fire Load? Compartment temperature? Material Temperature?)

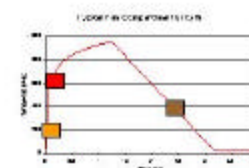
Question: Who is the methodology geared toward - fire modeler, structural engineer, mechanical engineer?

## Fire Performance Simulation



### Fire Scenario & Time History Analysis:

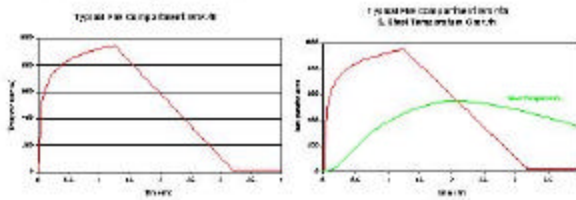
- compartment fire curve (Temp. & Time)
- spatial distribution (spreading)
- temperature of structural members



Question: How to describe each scenario? How many scenarios? How severe?

## Intensity Measure?

- Fire Load, Ignition, Growth Parameters?
  - Fuel load, ventilation, compartment size, ...
- Compartment Temperature (fire curve)?
- Steel Temperature?



## Engineering Demand Parameters?

- Global Deflections (sag, drift, ...)
- Local Deformations (hinge rotations, strains, ...)
- Component Forces
- “Hidden” effects (residual stresses, loss of material integrity, etc.)



BSI Website, 2003

## Structural Simulation (IM to EDP)

- Material and Geometric NL Response
  - member and frame stability
- Temperature Loading Input
  - temporal and spatial
- Temperature Effects
  - thermal expansion
  - material degradation ( $F_y$ ,  $E$ , other ...)

*Question:* How faithfully can (must?) global analysis model localized degradation (members, connections, composite action, ...)

## Damage Measures

- Safety - Collapse or Partial Collapse
- Repair – member distortion, out of plumb, deck debonding, other loss in strength/stiffness



SCI Investigation of Bradford Plaza 2 Fire, 1991

## Decision Variables

- Casualties (injury or death)
  - building inhabitants
  - emergency responders
- Repair Costs
  - contents, nonstructural, structural
  - correlations (water/smoke damage, burning, collapse)
- Downtime (repair time)

*Big Issue:* Risk tolerance (earthquake versus fire)

*Issues:* Minimum protection and benefits of higher performance levels

## Issues and Needs

- Comprehensive Methodology
  - consistency with other hazards (earthquake, wind, ...)
  - consistent with evolving code provisions (e.g., stability)
- Probabilistic Fire Hazard Assessment
  - or scenario (worst case) fire?
- Codification of Acceptance Criteria
  - explicit Decision Variables (casualty, \$, downtime rates)
  - component strength checks (calibrated)
  - survival duration
- Structural Simulation Tools
- Validation (lab tests and field reconnaissance)

Q. A Consultant's Wish List for a Numerical Model of Structural Response to Fire Conditions  
 Barbara Lane, Arup Fire  
 London, UK

**A wish list of items to develop a numerical model for structural response to fire conditions - a consultant's view**

Barbara Lane PhD  
 ArupFire

ARUP

**Overview**

- > The current status - a need to establish agreed concerns?
- > Components for a numerical model of structural response to fire conditions - status of current models
- > The wish list...

ARUP

**Agreed? Concerns with the Standard Test**

- > Temperature / time relationship not the same as real fire behavior
- > Structural response AND fire protection materials response
- > But what about huge body of data existing?
- > How can we (Should we??) relate this data to a numerical model for structures in fire?
- > Do we need a new test?

ARUP

**Agreed? Mechanical response not addressed**

- > Single elements tested
- > In general single elements "analyzed"
- > So real frame behavior ignored
- > For example:
  - > Effects of restrained thermal expansion
  - > Load transfer through connections to cooler elements
  - > Slab action identified in the Cardington tests as key to increase in overall strength of composite frames in fire
- > But what about other assemblies - non Cardington frames?
- > Single element analysis cannot capture these responses - is this the case?
- > Current FE modeling techniques just beginning to capture complex responses - but not part of "mainstream" design work

ARUP

**Advanced Calculation Models**

- > In Europe principles laid out in, for example:
  - > Eurocode 3 Part 1.2 Structural fire design
  - > CIB W014 Rational Fire Safety Engineering Approach to Fire Resistance in Buildings
- > In USA:
  - > Subject of AISC work, ASCE/SFPE work, new NIST program of work

Information required:

Reference document for consultants, authorities having jurisdiction etc

Stating design objectives, means of achieving acceptable results

ARUP

**Summary of Advanced Method**

1. Thermal Action/Design Fire

Do we:

- Create new standard fire resistance test?
- Use temperature-time relationships from real fire data?
- Use Natural/Real fire calculation; fire load, ventilation, boundary properties etc?

