NIST GCR 04-872

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

Building and Fire Research Laboratory
Gaithersburg, Maryland 20899-8600

Fire Protection of Structural Steel in High-Rise Buildings

Michael G. Goode, Editor

NIST GCR 04-872

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

Building and Fire Research Laboratory
Gaithersburg, Maryland 20899-8600

Fire Protection of Structural Steel in High-Rise Buildings

Michael G. Goode, Editor
Civil Engineering Research Foundation
1801 Alexander Bell Drive, Suite 630
Reston, VA 20191-4400

Prepared For:
Paul D. Domich
Building and Fire Research Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899-8600

Under Contract 50SBNB0Cl018

July 2004

Foreword

The National Institute of Standards and Technology (NIST) develops and promotes measurement, standards, and technology to enhance productivity, facilitate trade, and improve quality of life. In the aftermath of the attacks of September 11, 2001, NIST has taken a key role in enhancing the nation's homeland security. Through projects spanning a wide range of research areas, NIST is helping millions of individuals in law enforcement, the military, emergency services, information technology, the construction industry, and other areas to protect the American public from terrorist threats.

NIST's Building and Fire Research Laboratory (BFRL) has as its mission to meet the measurement and standards needs of the building and fire safety communities. A key element of that mission is BFRL's commitment to homeland security. Specifically, the goal of BFRL's homeland security effort is to develop and implement the standards, technology, and practices needed for cost-effective improvements to the safety and security of buildings and building occupants, including evacuation, emergency response procedures, and threat mitigation. The strategy to meet this goal is supported by BFRL's:

- research and development (R&D) program to provide a technical foundation that supports improvements to building and fire codes, standards, and practices that reduce the impact of extreme threats to the safety of buildings, their occupants and emergency responders; and

- dissemination and technical assistance program (DTAP) to engage leaders of the construction and building community in implementing proposed changes to practices, standards, and codes. DTAP will also provide practical guidance and tools to better prepare facility owners, contractors, architects, engineers, emergency responders, and regulatory authorities to respond to future disasters.

This report, prepared for NIST by the Civil Engineering Research Foundation, was funded by DTAP. This report discusses three important topics in the Fire Protection of Structural Steel in High-Rise Buildings. The first is an overview of the current state-of-the-art in fire protection technologies for structural steel. This includes the range of fire protection technologies, a discussion of which technologies are commonly used today, how they work, their advantages and disadvantages, and some of their primary applications. The second is an overview of the standards and performance requirements for the fire resistance of structural steel in high-rise buildings. The final topic discusses the requirements for test beds and test methods intended to evaluate the fire endurance and performance of structural steel. These three topic areas served as the framework for discussions at a workshop held at NIST on February 5 & 6, 2004. The workshop participants, representing a broad range of stakeholder groups, discussed these issues at length and made recommendations for future work in this important area.

An earlier workshop also sponsored by the National Institute of Standards and Technology's Building and Fire Research Laboratory was held on October 2 & 3, 2003, in Baltimore, MD, and was titled "National R&D Roadmap for Structural Fire Safety Design and Retrofit of Structures: A Report of a Workshop Sponsored by the National Institute of Standards and Technology". The conclusions and recommendations from these two studies provide important perspectives in understanding the future work that is needed for developing and implementing new technologies, materials, and systems for the protection of structural steel in high-rise buildings; and better guidelines and practices for their design development.

Paul D. Domich
Building and Fire Research Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899-8600

Abstract

This report summarizes activities, conclusions and recommendations of the National Institute of Standards and Technology (NIST) sponsored study on fire protection of structural steel in high-rise buildings. The report includes an overview of existing, new, and potential materials, systems, and technologies for fire protection of structural steel. We provide an overview of the current requirements and a review of the evolution of these performance requirements for building construction, and a discussion of appropriate test methods and procedures to evaluate fire endurance performance of structural steel. These objectives were addressed in a two-day (by invitation) experts workshop, with the development and priority ranking of recommendations to improve upon the status quo. The top three recommendations are to develop: an improved structural design methodology; improved testing procedures for fire resistive materials, technologies, and systems, and; an acceptance of increased responsibility by building operations and maintenance personnel for sustaining the technologies, systems, and materials that constitute the fire protection system.

Keywords

Fire protection, fire resistive materials, fire endurance performance for structural steel, test and performance evaluation procedures and methods.

Fire Protection of Structural Steel in High-Rise Buildings

TABLE OF CONTENTS

Fire Protection of Structural Steel in High-Rise Buildings

EXECUTIVE SUMMARY

Objectives of Study

This report summarizes activities, conclusions and recommendations of the National Institute of Standards and Technology (NIST) sponsored study on fire protection of structural steel in high-rise buildings. The objectives of this study were four-fold, namely:

1. *Scan for existing, new and potential materials, systems and technologies for fire protection of structural steel.*
2. *Define what performance is really needed from structural steel in high rise buildings; what protection systems for the steel will be required under multiple hazard scenarios, including fire; what performance requirements we must demand of those protection systems, particularly in defense against fire.*
3. *Define how testing is/should be structured (parameters for test samples, test beds and test protocols) in order to reliably predict the performance of materials, systems and technologies in full scale application, given these performance requirements, and*
4. *Frame findings in the context of the marketplace and realistic price/demand considerations.*

These objectives were addressed through an approach that included the development of three white papers, a two-day (by invitation) experts workshop, development and priority ranking of recommendations to improve upon the status quo and, finally, the preparation of this report.

The avoidance of fire within a structure or constructed facility has taken many forms, the most proactive of which has been the search for methods and means whereby the negative aspects of fire within a structure are mitigated or prevented altogether; an elegant and succinct statement of this goal for a building is simply that *Fire Resistance ≥ Fire Severity*. To achieve this result requires a robust basis upon which both sides of the inequality can be evaluated.

Although history has shown that the statistical risk of life and limb from fire in structural steel high-rise buildings is very small, we now know with certainty that fires, including those in high-rise steel frame buildings, may also be the consequence of other hazards, both natural and man-instigated. The horrific but, as yet, singular example of this is the fire component of the 2001 World Trade Center terrorist attack.

Study Recommendations

The workshop resulted in a prioritized list of recommendations. We group the recommendations into the following action plans with suggested assignment of responsibility for the actions.

Improved Structural Design Methodology

There is a need to take a holistic approach to integrating thermal loads and effects of fire into the analysis and design of steel structures. Analysis and design should no longer focus on simply providing fire rated construction based on fire resistance testing of single elements such as a column, beam or floor assembly. Methods should be developed with the fire protection engineering community such that the response of the entire structural system to design fire scenarios would be considered. Such methods should be developed as a component of a Multi-Hazard design approach, and requires collaboration among architects, structural engineers, fire protection engineers, and other professionals in the design process. We recommend that the architecture and engineering professional communities in conjunction with industry, address this need with NIST/BFRL maintaining a facilitation role. This initiative fits within BFRL activity as part of their oversight of the WTC studies, is part of their mission of promoting advances in fire safety and protection, and will also be a key element of the NIST National R&D Road Map in this domain.

Improved Testing for Fire Protection Materials, Technologies, and Systems

The current approach provides a set of barriers to innovation. The overly simplistic ‘fire rating’ system is not useable for many new systems and products. It also does not support the need to conduct holistic modelling of combined performance (protection system and entire structure) under varying types of fire conditions. Codes also are too simplistic for special buildings. Ensuring that test beds and test methods accurately measure and predict expected performance in the field environment is another key conclusion from this study. We recommend that NIST/BRFL continue to advance the correction of these shortcomings to enable the entry of innovative methods and materials into the fire protection arena by fostering better definition of performance requirements and testing programs tailored to demonstrate this performance. We recommend that the code developing organizations provide for special buildings to be defined and permitted outside the boundaries of current codes and standards. We urge that both these elements also be included in the NIST National R&D Road Map.

Charging Building Operations and Maintenance Functions with Sustaining the Technologies, Systems, and Materials that Constitute Elements of the Fire Protection System

Workshop participants observed that there are not only problems of quality in the installation of fire protection systems that severely compromise their effectiveness, but also problems of maintaining these systems through the life-cycle of the building. We recommend that the professional societies and NIST/BFRL work with industry and the code enforcement jurisdictions, the insurance companies, and the building owners, to establish a standard of care for maintenance of fire protection systems.

Maintaining Stakeholder Involvement in Development of Improved Methodologies

Movement toward change in standard of care, design protocols, codes and standards and material and systems testing, creates substantial upheaval among stakeholders in the design and construction activity of the building industry. Although the prospect presently is that substantial change need only take place initially in the design approach for the special buildings category – those exceptionally tall or otherwise unusual buildings, there will likely be evaluation and incremental application of change in the fire ratings system for testing and approval of materials, systems, and technologies used more universally. The champions and stewards of such changes have a special responsibility to secure ownership of, and consensus around the proposed changes among all the stakeholders. The professional societies and NIST have a shared responsibility to work with industry to make this happen as they champion change in design, construction, and maintenance practices.

Providing Incentives for Improved Approaches to Design, Construction, Maintenance for Hazard Resistance in Buildings

Through history there have been incentive systems promulgated by the indemnity industry to encourage building owners to make their buildings safer. The workshop participants encouraged development of a rating system that would take into account, design to a higher fire resistance level. The concept is that such investment by the building owner to achieve additional protection warrants a reduction in building insurance premiums consistent with the reduction in risk. This effort should be a collaboration among the owners, the insurers, and the design professionals.

Adjustments in Professional Education to Adapt to Multi-Hazard, Holistic Approaches to Design, Construction, and Maintenance of Buildings

The Workshop participants recommended that the collaborative, multi-disciplinary design approach among architects, structural engineers, and fire protection engineers necessary to achieve the holistic, multi-hazard standard, be embraced in the curricula of engineering and architecture schools. Further, graduate and post-graduate programs should be designed to promote the cross-disciplinary approach among these areas of study. This should be championed by the education arms of the professional societies with the support of NIST.

Call To Action

In summary, only the will to proceed is required for action. The National Institute of Standards and Technology must support these actions through their funding and as a catalyst and facilitator for change.

Fire Protection of Structural Steel in High-Rise Buildings

Objectives of Study

This report summarizes activities, conclusions and recommendations of the National Institute of Standards and Technology (NIST) sponsored study on fire protection of structural steel in high-rise buildings. The objectives of this study were four-fold, namely:

1. Scan for existing, new and potential materials, systems and technologies for fire protection of structural steel.
2. Define what performance is really needed from structural steel in high rise buildings; what protection systems for the steel will be required under multiple hazard scenarios, including fire; what performance requirements we must demand of those protection systems, particularly in defense against fire.
3. Define how testing is/should be structured (parameters for test samples, test beds and test protocols) in order to reliably predict the performance of materials, systems and technologies in full scale application, given these performance requirements, and
4. Frame findings in the context of the marketplace and realistic price/demand considerations.

These objectives were addressed through an approach that included the development of three white papers, a two-day (by invitation) experts workshop, development and priority ranking of recommendations to improve upon the status quo and, finally, the preparation of this report.

Introduction

The fear of uncontrolled fires and the desire to avoid their consequences is as ancient as human civilization; certainly, the nature, causes and scope of such events have changed considerably over millennia but fear and avoidance have remained as a primary human reaction and as an important human objective, respectively, for virtually every society.

The fear of uncontrolled fire has obvious, enduring roots: fire is a taker of human life and a destroyer of human assets.

The avoidance of fire within a structure or constructed facility has taken many forms, the most proactive of which has been the search for methods and means whereby the negative aspects of fire within a structure are mitigated or prevented altogether; an elegant and succinct statement of this goal for a building is simply that *Fire Resistance* ≥ *Fire Severity*. To achieve this result requires a robust basis upon which both sides of the inequality can be evaluated.

Unlike so many other adverse aspects of human life, the incidence and consequences of fires has not lessened, in aggregate, as technology and knowledge have advanced. Indeed, as the human condition has improved (often in dramatic ways as, for example, in disease elimination, habitation and transport) the potential causes for unwanted, uncontrolled combustion have grown as well. Fortunately, individual precautions and collective protection, such as communal fire fighting capabilities, are critical factors in minimizing the number of incidents and their impact. Even so, fires are enormously destructive! In 2002, according to the National Fire Protection Association (NFPA), there were almost 1.7 million fires reported in the United States, causing property losses estimated at $10.3 billion. Most tragically, these fires resulted in 3,380 deaths and over 18,000 injuries. One hundred firefighters lost their lives while battling these fires. Fires killed (as well as injured) more Americans than all natural disasters combined in 2002; this statistic is an unfortunate norm.

The consequences of fires in the United States are also selective! In 2002, twenty percent of fire deaths occurred in other-than-residential occupancies while non-residential fires accounted for over 26 percent of the 2002 estimated property loss.

A relatively small subset of non-residential structures has the distinction of causing the most apprehension with respect to fire. These are “high-rise” structures. What are they and, why is this so?

“High-rise” as a definition is, if anything, elastic. Ask the average American and the answer is likely to be a very tall building, with the center of any large metropolis as a central image. At the other extreme may be any structure high enough to warrant elevators. For the purpose of this study, a “high-rise” building was considered as defined by the National Fire Protection Association study of high-rise fires (*High-Rise Building Fires, 11/03, NFPA Fire Analysis and Research, Quincy, MA*). That study cites paragraph 3.3.27.7 of the *Life Safety Code*® 2003 edition, in which a high-rise building is defined as a structure more than 23 meters (75 feet) in height as measured from the lowest level of fire department vehicle access to the floor of the highest occupiable story. Within this definition are four sub-categories: 7-12 stories, 13-24 stories, 25-49 stories and 50 or more stories. There are also four property classes: apartment buildings, hotels and motels, hospitals and other facilities that care for the sick, and office buildings.

The NFPA study notes that within the high-rise building categories, one category is the most fire prone: apartments. The study estimates that 734 deaths occurred in high-rise apartments between 1985-1999; in contrast, during these 15 years there were 40 deaths in hotels/motels, 31 in hospitals and related facilities and 7 in high-rise office buildings.

The NFPA study also demonstrates the special concern that exists for fire in high-rise buildings, concerns that are reflected in more stringent code safety requirements. A modest seven percent of the total (43) annual deaths occurred in high-rise apartments; 5.6 percent of this total occurred in buildings with 7-12 stories, 1.2 percent in buildings with 13-24 stories and 0.2 percent in buildings exceeding 25 stories. The data for hotels/motels is even more striking; an average of 3 deaths per year, with 2 occurring in 7-12 story buildings, 1 in the 13-24 story category and none in taller buildings. Two deaths per year was the average for hospitals and related facilities, both occurring in the 7-12 story category. High-rise office buildings averaged less than one death per year during 1985-1999.

We now know with certainty that fires, including those in high-rise steel frame buildings, may also be the consequence of other hazards, both natural and man-instigated. The horrific but, as yet, singular example of this is the fire component of the 2001 World Trade Center terrorist attack.

Given the intrinsic concern about fire and the potential devastating impact of fires in high-rise steel framed buildings, does past experience and the future prognosis, including multiple-hazard scenarios, mandate actions to improve the fire safety protection for this class of structures?

If so, how do these actions correlate to the objectives established by NIST for this study? Further, which actions deserve priority status and how can those actions be accomplished? These issues are the focus of the sections that follow.

Objective 1: Materials, Systems and Technologies

This study objective was addressed in a white paper authored by Chris Marrion, M.Sc., P.E., Richard L. P. Custer, M.Sc., FSFPE, Matt Johann, M.Sc., and Brian Meacham, Ph.D., P.E., of Ove Arup & Partners Consulting Engineers PC. The full text of this comprehensive white paper follows in this section.

Introduction

This report provides an overview of the state-of-the-art in fire protection technologies for structural steel. An overview of the field of fire protection technologies, including a discussion of which technologies are commonly used today, how they work, their advantages and disadvantages, and some of their primary applications are presented.

Leading technologies are also discussed with regard to the newest technologies available on the market today, their use, limitations, and barriers to their increased implementation.

Current research and development efforts are discussed. Included are discussions of new areas and technologies that are being explored for the fire protection of steel structures, specific challenges and issues these technologies are intended to address, and possible impacts that these technologies may have on current practices.

It should be noted that this report is not intended to recommend one protection technology over another for any or all applications. Further, this report acknowledges that many common and simple protection technologies have been available within the industry for many years, and have served the building industry well for that time. There are, though, a few new technologies that currently exist in the field of structural fire protection materials. However, advancements are coming in design approaches and techniques, and these may have a significant positive impact on the industry.

Field Overview

There are numerous fire protection technologies currently available for protecting structural elements during a fire and providing a fire resistant rating. These use different methods to achieve their fire ratings including directly applied materials that insulate the steel, membrane protection, and more 'active' type systems that intumesce, block radiation, discharge water, or circulate water to cool the structure.

The following provides a brief overview on materials currently in use with discussions as to their performance for different types of fires, as well as other factors that may impact their use and choice.

It is important to understand what the performance criteria are intended to be when selecting a particular material or method, including exposure fire, duration, aesthetics, cost, maintenance, blast/impact resistance, etc. As there are numerous stakeholders (architects, owners, insurers, manufacturers, etc.) involved in a project, each with their own desires for performance criteria, (which may often compete with each other), these criteria should be discussed during selection of appropriate materials.

Insulation Technologies

Overview

Application of insulating materials is one of the most common means of protecting structural members from fire. Insulation protects the structure from direct fire exposure, and also has low heat conduction properties such that the time required for heat to transfer to the structural element is increased. In the past, various materials, including concrete, brick, tile, and asbestos, were quite prevalent because they perform well at elevated temperatures. In the past, the mineral fiber asbestos was used with a cementitious binder and sprayed onto structural elements to provide fire protection.

It was also combined with other materials to make asbestos board and asbestos wood. Due to health hazards associated with construction and occupancy periods, asbestos has been banned.

Gypsum is a very good insulator. It contains a high percentage of water that is chemically combined with the calcium sulfate (gypsum) base, and a large amount of energy is required to dehydrate and evaporate this water. This makes gypsum a good and relatively inexpensive fireproofing material.

Some of the more popular technologies for using insulation to protect structural elements are discussed below. These are typically used in commercial buildings, residential, hospitals, factories and schools. The performance of these systems is dependent on a number of factors including installation and method of attachment. If these become damaged, their fire rating can be adversely impacted.

Concrete Encasement

One of the more traditional methods of protecting structures involves encasing the steel member in concrete. Concrete is a good thermal insulator (thermal conductivity of 1-3W/m.K). It therefore delays heat transmission to adjacent structural elements. Increasing the thickness of the concrete increases the time required for heat to transfer to the steel. Lightweight systems such as boards, sprays, and intumescent paints have caused a decrease in the use of concrete encasement, along with that of concrete block work, brick, masonry, and tile encasement.

Depending on the thickness of the concrete, reinforcing may be necessary. When reinforced, the concrete may also at times be used to carry part of the load. This type of protection is very common in Japan, UK and the USA.

In addition to ordinary concrete encasement, autoclaved aerated concrete (AAC) is a concrete material that uses widely available concrete constituents (sand, cement, lime, gypsum and water) with an expansion agent that after heat treating under pressure results in a finished product that is up to five times the volume of the raw materials and has an air content up to 80 percent in a closed cell structure[1].

This type of material has achieved up to 4-hour UL fire resistance ratings in the ASTM E-119 furnace test. It is lightweight and has high strength and can be made in slabs that could be used for enclosure of structural elements or possibly applied directly to steel prior to the autoclaving process.

One of the most important advantages of this method is its durability. Concrete encasement performs very well in environments where resistance to impact, abrasion, weather exposure, and corrosive agents is important. Applications can include interior or exterior components. Typical applications therefore include car parks, external structures, oil drilling platforms, and warehouses.

Additional research is needed, particularly with regard to the effects of spalling on the overall fire rating as this is typically not addressed and may have an adverse impact on overall performance. Research that uses fibers in concrete to assist in enhancing performance should also be further assessed.

Concrete encasement has some notable disadvantages, however:

Aesthetics – many people find the aesthetic quality of concrete to be poor.

Space requirements – the required thickness of concrete may take up valuable space around structural elements.

Installation/application – concrete encasement is time consuming to install on-site. Off-site installation may be possible, too.

Weight – concrete is heavy and can increase the overall weight of the building. Transport and handling for off-site materials are difficult as well.

Cost – concrete encasement is relatively expensive.

Durability during fire – concrete encasement, like structural concrete, is susceptible to spalling.

These disadvantages can frequently limit the application of concrete encasement for protective purposes.

Insulating Board Systems

Insulating board systems are typically slab-type materials made from calcium silicate, gypsum plaster[2] or mineral fiberboard with resin or gypsum, and may contain lightweight fillers including vermiculite. They are typically attached to metal or wood framing, which is then attached to the structural member.

