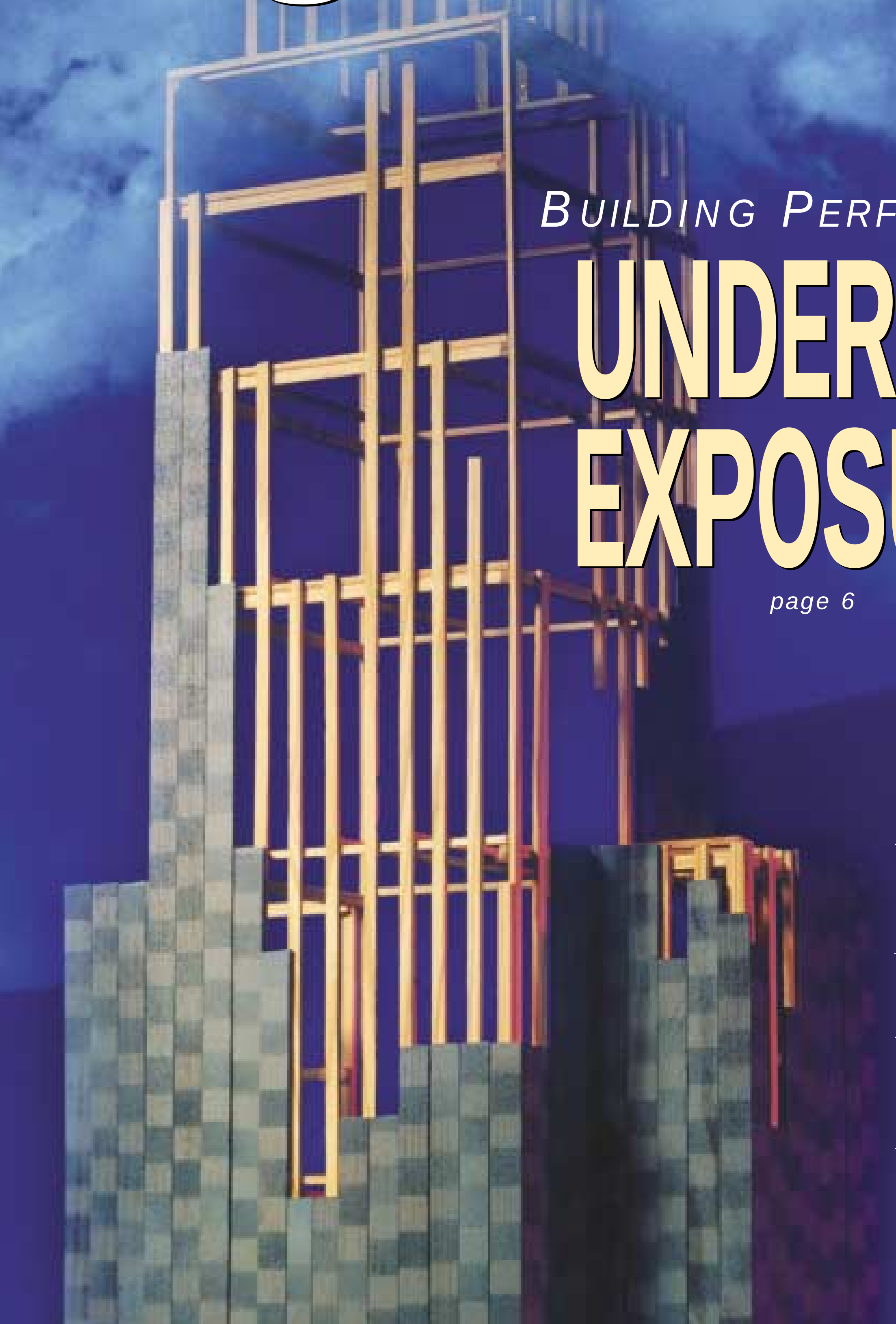
THE OFFICIAL MAGAZINE OF THE SOCIETY OF FIRE PROTECTION ENGINEERS

FIRE PROTECTION Engineering

SPRING 2003

Issue No.18



BUILDING PERFORMANCE UNDER FIRE EXPOSURE

page 6

ALSO:

SFPE

FIRE PROTECTION
Engineering

Fire Protection Engineering (ISSN 1524-900X) is published quarterly by the Society of Fire Protection Engineers (SFPE). The mission of *Fire Protection Engineering* is to advance the practice of fire protection engineering and to raise its visibility by providing information to fire protection engineers and allied professionals. The opinions and positions stated are the authors' and do not necessarily reflect those of SFPE.

contents SPRING 2003

Cover illustration by ©Will Crocker/The Image Bank

Online versions of all articles can be accessed at www.sfpe.org.