Information required:

- Clear guidance on design basis fires

ARUP

## Summary of Advanced Method

### 2. Thermal Response

Using defined design fire, calculate heat transfer to structural elements

Results in a temperature field in each structural element

#### Information required:

Have existing heat transfer models been assessed?

Do we need new heat transfer model for current construction materials?

To what detail do we need a temperature profile along the length and through the cross-section of each structural element?

How do we assess protected structural elements?

ARUP

## Summary of Advanced Method

### 3. Mechanical Response, as a result of design fire

Structural elements losing strength and stiffness

Restraint to thermal expansion produces compression forces

Higher restraint leads to greater deflections

Through depth thermal gradients imposing curvature (bowing)

Combinations of thermal expansion, bowing and restraint conditions can produce large range of deflection and internal force patterns

ARUP

## Summary of Advanced Method

### 3. Mechanical Response, as a result of design fire

#### Information required:

What model captures these effects for all construction assemblies?

Is there a means of carrying out a single element analysis that summarises these effects?

Can these models be translated into simple tables for mainstream design?

How can we incorporate the new understanding and future understanding into existing building codes?

ARUP

## Existing Numerical Models

It is not simple

Intensive work for 10 years in Europe only starting to make progress now

Essential to build on this work rather than start again

Not in format at this time that is useful in a design office

ARUP

## Status of current models

- Vulcan - University of Sheffield
- Composite steel framed buildings only
- Validated using Cardington results
- Geometric and material nonlinearities included
- Plate elements used to simulate floor slabs
- Stress resultant issues?
- Shear connectors incorporated using?
- Beam-column element to simulate beams and columns
- Spring elements to simulate steel-to-steel connections
- Reinforcement modelled?
- Heat transfer analysis not part of Vulcan - data incorporated from other sources
- Temperature non-uniform through cross-section but not along length for steel? Same for concrete??
- Implicit analysis

ARUP

## Status of current models

- ABAQUS - University of Edinburgh
- Composite steel framed buildings only
- Validated using Cardington results
- Geometric and material nonlinearities included
- Shell elements used to simulate floor slabs
- Stress resultant approach to describe behaviour of shells
- Shear connectors incorporated using rigid elements
- Beam-column element to simulate beams and columns??
- Pins used to model steel-to-steel connections
- Reinforcement included in slab as a smeared model
- Heat transfer analysis part of ABAQUS but not used by Edinburgh - Eurocode for Steel, HADAPT for concrete
- Temperature non-uniform through cross-section but not along length for steel
- Linear through depth gradient assumed for slab heating??
- Implicit analysis: ABAQUS explicit now exists

ARUP

### Status of current models

- SAFIR, CTICM models should also be reviewed
- What about explicit models such as LS - DYNA?
- Each element solved individually - can assess collapse even when some components no longer have stiffness
- Can cope with highly non-linear problems
- More computing power and time required
- Thermal analysis possible in parallel with mechanical analysis

#### Information required:

Capability of each model to date - what it can and cannot do, what aspects of each model holds the advantage?

ARUP

### This wish list...

- Agree concerns/issues/inaccuracies
- A reference document laying out acceptable principles required for AHU, consultants etc
- Establish design fire - criteria/data/model/input for codes
- Establish heat transfer analysis capabilities
- Compare and contrast existing 3D FE models
- Further develop these models to address complex behaviours associated with structural response to fire - not just Cardington type frame, not just office fire load, etc
- Develop commercially possible analysis tools - is it possible to reduce time/complexity of analysis once further understanding obtained?
- Develop means of translating results into quantifiable results for Building Codes, into simple design methods