Insulating board systems can achieve fire ratings of up to four hours. Thermal conductivity is often in the 0.1 W/m.K to 0.2 W/m.K range. The required number and thickness of the boards is dependent on the fire rating required and the type of board material being used. Thickness for protecting an I-section with Hp/A (Perimeter / section area) = 150 m^{-1} to achieve a one hour fire rating is approximately 15 mm to 20 mm, while for two hours the thickness is 25 mm to 40 mm. Empirical formulae to calculate the thickness of the gypsum board for a particular fire rating are available[3 4 5], and details for various fire rated assemblies are provided in the UL Fire Resistance Directory and manufacturers' catalogues.

Board manufacturers produce some systems for cellulosic and some for hydrocarbon fire protection and blast resistance.

Gypsum board is less expensive than calcium silicate, as calcium silicate typically is only exported from a few countries. Gypsum board's insulating properties are better than calcium silicate because it contains more water, and thus the time needed to heat the gypsum boards up and evaporate the water is greater than that for calcium silicate boards. However, loss of water also adversely impacts the strength of the remaining gypsum board.

Insulating board products are more typically applied to columns than beams due to aesthetic reasons and the fact that beams are not always visible in the finished building environment. They are also used for other applications including protecting ducts and fire rated barriers.

Advantages of insulating board systems include:

Aesthetics – board systems provide a clean appearance and can be finished/decorated as appropriate.

Steel preparation – boards can be attached directly to bare steel elements with little or no preparation.

Installation – installation is dry versus 'wet', boards are relatively easy to install, and they can be installed with limited impact on other trades. They are also relatively easy to finish off once applied. Off-site fabrication is often difficult.

Quality control – the boards are manufactured off-site where thickness, composition, etc. can be monitored.

Disadvantages of insulating board systems include:

Installation time – board products are often slower to install than some other types of systems.

Cost – board products may be more expensive, particularly where a 'decorative' finish is needed.

Installation – installing around elements and complex details may be difficult.

Maintenance – damage, service penetrations, etc., need to be fixed as they will compromise fire rating.

Performance in Hydrocarbon Fire Scenarios

Insulation board systems have typically not been tested for approval of fire ratings when exposed to the hydrocarbon fire curve. With regard to anticipated performance, plasterboard is likely to dehydrate in a hydrocarbon fire, where it may undergo rapid surface shrinkage due to decomposition of hydrates in the material. As some of these materials have ratings on the order of four hours with the standard cellulosic fire curve, they may provide some degree of protection in a shorter hydrocarbon fire test.

Calcium silicate boards have been tested up to four hours in cellulosic conditions. Like the other board products, moisture is driven off as heating occurs and the surface appearance is degraded. They have lower moisture content than gypsum based products (3-5%), and they maintain their integrity and continue to protect the steel in spite of the small amount of shrinkage that accompanies dehydration.

Impact and Blast Loading

Insulating boards are often mechanically fixed to the structure so the performance of the fasteners and the mechanical properties of the board are more important in the overall performance of the system and its ability to withstand impacts/blasts.

Failure of board systems under a blast load would be anticipated to occur either by pulling away of the boards at the fasteners or debonding/fracture of the board. Additional reinforcement, encasement, etc. could assist in enhancing its performance to blast and impact.

Man Made Mineral Fiber Systems

Man made mineral fiber (MMMF) type systems include those made of mineral wool. These are typically made from fibers of melted rock (97-99% by weight), organic binders and oils. It is often used as thermal insulation, and as fire protection to structural steelwork when bound into higher density slabs using a thermosetting resin.

The board systems can be installed by various means, although the use of stud-welded pins seems to offer the best mechanical properties.

One advantage of these types of systems is that they are not wet systems during installation, and thus they result in less impact on construction and other trades. These systems have relatively low costs when compared to other protection options. The major disadvantage is that they are not aesthetically pleasing and hence are not typically used where the structure may be exposed.

Fire ratings of up to four hours can be achieved through use of these methods. Thickness for an I-section with Hp/A (Perimeter over section area) = 150 m^{-1} is on the order of 20 mm to 25 mm (1 inch) for 1 hour, and 30 mm to 50 mm for 2 hours fire resistance. Thermal conductivities range from approximately 0.03 W/m.K to 0.05 W/m.K.

Performance in Hydrocarbon Fire Scenarios

The performance of MMMF in fire conditions depends on a number of factors. One of the more important conditions is the composition of volcanic rock used to make the fibers themselves as this affects their melting point.

Impact and Blast Loading

The MMMF slabs are not typically designed to resist blasts or impacts. However, providing mesh reinforcement or steel facing may improve their performance over unprotected or un-reinforced material. The influence of such reinforcement on thermal performance would need to be evaluated.

Spray Applied Fireproofing

Spray applied fireproofing materials are typically cement-based products or gypsum with a light weight aggregate (vermiculite, perlite, or expanded polystyrene beads) that have some type of cellulosic or glass fiber reinforcement. Some of the earliest spray applied fireproofing materials contained asbestos, which is no longer allowed due to health issues.

Spray applied fireproofing is typically one of the more inexpensive means to protect structural elements. Thicknesses required to achieve various ratings may be found on a generic basis in some publications[5], but typically are provided by the manufacturer.

Test methods exist to assess the adhesion and cohesion characteristics of the material.

Spray applied products are typically used more to protect beams than columns. However, it is reported that spray protection systems have decreased in popularity in the past decade in the UK, despite being relatively inexpensive.

Advantages include:

Application – it is easy to protect detailed features including connections, bolts, etc.

Installation – spray applied materials are quick to apply.

Durability – some spray applied materials may be used for exterior application, most though are used for interiors.

Preparation – some spray applied materials can be applied to unpainted steel.

Disadvantages include:

Installation – the process is wet and often can be messy, and this can also impact the construction schedule and potentially the overall costs of using this method if it impacts other trades.

Preparation - steel typically needs to be prepared.

Over spraying – protecting on-site areas from overspray is typically required.

Aesthetics – it produces a rough surface finish and cannot be easily finished to meet aesthetic requirements.

Durability – the material is relatively soft and should be protected when in a vulnerable area where contact could damage the product.

Quality control – sometimes difficult, labor intensive and time consuming to adequately control quality of installation in the field.

Performance in Hydrocarbon Fire Scenarios

Spray coatings would provide protection against hydrocarbon-based fires as some of these systems can provide up to a four-hour fire rating. Thicker coatings and more dense materials may likely be necessary. Additional research is needed though to better understand their performance including deformations, brittleness, adhesion, etc at higher temperatures.

Impact and Blast Loading

Spray coatings would likely provide some protection, similar to their performance when exposed to hydrocarbon type fires. However, additional research is needed to better understand their performance including deformations, brittleness, adhesion, etc.

Intumescent Paints

Intumescent paints have been available in Europe for over 25 years, although these materials have been known for centuries[6]. Over approximately the last 10 years, they have seen increased application in the United States[7] and in the UK. The products are broadly similar in terms of testing, performance and applicability among manufacturers.

Intumescent paints have two key components: a resin binder and a mixture of chemicals that decomposes and releases a gas when heated. During a fire, the material melts. A gas-producing reaction is triggered at a temperature corresponding to an appropriate resin melt viscosity, and the release of gas causes the resin melt to foam developing an insulating layer. This then produces a thick char, which insulates the steel from fire. Intumescents may typically expand approximately 15 times to 30 times their initial thickness during a standard fire test.

Intumescent paints can be divided into three broad categories:

- Single part solvent-based
- Single part water-based
- Two-part epoxy solvent free or solvent-based

Solvent-based intumescents are typically used for exterior applications, and are tested against weather, temperature variations, etc. They are also used for interior applications.

Water based intumescents have less odor, however they are less tolerant of humidity and low temperatures.

Intumescents are available in liquid form and are typically applied via airless spray equipment. Smaller areas may be rolled or brushed, however this often does not leave as smooth of a finish.

The required thickness of paint is dependent on the size of the structural element (i.e., structural elements with larger, heavier cross sections may require less insulation than lightweight members). Thickness of the applied intumescent paint materials is typically 0.5 mm to a few mm but can be as much as 5 mm.

The two-part epoxy system is typically used in more harsh environments, including the chemical industry and offshore operations, in areas that may be difficult to access for maintenance, or where high levels of impact damage may occur, and they are more expensive than the other intumescent paints. Additionally, they perform well with regard to hydrocarbon type fires. They are not grouped with the thinner-film intumescent materials due to their epoxy binder; however, the behavior during a fire is similar. The char formed however, is thinner, though mechanically it is much stronger in order to withstand the higher heat flux and erosive gases. The thickness of epoxy coatings is generally thicker, and may be more in the 5 mm to 25 mm range

There are currently debates with regard to advantages and disadvantages of on-site versus off-site application, particularly in the UK. Reasons for increasing off-site applications include:

reduced construction time, improved applicator safety, removal of a wet trade from site, favorable life cycle costs, less dependence on environment conditions for application, and easier to undertake quality assessment. Due to this, manufacturers are developing/refining paints to adjust to this including more volatile solvents for faster drying times.

Advantages include[8]:

> Installation – intumescent paints do not require a significant thickness relative to other materials.
>
> Durability – intumescent coating are typically quite durable, and do not readily flake off when struck. Also, they can be fairly easily repaired.
>
> Application – intumescents are relatively quick to apply. They are good at covering complex structural details. They can be applied on-site or off-site. Being applied off site can lead to decreased construction time[9].
>
> Aesthetics – the relatively thin coating is often aesthetically acceptable and can be left exposed to show the shape of the structure, and also can be given a colored finish.
>
> Maintenance – post installation repairs are relatively easy. Also, intumescent coatings are relatively easy to clean.

Disadvantages include:

> Cost – high relative cost when compared to spray on systems, particularly for higher fire ratings.
>
> Application – goes on wet and hence suitable environment is needed. Also, protection of adjacent areas from overspray is necessary. Solvent-based paints need to be applied in well ventilated areas.
>
> Installation – mechanical damage during installation of off-site prepared materials will need to be made.
>
> Identification – it can be difficult to verify the existence of intumescents at later dates.
>
> Maintenance/Inspections – regular inspections needed. Difficult to assess applied thickness without damaging material.
>
> Fire ratings – coatings typically provide 30 to 120 minutes of protection.
>
> Quality control – important that steel surfaces be appropriately prepared, paint properly applied, etc. and that proper thicknesses are applied.

Performance in Hydrocarbon Fire Scenarios

Intumescent paints are an effective means of providing fireproofing for cellulosic type fires. However, they have typically not been designed to perform in hydrocarbon fires and additional testing is needed under such conditions. One of the properties that needs further understanding is whether the balance between the resin melt viscosity at temperature and gas evolution, that are important for proper char formation, can be achieved under the rapid heating of a hydrocarbon fire. In cellulosic type fires, the charring occurs over the first ten minutes of exposure. However, in the typical hydrocarbon test such as UL 1709 (Standard for Safety for Rapid Rise Fire Tests of Protection Materials for Structural Steel) a temperature of 900 °C is achieved within four minutes.

Performance in a jet fire is also relatively untested, but the expectations are that it may not perform well due to the fact that the char is mechanically weak and rapid erosion may likely occur.

Impact and Blast Loading

Intumescent paints have not been specifically designed to withstand large blast and impact loadings. Prior to September 11, 2001, the manufacturers would likely have had limited incentive to perform such testing. Without such testing, no definitive conclusions regarding their performance can currently be drawn. They may adhere reasonably well during a blast because they are thin and quite flexible, or the bond between the coating and the substrate may be damaged to the extent that the protective layer is dislodged.

Sacrificial Layers on Concrete Elements

In certain situations, it may make more economical sense to effectively over-design concrete members such that the outer, extra layers of concrete act as sacrificial protective layers. Thus, as the fire affects the concrete, the portions that are not critical to the structural system will fail first, increasing the time to failure of the actual structure. Application of such an approach can be seen in the design of tunnels in Australia and elsewhere, and in other types of projects as well.

Protection with Timber

In some countries, timber has been used to provide fire resistance. The timber protects the steel by providing insulation, and charring of wood also assists in providing a thermal barrier. Work by Twilt and Witteveen[10] discusses fire tests and installation details for protecting steel columns with timber. Designers using timber should check to ensure that the steel structure is fully enclosed by the wood, that the wood is firmly secured in place, and that the wood is seasoned in order to limit or prevent shrinkage and cracking, which could reduce the ability of the timber to control heat transfer to the structure

Membrane Protection

Suspended ceilings composed of gypsum panels or lath and plaster can also be used to provide fireproofing. These systems limit heat transmission to the structural element. They can be supported either by a dedicated support system or through suspension from the structural elements above. It is reported[11], however, that the overall effectiveness of such systems may be questionable. This is primarily due to lack of quality control applied during construction and a lack of adherence to proper installation procedures. Specifically, it is important to allow for expansion in the suspension system such that panels do not buckle and dislodge, thus creating openings in the membrane and allowing the transmission of heat to the structure above. Also, there is often electrical, plumbing, and mechanical equipment above ceilings, and access may be made by persons unaware of the fire protection role the suspended ceiling plays. This may result in the improper replacement of the ceiling and the compromising of the membrane. However, it needs to be noted that in cases where the membrane has been properly designed, and effectively maintained, it has performed quite well in protecting the structure. One particular example is the 140 William Street fire in Australia.

Filling

Hollow structural elements can be filled in order to increase the heat capacity of the element, and/or to act as a heat sink. Typically, they are filled with either concrete or water.

Concrete Filling

Steel structural elements that are hollow can be filled with concrete in order to increase their fire resistance. When concrete filled elements are exposed to fire, the heat passes through the steel and begins to heat the concrete. As the yield strength of the steel is reduced, the load is transferred to the concrete. The steel encasement helps limit both direct heat impingement to the concrete and progressive spalling, and reduces the rate of concrete strength degradation. Either plain concrete or concrete w/either fiber or bar reinforcement can be used.

Due to the release of steam when the concrete is heated, it is very important to provide ventilation holes to relieve the pressure.

This method can be combined with other fire proofing methods to assist in reducing the fire proofing that may be required on the exterior of the element.

One advantage of concrete filling is that the steel is exposed and hence can be easily painted. In addition, the concrete can be used to assist in structural support.

Concrete may be reinforced or non-reinforced. If reinforced, it will also be able to accept load transfer from the heated steel column. Design guidance considering this effect is available from various sources[12 13].

Water Filling

Water can also be used to fill hollow structural elements to assist in cooling them. Water can be used in various ways to improve the fire performance of structural elements in the areas impacted by fire[14]. Structural elements can be filled with water to increase the heat capacity of the structure and thus decrease the temperature of the steel. Water can also be circulated through the structure, either mechanically or by the natural movement of the hot water being replaced by the cooler water, to remove the heat from the local heat source, and thus limit the chance of local boiling. Turning the water into steam, which may then rise into tanks to cool and condense, can also absorb the heat energy.

The fire resistance of water-filled elements is dependent on several variables, including the cross sectional area of the hollow void and the amount of water within the void, as well as whether the water is circulating or not.

It is estimated that there are on the order of 40 buildings[15 16], worldwide using water filled structural elements to provide fire resistance. Various design guides are available[17 18 19]. Water can be used to cool various structural elements including beams, columns, and trusses.

In the application of water-cooling techniques, the hollow structural members are either permanently filled, or filled upon detection of a fire. Issues related to freezing, water-filling times, and corrosion need to be considered when choosing between these two options. Durability of the steel is important, and can be enhanced by corrosion inhibitors and/or use of stainless steel pipes. Systems where water is continuously renewed by circulation can have a virtually unlimited fire resistance rating.

Advantages include:

Aesthetics – allows use of exposed steel

Space requirements – does not increase thickness of structural element.

Disadvantages include the following:

Weight - increases weight of structural elements

Durability – limited protection against blast/impact. Corrosion needs to be taken into account.

Maintenance – need to check that piping and system continue to be effective

Design – additional design work necessary to check proper flow of water, appropriate steel, additional pump systems, etc.

Radiation Blocking

Various methods are available for limiting the amount of radiation produced by a fire that reaches a structural element.

Flame Shields

Flame shields can be used to protect structural elements by limiting or reducing the heat transfer to the structural elements. This method has been used in the past to protect the flanges of a beam on the exterior of a building from direct impingement from flames coming out of a window. The shield can be placed on standoffs to create an air gap and can hold insulation materials in place, and therefore can increase fire resistance. Insulation is also accomplished by a combination of space separation and convective cooling from air movement in the air gap. Polished sheet metal has also been used to protect spandrel girders by reflecting the radiated heat away from the spandrel. While this approach may not have application for protection of an entire structural system, is may have application for protection of local exposures if shown to be effective by a performance-based analysis.

Sprinkler Protection

Sprinklers can be used to protect structural elements. The water is sprayed onto the structural member at a given density to cool the structure. NFPA 15-*Standard for Water Spray Fixed Systems for Fire Protection*[20] addresses this type of protection technology for both horizontal and vertical structural steel. This technology appears to be more prevalent in the US, and not an option typically used in the UK.

Unprotected Steel

Thermal Mass

In many instances, particularly in tall buildings or massive structures, the mass of steel required to support the loads and resist moments is very large and thus the thermal mass of the steel itself provides inherent resistance to weakening by fire exposure for periods of time that can be determined by engineering analysis. Such time periods can exceed those required by the building code. It is suggested that by increasing the mass of steel in the basic design of the structure, the need for fire resisting assemblies or spray-applied coverings could be eliminated. It is also suggested that the incremental cost of the additional steel may be less than the cost of the additional fire resistant materials and installation. Such an approach should be investigated as a performance-based alternative solution.

Bare Steel

It should also be remembered that bare steel has some degree of fire resistance. As temperatures increase, steel's yield stress decreases. It approaches 50% of its room temperature yield stress at approximately 550 °C. Depending on fire conditions, loading, connections, end restraints, geometry of the space, etc. bare steel may be shown to provide sufficient resistance to the design fire(s) deemed credible for that space. Common applications of structures with bare steel include low-rise buildings, open car parks and external structural elements.

Fire Resistant Steel

Structural fire resistant steel alloys have been developed that retain two thirds (2/3) of the specified room temperature yield strength at 600 °C[21] [22] [23]. This is accomplished with additive elements such as molybdenum that affect the yield strength. A number of structures have been constructed using this material. Additional fire endurance rating can be achieved by applying conventional FR coatings to fire-resistant steel.

Leading Technologies

General

The fire protection materials market has remained largely unchanged for a significant time. Gypsum-based products, cementitious products, intumescent paints and the like have been protecting buildings for many years, and there are no clear signs pointing to a change in this field. Nonetheless, several specific new developments have occurred recently, and these are discussed below. This is not meant to be a comprehensive review of all new research and technologies in this field, but a rather a snapshot of several new and interesting technologies that have been observed in the industry.

Note that the majority of new fire protection techniques rely on a performance-based approach for design and application, since codes specifically governing their use and tests for determining their performance are not common. These frequently fall under alternate means and methods (AM&M) provisions in US model building codes.

Structural Fire Engineering

The basis for requiring various levels and types of fire protection is an issue that has been debated by many within the industry for years. It may be said that the prescriptive code basis for structural fire resistance requirements relies upon test methods that do not accurately portray actual building fire conditions (construction, heating, etc.) in the modern built environment. The field of structural fire engineering has sprung from this and other similar observations.

Structural fire engineering gives the engineer the ability to consider a building, or a portion thereof, as a unique entity in which specific events and corresponding consequences may be possible. Rather than fulfilling a list of general requirements based on the building type and use, the engineer considers the structural system, possible fire scenarios, and any other contributing factors in developing a strategy to protect the structure. This approach results in numerous differences when compared to more traditional prescriptive approaches:

- Fire resistance ratings are not based on standardized tests, but rather on actual building performance.
- There is less reliance on fireproofing techniques, and additional emphasis on the inherent strength of the structure (as discussed further below).
- Fireproofing, or the lack thereof, is suited to the risks and consequences expected for a building, rather than standard test conditions.

A common approach to designing safe and robust, yet economical, buildings is to eliminate fire protection materials in areas where they are not necessary. Considering the inherent high-temperature strength of structural members or assemblies can do this. For example, recent tests[24] and analyses[25] have shown the potential benefits of considering catenary action within concrete floor slabs supported by steel joists. By redistributing loads throughout a properly supported concrete slab, a structure can remain stable even after individual steel members have failed locally. Thus, protective material can often be eliminated from specific members. Other structural mechanisms can be used in similar analyses, potentially with similar results. This is just one of the numerous examples of how structural fire engineering can be used to more efficiently and effectively protect buildings from fires and other hazard events.