Invitation to Submit Articles: For information on article submission to *Fire Protection Engineering*, go to http://www.sfpe.org/publications/invitation.html.

Subscription and address change correspondence should be sent to: *Fire Protection Engineering*, Penton Media, Inc., 1300 East 9th Street, Cleveland, OH 44114 USA. Tel: 216.931.9180. Fax: 216.931.9969. E-mail: asanchez@penton.com.

SFPE

LIFE SAFETY IN HIGH-RISE BUILDINGS AFTER 9/11

By W. Gene Corley, P.E.

Great catastrophies often cause major changes in the construction industry. The Chicago fire in the 19th century demonstrated the risks of combustible construction in large cities. During the rebuilding after the Chicago fire, many of the bright engineering and architectural minds of the world were attracted to the city to assist in the rebuilding. Among the many innovations that came out of this decades-long rebuilding effort was the invention of the "skyscraper." Use of the structural skeleton to permit buildings to be built higher, and thereby get more use out of expensive land, revolutionized the building industry.

Fires that followed the 1906 San Francisco earthquake demonstrated the need for fire protection in high-rise buildings. Lack of water to fight fires in San Francisco caused many buildings to completely burn after the earthquake. By 1927, the *Uniform Building Code*,[1] written by western United States building officials, required buildings that were taller than 8 stories or 85 feet (26 m) have fire resistance of structural elements of three hours for floors, four hours for columns and beams.

Following the adoption of fire-resistance requirements for high-rise buildings, the experience has been very good. No modern fire-protected building had collapsed as a result of a burnout prior to 9/11.[2] Similarly, the fire-related casualty rate for occupants of high-rise buildings has been extremely low.

In the 1970s it became clear to model code groups that sprinkler systems in high-rise buildings would further reduce the property losses during a fire. Properly operating sprinkler systems have had a good record of reducing the effects of fires.

As modern building codes evolved, two that have recently been developed are the *International Building Code*[3] and *NFPA 5000 Building Construction and Safety Code*.[4] Sprinkler systems are mandatory by these codes in all buildings that exceed 12 stories or 180 feet (54 m). While sprinklers can be expected to reduce property loss and contain many fires when they work properly, sprinklers cannot always be expected to function. Sprinklers can malfunction due to inadequate inspection, willful shutoff of valves, or catastrophic events interrupting the water supply. Since inspection and maintenance of sprinklers are seldom mandatory in commercial buildings, the potential failure rate is of concern.

Despite the recognition that sprinkler systems do not always function properly, model building codes have continued to reduce the fire-resistance requirements of structural elements where sprinklers are used. In the *International Building Code*[3] and *NFPA 5000 Building Code*,[4] required fire resistance for sprinkled buildings is two hours for beams, columns, and floors. NFPA 5000 requires that buildings over 420 feet (126) tall add an additional hour to columns, for a total of three hours. These reductions in structural safety are based on a growing belief that fire-protected buildings will not collapse, even in a burnout.

The experience after the 9/11 attack on the World Trade Center proved a building can collapse as a result of fire. *The Building Performance Study*[2] carried out for the American Society of Civil Engineers/Structural Engineering Institute and the Federal Emergency Management Agency concluded that fire played a major role in the collapse of four buildings. It is believed, even though badly damaged by the impact of very large aircraft, the twin towers would have been able to stand had there not been a second major event, the fire that followed the impact.

Of more importance to the fire protection community, however, were the collapses of buildings WTC 5 and WTC 7. These two buildings collapsed during burnout fires even though there was no evidence found that the collapsed areas had been seriously damaged by impact of debris.

Building 7, a 47-story fire-protected and sprinkled structure, burned from the time of the attack until it collapsed at 4:20 in the afternoon. It is apparent that this building had a fuel load that fed the fire throughout this long period of time. Although the sprinklers are believed to have fused, there was either no water or not sufficient water available to prevent the collapse of the building.