ARUP

## R. Summary of Red Breakout Session

### Priority List

- Communication between disciplines/AHJ etc
- Catalogue of design fires
  - Data from full-scale validation fires
- Review of predictive tools
  - fire, structural, material models
- Test methods and database of material properties at elevated temperatures
  - fire resistive materials and structural materials
- Assemble steering committee - performance, economic benefits
- Assemble themed development teams
- Model for structural response to fire
- Transfer responsibility for fire proofing from architect to FPE/PEs

### Limitations/research needed

Communication between disciplines - NEW ITEM

- fulltime positions at NIST
- educating younger designers etc
- Info to AHJ, structural engineers etc
- publishing now and future work
- development team - fire modelers, structural engineers, computer scientists and material scientists
- steering committee to define goals and objectives

Materials

- Clarify what we know
- set of thermal/physical properties
- standardized tests to achieve these
- Information on durability and reliability
- What maintenance is needed to achieve a given level of reliability
- Impact of materials on fire safe environment
- understand technical basis behind current prescriptive requirements
- Need total evaluation system
- concrete NB

### Limitations/research needed

Installation

- assess effects of material variability on installed performance

Test methods

- lack of understanding of science underlying existing methods and use of data derived
- Extrapolations of single element test to complex assemblies
- Many current test methods not well suited to collecting useful data
- new fire tests addressing the gaps
- using existing tests and current data essential

### Limitations/research needs

Predictive tools

- over reliance on empirical data, lack of scientific basis
- integration of gas phase models with structural models
- state of the art review and summary of existing tools
- develop public sector models for prediction of material properties
- full scale fully instrumented validation tests with interaction between modellers and experimentalists

### Research needs

Predictive tools

- Review fluid/structure interaction models within AND outside fire community
- Define a design fire
- Develop first stage prototype simulation methodology joining a selected specific choice of existing software for:
  - fire simulation
  - thermal/mechanical properties
  - structural response
  - incl. validation and performance ideas
- need practical predictive tools for progressive collapse in fire (based on existing models?)
- extend capabilities of current CFD models to better address flashover conditions

### Limitations/research needs

Maintenance and Inspection

- formal inspection and maintenance procedure for passive fire protection systems - prior to occupancy and throughout service life
- explore potential for smart buildings
- need information on time dependent degradation of passive systems



## **Funding/collaboration**

### **Primary need for Government funding**

results need to be public not favor a particular industry/business

### **Sweat equity from business/industry through Prof/trade**

### **Lobbying congress**

### **Associations**

Architects

AHJ

Insurance groups

Europeans but US must take the lead

FEMA, Fire Service

ASCE, AISC, ASME, SFPE, Trade groups, AIA

## S. Summary of Blue Breakout Session

### End Products

- Validated Engineering Tools
- Design Framework for new construction
- Design for retrofitting existing construction
- Integration of structural and fire: performance based design
- Education of engineers, designers, AHJs (Make them work together)

### Predictive/Design Tools

- **Fire Growth** – we could use approaches such as
  - Stick with specified, space independent model
  - Use simplified approach (including space/opening effects)
  - CFD Model
    - Can't be used for direct routine design but can be used to develop design tools and for special design issues
- **Bottom line, need to establish and define need based approach**

### Uncertainty/Reliability

- How much uncertainty is acceptable, i.e. sensitivity of response to the uncertainty
  - Depends on objective
- Development of a standardized process for uncertainty quantification and analysis techniques
- Integration of fire mitigation strategies

### Predictive Tools, cont.

- **Heating of the Structure – Insulating and fire proofing materials**
  - Need to be able to demonstrate stickability (mechanical performance)
  - Need information to determine destructive decomposition (mechanical and thermal) of materials such as mineral wool and fiberglass
  - Need thermal properties as a function of temperature and temperature rise
  - Need answer to importance and role of geometric issues (containment issues)

### Predictive Tools, cont.

- **Heating of the Structure – Structural Materials**
  - Thermal/mechanical properties as a function of temperature and temperature rise
    - Steel, A36 and similar (what are similar, for example HSLA) – creep at very high temperature
    - Special steel (light gage steel, high strength/performance steels, welds, bolts, rebar, pre-stressing) – all properties
    - High Strength Concrete –
    - Nominal Strength Concrete –
    - FRPs, Aluminum, timber, glass etc – all properties

### Predictive Tools, cont.

- Validation of existing structural response tools for assemblies (including connections) and systems under fire conditions (including soot and other fire phenomena effects)
- Development and validation of structural response engineering sub-models for specific fire phenomena
- Fire barrier analysis and design