Numerous barriers to the widespread implementation of structural fire engineering exist in the US, and these are discussed in the section on Performance-Based Design. Engineering approaches are more common in the UK and Australia, and are reflected in modern standards in those regions.

Water-based Intumescent Coatings

Solvent-based intumescent coatings have been in use for many years. Somewhat recently, new water-based intumescents have become available. These coatings provide similar levels of fire protection to those provided by solvent-based materials, although application is somewhat simpler, and water-based intumescents do not emit harmful vapors during application, as some solvent-based versions do. Water-based products also offer quick drying times, which may be favorable for in-shop application.

Ablative Coatings

Ablative coatings are those that gradually erode during exposure to a fire due to the absorbed heat energy input that changes the virgin solid coating into a gas composite. This action prevents heat transmission to the material that the ablative coating is applied to. These coatings are similar to intumescent paints, as they possess a resistance to mechanical damage. However, the application procedure is complex and this results in relatively high costs for application.

Subliming Compounds

Subliming compounds have an active ingredient that absorbs heat as it changes from the solid to a gas phase (i.e. sublimation). Similar to ablative coatings, subliming compounds are added to provide an additional layer for insulation. The effectiveness of subliming compounds is a function of various elements including the coating material thickness, compounds' sublimation temperature and enthalpy at sublimation, heat capacity of the substrate, and fire exposure. The fire depletes the subliming compounds. Therefore once exposed, the protection provided by the compound is reduced or eliminated. This can be a major disadvantage during long fires that exceed the design exposure period.

Aerogels

Aerogels are solid materials with nano-meter scale pores. These are typically made of silica, and are basically "puffed up" sand possessing a 99% open porosity. This material is almost transparent. Aerogels make very good insulators due to their lattice structure. Aerogels have been in existence since the 1930's, however until recently have been cost prohibitive for production. In the 1990's, a new fast and more efficient solvent extraction process was developed that allowed faster production. When exposed to heat it does not thermally degrade or generate toxic fumes. A version of this with a ¼ inch thickness was tested at 1000^{o} C for over 5 hours with limited physical and performance deterioration.

Fire Protection Techniques

Sprinkler and Water Mist Systems

Although sprinkler systems have been used for decades to protect against fire, direct application of water to structural elements is a relatively new approach in the US. Frequently, since most new buildings include fire sprinkler systems already, addition of sprinkler coverage for critical structural elements is not overly expensive or difficult. By drenching critical structural elements in water, a system can keep these elements cool for an extended period of time, and also can help prevent direct flame impingement upon the structural material.

Water mist systems can be used in place of traditional sprinklers to efficiently deliver large amounts of water, in small droplet form, to the surfaces of structural members, and thus to quickly dissipate heat and keep structural members cool.

General

At the present time, there is not a groundswell of research and development regarding fire protection technologies for structural steel. Although some research is underway with respect to fire protection materials, and with respect to fire resisting steel formulations, the bulk of the current research and development effort is focused on engineered (performance-based) analysis and design approaches for structural fire safety design.

This section primarily identifies current research and development efforts in the field of structural fire protection. It also highlights some areas where further work is sorely needed.

Materials

Demand for new technologies in fire protection materials is not great. The general industry opinion seems to be that the material technologies that are currently available perform well and are sufficient to meet the needs of the building industry in most cases. Some special situations exist (oil platforms, for instance), although these are comparatively rare and not within the general experience of most design firms. Additionally, novel protection materials generally carry significant cost impacts.

The majority of current research regarding fire protection materials concerns their application, rather than development of new materials. This is also true of needed future research in this field, as discussed below. Rather than developing new, specialized protective materials for use in limited special applications, it has been recognized that innovative use of existing materials based upon comprehensive knowledge of the mechanical and thermal properties of these materials can result in desired levels of performance in a wide range of situations.

There are also opportunities for applying current technologies to other applications. This includes materials comprised of cement, gypsum and proprietary materials that could be used for spray application. There is also the opportunity to enhance existing materials to improve fire resistance performance as has been done by adding polypropylene fibers or steel fibers[27] to concrete.

The available protective materials perform well if designed and applied correctly and appropriately. For example, critical members protected by spray-applied protective material can withstand significant fires if the protective layer is sufficiently thick based upon analysis considering the material properties of the spray-applied as well as the structural member material (steel, concrete, etc.). Current and future research should contribute to the understanding of how existing materials behave under fire conditions and how protective materials actually react to and protect against the heat of a fire.

Modern structural design approaches are based on requiring a certain level of performance for a given structure. Limit states are defined for specific failure mechanisms, and anticipated performance levels are compared to these limit states. Successful and acceptable designs react to failure mechanisms in a manner that does not exceed the defined limit states, or performance/failure criteria. A fire engineering approach must adopt a similar approach to determining if structural performance is acceptable. Analysis methods must be tailored to the analysis of specific failure mechanisms and the consideration of corresponding performance/failure criteria. To this end, the following research points should be considered:

> **Understanding of Protective Material Thermal Properties**. The application of common protective materials can be successful in providing adequate protection against a wide range of events, including blasts and severe fires, provided that such protection is designed with consideration of real performance. Such an approach requires understanding of the thermal properties of the protective material as a function of temperature. Only a limited range of thermal material property data is available for common protective materials, and this data is rarely utilized in the design of protective measures. An increased focus on the understanding of the thermal performance of protective materials is needed.
>
> **Understanding of Protection Material Mechanical Properties**. Protective materials provide a structure with little protection if they become mechanically unstable or highly brittle or otherwise decomposed, or if they physically separate from the associated structural members. An understanding of the mechanical properties associated with a material's response to high temperatures can help eliminate this concern. However, mechanical property data for common structural protection materials is greatly limited.
>
> **Understanding of Structural Material Thermal and Mechanical Properties**. The recent push towards performance-based design of structural systems for fire safety has made apparent the need for a comprehensive understanding of the material properties that govern

how a structural element reacts to elevated temperatures. This knowledge is important not only for understanding how an element will react as a fire heats up the surrounding environment, but also for understanding how the structure and any applied protective materials will work in unison to withstand the fire.

Durability of Protection Materials. This is an issue that has received much attention over the last several years in the U.S. and Europe. Improved tests are being sought to assess the impact resistance, vibration resistance, cohesion and adhesion, and resistance to the effects of harsh environments (i.e. wet/dry, hold/cold, corrosive, etc).

Regardless of the fact that currently available protection materials can be used successfully in a wide range of applications, there are some situations in which new materials can perform more favorably and make economic sense. Some situations require performance that cannot be derived through increased understanding and better application of existing technologies, but rather demand innovation in material formulation. It is difficult to foresee where such innovation is needed. However, at the current time, there appear to be no such needs in the general building industry. The building industry is more in need of innovation in technical understanding and design approach, as discussed in the section on Performance-Based Design.

Steel Formulation

Structural design of steel structures has long been based upon the assumption that structural steels have the same general strength characteristics at elevated temperatures. Failure has been described based upon standardized tests that more-or-less ignore the specific thermal and mechanical properties of different steels. This is largely because, at least in the US, a very limited range of structural steels is used. Generally speaking, these basic steel formulations have performed well for decades.

The past ten years have seen the emergence of new steel formulations resulting from innovative research and improved production practices. These new steels have seen limited use in Japan and other Asian countries, although they have not yet made their way to the United States. Referred to as fire-resistant steels, these materials have caught the attention of some within the industry.

Advocates of fire-resistant steels note that the characteristics of these materials at elevated temperatures provide for decreased loss of strength at elevated temperatures when compared to more traditional steel formulations[28]. The same advocates caution that fire resistant steels cannot replace passive protection measures, but rather can provide a structure with additional time to failure and can allow a structure to survive for a longer time after the failure of protection materials.

Examples of the use of fire-resistant steel exist in Japan, China and Germany. These include a car park, a sports arena, a rail station, and an office building, among limited others. While some data exists regarding the performance and material properties of fire-resistant steel, additional research is needed to determine the benefits (or lack thereof) and cost impacts associated with application in the US. Additionally, research is necessary to understand how and when such steels can be appropriately applied in structural design practice.

Performance Based Design

As already noted in this paper, current trends do not generally include the development of new protection materials. While some new protection and structural materials have been developed for use in specialized applications, the industry will benefit most if the general focus remains upon advancing the approaches taken in protecting a wide range of structures rather than developing new protection materials devoted to a small number of special structures.

Actual structural fire performance cannot be whittled down to a single factor or a small number of factors. In other words, simply considering such conditions as structural member surface temperature or member deformation may not be sufficient to adequately design a structural assembly for favorable fire performance. On the other hand, conservative assumptions built into relatively simplistic design approaches have served the industry well for many years. Questions come of this, however. Specifically, can structures be protected better and in a more cost and energy efficient manner than the current prescriptive design approaches provide for? To answer this question for any given structure, one must consider true performance.

Performance-based structural fire engineering, as already discussed, goes beyond traditional prescriptive-based approaches by considering the individual performance of individual systems and thus deriving the performance of a structure as a whole. This performance is compared to a set of criteria that considers the needs and objectives of all concerned parties. When observed performance does not meet the required performance, steps are taken to improve the design where deficiencies lie. This approach, though relatively infrequently applied in the current design field, is, when used, often applied to the topic of structural member protection. For instance, a study of the true level of protection needed on a beam may result in a reduction in the amount of protective material due to increased credence afforded to the inherent strength of the beam. Such an investigation can result in both cost and time savings in design, construction, and operations phases.

Significant barriers to the widespread application of structural fire engineering currently exist, and numerous research efforts are required to this end. These needs are discussed below. A general, accepted framework for structural fire engineering is lacking and will be critical in guiding future research efforts. Various specific regulatory changes are needed to support structural fire engineering:

Codification of design fires,
Integration of goals and objectives into codes,
Codification of performance/failure criteria,
Development of guidance resources for stakeholders

Educational opportunities should be provided to stakeholders, both to provide guidance in applying structural fire engineering techniques, and to clarify benefits. Specific technical issues that need to be addressed to support structural fire engineering include:

Development of design fire scenarios and design fires for codes,
Development of performance/failure criteria for codes,
Assessment of available analytical methods for heat transfer, structural response, etc
Development of comprehensive material property data

It is also important to remember that this is a multidisciplinary design issue involving owners, architects and engineers who need to work together in defining the above. This includes defining types of events (fire, arson, blast, impact) as well as performance requirements that should be established at the beginning of these assessments so that everyone understands what the end result should be. Performance requirements can include:

- Adequate egress times to safe areas
- Provide escape from building
- Provide fire service access
- Prevent spread of fire to exposed properties
- Prevent collapse

- Protect continuity of operations for essential facilities

As research progresses, additional needs will likely be developed. Various organizations have already undertaken programs to identify strategies for developing structural fire engineering. For example, the American Institute of Steel Construction has funded work to review the state-of-the-art in structural fire research and design methodologies focusing on performance based design approaches, and issues relating to engineering practice, enforcement and regulation[29 30 31 32].

Acknowledgements

The authors would like to thank the following for their efforts and contributions to this effort

David Barber, Arup Fire, Sydney, AU

Venkatesh Kodur, National Research Council Canada

Barbara Lane, Arup Fire, London

Jim Milke, University of Maryland, USA

Clare Perkins, Arup Materials, London, England

David Proe, Arup Fire, Melbourne, AU

References

1. Autoclaved Aerated Concrete – An Overview, AzPATH, Del E. Webb School of Construction, Arizona State University, Tempe, AZ, October 2001.
2. Buchanan, Andrew, H. Structural Design For Fire Safety, John Wiley & Sons, LTD, New York.
3. Milke, J.A., 'Analytical methods for determining fire resistance of steel members', Chapter 4-9, SFPE Handbook of Fire Protection Engineering, Third Edition, Society of Fire Protection Engineers, 2002.
4. Uniform Building Code (1997), International Conference of Building Officials, Whittier California, USA.
5. *Fire Resistance Directory.* Volume 1. Underwriters Laboratories, Inc., 2003.
6. Jackman, P. E, Intumescent Materials – Ancient Technology, Modern Application, Part I The Technology, Fire Engineers Journal, May 1998.
7. Swindlehurst, J. Fire Proofing Steel Structures - Decorative Intumescent Coatings are Becoming a Viable Option for Manufacturing Plants, July, 2001, www.plantservices.com/web_first/ps.nsf/articleid/hcok-4xvvbn
8. Fire resistance of Steel framed Buildings, Corus, www.corusconstruction.com
9. Off-Site Fire Protection Application for Commercial Buildings: Cost Benefit Analysis. Report RT433, Prepared by the Steel Construction Institute.
10. Twilt, L and Witteveen, J, 'The fire resistance of wood-clad steel columns.', Fire Prevention Science and Technology, No. 11, 1974.
11. Willse, PJG, Structural Integrity During Fire, Fire Protection Handbook, Section 12-4, National Fire Protection Association, Nineteenth Edition, 2003.
12. ASCE/SEI/SFPE 29-99. *Standard Calculation Methods for Structural Fire Protection.* American Society of Civil Engineers and Society of Fire Protection Engineers, 2003.
13. Kodur, V. 'Performance-Based Fire Resistance Design of Concrete-Filled Steel Columns.' *Journal of Constructional Steel Research.* Vol. 51. National Research Council of Canada, 1999.
14. International Fire Engineering Design for Steel Structures – State of the Art, International Iron and Steel Institute, Brussels, 1993.
15. Witte, H, Steel construction with water cooling, Studiengesellschaft fur Anwendungstechnik von Stahl und Eisen e.V., Dusseldorf – Germany, 1981.
16. Bouillette, JP, A building with water cooled structures in Marseille, Acier/Stahl/Steel, CBLIA, pp254-256, Brussels, Belgium, June 1971.
17. Seigel, L.G., 'Designing for fire safety with exposed structural steel', Fire Technology, 6, 4, 269-278, 1970.
18. Seigel, LG, Design of Liquid filled structural members for fire resistance, Acier/Stahl/Steel, CBLIA, pp266-270, Brussels, Belgium, June 1969.
19. Bond, GVL, Fire and Steel Construction – Water Filled Hollow Columns, Constrado, UK, 1975.
20. NFPA 15-Standard for Water Spray Fixed Systems for Fire Protection, National Fire Protection Association, 2001, Quincy, MA.
21. Fushimi, M., Chikaraishi, H and Keira, K., Development of Fire-Resistant Steel Frame Building Structures, Nippon Steel Technical Report No. 79, 66, July 1995.
22. Kubota, S. and Sakumoto, Y, Development of Fire-Protective System (Membrane System) Using Fire-Resistant Steel for Cooperative Houses, Nippon Steel Technical Report No. 79, January 1999.
23. Fire Resistant Structural Steel FR 30 from TKS, ThyssenKrup Steel, Duisberg, Germany. May 2001
24. The University of Edinburgh, 'Final Report of the DETR-PIT project: Behaviour of Steel Framed Structures under Fire Conditions. Technical Report.' www.civ.ed.ac.uk/research/fire/project/main.html. 2000.
25. Lamont, S., 'Structural Behaviour in Fire and Real Design', in Designing Structures for Fire Conferene, Society of Fire Protection Engineers and Structural Engineering Institute. Baltimore, MD, September 30 – October 1, 2003.
26. A breakthrough in Aerogel Technology: Developing the Ultimate Insulation, Aspen Aerogel,
27. Behloil, B, et al, Fire Resistance of DUCTAL® Ultra High-Performance Concrete, Proceedings of the 1st fib Congress, Osaka, Japan, October 2002.
28. Sakumoto, Y., Tokuno, K., and Wildt, R., 'Fire Resistant Steel', in Designing Structures for Fire Conference, Society of Fire Protection Engineers and Structural Engineering Institute. Baltimore, MD, September 30 – October 1, 2003.
29. Ove Arup & Partners, *Strategy for Integrating Structural and Fire Engineering of Steel Structures - Task 1: Assessment of Technical Issues and Needs.* October 9, 2003

30. Ove Arup & Partners, *Strategy for Integrating Structural and Fire Engineering of Steel Structures - Task 2: Assessment of Designer Capabilities and Educational Needs*. November 11, 2003.
31. Ove Arup & Partners, *Strategy for Integrating Structural and Fire Engineering of Steel Structures - Task 3: Assessment of Enforcement Official Capabilities and Needs*. December 3, 2003.
32. Ove Arup & Partners, *Strategy for Integrating Structural and Fire Engineering of Steel Structures - Task 4: Assessment of Regulatory and Guidance Situation and Needs*. December 31, 2003

Objective 2: Performance-the Sine Qua Non!

Professor Fredrick W. Mowrer of the Department of Fire Protection Engineering at the University of Maryland examined this study objective. His analysis follows in this section.

Introduction

This report provides an overview of the performance requirements for the fire resistance of structural steel in high-rise buildings. The traditional approach to requirements for the fire resistance of building elements is reviewed to provide background and a context for emerging performance-based approaches to fire resistance requirements. The concept of design performance levels is addressed in terms of the different performance groups and serviceability levels currently used for earthquake design and other extrinsic natural hazards. This concept is modified to address fire, which is an intrinsic technological hazard that requires a different treatment from these other hazards. A proposed framework is introduced to address fire from both deterministic and probabilistic perspectives.

Three questions related to the performance requirements of structural steel in high-rise buildings are addressed:

What performance is really needed from structural steel in high-rise buildings?

What protection systems for the steel will be required under multiple hazard scenarios, including fire?

What performance requirements must be demanded of those protection systems, particularly in defense against fire?

The answer to the first question, in particular, and to all three questions, in general, depends on what the performance objectives are.

The short answer to the first question can be stated simply, as noted by Buchanan[1]:

> "The fundamental step in designing structures for fire safety is to verify that the fire resistance of the structure (or each part of the structure) is greater than the severity of the fire to which the structure is exposed. This verification requires that the following design equation be satisfied:
>
> $$Fire\ resistance \geq Fire\ \ severity$$
>
> where *fire resistance* is a measure of the ability of the structure to resist collapse, fire spread or other failure during exposure to a fire of specified severity, and *fire severity* is a measure of the destructive impact of a fire, or a measure of the forces or temperatures which could cause collapse or other failure as a result of the fire."

For many buildings, particularly tall structures that are typically constructed of steel and concrete, this is the most common performance objective, while for many other buildings lower fire resistance levels have been allowed. For these buildings, Buchanan's design equation can be modified as:

$$Fire\,resistance \geq \begin{Bmatrix} SF \times Evacuation\ \ time \\ SF \times Fire\ \ severity \\ SF \times Suppression\ \ time \end{Bmatrix}$$

---

[1] Buchanan, Andrew H., *Structural Design for Fire Safety*, John Wiley & Sons Ltd., 2001, p. 91.

where *SF* represents an appropriate safety factor.

The level of fire resistance required for different elements of a structure has traditionally been governed by building codes based on the occupancy, height and area of a building. Such requirements, which are specified in terms of fire resistance ratings for different elements and assemblies, can be traced at least as far back as the publication of the first edition of the Uniform Building Code in 1927. An historical perspective on the fire resistance requirements embodied in the model building codes is presented in the next section.

It has long been recognized by knowledgeable fire safety professionals that fire resistance ratings derived from standard fire resistance tests should not be construed literally despite the fact that they are expressed in terms of hourly ratings. In other words, a 2-hour fire resistance rating represents the period of time that a rated element or assembly withstands the standard fire resistance test without exceeding any of the failure criteria specified in the test standard. It does not represent the period of time that the same element or assembly will perform acceptably in the field. Differences between test and field performance may occur due to differences in fire exposure conditions, connection details and construction methods. This distinction is important with respect to performance requirements for the fire resistance of structures.

Within the fire safety engineering profession, there has been increasing interest in performance-based design in recent years. With this increasing interest, there is increasing demand for analytical methods that address performance in terms of physically valid objectives and quantitative performance criteria. Structural design for fire safety is one aspect of performance-based fire safety analysis and design of buildings. Over the past decade, there has been considerable interest in performance-based structural design for fire, particularly internationally. With the total progressive collapse of three steel-frame high-rise buildings at the World Trade Center in New York City on September 11, 2001, there has been increased interest in this topic within the United States as well. This report presents a proposed framework for addressing structural fire design from both deterministic and probabilistic perspectives.

Background

Introduction

Requirements for fire resistance of tall buildings have existed for more than 100 years and have been standardized in virtually their current form for more than 75 years. In light of the World Trade Center disaster, it is ironic but not surprising that some of the earliest requirements for fire resistance of tall buildings were imposed in New York City, “necessitated by the rapid development of the skyscraper” [2] around the turn of the last century. Efforts to establish an acceptable test procedure were initiated at that time by Professor Ira H. Woolson of Columbia University and Rudolph P. Miller, chief engineer, Building Bureau, New York City.