Building 5 sustained collapse of several floors that were not directly hit by debris. This structure had no extraordinary fuel load in it but still collapsed when the sprinkler systems were unable to control the fire and a burnout of the office contents occurred. Buildings 5 and 7 became the first documented collapses of fire-protected and sprinkled buildings in the more than 100-year history of high-rise structures.

Sprinklers should continue to be mandatory in high-rise buildings. However, it is clear some fires in buildings, both low-rise and high-rise, cannot be controlled. When control is lost, a burnout will occur. For the life safety of those who may be trapped in the building and of those who must fight these fires, the design objective should be that no collapse occurs with a burnout. Also, the burnout considered should be related to the amount of fuel in the building if fuel exceeds the amount that would produce a standard ASTM E119 fire.

Fire-related collapses that occurred after the 9/11 attack on the World Trade Center provided information that should be used to guide our future fire protection of high-rise buildings. The lessons from the horrible tragedy of 9/11 should be used to improve the safety of later generations who live and work in high-rise buildings.

W. Gene Corley, SE, PE, is with Construction Technology Laboratories, Inc.

REFERENCES

1. *Uniform Building Code*, 1927 Edition, International Conference of Building Officials, Long Beach, California, 1928.
2. Corley, W.G. et al, "World Trade Center Building Performance Study: Data Collection, Preliminary Observations, and Recommendations," *Federal Emergency Management Agency Mitigation Directorate*, FEMA 403, Washington, D.C., May 2002.
3. *International Building Code*, International Code Council, Falls Church, Virginia, 2000.
4. *NFPA 5000 Building Construction and Safety Code*, National Fire Protection Association, Quincy, Massachusetts, 2003.

NFPA Addresses Safety Issues in Public Assembly Buildings

On February 26, 2003, the National Fire Protection Association (NFPA) called upon its Technical Committee on Assembly Occupancies to convene in Quincy, MA, for an immediate review of the safety issues relevant in public assembly buildings.

At issue are several core components of a total system of building safety that have come to light following the two recent deadly nightclub incidents in Chicago and Rhode Island.

"We must not waste any time in examining all the available information about public assembly occupancies in the wake of these building emergencies," said NFPA Executive Vice President Arthur E. Cote, P.E. "Although we still don't have all the facts about these terrible incidents, we know enough right now to warrant a serious review and scrutiny of the future direction of codes and standards, and their enforcement locally. We must learn from these tragedies, and the time to act is now."

NFPA is calling for a review of the following issues addressed or affected by NFPA codes:

- The minimum thresholds for requiring automatic fire sprinkler protection.
- Allowable interior finish and decorations.
- Adequate egress.
- Exiting arrangements.

SFPE Releases New Engineering Guide Evaluating Computer Model

The Society of Fire Protection Engineers (SFPE) recently released a new engineering guide entitled, *The Evaluation of the Computer Model DETACT-QS*. DETACT-QS is a model for predicting thermal detector response. The guide is the first in a series of evaluations undertaken by SFPE's Computer Model Evaluation Task Group.

The evaluation addresses the model definition and evaluation scenarios, verification of theoretical basis and assumptions used in the model, verification of the mathematical and numerical robustness of the model, and quantification of the uncertainty and accuracy of the model predictions. This evaluation is based on comparing predictions from DETACT-QS with results from full-scale compartment fire experiments.

An extensive set of references and background on the technical basis of the model is provided.

For more information, go to *www.sfpe.org*.

Study of Building Performance in the WTC Disaster

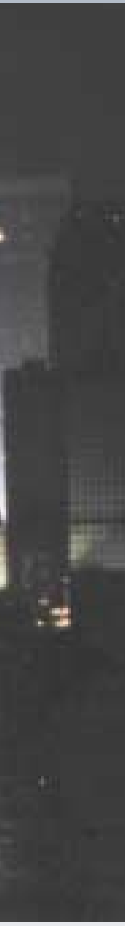
By James Milke, Ph.D., P.E.