## Predictive Tools

- Structural Response
  - Need incorporation of high strength concrete behavior in analysis and design
  - Need knowledge to develop a simplified model; this then needs to be validated
  - Need to know how to apply the “fire load” as a load combination to the entire structure.
  - Need to define design limit states (i.e. objectives of design)

## Other Objectives

- Develop performance criteria for insulating materials
  - In service issues including impact
  - Maintenance and inspection over the life of the structure
- Develop performance criteria for structural materials, products and systems

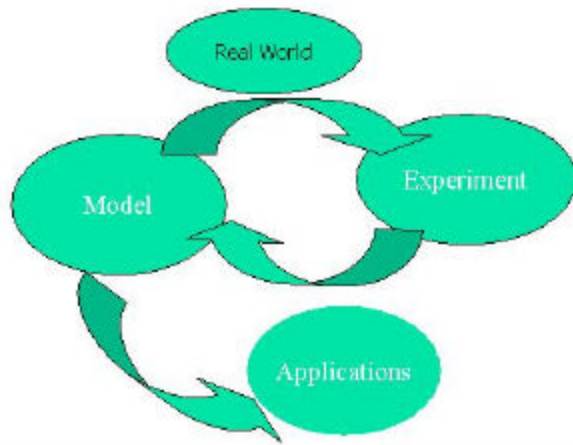
## Experimental Studies

- Establish methods for validation
- Develop improved fire measurement technologies, esp. heat transfer
- Evaluate use of existing ASTM standard for fire model validation
- Develop standardized test methods for material property determination
- Develop standardized test methods for structural components such as connections.

## Validation

- Round Robin testing of models and experiments including material measurements

## T. Summary of Green Breakout Session



### Needs

- Fire exposure
- Thermal response
- Structural response
- Mitigation strategies
  - Redundancy
  - Prevention
    - Design with fire safety in mind
- Communications
  - Engineers
  - Consultants
  - Regulators



### Fire exposure

- Instrumentation of real fires to obtain better
  - Fuel load characterization
    - Impact of spatial distribution
  - temperature/oxygen histories
  - Heat flux
  - Products of combustion
  - Full cycle (heating and cooling) data
- Model behavior of non-structural elements



### Thermal response

- Material properties, particularly of slabs
  - Data base of existing properties
- Dehydration and cracking need to be understood
- Impact of fireproofing materials
- Improved high temperature performance/data
  - Modification of HSC (polymer inclusion)
  - Composite
- Hysteresis (Short-Hot vs Long-Cool)



### Structural response

- Deflections and stresses
- Connections
- Fire proofing materials
- Heating and cooling cycles
- Coupling fire and structural models
  - Zone with frame models



### Multiple level of models

- Couple models with experiments
  - validation of models
  - design of experiments/measurements
- Models of fundamental properties
  - Computational chemistry, molecular dynamics, crack development
- Models of pyrolysis behavior
  - Impact of exposure history
  - Product distribution: heating content, environmental impact
- Models of behavior under prescribed temperature/oxygen histories
  - Zone models
  - Need to model non-loading (glazing) as well as load-bearing
  - Detailed CFD/Finites element models



## Validation/Measurements

- Fundamental properties
  - Particularly **effect of temperature**
  - Constitutive properties of slabs (concrete)
- Single step experiments
  - Ignition, fire spread
- Multiple step experiments
  - Corner fires
  - Flash over
- Integrated tests
  - Enclosure tests
  - Building fires
    - Proper instrumentation to capture spatial and temporal aspect of fires
    - Non-structural components, e.g., glazing behavior
    - Local stresses and deflection
    - Heat transfer through connections
- Real world
  - Characterize real world buildings from a fire perspective
  - Document data from accidental fires



## Performance Objectives

- Performance prediction
  - Test conditions versus real world
  - Temperature time curves
    - Real world has dimensionality, which has important implication that determines the response
      - e.g. plume impacting on the ceiling has not deconvoluted convection and radiation; problems of flash over; impact of air availability
    - Need to translate test results into real world situations
      - Integrity of fire walls major factor
      - Fire test data need to be used to validate models
      - There is need of data on more complex structures
      - Need to have data from small, to intermediate, to full scale