Following the Baltimore conflagration of 1905, the ASTM established a committee to standardize the fire test method, with Prof. Woolson as chairman and Mr. Miller as secretary. ASTM adopted a test method for floor constructions in 1907 and a procedure for testing wall and partition constructions in 1909. After a new committee composed of representatives of eleven engineering societies was organized in 1916, the fire test standard was revised and adopted as a tentative standard, ASTM Standard C19T, in 1917, and as a full standard, C19, in 1918. The

[2] Fitzgerald, Robert W., STRUCTURAL INTEGRITY DURING FIRE, Section 7/Chapter 4, Fire Protection Handbook, 18th edition, National Fire Protection Association, Quincy, MA, 1997.

primary features of the standard, including the fire test furnace and the standard temperature-time exposure curve, remain unchanged to the present version of ASTM E119.

From the start, it has been recognized that the standard temperature-time curve used in the ASTM E119 test standard represents only one fire exposure condition, albeit a relatively severe one. Almost immediately after the temperature-time curve was standardized, S. H. Ingberg, a research scientist at the National Bureau of Standards, began to develop methods to normalize the severity of the standard exposure condition with expected exposure conditions in the field. By 1928, Ingberg had developed the "fire load concept,"[3] which suggested that there was a relationship between the amount of combustibles present within a space and the fire severity, which is a term used as a measure of the intensity and the duration of a fire. Despite shortcomings in the fire load concept, some of which Ingberg recognized as he developed the concept, the fire load concept continues to serve as one of the primary implicit bases for evaluating expected fire severities and, consequently, required fire resistances in buildings.

Requirements in the First Edition of the Uniform Building Code - 1927

The first modern model building code published in the United States was the first edition of the Uniform Building Code (UBC) in 1927. Much as the ASTM E119 fire test standard remains virtually unchanged since first published as standard C19 in 1918, many of the requirements in the current model building codes remain similar to those in this first edition.

The 1927 UBC identified five types of construction "based upon their resistance to fire," with Type I "deemed to be the most fire-resistive and Type V the least fire-resistive Type of Construction."[4] The five types of construction were identified as:

Type I – FIRE-RESISTIVE Construction
Type II – HEAVY-TIMBER Construction
Type III – ORDINARY MASONRY Construction
Type IV – METAL FRAME Construction
Type V – WOOD FRAME Construction

It was recognized that the various types of construction represented "varying degrees of public safety and resistance to fire."[5] The concept of "equivalency" was also recognized: "Where specific materials, types of construction or fire-resistive protection are required, such requirements shall be the minimum requirements and any materials, types of construction or fire-resistive protection which will afford equal or greater public safety or resistance to fire … may be used." Interestingly, the 1927 UBC also had a performance requirement that "Any system or method of construction to be used shall admit of a rational analysis in accordance with well established principles of mechanics."[6] This requirement was not extended to fire analysis.

Type I: FIRE-RESISTIVE Construction

For Type I buildings, the structural frame was required to be of concrete or of fireproofed structural steel or iron. Structural steel or iron members were required to be "thoroughly fire-proofed with not less than four-hour fire-resistive protection for columns, beams and girders and three-hour fire-resistive protection for floors, for all buildings more than eight (8) stories or

[3] Ingberg, S.H., "Tests of the severity of building fires," Quarterly of the NFPA, Vol. 22, No. 1, 1928.
[4] Uniform Building Code, 1st edition, Sec. 1702, 1927, p. 56
[5] Uniform Building Code, 1st edition, Sec. 1701, 1927, p. 56
[6] Ibid.

eighty-five (85) feet in height; and with three-hour fire-resistive protection for columns, beams and girders and two-hour fire-resistive protection for floors for all buildings which are eight (8) stories or eighty-five (85) feet or less in height."[7]

Type II: HEAVY TIMBER Construction

For Type II buildings, the structural frame was required to be of concrete, masonry, fireproofed structural steel or iron, or of heavy timbers. In buildings not exceeding one (1) story and sixty-five (65) feet in height, the fireproofing could be omitted from the steel or iron. Otherwise, structural steel or iron members were required to be "thoroughly fire-proofed" with "three-hour fire-resistive protection for columns and two-hour fire-resistive protection for beams, girders and floor systems."[8]

The maximum height for buildings of Type II construction was limited to seventy-five (75) feet with not more than seven (7) stories under the 1927 UBC. The maximum floor area for buildings of Type II construction depended on the occupancy of the building.

Type III: ORDINARY MASONARY Construction

For Type III buildings, the interior load bearing construction could be masonry or reinforced concrete walls or a structural frame of steel, reinforced concrete or wood. Foundations and exterior walls were required to be of masonry or reinforced concrete. In general, the fireproofing of steel, iron or wood structural members could be omitted unless otherwise required based on occupancy or location.[9]

The maximum height for buildings of Type III construction was limited to fifty-five (55) feet with not more than five (5) stories under the 1927 UBC. The maximum floor area for buildings of Type III construction depended primarily on the occupancy of the building.

Type IV: METAL FRAME Construction

For Type IV buildings, the structural framework was required to be of concrete, masonry, steel or iron and the exterior walls and roof were required to be of metal or other noncombustible material. Fireproofing of structural members was not required.[10]

The maximum height for buildings of Type IV construction was limited to forty-five (45) feet with not more than one (1) story and a mezzanine floor under the 1927 UBC. The maximum floor area for buildings of Type IV construction depended primarily on the occupancy of the building.

Type V: WOOD FRAME Construction

For Type V buildings, structural members were permitted to be of wood or of wood in combination with other materials.

The maximum height for buildings of Type V construction was limited to thirty-five (35) feet with not more than three (3) stories under the 1927 UBC. The maximum floor area for buildings of Type V construction depended primarily on the occupancy of the building.

Summary of 1927 UBC

[7] Ibid., Sec. 1809, p. 58
[8] Ibid., Sec. 1909, p. 63
[9] Ibid., Sec. 2009, p. 68
[10] Ibid., Sec. 2109, p. 70

The 1927 UBC recognized five different types of construction based on the combustibility of the construction materials and the fire resistance of different structural elements and assemblies. These construction types are very similar to the construction types recognized in current model building codes, although the current model building codes recognize more subcategories under each construction type. Building height and area limitations based on type of construction and occupancy classification are also similar today, although the specific requirements have changed.

The 1927 UBC would have required very tall buildings (greater than 85 feet or 8 stories) to be of Type I construction, with not less than four-hour fire-resistive protection for columns, beams and girders and three-hour fire-resistive protection for floors. These requirements generally exceed the requirements contained in the current model building codes. This begs the question: Were these requirements too conservative, have building fires become less severe or are safety margins simply being reduced to decrease building construction costs?

Fire Resistance Classifications of Building Constructions – BMS92 - 1942

In 1942, the Subcommittee on Fire-Resistance Classifications of the Central Housing Committee on Research, Design, and Construction published its Report BMS92 on "Fire-Resistance Classifications of Building Constructions." This report was published (with a cover price of 30 cents!) by the National Bureau of Standards, the predecessor organization to the National Institute of Standards and Technology. The subcommittee was comprised of representatives of Federal agencies concerned with the design, construction and operation of buildings, including the Public Buildings Administration, the Federal Housing Administration, the United States Housing Authority and the Home Owners' Loan Corporation. S. H. Ingberg of the National Bureau of Standards served as the Technical Advisor to the Subcommittee. A distinguishing feature of this report was its effort to document the rational bases for recognition of different types of building construction and for restrictions and limitations on these types.

The Subcommittee concluded that by considering only the basic properties having a bearing on fire hazard and fire resistance, four types of building construction classifications were sufficient to cover the whole range of building construction. Within each type, two or more classes are defined based on the fire resistance required for their structural members. The types of construction identified in BMS92 include:

Type I. Fireproof Construction
Type II. Incombustible Construction ("noncombustible" is now used in place of "incombustible")
Type III. Exterior-Protected Construction
Type IV. Wood Construction

These types of construction are similar to those that were identified in the 1927 UBC 15 years earlier, although some of the type designations are different. The Heavy Timber type of construction recognized by the UBC is included along with the Ordinary Masonry type of construction under the Exterior-Protected Construction recognized in BMS92.

The Subcommittee believed that "the idea of designing some buildings for the full fire severity corresponding to the occupancy and others for a given established fire resistance, is a logical advance in fire protection engineering."[11] This statement explicitly addresses the premise, implicit in the identification of different construction types, that the fire resistance of some

[11] Report BMS92, *Fire-Resistance Classifications of Building Constructions*, National Bureau of Standards, 1942, p. 4.

buildings should be sufficient to withstand the "full severity" of a fire, while other buildings could be designed for lesser levels of fire resistance. This statement also assumes that there is an implicit relationship between the occupancy classification of a building and the expected fire severity.

Report BMS92 outlined the "relations between combustible contents, fire severity, and fire-resistance ratings" and provided "a method of evaluating the combustible contents of a building." In this way, this document attempts to lay out a rational basis for fire resistance requirements in buildings. Unfortunately, once this rational basis was outlined and fire resistance requirements were established from this basis, the connection between the performance objective and the design concept became implicit rather than explicit. In other words, once the fire severities and fire resistance requirements for different occupancies were established, the design objective became "meet the required fire resistance rating" rather than "provide a level of fire resistance sufficient to withstand the full fire severity."

In BMS92, the term fire severity "is used herein as a measure of the intensity and duration of a fire. It is expressed in terms of time of exposure equivalent to that in the standard furnace test as defined in American Standards Association Standard A-2, 1942."[12] Since Ingberg was the Technical Advisor to the subcommittee, it is not surprising that the fire severity referenced in BMS92 is the fire load concept that Ingberg had developed during the 1920s. This is expressed in BMS92 as: "It has been found from burn-out tests performed in fireproof structures with various concentrations of combustibles having a calorific value in the range of wood and paper (7,000 to 8,000 Btu/lb) and assembled to represent building occupancies, that the relation between the amount of combustibles present and the fire severity is approximately as given in table 5."[13] The contents of table 5 from BMS92 are reproduced in Table 1.

Table 1. Relationship between combustible loading and fire severity from BMS92.

Avg. weight of combustibles, lb/ft^2 of floor area	5	7.5	10	15	20	30	40	50	60
Fire severity, hours	0.5	0.75	1	1.5	2	3	4.5	6	7.5

For products with different calorific values, BMS92 indicated that "It is considered sufficiently accurate in computing combustible contents to take wood, paper, cotton, wool, silk, straw, grain, sugar and similar organic materials at their actual weights and to take animal and vegetable oils, fats, and waxes, petroleum products, asphalt, bitumen, paraffin, pitch, alcohol, and naphthalene at twice their actual weights."

Knowledgeable fire safety professionals have recognized for many years that the fuel load concept developed by Ingberg has technical shortcomings. Ingberg himself recognized some of the shortcomings in the fuel load concept even as he developed and promoted it. As noted in the commentary to the ASTM E119 standard, "It is now generally conceded that fire severity as well as the temperature-time relationship of a fire depends on several factors, including:

1. Fire load—Amount and type.
2. Distribution of this fire load.
3. Specific surface characteristics of the fire load.
4. Ventilation, as determined by the size and shape of openings.
5. Geometry of the fire compartment—Size and shape.
6. Thermal characteristics of the enclosure boundaries.

[12] Ibid., p. 9.
[13] Ibid., p. 9.

7. Relative humidity of the atmosphere."[14]

The fuel load concept explicitly addresses only the first of these factors and implicitly addresses the second. Despite this recognition of its shortcomings, the fuel load concept continues to be widely used, and is even referenced in the ASTM E119 Standard right after the reference to these potential factors that can influence fire severity: "For the purposes of this commentary, fire severity is defined as a measure of the fire intensity (temperature) and fire duration. It is expressed in terms of minutes or hours of fire exposure and in Test Methods E 119 is assumed to be equivalent to that defined by the standard temperature-time (T-t) Curve, that is, the area under the T-t curve."

Type I: Fireproof Construction

In BMS92, Type I – Fireproof Construction is defined as "That type of construction in which the structural elements are of incombustible materials with fire-resistance ratings sufficient to withstand the fire severity resulting from complete combustion of the contents and finish involved in the intended occupancy but not less than the rating specified in table 1 ..."[15] Table 1 of BMS92 laid out the minimum fire-resistance ratings of structural elements for Type 1 construction. Six different subtypes were established, based on the expected fire load, expressed in terms of the weight of combustibles per unit floor area, lb/ft^2. The general fire resistance ratings for the different subtypes are summarized in Table 2.

Table 2. Construction subtypes for Type I construction in BMS92.

Construction subtype	I-A	I-B	I-C	I-D	I-E	I-F
General fire resistance rating in hours	>4	4	3	2	1.5	1
Fire load, lb/ft^2	>35	35	30	20	15	10

BMS92 defines "Fireproof Construction" in terms of actual performance, rather than in terms of specific fire resistance ratings: "The Fireproof type includes all buildings of incombustible (noncombustible) structure which will either withstand complete combustion of their contents without collapse or which will have a general fire-resistance rating of 4 hr and in addition other safeguards designed to prevent a more severe fire. Within this type, the classification is such that a building may be designed to have a fire resistance corresponding to the fire severity that may be created by the occupancy. This eliminates the common practice of requiring a uniform fire resistance for all Fireproof-type buildings, which results in excessive resistance for occupancies having light combustible contents and insufficient resistance where combustible contents are very heavy. Economies are thus made possible in the former case and increased protection is required in the latter for buildings classed as Fireproof."[16]

BMS92 also recognized that changes in the use or occupancy of a building could result in changes in the expected fire severity that needed to be considered: "It is assumed that in setting the required degree of fire resistance for Fireproof buildings, due consideration will be given to possible changes in occupancy and tenancy that may increase the amount of combustibles above that estimated for the occupancy immediately contemplated ..."[17]

---

[14] ASTM E 119 – 00a, Standard Test Methods for Fire Tests of Building Construction and Materials, Sec. X5.3.
[15] Report BMS92, *Fire-Resistance Classifications of Building Constructions*, National Bureau of Standards, 1942, p. 6.
[16] Ibid., p. 5.
[17] Ibid., p. 5.

Type II: Incombustible Construction

In BMS92, Type II – Incombustible Construction is defined as "That type of construction which has exterior walls, bearing walls, floor and roof construction, and other structural members, of incombustible materials all assembled to have fire-resistance ratings as given in the titles of the following subtypes ..."[18] Two subtypes were then defined, with Type II-A having a general fire-resistance rating of ¾ hour and Type II-B having a general fire-resistance rating of less than ¾ hour.

Fire walls and party walls were required to be "ground-supported and of masonry or other incombustible construction, suitably proportioned as to strength and stability, and shall have fire-resistance ratings not less than those given below. Connections of building members with such walls shall be made so that failure of the floor or roof construction due to fire on one side will not cause collapse of the wall." The purpose of this requirement was to permit complete burnout on one side of a fire wall or party wall while maintaining the structural integrity of the wall to prevent fire spread through the wall. Table 2 of BMS92 provided the minimum fire-resistance ratings for fire walls and party walls for Type II construction. This table is reproduced below as Table 3.

Table 3. Minimum fire resistance ratings for fire walls and party walls in Type II construction from BMS92.

Total weight of combustibles, lb/ft^2 of ground area	Minimum fire resistance rating (hours)		
	Lower 8 ft	8 to 20 ft above base	Over 20 ft above base
Less than 25	2.5	2	2
25 to 50	4	2.5	2
50 to 75	5	3	2
75 to 100	6	4	2.5
100 to 150	8	5	3
150 to 200	9	6	3.5
200 to 250	10	8	4
Over 250	12	10	5

A couple of points are worth noting about this table. First, the fire load is expressed per unit of ground area, not per unit of floor area. All the combustible loading, including contents and finishes, for all floors is projected per unit of ground area. This results in the very high combustible loadings expressed in the table and the related high fire resistance ratings. Second, higher fire resistance ratings are required at the base of a fire wall or party wall than at higher elevations. The premise here is that structural collapse will cause the combustible loading to fall to the base of the building, causing the combustible loading to be larger at the base of the building.

[18] Ibid., p. 7

Type III: Exterior-Protected Construction

In BMS92, Type III – Exterior-Protected Construction is defined as "That type of construction in which the exterior walls, party walls, and fire walls are ground-supported and of masonry or other incombustible construction, suitably proportioned as to strength and stability, and the interior framing is partly or wholly of wood or other similar materials, all assembled to have fire-resistance ratings not less than the minima indicated in table 3 ..."[19] Two subtypes were then defined, with Type III-A having a general fire-resistance rating of ¾ hour and Type III-B having a general fire-resistance rating of less than ¾ hour.

Type IV: Wood Construction

In BMS92, Type IV – Wood Construction is defined as "That type of construction which has exterior and bearing walls and floor and roof construction, wholly or partly of wood or other combustible materials, all assembled to have fire-resistance ratings as given in the titles of the following subtypes ..."[20]

Restrictions and Limitations Based Upon Types of Construction

BMS92 provided a discussion of the rational bases for the different restrictions and limitations that prevailing building codes were placing on different types of construction. The report identifies factors that influence safety to life and property from fire, including: "hazards due to location, occupancy, and contents; the height and area of buildings; the size and areas not effectively separated with respect to fire; and the materials and construction of the building."[21] The report goes on to say that "It is usual, therefore, to apply restrictions and limitations to certain of these factors for the purpose of obtaining safe conditions to the degree considered economically possible and desirable from a public standpoint." In this way, the need to consider cost is addressed in BMS92.

BMS92 notes that height restrictions are not generally applied to buildings of Fireproof construction, except in occupancies deemed specially hazardous. "This may be justified on the basis that the building should withstand a fire completely consuming all combustible contents and trim without collapse of structural members, or that for the higher amounts of combustible contents, the fire resistance incorporated in the building, in combination with its fire-extinguishing equipments and the public fire protection, is deemed adequate to prevent such collapse."[22]

This statement is interesting for two reasons. First, it reiterates that buildings of Fireproof construction should be designed to prevent collapse resulting from fire, either by withstanding complete burnout of all combustible contents or through a combination of fire resistance, automatic and manual fire suppression. Second, this discussion recognizes "tradeoffs" for fire resistance, but only if they are adequate to prevent collapse.

BMS92 addresses the rationale for height restrictions in buildings of other types of construction. The primary reason for these height restrictions is the recognition that buildings of other types of construction may collapse due to fire. "Hence, provision for prompt egress of occupants must be made. Also, the possibility of conducting fire-fighting operations from within the building is not assured unless the fire is of low or moderate severity or is controlled in its early stage."[23] Thus, height restrictions were tied to the need for prompt evacuation and exterior fire-fighting, with

---

[19] Ibid., p. 8
[20] Ibid., p. 9
[21] Ibid., p. 11
[22] Ibid., p. 12
[23] Ibid., p. 13

this latter issue addressed in terms of the distance from a building a fire truck would be located to avoid the collapse as well as the maximum distances hose streams could throw water.

BMS92 addresses the issue of restrictions that have been imposed on buildings based on the degree of fire resistance of structural members. Here, BMS92 takes some issue with the relatively high levels of fire resistance mandated by some of the prevailing building codes, but does recognize that there can be significant uncertainties related to combustible loads and actual fire resistance of structural members. "Assuming that Fireproof buildings are designed to withstand a complete burning-out of contents and combustible trim without collapse, there should in effect be no limitations imposed on the score of degree of fire resistance other than in its relation to the expected fire severity for a given building. However, considering that public control over the amount of combustible contents in a given building can be exercised only within limits even where the occupancy is subject to control, and further, that the degree of fire resistance of building members cannot be achieved within very definite limits, there is justification for applying more rigid restrictions to buildings with the lower degree of fire resistance, particularly from the standpoint of height."[24]

While building codes such as the 1927 UBC were generally requiring fire resistance ratings of 4-hours for primary structural members, BMS92 suggested that such levels of fire resistance might not be justified. "For buildings generally associated with the lower range in combustible contents, such as residential and office buildings, it does not appear justifiable even from this standpoint to apply an unduly large factor of safety. Where the expected fire severity is in the range ½ to 1½ hr, a 2-hr requirement for high buildings should give good assurance of stability under fire conditions."[25]

Part of the rationale for this statement was the fire resistance inherent in larger structural members and in continuous structural frames. "It is noted that fire-resistance ratings are based on the performance of members near the lower range in size. For the larger size of members used in all but the upper stories of such high buildings, there would be considerable increase in fire resistance above the nominal ratings for the same kind and thickness of protecting materials. Also, the structural continuity inherent in the type of construction increases the margin of safety on stability above that indicated in test furnaces for comparable fire exposure and loading of segregated columns, beams, and floor and wall assemblies."[26]

BMS92 addresses a number of other factors, including building area and occupancy, which were being used to restrict types of construction when BMS92 was published in 1942. Many of these factors are still used to restrict the types of construction under current building codes. They are not discussed here because they are not as relevant to the current discussion as the factors discussed above.