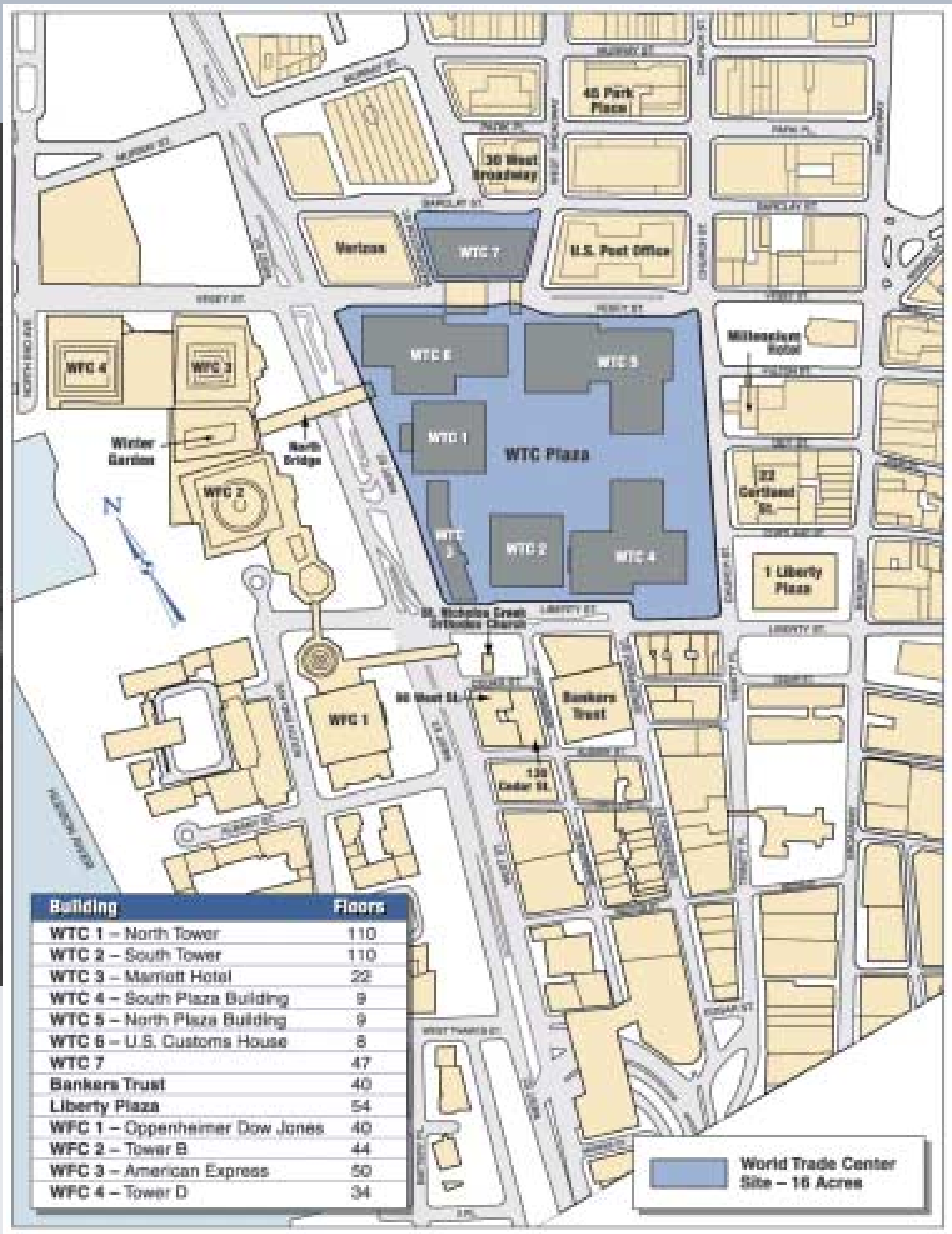
INTRODUCTION

The impacts of aircraft into the twin towers of the World Trade Center set off a chain of events seen via television coverage by many of the world's population on September 11, 2001. These aircraft damaged portions of the structure of the twin towers and also initiated fires on several floors. By the end of the day, four buildings collapsed, three buildings were severely damaged by fire, and seven buildings sustained significant damage, while numerous others suffered minor damage.

In late September, the Building Performance Study (BPS) team was formed to study the response of the affected buildings to impacts and fires. The principal support for the study was provided by the Federal Emergency Management Agency (FEMA) and the Structural Engineering Institute of the American Society of Civil Engineers. Also supporting the effort was a coalition of organizations including the Society of Fire Protection Engineers and National Fire Protection Association (NFPA).

Team members included structural engineers and fire protection engineers. Some of the structural engineers specialized in the response of buildings to static loads, the effects of dynamic loadings on buildings, or metallurgy. Fire protection engineers included on the team had backgrounds in fire behavior and response of structures to fires. Individuals selected for the team with fire protection expertise included:





Building	Floors
WTC 1 – North Tower	110
WTC 2 – South Tower	110
WTC 3 – Marriott Hotel	22
WTC 4 – South Plaza Building	9
WTC 5 – North Plaza Building	9
WTC 6 – U.S. Customs House	8
WTC 7	47
Bankers Trust	40
Liberty Plaza	54
WFC 1 – Oppenheimer Dow Jones	40
WFC 2 – Tower B	44
WFC 3 – American Express	50
WFC 4 – Tower D	34

Figure 1. Map of Buildings included in BPS[1]

Jonathan Barnett, Ph.D., P.E., *Worcester Polytechnic Institute*
Robert Duval, *NFPA*
Richard Gewain, P.E., *Hughes Associates*
Venkatesh Kodur, Ph.D., *National Research Council of Canada*
Chris Marrion, P.E., *ArupFire*
James Milke, Ph.D., P.E., *University of Maryland*
Harold "Bud" Nelson, P.E., *Hughes Associates*

The team met in New York in early October 2001, visiting Ground Zero and also the recycling yards. During the seven-month period of the study, the team met with members of the design teams for the World Trade Center buildings and spoke with eyewitnesses and emergency responders. Information reviewed by the team included videotapes from television networks and private individuals, photographs of the incident, audio tapes from New York's Emergency Operations Center, plans, engineering documents, and aircraft data.[1] In addition, the team returned to the recycling yards many times. The team conducted some elementary numerical analyses and also reviewed the results of elementary analyses conducted by others. In addition, a limited number of metallurgical laboratory analyses were conducted on steel samples recovered from the recycling centers.

SCOPE OF STUDY

The principal purpose of the BPS was to establish the basic facts involving the performance of the affected buildings. In addition, the study team sought to provide preliminary thoughts about the probable collapse mechanisms and identify areas for future study.

While much of the attention of the BPS was directed to the twin towers, the performance of a total of 16 affected buildings was addressed in the study. The buildings included in the study and indicated in Figure 1 are:

- WTC 1, 2, 3, 4, 5, 6, and 7
- Banker's Trust
- The Winter Garden and WFC 3 (The American Express Building) of the World Financial Center
- Verizon Building
- 30 West Broadway
- 130 Cedar Street
- 90 West Street
- 45 Park Place
- One Liberty Plaza

The emphasis of the Building Performance Assessment Team (BPAT) report was to describe the structural performance of the affected buildings. A brief description of the evacuation of WTC 1 and 2 was also included in the report based principally on media accounts. The focus of this paper will be on the structural performance of WTC 1, 2, 5, and 7. A description of the performance of the other 12 buildings is included in the BPAT report.[1] An analysis of the evacuation behavior of the occupants of WTC 1 and 2 is ongoing.

WTC 1, 2

Each building was 110 stories tall, with seven subgrade levels. The floor plate for each building was 63.1 m square, with chamfered 2 m corners. The area per floor was approximately 3,980 m^2. The buildings were steel frame buildings. Because of their tall height, weight was a design constraint, with lightweight alternatives used where possible.

Most of the interior columns were hollow sections up to about the 80th floor, above which the columns were wide flange sections. The exterior columns were nominally 356 mm square, hollow sections (wall thickness approximately 12 mm at the impact floors). Sets of three exterior columns were welded to plates forming spandrels. The floor assembly consisted of lightweight concrete poured on a metal deck supported by steel bar joists.

The exterior columns were designed to carry 60 percent of the gravity load. The closely spaced exterior columns (990 mm o.c. spacing) carried the remainder of the gravity load and were also specifically designed to withstand the design wind load posed by a storm. In general, the columns were lightly loaded relative to their allowable load capacity.

The interior core was approximately 26.5 m x 41.7 m. The bar joists spanned the distance between the interior and exterior columns. One-way spans of 18.3 m or 10.7 m were oriented between the core and exterior as indicated in Figure 2. Two-way framing was provided in the corners.