Summary

BMS92, a report published more than 60 years ago, lays out a number of rational performance objectives for the fire resistance of buildings of different types of construction that are still relevant today. BMS92 is useful from the standpoint that it explicitly discusses the rationale for different restrictions and limitations based on types of construction that have become implicit, and therefore less clear, in the intervening years. Of particular note, for "fireproof" buildings BMS92 identifies the same performance objective noted by Buchanan, which is that the fire resistance of a structure, or part thereof, should be greater than the fire severity to which the building, or part thereof, is expected to be exposed.

[24] Ibid., p. 19
[25] Ibid., p. 19
[26] Ibid., p. 19

While the performance objectives described throughout BMS92 remain relevant today, the approach to achieving these performance objectives outlined in BMS92 has technical shortcomings. These shortcomings include reliance on Ingberg's fire load concept as the means to establish the expected fire severity in a building and reliance on occupancy classifications as a means to establish the expected fire loads.

Current Model Building Code Requirements

There are currently two model building codes being published in the United States. These include the International Building Code published by the International Code Council and the NFPA 5000 Building Construction and Safety Code published by the National Fire Protection Association.

Fire resistance requirements in current model building codes do not differ dramatically from those in the 1927 UBC, although there has been a general reduction in fire resistance requirements in recent years.

International Building Code-2000

The International Building Code (IBC) recognizes five different types of construction with two subtypes under each major type except for Type IV. The construction type designations under the IBC include:

Type I (A or B)
Type II (A or B)
Type III (A or B)
Type IV (Heavy Timber)
Type V (A or B)

The descriptive names associated with each construction type have been dropped, but the five construction type designations remain virtually unchanged since the 1927 UBC, with the exception that the Type II and Type IV designations have been reversed. Type I is still representative of fire-resistive construction, Type II of noncombustible construction, Type III of ordinary masonry construction, Type IV of heavy timber construction and Type V of wood frame construction.

The fire-resistance requirements in the 2000 IBC have been reduced since the 1927 UBC, with Type IA construction requiring 3-hour fire resistance ratings for structural frames and 2-hour fire resistance ratings for floors. These are 1-hour less than the similar requirements in the 1927 UBC. For Type IB construction, both structural frames and floors are required to have 2-hour fire resistance ratings under the 2000 IBC.

In general, the 2000 IBC permits buildings of Type IA construction to have unlimited heights, except for some hazardous occupancies, while restricting Type IB construction to a height limit of 160 feet or a specific number of stories based on the occupancy classification. However, under the section on high-rise buildings (Section 403), the 2000 IBC permits buildings required to be of Type IA construction to be reduced to Type IB construction if the required automatic sprinkler system is equipped with supervisory initiating devices and water-flow initiating devices for each floor.

NFPA 5000 Building Construction and Safety Code - 2003

The 2003 NFPA 5000 Code recognizes the same basic construction types as the 2000 IBC, but includes different subtypes within each major type. Under the NFPA classification scheme, the construction type designations include:

Type I (442 or 332)
Type II (222, 111, or 000)
Type III (211 or 200)
Type IV (2HH)
Type V (111 or 000)

In the NFPA designation scheme, the three numbers in parentheses represent the required fire resistance ratings for the exterior walls, the structural frame and the floor assemblies, respectively. Thus, the 2000 IBC does not have a construction type analogous to Type I (442), while the other construction types are analogous to each other as shown in Table 4.

Table 4. Comparison of fire resistance requirements for different construction types under the IBC and NFPA 5000 codes.

NFPA	I(332)	II(222)	II(111)	II(000)	III(211)	III(200)	IV(2HH)	V(111)	V(000)
IBC	IA	IB	IIA	IIB	IIIA	IIIB	IV	VA	VB

In general, the 2003 NFPA 5000 Code permits buildings of Type I (442) construction to have unlimited heights with or without automatic sprinkler protection for most buildings. Buildings of Type I (332) construction are limited to a maximum building height of 420 feet for sprinklered buildings and 400 feet for unsprinklered buildings, while buildings of Type II (222) construction are limited to a maximum building height of 180 feet for sprinklered buildings and 160 feet for unsprinklered buildings.

Similar to the 2000 IBC, the 2003 NFPA 5000 Code permits a one-class reduction in construction type in buildings with exits constructed as smokeproof enclosures and that are equipped with supervisory initiating devices and waterflow initiating devices on each floor. Thus, buildings required to be of Type I (442) construction can be reduced to Type I (332) and buildings required to be of Type I (332) construction can be reduced to Type II (222).

Design Performance Objectives

Introduction

The degree of fire resistance of different structural elements and assemblies in buildings depends on the performance objectives for the fire resistant elements or assemblies. In the deterministic prescriptive regulatory environment that has prevailed in the United States for most of the last century, evaluation of fire resistance reduces to the selection of structural elements and assemblies with fire resistance ratings that meet or exceed the minimum fire resistance requirements in the prevailing building code. Unfortunately, this only demonstrates code compliance, which may bear little correlation with actual field performance and does not address the serviceability of a building or the structural elements and assemblies following a fire.

In a probabilistic performance-based design environment, evaluation of fire resistance depends on a number of factors, including the likelihood and severity of different expected fire scenarios, the expected thermal and structural responses of fire resistant assemblies and structural frames to these fire scenarios and the performance criteria being used to judge the adequacy of a design.

Deterministic Performance Objectives

Most of the performance objectives currently used for fire resistant assemblies were established when the concept of fire resistance ratings was first developed a century ago. These deterministic performance objectives include:

Prevent the total or partial collapse of a building (structural integrity);
Limit the spread of fire within a building (compartmentation);
Limit the spread of fire between buildings (exposure protection).

To each of these objectives, the phrase "for a specified period of time" could be appended to make the objectives more general.

For tall buildings, the structural fire resistance performance objective has implicitly been to prevent the collapse of the building with complete burnout of combustibles within the building, i.e., for the fire resistance of the structure to exceed the expected fire severity, as noted in Section 1.0. This could also be stated as an explicit performance objective.

As noted by Buchanan,[27] there are three methods for comparing fire severity with fire resistance. Verification may be in the time domain, the temperature domain or the strength domain. These are summarized in Table 5.1 of Buchanan's book, which is reproduced as Table 5.

Table 5. Domains for evaluating fire resistance and fire severity.

Domain	Units	Fire Resistance >	Fire Severity
Time	Hours	Time to failure >	Fire duration as calculated or specified by code
Temperature	°C	Temperature to cause failure >	Maximum temperature reached during fire
Strength	kN or kNm	Load capacity at elevated temperature >	Applied load during the fire

The most common application of this concept has been in the time domain, with the fire resistance rating of an assembly being implicitly taken as the time to failure and the fire resistance requirement specified in a building code taken as the expected fire severity. As noted previously, this implicit relationship between fire resistance ratings and actual fire resistance requirements may not be well founded.

The most analytical application of this concept is in the strength domain, where a three-step process is used to evaluate:

The expected fire exposure conditions;

The thermal response of the structure to the fire exposure conditions;

The structural response of the structure to the thermal conditions resulting from the fire exposure.

This type of approach has rarely been used in the United States, but is gaining headway, particularly in the international structural fire design community.

[27] Buchanan, Andrew H., Structural Design for Fire Safety, John Wiley & Sons Ltd, 2001, p.91.

Probabilistic Performance Objectives

In a probabilistic framework, the same deterministic performance objectives can be used along with statements of expected success probabilities. For example, the deterministic performance objectives could be expressed as:

Prevent the total or partial collapse of a building to a specified level of confidence;
Limit the spread of fire within a building to a specified level of confidence;
Limit the spread of fire between buildings to a specified level of confidence.

Appropriate statistical methods could then be used to demonstrate compliance with such probabilistic performance objectives.

While this probabilistic approach introduces the concept of reliability that is lacking in the deterministic approach, it is still based on single occupancy importance factors and tolerable damage performance levels for all buildings. To address the different occupancy importance factors and tolerable damage performance levels that are currently being used for earthquake and other natural hazard design, an alternative approach is presented in the next section.

Framework for Performance-Based Structural Fire Design

In recent years, the concepts of occupancy importance factors and tolerable damage performance levels have been introduced into performance-based codes.[28] These concepts have been implicit in the building codes since modern building codes were first introduced, but with the development of performance-based codes, there has been an effort to explicitly consider and define these importance factors and tolerable damage performance levels.

Four occupancy importance factors have been described to address the range of buildings from the virtually insignificant (e.g., a private shed) to the most important (e.g., hospitals) for public welfare:

Occupancy Type I includes structures such as sheds or agricultural buildings that are normally unoccupied. The failure of such buildings is unlikely to result in significant probability of life loss. Consequently, relatively little protection is required for such structures and it could be considered acceptable if they collapse in a rare event.

Occupancy Type II includes most types of buildings, including most commercial, residential and institutional structures. Under extreme loading, these structures are expected to be heavily damaged but not collapse.

Occupancy Type III includes important buildings that accommodate a large number of people, that provide important public services (such as utilities), or that house occupants with limited mobility such as schools or detention facilities. Greater protection against collapse is warranted for these structures for rare events, and less damage is acceptable for more moderate events.

Occupancy Type IV includes buildings that are deemed essential to the public welfare, such as hospitals, fire and police stations, and essential communication, transportation and water storage facilities. It is highly desirable that these facilities be capable of functioning following even a rare event.

Under this classification scheme, tall commercial buildings might be classified as Type II, based on the commercial nature of the structure, or as Type III, based on the large number of people accommodated in tall buildings. As the collapse of the World Trade Center buildings so vividly

[28] Johnson, Martin W., "Fundamentals of Safe Building Design," Section 1/Chapter 2, Fire Protection Handbook, 19th Edition, National Fire Protection Association, 2003, p. 1-48 – 1-49.

demonstrated, the collapse of large buildings in urban areas can have devastating effects on surrounding buildings, on the local and regional infrastructure as well as on the local, regional and even on national and international economies. In these respects, such major buildings in urban settings should be considered at least as Occupancy Type III and arguably as Occupancy Type IV under this classification scheme. In other words, the location of a large building should influence its importance factor classification along with its occupancy, with buildings located in concentrated urban areas having higher importance factors than similar buildings on large isolated campuses.

Three performance levels have been defined to describe tolerable damage levels, including:

Serviceability performance or mild damage, which is a state in which structural elements and nonstructural components have not sustained detrimental cracking or yielding, or degradation in strength, stiffness, or fire resistance requiring repair, that is troubling to building occupants or disruptive to building function. Nonstructural components and permanent fixtures and features have also not become displaced or dislodged.

Immediate occupancy performance or moderate damage, which is a state in which minor, repairable cracking, yielding, and permanent deformation of the structural and nonstructural elements may have occurred. Although repair may be required, the structure would not be considered unsafe for continued occupancy.

Collapse prevention performance or high damage, which is a state in which the building may experience substantial damage to structural and nonstructural elements, with some failures occurring. However, collapse is avoided and emergency responders can effect occupant rescue and building evacuation.

A fourth performance level would be partial collapse, or severe damage, while a fifth performance level would be total progressive collapse, or very severe damage. These performance levels are generally considered unacceptable in buildings of all types other than Occupancy Type I, except under extremely rare conditions involving extremely high loadings.

These concepts of occupancy importance factors and performance levels have been developed for naturally occurring extrinsic events, such as earthquakes, wind and snow loads. For such events, the magnitude of the imposed load is independent of the building design, although building design is important to the response to the imposed load. For these natural events, there also tends to be an inverse relationship between the frequency and the magnitude of the imposed load. For example, relatively small earthquakes occur relatively frequently while relatively large earthquakes occur relatively rarely. For such natural external events, historical data is generally available to assess loading frequencies.

Performance Matrix for Natural Hazards

The 2001 ICC Performance Code includes a matrix that describes the relationship between the occupancy performance group and the expected level of performance for events with different magnitudes and frequencies. This matrix is reproduced as Table 6.

For application to fire, the concepts presented in the ICC performance matrix need to be considered differently. Due to the technological and intrinsic nature of fire, neither the frequency nor the magnitude of a fire incident will be independent of the building design. The frequency of fire depends on a number of factors, including compliance with recognized standards for the installation of utilities, good ignition prevention practices, and the potential for arson and other terrorist acts, which may be related to building security design and management. The magnitude of fire incidents also depends on a number of building design factors, including the flammability properties, quantity and distribution of combustible materials, fire detection and alarm notification, automatic and manual fire suppression systems and activities, and fire confinement and ventilation. To a large extent, the magnitude and severity of a fire incident depends on the fire intervention strategies and their timing.

Table 6. ICC performance matrix for natural hazards.

Event magnitude (frequency)	PERFORMANCE GROUPS			
	I	II	III	IV
Very Large (Very Rare)	SEVERE	SEVERE	HIGH	MODERATE
Large (Rare)	SEVERE	HIGH	MODERATE	MILD
Medium (Infrequent)	HIGH	MODERATE	MILD	MILD
Small (Frequent)	MODERATE	MILD	MILD	MILD

Fire Event Tree

One way to modify the performance matrix shown in Table 6 for fire assessment is to consider the event frequencies and magnitudes in terms of an event tree, as suggested by Mowrer.[29] This provides a way to consider the progress of a fire as well as the effectiveness and reliabilities of the different intervention strategies and systems that are brought to bear on a fire as it develops in magnitude. This concept, sometimes referred to as "defense-in-depth," is presented in Figure 1, which also shows the different fire protection strategies and systems that typically interact with the fire development at each stage.

This event tree presents a perspective on building fire safety that helps to convey both the breadth and complexity of the problem as well as the temporal nature of the threat. For the purposes of this paper, the primary interest is related to the fire resistance of structural steel. In this regard, this event tree also helps to convey that this issue is a relatively small part of the overall building fire safety system, but a vitally important one because it is the primary system designed to prevent the collapse of tall buildings for fires that become severe enough to threaten the structural integrity of the building.

The different event outcomes or damage levels associated with fire need to be described in terms analogous to those used for evaluation of post-earthquake structural damage. For structural fire resistance applications, the following definitions are proposed for the different performance levels:

Mild damage is a state where no structural elements are damaged and the fire resistance of structural elements is maintained without need for repair or replacement. Superficial smoke damage may occur, but the basic integrity of the fire resistant treatment is maintained. With minor cleanup, the building can be returned to service.

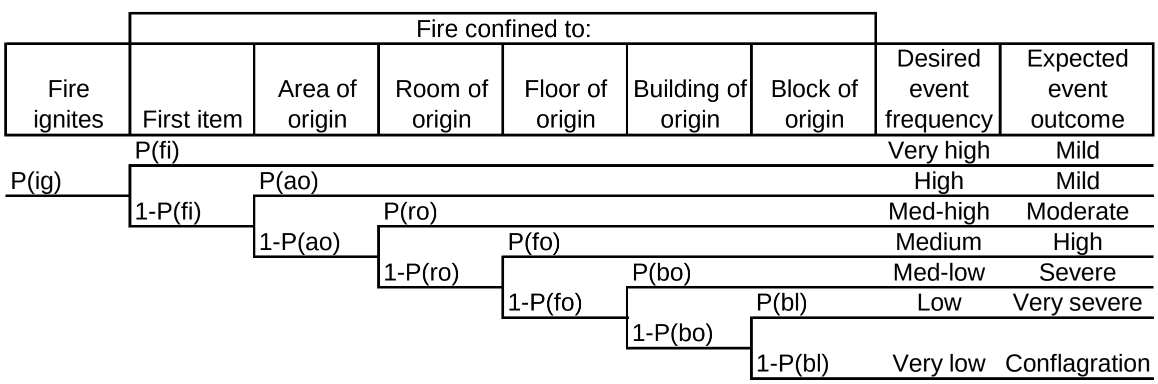
[29] Mowrer, Frederick W., "Overview of Performance-Based Fire Protection Design," Section 3/Chapter 14, Fire Protection Handbook, 19th Edition, National Fire Protection Association, 2003, p. 3-204.

Moderate damage is a state where no structural elements are damaged, but the fire resistance of structural elements may be compromised and the fire resistant treatment may require repair or replacement. With relatively minor cleanup and repair or replacement of damaged fire resistant treatments, the building can be returned to service.

High damage is a state where secondary structural elements may be damaged and localized deformation of secondary members may occur, but the primary structural frame remains undamaged. Some secondary members may need to be replaced along with damaged fire resistant treatments. An example of this fire damage state is the First Interstate Bank building in Los Angeles following the fire in May of 1988.

Severe damage is a state where primary and secondary structural elements are damaged, with localized deformation of both primary and secondary members, but disproportionate collapse does not occur. Primary and secondary elements may require replacement or, in the extreme, the building may need to be demolished, at least down to the level of structural damage. An example of this fire damage state is the One Meridian Plaza building in Philadelphia following the fire in February of 1991.

Very severe damage is a state where primary and secondary structural elements are damaged to the point where partial or total progressive collapse occurs. An example of this damage state is the World Trade Center 7 building in New York City during the fire on September 11, 2001. (The twin towers could be included here, but it should be recognized that the twin towers had already suffered “severe” structural damage as a result of the jet impacts that initiated the fires.)



Fire protection systems and strategies affecting probabilities at each stage:

Control of energy sources / fuels
Flammability of fuels / early detection
Early detection / automatic suppression
Automatic suppression / fire confinement
Fire confinement / fire department operations
Building construction / fire department operations
Fire department operations

Figure 1. Fire event tree for evaluating fire progression and mitigation strategies and reliabilities.

Proposed Fire Performance Matrix

Based on the distinctions between intrinsic technological hazards such as fire and extrinsic natural hazards such as earthquake, an alternative performance matrix to the ICC performance matrix is suggested that is based on the frequency of exceeding a particular damage state during a fire. This proposed fire performance matrix is illustrated in Table 7.

Table 7. Proposed fire performance matrix.

	PERFORMANCE GROUPS			
PERFORMANCE LEVEL	I	II	III	IV
Severe	Infrequent	Rare	Very rare	Extremely rare
High	Frequent	Infrequent	Rare	Very rare
Moderate	Very frequent	Frequent	Infrequent	Rare
Mild	Very frequent	Very frequent	Frequent	Infrequent

To implement the concepts presented in this proposed fire performance matrix, the relative frequencies associated with this matrix need to be defined. As a first step towards this definition, an order of magnitude approach is taken in which the conditional probability of exceeding each subsequent state decreases by an order of magnitude. This concept is illustrated in Table 8.

Table 8. Proposed probabilities associated with different relative frequencies.

Relative frequency	Conditional probability (per fire)	Cumulative probability of exceedance (per fire)
Very frequent		$> 10^{-1}$
Frequent	90%	10^{-1}
Infrequent	90%	10^{-2}
Rare	90%	10^{-3}
Very rare	90%	10^{-4}
Extremely rare	90%	10^{-5}

As an example, when considered in terms of the proposed fire performance matrix, Table 8 suggests that in Performance Group III occupancies it would be tolerable to exceed a mild damage level in 10 percent of the fires, a moderate damage level in 1 percent of the fires, a high damage level in 0.1 percent of the fires and a severe damage level in 0.01 percent (1/10,000) of the fires.

Implementation Issues

Implementation of the proposed framework for structural fire design would require the designer to demonstrate how the design performance objectives would be achieved. Procedures and data will need to be developed for this purpose. Within a deterministic design framework, this would entail the selection of a combination of fire protection features and systems that would maintain the probabilities of exceeding the tolerable damage states within acceptable limits. Statistics on the effectiveness and reliabilities of different fire protection features and systems are needed to support this approach. Within a probabilistic design framework, the same fire protection feature and system selection process would be used along with a more detailed analysis of system reliabilities and probability distribution functions for fire severities and fire resistances of different building elements and assemblies.

Deterministic Design Framework

Within a deterministic design framework, the designer would select the fire protection features and systems needed to meet the design performance objectives. Either more fire protection features or higher safety factors, or both, would be included for buildings with higher importance factors. In some respects, this is already done implicitly in the model building codes. For example, in hospitals, which are included in Occupancy Type IV, it is common to control combustibles, to include early detection and alarm systems, to provide automatic fire suppression and to provide a high level of fire resistance and compartmentation of the building. It would be instructive to map the current fire protection requirements for different buildings onto the occupancy important factors to determine how extensive such implicit connections might be.

An alternative approach would be to apply different safety factors to individual fire protection features based on the occupancy importance factor. This approach has not generally been applied to the design of fire detection systems (e.g., closer detector spacings) or suppression systems (e.g., higher design densities or design areas), although in some respects the reduced sprinkler system requirements associated with NFPA 13D relative to NFPA 13 could be considered in this way. This approach could also be readily applied to structural fire protection (e.g., higher fire resistance ratings). To some extent, this approach is implicit in the model building codes in terms of the height and area limitations based on occupancy classifications. This approach is analogous to the higher safety factors applied to the maximum calculated earthquake loads required by NFPA 5000 for different occupancy importance factors that are shown in Table 9.