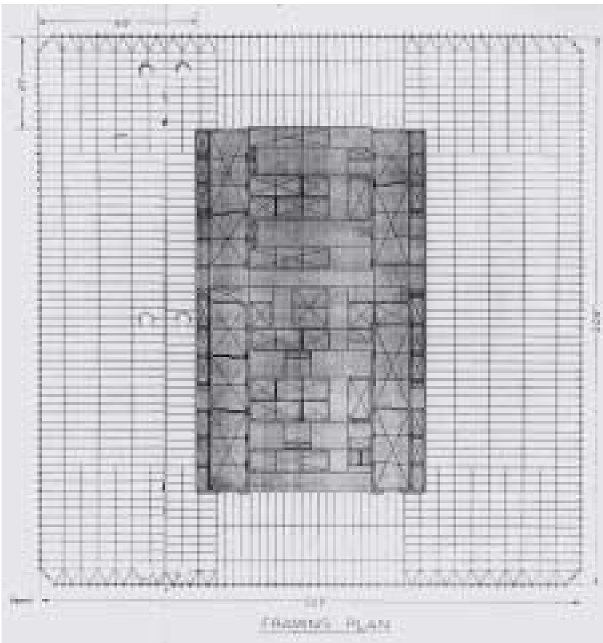


Figure 2. Floor System in WTC 1, 2

A Vierendeel truss was located between the 106th and 110th floors of WTC 1 and 2. Conceptually, the truss served to connect the interior and exterior columns together. Consequently, the truss provided stiffening of the frame for wind resistance, increased the resistance of the structure to wind-induced overturning, and supported the antenna on the roof (WTC 1 only).

The fire resistance ratings provided included three-hour designs for the columns and a two-hour floor assembly. The core columns were protected by a combination of spray-applied fire-resistive material (SFRM) and gypsum wallboard shaft walls. Exterior columns were protected with a plaster material on the surface facing the inside of the building and also had a spray applied insulating material applied to the surfaces facing the exterior to limit the solar heating of the columns.

The bar joists were also protected with an SFRM. The original installation provided 19 mm of thickness of the SFRM as a result of an analysis conducted comparing the insulating abilities of the mineral fiber SFRM selected for the project as compared to a cementitious material. (The analysis indicated a thickness of 13 mm was needed, though inspections following the initial application indicated that the average protection thickness on the bar joists was 19 mm.) In the early 1990s, a decision was made by the Port Authority of New York and New Jersey (the building owner at that time) to increase the protection thickness to 38 mm as spaces were being renovated. As of September 11, 2001, the impact floors of WTC 1 were all provided with 38 mm of protection, while the protection thickness was increased to 38 mm on only one of the impact floors of WTC 2.

The top and bottom chord of the bar joists were connected to the exterior columns, though only the top chord was attached to the core columns. Connection to an exterior column was via a steel angle. The bar joist was bolted to the angle and also welded to the angle. A damper connected the bottom chord to the exterior column. The damper was provided to limit movement of the building under wind conditions. The angle was protected in the same manner as the column, though the damper was left unprotected to preserve its functionality. The connection of the bar joist to the core column consisted of two bolts to a plate connected to a channel that was welded to the column.

The stairwell and elevator shaft walls consisted of two layers of Type X gypsum wallboard on each side of steel studs. This shaft wall design was selected based on its lightweight characteristic.

At 8:46 a.m. on September 11, 2001, American Airlines Flight 11 impacted WTC 1, also referred to as the North Tower, on its north face between the

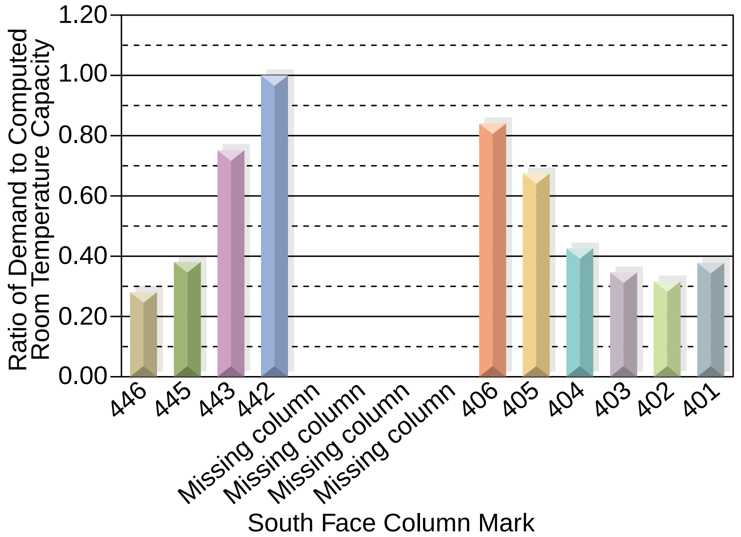


Figure 3. Load Redistribution for Exterior Columns

94th and 98th floors. The aircraft was a Boeing 767-200ER, traveling at an estimated speed of 750 km/hr. The impact fractured approximately two-thirds of the exterior columns on the north face of the building, damaged floors in the vicinity of the impact location, inflicted some damage to interior core columns and shaft walls, dislodged fireproofing material, and initiated fires on multiple floor levels.