Table 9. Safety factors for maximum calculated earthquakes from NFPA 5000.

Component	Performance group			
	I	II	III	IV
Structural	0.67	1.0	1.25	1.5
Nonstructural	0.67	0.67	0.83	1.0

Based on this concept, suggested safety factors for primary and secondary structural elements and assemblies and for nonstructural fire barriers are provided in Table 10.

Table 10. Suggested safety factors for fire resistance of structural elements.

Component	Performance group			
	I	II	III	IV
Primary structural	1.0	1.25	1.5	2.0
Secondary structural	0.75	1.0	1.25	1.5
Nonstructural	0.50	0.75	1.0	1.25

For example, assume a high-rise office building has an equivalent fire severity of 2-hours, using the traditional terminology associated with fire severity and fire resistance. If this building were classified as Performance Group II, then Table 10 would suggest that primary structural elements and assemblies should have a fire resistance of at least 2.5-hours (1.25 x 2). Similarly, if the building were classified as Performance Group III, then components of the primary structural frame should have a fire resistance of at least 3.0-hours (1.50 x 2), while if the building were classified as Performance Group IV, then the primary structural frame should have a fire resistance of at least 4.0-hours (2.0 x 2).

As noted previously, large buildings located in urban areas could be classified in higher performance groups than similar buildings located in less concentrated areas, thus justifying higher fire resistances for buildings located in concentrated urban areas. While the severity of the fires in such similar buildings would be expected to be similar regardless of the building location, the potential consequences of building collapse would be different based on the building location. Consequently, it would be reasonable to require a higher level of fire resistance for buildings located in urban areas than for similar buildings in isolated locations.

Probabilistic Design Framework

Within a probabilistic framework, the designer would select the fire protection features and systems needed to meet the design performance objectives, as in a deterministic design framework, then would support this selection with probabilistic analyses to demonstrate that the design performance objectives would be met with a specified level of confidence. The concept of the stress-strength interference model[30] is widely used for this purpose. This concept is illustrated in Figure 2.

Figure 2 demonstrates that even though the mean "strength" (e.g., fire resistance, or capacity) may be greater than the mean "stress" (e.g., fire severity, or demand), the "stress" may be greater than the "strength" for some fraction of the cases. Figure 2 also demonstrates that the region where the "stress" exceeds the "strength" can be reduced through the use of larger safety margins. While the shapes of these curves are intended only to be qualitatively illustrative, they do demonstrate these two important points. For example, note how there is virtually no overlap between the "stress" curve and the "strength" curve associated with 2.00 times the stress curve while there is considerable overlap for the strength curve associated with 1.25 times the "stress" curve and lesser overlap for the "strength" curve associated with 1.50 times the "stress" curve.

[30] Modarres, Mohammed, and Joglar-Billoch, Francisco, "Reliability," Section 5 / Chapter 3, SFPE Handbook of Fire Protection Engineering, 3rd Edition, National Fire Protection Association and Society of Fire Protection Engineers, 2002, p. 5-25.

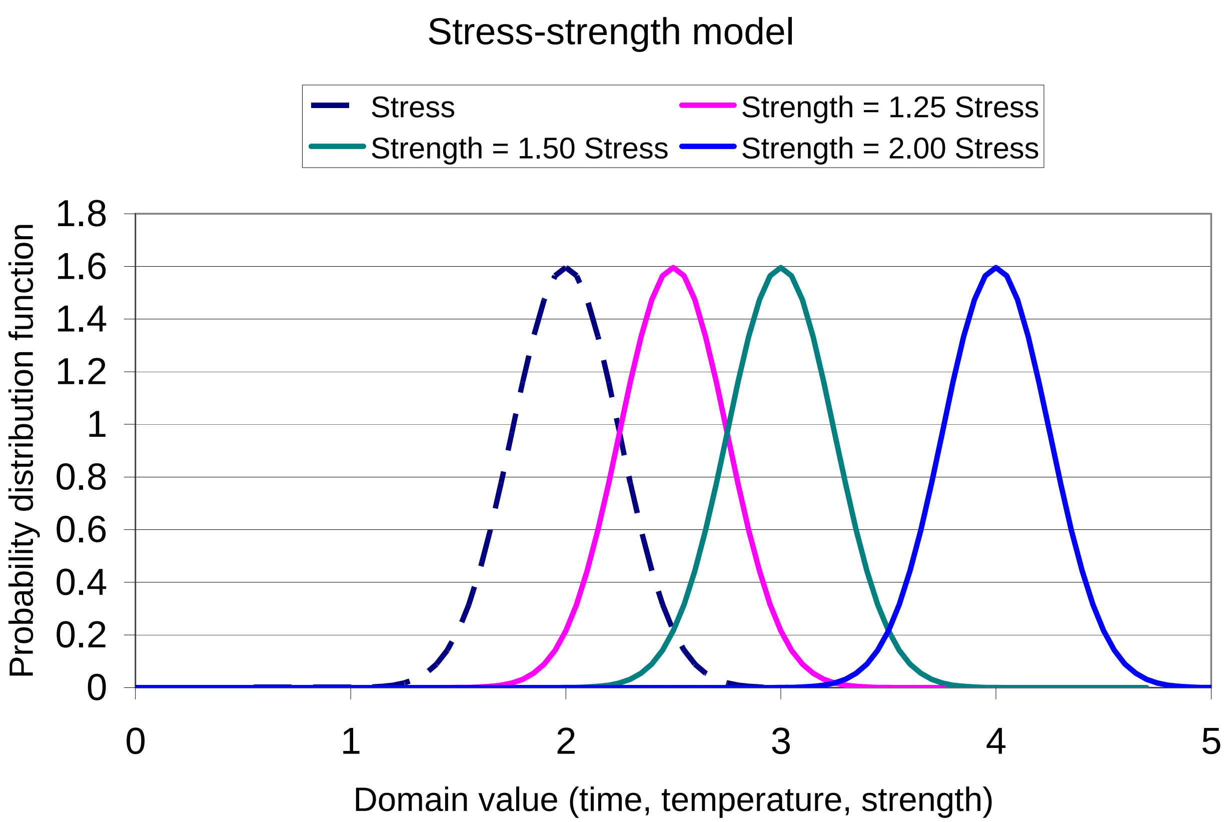


Figure 2. "Stress"-"strength" interference model for probabilistic analysis of fire severity and fire resistance.

In order to apply a "stress"-"strength" interference model to the issue of fire severity versus fire resistance, it will be necessary to develop appropriate probability distributions for fire severities as well as for the fire resistances of different structural elements and assemblies. In turn, this would require that fire severities be addressed in terms of all the variables that influence fire severities, not just the fire load concept upon which fire severity has traditionally been based. It will also require the development of probability distributions for the fire resistance of different elements and assemblies; such fire resistance values are currently available only as the point estimate ratings associated with standard fire resistance tests.

Other Factors and Research Needs

Introduction

Implementation of the proposed framework for structural fire design will require consideration of a number of factors in addition to those already addressed. It will also require research to further develop the framework and to develop the data and models needed to support the framework. Some of these factors and research needs are discussed in this section.

Multi-Hazard Scenarios

The treatment of multi-hazard scenarios needs to be considered in the development of a comprehensive framework for structural fire design. This should include traditional load factors such as dead loads, live loads, snow loads and wind loads, but should also address extreme events, such as blast and impact. With the increase in terrorist activity over the past decade, such extreme events are now recognized to be significant threats to structural integrity. Methods similar to those used in LFRD structural design could be developed with fire as either a load or a resistance factor to address multi-hazard scenarios. How to combine load factors, including traditional loads, extreme events and fire, requires further consideration.

A multi-hazard approach to design that includes fire as a design parameter provides the opportunity to enhance the fire performance of buildings while improving their performance against other hazards as well. For example, it may prove cost-effective to improve fire performance through structural enhancements that also improve earthquake and wind performance rather than through thermal enhancements that do not affect these other hazards. Such structural enhancements may also improve building comfort, for example by reducing building sway and vibrations felt by building occupants.

Research and Development Needs

The research needed to support the proposed framework for structural fire design is extensive. The following list of research needs is not exhaustive, but does summarize most of the issues identified in this paper.

There is a need for better definitions for fire severity and fire resistance based on building fire dynamics. Fire severities are still expressed in terms of the fuel load concept developed by Ingberg more than 75 years ago despite longstanding recognition of deficiencies in this concept. Similarly, fire resistance of structural elements and assemblies is still expressed in terms of hourly ratings based on standard fire resistance test methods that were developed more than 85 years ago.

Once an improved definition is developed for fire severity, there is a need to develop probability distributions for fire severities in buildings with different occupancies. There is a similar need to develop probability distributions for the fire resistance of different structural elements and assemblies, including the reliability and durability of different fire resistive treatments of these elements and assemblies.

Load factors and combinations need to be developed and established for multiple hazard scenarios that include fire and extreme events. Research is needed to evaluate structural enhancements that are cost-effective for mitigation of multiple hazards.

The effectiveness and reliabilities of different fire protection features and systems need to be established along with the impact of inspection, testing and maintenance on system effectiveness and reliability.

Finally, there is a need to develop authoritative design methods and documentation to support the structural fire design framework. Such developments should follow the processes used to develop design methods for other hazards, such as earthquake, and take advantage of the lessons learned during those processes. Designers and regulators need such authoritative design methods and documentation before they can rely on the proposed structural fire design framework.

Summary

Performance requirements for the fire resistance of buildings have existed in very near their present form for more than 75 years. These requirements are based on the occupancy, height and area of a building. When first introduced in the early 1900s, fire resistance requirements were considered to be a performance-based alternative to prescriptive material specifications. Today, they are considered to be a prescriptive specification, as they should be because the primary performance objective for the fire resistance of large buildings, collapse prevention, has been lost along the way.

For tall buildings, collapse prevention has always been the paramount performance objective. When fire resistance requirements were first being developed, this performance objective was explicitly stated. Once relationships were proposed between fire severities and combustible loads as well as between combustible loads and occupancy classifications, this performance objective became implicit and was addressed in terms of building code-mandated fire resistance specifications.

In a performance-based design and regulatory environment, different performance levels can be established for buildings with different importance factors based on different frequencies and magnitudes of hazard occurrence. Such an approach has been developed for extrinsic natural hazards, such as earthquakes, wind and snow, and is now incorporated into structural design documents such as the ICC Performance Code and ASCE 7. This approach needs to be modified for application to fire because of the intrinsic technological nature of fire. A framework for structural fire design has been outlined here for further development.

The structural fire design framework outlined here recognizes that the frequencies and magnitudes of fires are not independent of building design. The severity of a fire depends on building design features, such as the combustible loading, as well as on the types and reliabilities of fire protection features and systems included in the building design to mitigate the fire consequences. Within this structural fire design framework, the objective is to maintain damage levels within acceptable limits based on the importance factor associated with a building, with lower levels of acceptable damage associated with buildings of increasing importance.

The application of this framework to structural fire design has been addressed from both deterministic and probabilistic design perspectives. From a deterministic standpoint, additional fire protection features and higher safety factors are associated with buildings of increasing importance, while from a probabilistic standpoint, the effectiveness and reliabilities of these same additional fire protection features and safety features are evaluated in probabilistic space. Implementation of this structural fire design framework will require further research and development.

Objective 3: Testing to Predict Performance

Robert Berhinig, the Principal Engineer for Fire Resistive Construction at Underwriters Laboratories, Inc, addressed this NIST objective in the following white paper.

Introduction

This paper is intended to introduce and stimulate workshop discussion on the topic of needs of test beds and test methods intended to evaluate the fire endurance performance of structural steel.

The methods and performance criteria used to quantify the fire endurance of building systems have changed little over the last 50 years in Europe and North America. During this period, improvements have focused on sample selection, data collection, accuracy of the data and reproducibility of results on an inter-laboratory basis and the application of data. In 2003, the National Institute of Standards and Technology (NIST) published a report[1] that summarized the features of twenty-seven test facilities used to determine the fire resistance of building assemblies.

These present tools do not focus upon the fire performance of structural steel but rather apply to all forms of construction and construction materials including structural steel.

Numerous papers have been written identifying concerns regarding the present test methods such as ASTM E119[2] and ISO 834[3] and the application of results from these tests in determining the fire endurance of building structures. It is not the intent of this paper to convey an in-depth discussion on these identified concerns. These concerns will be highlighted for discussion purposes. It is understood that ASTM E119 and ISO 834 represent standardized test methods generating benchmark fire endurance performance for building assemblies for regulatory and certification purposes.

The intent of this paper is to focus on the criteria for test beds and for data that will satisfy the future needs of the public's health and safety in steel framed structures during fire. It is anticipated fulfillment of these needs will fall heavily upon the regulatory community and the fire protection engineering community. It is also anticipated that the application of performance based technology in place of prescriptive practices will expand and that computer modeling will play a greater role in expanding the database for prescriptive solutions.

Current Testing Beds and Methods

Today there are approximately twenty-seven testing laboratories that contain facilities to conduct standardized fire tests in accordance with the requirements of Standards ASTM E119 and ISO 834. The samples for these tests are nominally 4 meters by 5 meters for floor assemblies, 3 meters by 3 meters for wall assemblies with beams and columns being 3 meters. These samples have traditionally been identified as "full-scale" samples. When tested, these samples are subjected to a standardized temperature exposure and, except for steel columns in North America, loads intended to approach the structural limits of the samples.

In addition to "full-scale" samples, many laboratories also conduct tests on "small-scale" samples that are basically 1-meter samples exposed to the same temperature conditions but not the structural loading. Data from these "small-scale" tests are typically used to supplement data from the "full-scale" samples.

Performance of the "full-scale" samples is determined by the ability to support the applied load, insulate the structural members, and for the floor and wall assemblies, maintain a sufficient barrier to the passage of heat and flames to avoid the ignition of combustible materials on the surface away from the fire exposure.

During the past 75 years, these prescriptive approaches have been successful. In the NIST report, six occurrences of collapse in steel framed structures were cited. Four of these six were at the World Trade Center site. It would appear this performance has resulted from a balance of redundancy in structural design and the conservatism in the assessment of fire test data.

Specialized structures have been constructed in addition to the standardized testing equipment. Two examples include one at NIST and one at the Cardington facility of the British Research Establishment. Both were steel structures with the focus being to obtain information on the redistribution of loads within the frame during a fire exposure. Unlike the standardized equipment, these facilities have had a short life in terms of being used for a relatively few fire exposures.

Buildings have also been used as fire test facilities. Like the specialized structures, these buildings have been few and their life as test beds, very short.

These testing facilities, whether standardized samples, specialized construction or as-built structures, have focused on the performance of the assemblies during fire. The FEMA[4] preliminary report on the performance of structures at the World Trade site identified a need to address the durability of materials intended to provide the fire protection to the structural steel. The FEMA report also cited concern for a lack of data on the performance of connections between structural members. Except for limited applications such as welded connections between steel beams and steel bar-joist and connections between steel beams and steel deck sections, the standardized samples have typically not addressed connections between structural members. The Significance and Use section of ASTM E119 states, "The test standard does not provide the following: Full information as to the performance of assemblies constructed with components or lengths other than those tested and Simulation of the behavior of joints between building elements such as floor-wall or wall-wall, etc.".

Current performance criteria for testing equipment are somewhat limited. Both standards include tolerances with respect to variation from prescribed temperature levels. The ISO 834 standard provides criteria in addition to that specified in ASTM E119. The ISO standard specifies the minimum thickness and density of the furnace lining material, the pressure conditions within the furnace chamber and the minimum stiffness of the restraining frame into which test samples are constructed. ASTM E119 is silent on all these topics.

Neither of the test methods addresses the type or amount of heat flux received by the sample or the magnitude of the restraint applied by the testing equipment to the sample during the fire test.

With respect to heat flux, the ISO 834 method does specify a plate thermometer to be used to monitor temperature within the furnace chamber. The plate thermometer can be considered as a simplified directional radiometer in a test furnace because the dominant means of heat transfer in the furnace is by radiation and the receiving face of the plate thermometer is positioned parallel with the exposed face of the test sample.

Current Trends

In most every field of business, our ability to assess data and construct "what if" scenarios has increased tremendously during the past 30 years. Be it agriculture, finance, materials science, or architecture, computer science has enabled us to consider design to ultimate limits with a greater degree of confidence. Our structures have become larger and lighter. It has been reported[5] that fourteen grades of steel were used to construct the World Trade Center Towers. Has our understanding of structures in fire kept pace with these advances?

Work is underway in ASTM to further define specifications for testing equipment and the testing environment. The focus in ASTM is presently directed towards the operation of test equipment with respect to monitoring pressure conditions.

At Underwriters Laboratories Inc. (UL), in response to comments in the FEMA report, effort has begun to publish a standard focusing on the durability of materials used to protect structural steel in fire resistive assemblies. For many years, UL's certification for intumescent type coatings applied to structural steel has included durability tests. These tests have included exposure of coated steel samples to accelerated aging environments and high humidity conditions. The accelerated aging was achieved by subjecting samples to 70 ^{o}C for 270 days. The high humidity conditions have included subjecting samples to a minimum relative humidity of 97% at 35 ^{o}C for 180 days. The samples consist of 150 mm by 150 mm by 5 mm thick, 610 mm long steel tubes coated with the intumescent material. After conditioning, the samples are exposed to the temperatures specified in ASTM E119. Performance is determined by measuring temperatures on the steel samples during the fire exposure. For acceptable performance, the time for the steel tube to reach a temperature of 538 ^{o}C must not be less than 75 % of the time for a similar sample that has not been subjected to the aging and humidity conditions to reach 538 ^{o}C.

Assemblies tested in accordance with ASTM E119 and ISO 834 are intended for indoor applications. Protective materials on assemblies that are classified by UL for outdoor application are also subjected to simulated environmental conditions in addition to the ASTM E119 fire test. The samples are again typically 610 mm long steel tubes. In addition to aging and high humidity, the simulated environmental conditions include exposure to: (1) a carbon dioxide and sulfur dioxide air mixture, (2) a wet-freeze-dry cycling and (3) salt spray. As with the intumescent materials, acceptable performance of the protection system is determined by the ability of the protective system to limit the temperature rise on the steel tube to 538 ^{o}C for a time period at least equal to 75% of the time determined from "unconditioned" samples.

Expanding upon these concepts, the initial draft of a standard addressing durability included the following exposures in addition to those identified for exterior applications: (1) abrasion, (2) air erosion, (3) impact resistance and (4) vibration.

In response to comments, the scope of the proposed standard will focus upon sprayed or troweled applied fire resistive materials intended for application to structural steel. Three working groups have been formed to address: (1) the test sample, (2) the exposure conditions and (3) the acceptance criteria.

Reports from the working groups are expected by July 2004 after which it is anticipated that the initial ANSI ballot for the proposed standard will be circulated.

Meeting Future Needs

The expanding application of fire protection engineering and the acceptance of performance based codes have increased the demands for performance data related to fire resistive assemblies. Proposals to modify fire test standards, including test equipment, sample characteristics, data reporting requirements and acceptance criteria are expected. So what is needed? The FEMA report cited the need for performance data on connections between structural members. This need would appear to be feasible with existing equipment with guidance being provided by standard writing bodies. Connections such as splices in columns members (compression members) would probably require extensive modifications to typical horizontal furnaces to ensure all surfaces of the element under test would be exposed to the required temperature or heat flux requirements.

Results from specially built steel frame structures have demonstrated that a degree of load redistribution occurs within the frame because of the frame's stiffness and thus its ability to resist the resulting thermal expansion. Today, test frames do not include a mechanism to quantify the thermal thrust developed by the expansion of the assembly under test or a means to apply a level of resistance or restraint that would be representative of a structural frame. Is this data desirable? How should it be accomplished? During the 1960's, fire test facilities operated by the Portland Cement Association had horizontal test frames that included perimeter hydraulic jacking.

Another basic concern is the size of "full-scale" test specimens as compared to as-built structures. Today, effort is made at testing laboratories to arrive at a balance between the size of the structural item under test and the limiting factures with respect to the magnitudes of loads applied to the specimen. From a certification viewpoint, minimum and maximum values are established for critical components of the tested assembly. Is this an acceptable approach? Can the fire protection engineers prepare a performance-based solution with available information? If not, what additional data are necessary?

A final point of concern is the application of new materials and methodologies to existing data. Fire endurance ratings are established for complete assemblies. The majority of tests are sponsored by manufacturers of proprietary materials such as coatings applied to structural steel as compared to manufacturers of commodity items such as steel and concrete. Projects are naturally focused upon the performance of the sponsor's products. In today's regulatory environment, the application of these test data is acceptable so long as changes do not occur in the proprietary product. The influence of these advances in the properties of commodity materials, such as concrete and steel, in these previously tested assemblies may at times be overlooked. For example, the trend during the past 5 to 10 years has been the introduction of higher strength structural materials and new methodologies for determining the magnitude of allowable loads to be applied to the structure. Can the structure with higher strength materials support the applied loads calculated using newer methods at elevated temperatures? Are data determined from previous tests still relevant? Significant fire research projects have been and are being sponsored by trade associations funded by manufacturers of these commodity products. Do significant questions remain? How is research data transferred to the certification community, the fire protection engineering community and the regulatory community?

Recommendations

The following attempts to summarize the recommendations of four independent discussion groups. The discussion groups met immediately following the presentation of the paper.

For the traditional type of fire tests that evaluate the fire containment performance of building assemblies, such as ASTM E119, the test equipment, the test method and the reporting requirements should be more responsive to the needs of the fire protection engineering community. Data on the material and assembly performance should span a range of fire exposure conditions. A need was identified to establish a precision and bias statement for the test method in response to concerns raised regarding the repeatability of the test from both an inter and intra laboratory perspective.

At times the recommendations were conflicting. For example, it was recommended that the fire test be conducted until structural failure occurred and that data be provided documenting the performance of the test assembly during the "cool-down" phase.

A need for standardized test methods for determining material properties such as density, specific heat, heats of reaction, and conductivity as a function of temperature was identified. Various participants voiced a desire for public disclosure of these material properties to enhance the ability of the engineering community to use available computer fire modeling techniques. A need for standardized test methods was also identified to:

- Document the durability of materials used in fire resistive assemblies
- Evaluate the structural interaction between components of a building structure such as the horizontal and vertical members
- Identify equipment of sufficient size to evaluate the connection details of structural members.

It was also suggested that revisions be made to ASTM E119 to provide guidance in the scaling of the test assembly to be better representative of "as-built" construction.

References

NIST GCR 02-834, Analysis of Needs and Existing Capabilities for Full-Scale Fire Resistance Testing, U.S. Dept. of Commerce, Building and Fire Research Laboratory, National Institute of Standards and Technology, Gaithersburg, MD, December 2002

ASTM International, "Standard Test Methods for Fire Tests of Building Construction and Materials", ASTM 119-00a, West Conshohocken, PA, 2000

International Organization for Standardization, "Fire resistance test – Elements of building construction – Part 1: General Requirements ISO/FDIS 834-1, Geneva, Switzerland, 1999

FEMA 403, "World Trade Center Building Performance Study: Data Collection, Preliminary Observations, and Recommendations", Federal Emergency Management Administration, Washington, DC, May 2002.

Reliving 9/11, With Fire as Teacher, James Glanz, January 6, 2004

Objective 4: Reality - the Marketplace, Price/Demand Factors

No separate white paper addressed this NIST study objective. Rather, the response to this objective was synthesized here by CERF based on the interaction of participants in the workshop and their analysis of issues addressed in the white papers and is presented below.

More is Needed!

It is tempting to say that the concerns with fireproofing of steel structures that were discussed in this workshop are solely a consequence of the collapse of the World Trade Center; and therefore, since that was a singular event, reality suggests that our response should be directed at preventing terrorists from hijacking airplanes and flying them into buildings. In fact, the workshop experts did recognize that while more can be done to improve fire protection safety in high-rise structural steel buildings, it is not feasible to design for such events as occurred on 9/11. As one breakout group noted, "Fire hazard mitigation should be a top priority, instead of focusing on products to protect from worst case scenarios."

This statement, however, does not negate the need to address pre-existing technical, economic and life-safety issues that surrounded fireproofing of steel structures prior to 9/11. The magnitude of the destruction in New York City simply brought to the American public, through the front pages of newspapers and television reporting, an awareness of issues that had long existed in the fire engineering and research communities.

A particularly important pre-existing life-safety issue stems from the fact that fire protection standards for high-rise buildings have been liberalized in the current building codes. As Mowrer notes in his white paper:

"there has been a general reduction in fire resistance requirements in recent years"

More specifically,

"The fire resistance requirements in the 2000 IBC have been reduced since the 1927 UBC, with Type IA construction requiring 3-hour fire resistance ratings for structural frames and 2-hour fire resistance ratings for floors".

Similar provisions are embedded in the 2003 NFPA 5000 Code; for example, if certain conditions are met (smokeproof exit enclosures, supervisory initiating devices and waterflow initiating devices) Type I(442) may be reduced to Type I(332) and Type I(332) is allowed to meet standards of Type II(222).

The technical bases for these apparent reductions and trade-offs in fire protection have not been established.

Marrion et al (the authors of White Paper No. 1) note that the currently used materials for fireproofing have remained unchanged for a significant time since they "perform well if designed and applied correctly and appropriately". They then focus on the challenges faced by new technologies, namely that these new fire protection means generally rely on performance criteria and thus fall outside of the current building codes and must rely on the alternate means and methods provisions in model codes. This is a situation that also existed prior to 9/11. Coherent guidance for the code officials and authorities having jurisdiction that would allow them to consider innovative materials and methods is still unavailable.

The professions' inability to establish a sound technical basis for changes in codes and/or standards, or to provide guidance to the authorities having jurisdiction, follows directly from Mowrer's statement that current design objectives have focused on "meet(ing) the required fire resistance rating" even though fire safety professionals have "long recognized" that ratings derived from standard fire resistance tests do not accurately predict how that building element or assembly will perform "in situ".

An examination of the materials used for fireproofing, the thermal resistance of the steel structure itself, the approaches used to assemble and erect steel structures, and the test methods and codes that ensure the safety for the occupants and first responders may reveal a need for change. The examination may also reveal economic opportunities. A good example is provided by the collaboration in the 1990s among the steel industry, academia and the British government to examine the fire resistance of full-scale steel frames with varying amounts of fireproofing. A general conclusion from their study was that the inherent ability of steel structures to effectively redistribute load justifies the elimination or reduction of fireproofing to below the requirements of the then-current British standard. While the concept of reducing the fireproofing on the steel frame without compromising its integrity was nicely demonstrated, generalization of these results and the development of sound guidance for moving in this direction will take considerably more effort. However, the economic payoff could be considerable.

The simple and obvious statement that the benefit (or reduction in risk) of any change in materials, methods, or regulations should outweigh the cost (or increase in risk) of implementing the change belies the complexity of quantifying the true benefits, the full costs, and the multiple perspectives of the many interest groups as to their specific risk (or cost) and benefit. The huge risk associated with a singular event such as the collapse of the World Trade Center needs to be somehow combined with what may be a minimal risk based upon the historical record. In the end, however, the perception of risk to an individual or organizational stakeholder is more important than the actual risk.

What should be done to ensure that requirement expressed by Buchanan, i.e., *Fire Resistance ≥ Fire Severity,* is attained in the most economic manner? An innovative, multi-dimensional approach is suggested, involving better, performance-based understanding of fire protection materials, both old and new. New insights, through research, are needed relative to the thermal, mechanical and durability properties of both fire protection and structural components, acting separately and in combination. Such new knowledge and technologies can be applied both to increase benefits and help reduce the actual and perceived risks, and not just in high-rise structural steel buildings, but across the built environment.

Two institutional "barriers" that impede this proposed effort are noted: first, the current lack of a generally accepted framework for structural fire engineering and, second, the inescapable fact that progress invariably requires consensus by all stakeholders, perhaps especially among owners, architects, engineers, and others with responsibility for ensuring the safety of the public.

A Synthesis of the Workshop and White Paper Deliberations

The synthesis emerging from the workshop identifies both specific recommendations and actions and the issues that require resolution to attain our objectives. These actions and issues encompassed both technical and procedural/organizational issues. And, importantly, the synthesis encompasses the diversity of constituents, the economic imperatives and the inclusion of fire safety protection as one component of a multi-hazard construct.

The scope of our discussion is, centrally, the fire protection of structural steel in high rise buildings, but the ramifications of the concepts identified go well beyond these boundaries to offer potential for improvements in risk management throughout the built environment.

The specific recommendations for improving the state-of-the-art derived from this study include:

- Viewing fire safety protection for any building as a system, not as isolated elements.
- Developing accurate performance-based design approaches and appropriate standards.
- Ensuring that structural fire protection is inter-disciplinary among architect, structural engineer and fire protection engineer.
- Including all "stake-holders" at project inception; i.e., architects, owners, structural engineers, fire officials, jurisdictional authorities, security, facility management, etc. The inclusion of "non-traditional" stakeholders, such as security agencies, insurers, among others, reflects the changing view of fire protection as multi-dimensional and multi-hazard.
- Developing incentives/requirements for building owners to fully incorporate fire safety protection (through, for example, fire risk ratings and an attached scaling of insurance premiums).
- Defining roles; i.e., responsibility for fire safety protection; both in design and in operations.
- Improving knowledge of as-built conditions
- Incorporating applicable model data from other hazard disciplines
- Developing needed "tools" to enable accurate modeling/prediction
- Evaluating/adopting/adapting, as appropriate, provisions of fire safety protection models/standards developed in other countries

Significant barriers (issues) exist that, in different ways, may impede attainment of these specific objectives. These include:

- Shifting from prescriptive to performance based fire safety protection entails research to develop models and tools, significant resources and time.
- Balancing the ideal with the attainable
- Enlisting effective cooperation from all constituents and stakeholders, especially the codes and standards organizations and the authorities having jurisdiction at the local levels of government.
- Developing appropriate incentives
- Delineating responsibility and accountability

This synthesis is at this point only an intellectual construct. The path from ideas to reality was given a firm foundation by workshop participants in their prioritization of required actions, as documented in the following recommendations and conclusions.

The “costs” of implementing any recommendation for change were recognized as a reality! The admonition from one study participant (R.J. Wills) speaks for all: “Allocate resources in a focused, rational manner that will lead to real improvements in life safety and property protection”.

Finally, it is likely, if not evident, that any effort undertaken to improve upon fire safety protection in high-rise structural steel buildings will have beneficial impact upon other constructed facilities.

Recommendations and Conclusions

The "synthesis" that emerged from the workshop is evident in the priority ordering of recommendations. These are depicted in the Table below.

The workshop participants developed and nominated the candidate recommendations for action during their breakout sessions (small group) and brought them to the closing plenary session. There was a collaborative process to eliminate duplicative candidates and to combine those that overlapped. A simple voting process by all participants yielded the following result.

Rankings of Workshop Recommendations

Rank	Recommendation	No. of Votes	Percent
1	Form An Industry-Wide, All Stakeholder, Blue-Ribbon Committee To Develop Integrated Design Methodology Based On Proposed Fire Performance Matrix Presented By Mowrer (White Paper 2 – Table 7).	22	14.4%
2	Develop Holistic Design Models/Methods to Consider Design Fire Response and Performance of Entire Structural Systems. Consider Multi-Hazard Approaches and other Engineering Disciplines	20	13.1%
3	Evaluate The Current Precision And Bias Of Existing Fire Resistance Test Methods	13	8.5%
4=	Review And Assess Current And Past Trends Toward Reducing Passive Fire Resistance In Codes; Correlate With Models	12	7.8%
4=	Develop/Correlate Models with Fire Test Data	12	7.8%
4=	Define Performance Objectives For Fire Protection Materials (FPMs) And The In-Situ System Of FPM And Structure, Operating Together. Use This Approach To Level The Playing Field To Stimulate New Entries Into The FPM Market – Allowing For New Systems And Technologies, Also.	12	7.8%
7=	Standardize Third-Party Inspection and Label Service Requirements in the Codes (Includes Laboratory Accreditation)	10	6.5%
7=	Develop a 'Marketing Plan' to Convince Industry Stakeholders of Need to Embrace Change and Improvements in Processes	10	6.5%
7=	Introduce Voluntary Certified Ratings for Buildings (Compare with Programs Such As LEED and Code Plus)	10	6.5%
10	Develop and Implement Durability Standards for Use in Design and Construction, and Incorporate Requirements for Installation Quality in the Field and For Periodic Inspection During Lifecycle	8	5.2%
11	Establish Basis (Need) for Change (see Marketing Plan above)	7	4.6%
12=	Incorporate Risk/Benefit Tools in Model Codes to be Accessible to Local Communities and Designers; Educate on Risk	5	3.3%

12=	Introduce Undergraduate and Graduate Cross-Disciplinary Training in Architecture/Design/Structures/Fire Protection	5	3.3%
14	Revise ASTM E119 to Run Test-To-Failure and Provide Data for Structural Scaling	4	2.6%
15	Change Public/Cultural Perception that High-Rise Buildings are not Safe	2	1.3%
16	Define Scope For What Buildings To Address In Using New Approaches, Such As Modeling, Because The Cost Will Not Permit Universal Application At Present	1	0.7%

What definitive conclusions may be drawn from the results of this study?

First, it should be acknowledged that the American population has been well served by the design and construction industry regarding fire safety in high-rise structural steel buildings exposed to historical threats. As was noted in the workshop and was highlighted in the *Engineering News Record* article that covered the workshop (February 12, 2004, p. 15), in recorded history only seventeen buildings of four stories or taller have suffered structural damage from fire. And of these only two had structural steel frames.

Despite this notion, often repeated during the workshop, that the status quo is working well.....is not broken....etc., it was also clear to most participants that there are areas of design, construction, maintenance, and testing that can be improved upon. In fact, the consensus drawn from the expert attendees is that the future paradigm for fire safety in high-rise structures (if not all structures) should shift from a deterministic toward a probabilistic basis. The power in computational capabilities afforded by today's computers enables a substantial step forward in cost-effective modeling of behavior and integrating scalable test data to predict conditions under all types of loads. The question that remains is at what threshold scope and scale and character of building is it economically viable to conduct the more comprehensive and analytical design activities and in some cases even conduct scalable testing of structural components under fire and other loads?

We group the recommendations into the following action plans with suggestions on how best to carry them forward.

Improved Structural Design Methodology

A number of the participant discussions suggested that there is a need to take a holistic approach to integrating thermal loads and effects of fire into the analysis and design of steel structures. Compare the current standard of design for seismic loads which requires consideration of systemic actions and reactions of the structural systems to the test loading conditions. Analysis and design should no longer focus on simply providing fire rated construction based on fire resistance testing of single elements such as a column, beam or floor assembly. Methods should be developed with the fire protection engineering community such that the response of the entire structural system to design fire scenarios would be considered. This approach would include development of fire scenarios and time temperature histories as well as methods for prediction of the impact of fire on structural strength and dimensional stability of elements including load redistribution to less exposed or unexposed portions of the structural system. Such methods should be developed as a component of a Multi-Hazard design approach, and requires collaboration among architects, structural engineers, fire protection engineers, and other professionals in the design process.

We recommend that the architecture and engineering professional communities work with industry to address this need with NIST/BFRL maintaining a facilitation role. This initiative fits within BFRL activity as part of their oversight of the WTC studies, is part of their mission of promoting advances in fire safety and protection, and will also be a key element of the NIST National R&D Road Map in this domain.

Improved Testing for Fire Protection Materials, Technologies, and Systems

The current approach provides a set of barriers to innovation. The overly simplistic 'fire rating' system is not useable for many new systems and products. It also does not support the need to conduct holistic modelling of combined performance (protection system and entire structure) under varying types of fire conditions. Codes also are too simplistic for special buildings: Marrion et al identified a spectrum of fire protection technologies/materials that are currently available and noted that the incentives for use of such new materials are often impeded by the current need to just satisfy building code requirements. Ensuring that test beds and test methods accurately measure and predict expected performance in the field environment is another key conclusion from this study. As noted in several of the white papers, this is a well-known deficiency in current evaluation procedures.

We recommend that NIST/BRFL continue to advance the correction of these shortcomings to enable the entry of innovative methods and materials into the fire protection arena by fostering better definition of performance requirements and testing programs tailored to demonstrate this performance. We recommend that the code developing organizations provide for special buildings to be defined and permitted outside the boundaries of current codes and standards. We urge that both these elements also be included in the NIST National R&D Road Map.

Charging Building Operations and Maintenance Functions with Sustaining the Technologies, Systems, and Materials that Constitute Elements of the Fire Protection System

Workshop participants observed that there are not only problems of quality in the installation of fire protection systems that severely compromise their effectiveness, but also problems of maintaining these systems through the life-cycle of the building.

We recommend that the professional societies and NIST/BFRL work with industry, the code enforcement jurisdictions, the insurance companies, and the building owners, to establish a standard of care for maintenance of fire protection systems.

Maintaining Stakeholder Involvement in Development of Improved Methodologies

Movement toward change in standard of care, design protocols, codes and standards and material and systems testing, creates substantial upheaval among stakeholders in the design and construction activity of the building industry. Although the prospect presently is that substantial change need only take place initially in the design approach for the special buildings category – those exceptionally tall or otherwise unusual buildings, there will likely be evaluation and incremental application of change in the fire ratings system for testing and approval of materials, systems, and technologies used more universally. The champions and stewards of such changes have a special responsibility to secure ownership of, and consensus around the proposed changes among all the stakeholders, providing continuous education on the impacts of the change and bringing them along.

The professional societies and NIST have a shared responsibility to make this happen, working with industry, as they champion change in design, construction, and maintenance practices.

Providing Incentives for Improved Approaches to Design, Construction, Maintenance for Hazard Resistance in Buildings

Through history there have been incentive systems promulgated by the indemnity industry to encourage building owners to make their buildings safer. The workshop participants encouraged development of a rating system that would take into account, design to a higher fire resistance level. The concept is that such investment by the building owner to achieve additional protection warrants a reduction in building insurance premiums consistent with the reduction in risk.

This effort should be a collaboration among the owners, the insurers, and the design professionals.

Adjustments in Professional Education to Adapt to Multi-Hazard, Holistic Approaches to Design, Construction, and Maintenance of Buildings

The Workshop participants recommended that the collaborative, multi-disciplinary design approach among architects, structural engineers, and fire protection engineers necessary to achieve the holistic, multi-hazard standard, be embraced in the curricula of engineering and architecture schools. Further, graduate and post-graduate programs should be designed to promote the cross-disciplinary approach among these areas of study.

This should be championed by the education arms of the professional societies with the support of NIST.

In summary, only the will to proceed is required for action. The National Institute of Standards and Technology must support these actions through their selective funding and as a catalyst and facilitator for change.

Appendix A: Workshop Implementation Notes

Planning for the Workshop focused on using the three white papers to frame and stimulate discussion in three of the four workshop objectives, and using the breakout groups to review their findings and discussion against the fourth objective. The essence of the fourth objective was to ensure that we were continually injecting the realities of professional practice and the marketplace and economic decision-making into the development of recommendations and conclusions.

Cycling of the participants between plenary and breakout sessions was designed to balance cross-over fertilization of ideas with crystallizing specific actions derived from the brainstorming.

Substantial effort was invested in achieving a good representation of stakeholders in the effort. Despite that effort we did lack in representation of design architects and in representation of building owners. On the other hand, we were able to get a good representation of manufacturers of fire protection materials and systems, and we had some representatives of other domains of fire protection activity such as the ship-building business. The latter made a good contribution to the discussion with descriptions of their experiences.

Feedback from participants on the conduct and value of the workshop was very positive.

Appendix B: Workshop Breakout Session Notes

Summary Agenda

Day 1:

Introductory Session

Session A – Spectrum of Technologies, Materials and Systems

Breakouts – Group I – Technologies/Materials

Group II – Performance

Group III – Testing

Group IV – Practice and Marketplace Considerations

Session B – Performance

Breakouts – Same 4 Groups

Day 2:

Session C – Testing and Performance Prediction

Breakouts – Same 4 Groups

Session D – Implementation and Action Plans

[These notes from the breakout groups are 'raw' and may not be understood by all readers; nonetheless they capture much of the brainstorming of the workshop participants and are thus believed to be a useful reference.]

Session A

State-of-the-Art of Fire Protection Materials, Systems, and Technologies

Breakout Group I

Materials of Promise Not Mentioned in the Presentation:

- Steel shielding
- Thermal mass

- Autoclaved aerated concrete
- Subliming products
- Cement-gypsum products
- Plastic --- "Starlite"
- Fire protection steel
- Silicon-based products
- Ceramics, barrier gel
- Addition to conventional products to enhance durability (such as gypsum, spall-proof concrete, etc.)

Problem with Existing Methods and Materials:

- Fire protection covers cracks in structural elements from detection, which hinders inspectability
- No concrete determination of effectiveness under multiple hazards
- Durability
- Repairability
- Labor-intensive cures
- Quality of application
- Health and safety

Other Issues & Comments:

What about concrete?
What about other types of steel systems that are not used in high-rise?
Consider fire protection of whole system, not single elements
The approach to structural fire protection should be inter-disciplinary between architect, structural engineer, and fire protection engineer
There is a need to integrate modeling of fire and structures
What are the performance requirements?
There is a lack of basic engineering property data
Fire protection cannot be looked at in isolation
Modeling should be given a bigger push, along with testing
What are the initiating events that affect the fire? Fire hazard mitigation should be a top priority, instead of focusing on products to protect from worst case scenarios

Breakout Group II

General Discussion:

Integral fire protection (fire resistance is part of the structure) or "superficial" (FP's only purpose is FP).
Concrete filling
Concrete encasement
Spray material, board
Are there ways to enhance the structure fire performance for multi-hazard?
A gentleman from Manchester published a book 6 months ago. Expressed motive: produce "natural" fire protection, intrinsic, inherent. Describes various means. Carrington, Broadgate fire in Great Britain. Meet perfect conditions without

adding superficial elements. Recommendations: Different performance scenarios. Events: no damage, no collapse. Intermediate degree (serviceability, occupancy). A combination of inherent and superimposed FP may achieve it.

Is it appropriate to make the assumption that FP will be damaged? Problem of inspection. Allowance for patching.

There are inherent differences.

There is no license for applicators of FP. There is no program that sets standards for durability. A standard is being developed for SFRM (Spray-applied Fire Resistant Materials). Another standard for periodic inspection. Must test active systems. There is a special inspection requirement. Global requirement: maintenance of fire safety system, inspect for performance level it was designed for. Can also modify structure (concrete, steel).

Chose the lowest level that meets the code. Tree-top presentation by Dick. Not enough emphasis on new materials (ceramic, fire-resistant steel).

Performance AHJ

How do you evaluate?

What is there?

FP spray. Why can't we use bigger steel? A building is like an aircraft on the ground. Limitations: cost, "erectability".

Face the realities of "erectability", "buildability" of today's world.

The market will drive what will be used.

Mass doesn't always protect from fire. Chief Vincent Dunne. Collapse of burning structure.

O'Hagen's book 1977.

Discussed differences between thermal mass of Empire State Building and WTC1. WTC couldn't have been built without pan decks.

Look into facts. Fire resistance we specify vs. that in the field. There is maintenance over the life of a building. There aren't any code requirements.

Address structural steel.

Requires thermal protection generally.

Has inherent (limited) fire resistance.

Reduction of strength with temperature.

Typical approach: thermal insulation.

2 issues: adequacy to protect (performance level), reliability.

<u>Adequacy</u>:

Codes

Performance (actual)

Experience (track record)

Do not confuse code compliance with engineering design.

There is no relation of codes to science. More politics.

<u>Reliability Aspects</u>:

Durability, maintainability, inspection ("inspectability" throughout life)

Enforceability

Don't stop at getting approval of AHJ

Experience (track record)

Issue of retrofit?

Other factors.
Cost/cost Materials, installation
Weight / space
Aesthetics
Suitability for retrofit
Exposure conditions (e.g. degradation)
Retrofit suitability
Environmental impact
Aging
In addition to thermal insulation we may have active systems (sprinklers) and limiting the "combustability" of content.
Alternative protections
Control of content (combustibles)
Performance level
First Interstate Bank
One Meridian Plaza
WTC, particularly WTC # (progressively collapsed)
Can't reliably count on firefighting as a strategy.
Ventilation is another factor.
There are reports on steel after fire (US Fire Administration).
Missing link: ability to predict performance.
Extreme events, conditions
Environmental /external man-made causes
Need different durability standards depending on use
Durability issues

Durability Issues:
Now and in the future
Adhesion to substrate
Corrosion/ chemical resistance
Weathering
Maintain fire performance throughout its life
Weather/ environment
Freeze-thaw
UV
Rain/ dampness
Impact
Air erosion
Vibration

Strategies/Tactics:
Understanding current performance and the limits of it
Developing new technologies

Barriers:
Need?
Perception of need?
Is there a need for improvement?

Perception
Closed system of reporting on fire test results
Get info publicly accessible – concerns life and health
Shouldn't be in the proprietary domain.
Proprietary data
Cost of development and approval
Risk-based environment
No clear-cut answer
Lack of good science (material science).
Constructability (field construction)
"Inspectability"

Breakout Group III

It was decided by the group that the presentation on materials and techniques covered all the necessary aspects on the issue. Therefore, the discussion was focused primarily on performance characteristics.

Performance characteristics:

- Life safety
- Burnout survival; post-fire serviceability
- Risk analysis based on event severity
- Expectations related to aesthetics
- Space availability and accessibility
- Fire resistance
- Durability
- Aging
- Installation requirements/quality assurance
- Lifecycle analysis
- Durability
    - Mechanical impact and abrasion
    - Moisture durability
    - Freeze/thaw
    - Flexural and lateral strength/strain
- Multiple threats
- Scenario where an earthquake is followed by fire (active suppression gets incapacitated in such a case).
- Nature of performance requirements versus material properties

- There are various applications based on different factors, but our focus should be on system-wide application.

- Since cost is a product of price and the rate of application, a very expensive product can be use of little application (where needed), or a less expensive product can be used for extensive system-wide application.

Breakout Group IV

The group believed that the speaker spoke about the technologies completely. The only addition that the group made was to identify insulated blankets as a system previously not addressed.

Session B

Performance Requirements

Breakout Group I

- Certain material properties are needed that are specific to products under consideration, such as steel properties, k versus temperature, rho, c versus temperature, expansion, impact resistance, shear strength, bond strength, toxicity, abrasion resistance, etc.
- Pre-fire and post-fire analysis of performance of structure and structural protection is needed
- Need some factor to classify building performance in fire that is tradable to an analysis method --- model after earthquake design
- Design fire should be standardized as a thermal load – "live load" (kg/m^2)
- Burn rate --- "impact load"
- Analyzing for worst case may be the best approach

Breakout Group II

General Discussion:

We don't want high-rise buildings to fall in urban areas when there is fire.
Multi-hazard (FEMA needs to include fire).
Cost-effective solutions.
Andy Buchanan's recent book. Steel looses half its strength at 1000 °F
Fire resistance > fire severity
Keep the objectives in mind when revising the requirements.
Importance: ICC hierarchy
Design performance goals
Performance requirements
Acceptable method
Prescriptive
Authoritative (engineering design)
Multi-hazard tools and models
Framework issues
Data needs
Framework: multi-hazard analysis of structural response
Restricted to structure
Dependencies: fire following earthquake (FFE).
New and retrofit of existing
Design Life Exposure Conditions (performance envelope), FFE
Database of reports/findings
Load/event combinations including fire
Extension of LFRD?
Design Fire Loads
How to characterize the severity of the fire?

Performance prediction
General model
Fire conditions: E 119/ UL 1709 (standard exposure)
Predicted time-temperature
Expected envelopes
Thermal response model (of protective coating, how much heat goes into the structure)
Thermal properties
Material degradation (e.g. delamination)
Mechanical properties
Record displacements
Structural response model (displacements)
High temperature properties
Collapse mechanism
Record displacements
Structural failure criteria
Fire severity envelope
How to interpret the database of fire tests?
Differences based on occupancy.

Tools & Models:
Tool to translate existing or future test data to expected field performance.
Connection performance
Spatial resolution: Do we need to go to exact temperatures?

Strategies:

- Use "lumped" models whenever possible
- Use minimum resolution appropriate to issue
- Take advantage of other disciplines (earthquakes, blast).

Barriers:

- Lack of material data (thermal performance of fire proofing)
- Characterize material data at elevated temperatures
- Labor "intensivity" of data entry
- Knowledge of as-built conditions

Breakout Group III
Performance Issues:
Performance objectives for structures
Multi-hazard analysis such as fire followed by an earthquake, fire followed by a blast, fire followed by a tornado, or fire followed by a planned attack.
Defining the performance envelope required of insulating material
Data on performance to failure
Probability distribution function
Full-scale evaluation versus small scale evaluation --- interactions with systems
Validation of test design
What is "full scale"?
What data is needed for scaling?

Insulation properties:
- Cohesion
- Thermal conductivity
- Impact resistance
- Abrasion resistance
- Aging (such as impacts of moisture, durability, etc.)

Engineering design tools for predicting structural response to fire scenarios
Specification of data needed from fire resistant tests.

Strategies for Implementation:

Apply modern tools to forensic investigation of previously well-documented significant fires.
Multiple scale strategic tests.
Undergraduate or graduate disciplinary training in fire/structures/design
Quantifying risks/benefits to the community
Incorporate risks/benefits tools in model codes to be accessible to local communities/designers
Education of AHJs
Development of methods for measuring material properties under fire conditions

Barriers:

Unclear rationale for prescriptive codes
Misrepresentation of what a fire-resistance rating (1 hour, 2 hour etc.) means for actual fire performance
Difference perceptions of fire and structural engineers
Hand-off of responsibility from designers/builders/owners and multiple ownership transfers
No beneficiary of risk analysis
Decision level of risk benefits analysis is local
Vested interests resist change. Can't analyze impact due to complexity.
Diversity of AHJs
Conflict of interest over proprietary information

Breakout Group IV

Fire Resistant Steel: We discussed the barriers to the implementation of fire resistant steel at length. With temperature as the limiting criteria in E119, it is not able to test the steel's ability to carry the load. Because of the lack of failure criteria or deflection criteria, E119 cannot capture the advantages of fire resistant steel.

E119**:** It was the opinion of many in the room that E119 is too severe in some situations and not severe enough in others. Boundaries are not categorized correctly.

Ceramics as Structural Materials: No one in the room was familiar with the use of ceramic structural members in the upper floors of buildings as mentioned by Mike Goode.

Quality Assurance: Quality assurance is a major issue throughout the life of the project.

Design: Some members of the group thought that security is forgotten after the design/development stage. Many times, after the fire safety experts aren't involved anymore, value-engineering of the project will reduce the thicknesses of fire protection after design/development. Quality control is a major issue. We aren't sure if we have the protection we want.

Construction: Disturbances of the spray-applied fire protection in the field and small weaknesses in the application of the material is a problem. If the installer misses a small portion, that spot becomes a hot spot. Also, inspections do not always pick up major gaps in the fire protection. A worker putting up a partition may remove fireproofing in order to install his wall, and the fire proofing isn't replaced.

Building's Life: There was some thought that inspection of fire proofing should be required every 5 years.

Costs: If competing goals aren't examined and optimization doesn't occur, than cost becomes an issue. The owner needs to see the benefit to designing a 'secure' building. What buildings do we need to make a difference with? In which buildings could you sell security? Possibly if things change, than the older buildings might be considered less valuable. What buildings must follow additional guidelines? Currently, design is 100% regulatory driven and cost driven.

Bare Steel: In Europe, the trend is to reduce or eliminate the fire protection. Many times, if the connections are ok, the building is ok. There was a thought that maybe, for some situations, only the connections need to be fireproofed. This may be true with low rise buildings, but high rise buildings and hospitals are different.

"Super High-Rise" Code: Some in the group believed that a super high-rise code would be appropriate. The needs for high-rises are very different, and there is no need for designers to follow the same guidelines for low-rise buildings. Each building should have different requirements. Of course, a high-rise must first be defined.

Problems:

- End point criteria not standardized
- Durability isn't tested – There is no standard
- Structures aren't tested – only assembles
- Quality assurance
- Thermal conditions of test is less severe than reality
- Limited engineering parameters come out of testing.

Discussion about ICC Performance Code: In the future, designers for major buildings can literally write a code for a specific building based on the requirements of the local jurisdiction and the owner. Something similar to this is done now in Las Vegas. All stakeholders would sit down in the beginning of the project and decide what the objectives are. Before this can become a reality, we need more tools to help us make these decisions. We are engineers – we need numbers!

Collaboration: Many in the group looked positively on the presentation. Fred Mowrer referred to a presentation by Deerborn, who, as a structural engineer, took a step toward communication with fire protection engineers. Mowrer stepped toward structural engineers in his presentation today. It looks like both communities may be looking favorably on fire as a load on steel.

How can this communication continue?
We need to have a consensus among the key players in fire protection and structural engineering. We need a small group of people (10 people) to get together and hash out the details of developing structural loads for fire.

Tools Required:

- Models
- Standardized methods
- Before we can come up with adequate models, we need research to back it up. In order to make this a reality, we need to expand our knowledge of: fire load, material properties at high temperature (referring to insulation, etc.), structural details and ventilation.
- Need validated tools with limitation determined

Issues:

- Life-cycle isn't considered. This is true because it is not cost-effective since many owners sell their buildings in 10 years. No economic incentive.
- Structural engineers don't want to be involved. (high risk and low/no rewards)
- There is some discussion that the current tools are not validated with data.
- Renters may not care whether the building is safer or not. A fire certification may not make a difference.
- We need rational fire design in steel code. AISC is working on this. Well before 9/11, AISC had a fire safety engineering committee.

Ideas:

- Lower premium from insurance companies for buildings designed for fire
- We need to set a high standard and have the engineers prove that the protection can be reduced. (This is not an option yet since we don't have all of the tools we need)
- Maybe a certification program can be developed similar to LEEDS for green construction. New York City provides tax relief for green buildings that follow the LEEDs guidelines. Should it be voluntary certification or required? Maybe it could start out as voluntary, but some officials may require it eventually. This would only be applicable to specific buildings. The APA also has a similar certification called 'Code Plus'

How would the ideal design process work?
Everyone needs to get together before the project inception. Architects, owner, structural engineering, fire official, authority having jurisdiction, fire protection engineer, safety and facility management people, security, civil. They decide what the performance objectives and design parameters are.

This group would determine who else is needed. Together, they would consider life cycle issues and determine the methods used in design.

What is the goal?
More rational approach to design AND/OR more protection?
The sentiment of the group is, let's get the tools we need and then we can decide what is needed for each building. Currently, the codes are conservative, but they aren't efficient.

We talked about the history of building codes. One member of the group mentioned that the original building codes were performance based, but no one had the tools required to determine how to reach that performance. So the codes went to prescriptive so that the designers didn't have to make the decisions. Now, we should go back to performance-based because we have a lot of the tools needed to make decisions. They just need to be developed a bit further.

Conclusion

- The lack of validated tools is a barrier to better design
- The current codes meet the needs, but are they best?
- In the future, all of the players for each building need to get together and determine the specific requirements for each building.
- There needs to be incentives for owners to design for fire.

Session C

Test Beds and Test Methods

Breakout Group I

General Discussion:

- Computational fire approach for fire resistance
- Can mathematical model; replace testing? Special effects in Hollywood are Physics based.
- Computational models will make fire protection transparent.
- AHJs are the weak links- not enough education or experience to accept computational models.
- Present tests may be misleading, does not represent actual fire. Test should relate to end use and actual fire.
- Data should not be from a single point, should include statistical distribution and standard deviation for material data.
- Heat release data should taken from multiple points.
- Defense industry has everything the building industry needs.
- Consider Defense Department data for civilian use. Military has wide range of test beds and large scale testing facility at Mobile, Alabama. Military has blast protection and other tests that can be easily adapted.
- Limitations of current tests may not be known by the users (designers).

Issue of proprietary data for modeling

Strategies:

Change perception that high-rise buildings are not safe.
Cultural change at AHJs and practicing community

Barriers:

AHJ's, NFPA and other organizations
Recognizing registered fire protection engineers (FPE)- Seal and signature of FPE on the design.
Frequency of occurrence of wind and other forces vs. fire
Development of tools vs. use of tools.
Basis to justify a change
Political and economical barrier
Cultural barrier.

Breakout Group II

General Discussion:

Taking advantage of the gray areas ("cheating")
Application method for sample sent to lab is different than in the field.
NIST leaning towards multi-axial loading and restraints to get a more accurate prediction.
"Structural Fire Protection Test Facility"
Is there a need?
Has some merit.
What kind of data should be collected so that we can model better?
What is it that we need?
e.g. heat-up curve
Failure criteria will change with different materials.
Deflection?
Rate of Deflection?
Exposure conditions?
Temperatures
It is gathered but not reported.
Are there needs that should be addressed?
Application should be documented.
Age of test furnace (refractory) may affect results.
Reporting gas use?
Flag exceptions in a prominent way.
Exposure conditions
Structural loading
Measurement needs
Method of measurement for temperature & deflection
Data for modeling/ analysis
Pass/ fail criteria
Deflection / rate of deflection
Installation issues

Test standard standardization
Exposure conditions
Worst-case scenario
Max Design load (of structure) (weight)
Dead, Live, Firefighting loads
UL 1709 or other thermal envelope (family of suitable fire curves)
(How much time we have before the collapse?)
SDHI/LDLI (Short duration high intensity/ Long duration low intensity)
Pick a scenario for exposure that is reasonably severe
Revisit what the performance envelope should be (address the issue).
Thermal envelope
Temperature
How/ where measured?
Heat flux (more representative)
Driving force that is causing changes. Measures energy input going into the materials.
Standardization between laboratories
Inter-laboratory reproducibility; inter- and intra-laboratory.
Reproducibility
Verification/documentation of repeatablity
Can NIST look at a furnace that could generate many temperatures?
Vestiges of the past- high refractories.
We could have a much faster rise.
Cooling down phase?
Advances in furnace technologies
What kind of regimes can be achieved in a furnace?
Non-standard curves
E.g. cooling regime
Thermo-couple placement
Structural loading
Need or a loaded column furnace
U. Of Ottawa; Taipei
Need for "loaded" column furnace
Beam/column connection testing need
Restraints
End restraints (simulate end use)
Scaling relations (Kl/r)
Load factors for design
Installation issues
Correlation between Lab and Field
Periodic inspection during the course of use? What if FP hidden?
Certification of contractors (with periodic inspection by UL)
Durability standards by application (according to expected use)
Test Standards Standardization:
Exposure conditions
Durability under intended conditions

Strategies:

- Revisit fire exposure conditions
- e.g. Swedish design standard
- Other ABS American Bureau of Standards
- Fuel-load/ ventilation effects
- Develop durability standards
- Implement durability standards
- Installation quality
- Review Taipei Taiwan testing facility
- Joint Venture with Architectural Building Research Institute on multi-axial testing (calibration)
- Loaded assembly, prototype testing
- Calibrate with respect to UL test data.
- Develop/ correlate models with fire test data
- Identify needed data

Barriers:

- Cost
- Inertia of existing process
- Make use of existing data
- Demand for test bed
- Current equipment is limited
- National need

Breakout Group III

General Discussion:

Precision and bias between laboratories --- need to investigate E119

Products and systems will be value engineered to optimize performance for the specific parameters measured --- need model to translate test results in the real world

Model test results to correct for standardized exposure

Issues:

Test terminated when target rating achieved --- test should be run to failure

Third party inspection of production material is not a code requirement --- independent quality assurance inspection should be made a requirement

Classification is sum of all factors --- classify individual properties and parameters

What constitutes large scale? How to get a structurally meaningful test? --- Provide more detail in reporting structural testing and aspects for scaling

What level of complexity is needed for joints, intersections, connectors, etc.?

Since there are no standards for third-party inspection and assessment, the code should require third-party assessments, and also the provision of labs to get accredited by third party organizations

General Overall Recommendations from Group-III:

Develop models for predicting structural performance from fuel loads
Develop matrix of performance requirements versus end use applications
Undergraduate and graduate cross-disciplinary training in structures/design/fire
Review and assess current trends to reduce passive fire resistance codes
Determine precision and bias of existing fire resistance test methods
Develop models to normalize test results and translate to real building scenarios
Incorporate risk/benefit tools in model codes to be accessible to local communities/designers
Standardize third-party inspection and labeling service requirements in the code (include lab accreditation)
Revise E119 to run test to failure, and provide data for structural scaling

Other Comments:

Material provided by international vendors should be tested, because their own test results could be of varying degree of accuracy and reliability. We need an authority to develop a standard testing protocol, which should be made mandatory to be used by the international vendors.
There should be more people in ASTM E119 with background in structural engineering

Breakout Group IV

General Discussion:

- General dissatisfaction with status quo of testing --- add some elements of testing above E119
- One possible addition could be measurement of variables to help with the modeling such as range of thermal conductivity with time, including recognition of anomalies, special events, etc.
- There is a need for standards for measuring material properties and high temperatures
- There is a need for models to identify critical properties
- There is a need to determine thermal and mechanical properties
- The incentives for owners include better and cheaper building. There are professional responsibility and profitability issues.

Some of the challenges for testing include:

- Where to test?
- What to test?
- Testing of connectors
- Other challenges include cooling off of deformed members, lack of knowledge of mechanisms, performance prediction from testing

Quality assurance of installations needs to be improved.