An elementary analysis was conducted to determine the load redistribution along the exterior columns to assess the level of damage caused by the aircraft impact. The analysis assumed that none of the core columns were affected. The results of the analysis indicated that columns in the immediate vicinity around the severed exterior columns were highly stressed, as indicated in Figure 3. However, the stress level decreased to approximately 20 percent of load capacity, near preimpact levels, within a few column lines of the impact area.

Sixteen minutes later, at 9:02 a.m., another Boeing 767-200ER, United Airlines Flight 175, impacted WTC 2, also referred to as the South Tower, on its south face between the 78th and 84th floors. The speed of this aircraft was estimated to be 950 km/hr at impact. The impact resulted in the same type of effects as in WTC 1.

At 9:59 a.m., 57 minutes after impact, WTC 2 collapsed. During the collapse of WTC 2, sections of the building impacted WTC 3 and 4, and Banker's Trust, and fires were initiated in 90 West St. and 130 Cedar St. In addition, fires were also observed in WTC 7 following the collapse of WTC 2.[2] Later at 10:28 a.m., 102 minutes after its impact, WTC 1 collapsed. WTC 3, 5, 6, and 7, The Winter Garden, and WFC 3 were all impacted by debris from the collapse of WTC 1.

FIRE BEHAVIOR

Much of the initial media accounts of the performance of WTC 1 and 2 suggested that the collapse of the buildings was attributable to the jet fuel being the principal fuel source for the fires in these buildings. With so much of the initial attention being paid to the jet fuel, the team conducted an analysis to assess the early fire behavior and the role of the jet fuel in WTC 1 and 2.

At impact, each aircraft was estimated to be carrying 38,000 liters of jet fuel.[1] In addition to being released on the impact floors, the jet fuel was consumed in the fireballs, flowed down shafts (in some cases igniting in shafts or the concourse of WTC 1, and some may have flowed down the outside of the building. The amount of jet fuel needed to support a fireball of a particular size can be estimated from correlations in the literature.[3]

$$D = 5.25m^{0.314}$$

where D is the diameter of the fireball (m) and m is the mass of fuel vapor (kg). The fuel consumed for different fireball diameters is presented in Figure 4. A photograph of the fireballs following the impact of WTC 2 is presented in Figure 5. In Figure 5, the diameter of the fireball

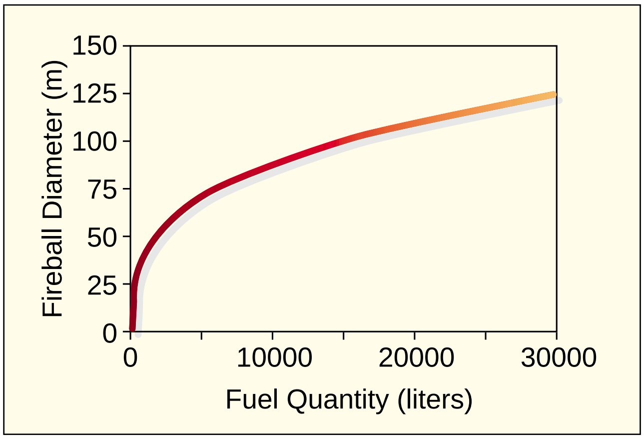


Figure 4. Fuel Consumption versus Fireball Diameter

Figure 5. Fireballs Following Impact of WTC 2.

from the north side of WTC 2 appears to be approximately the same as the length of a side of the building, *i.e.* 60 to 70 m. Based on the correlation from the literature, approximately 3,700 liters of jet fuel were consumed in each fireball. Given the presence of three fireballs, this represents approximately 11,000 liters.

An estimate of the time required for the remaining jet fuel to be consumed was generated by neglecting any fuel that may have flowed down shafts or otherwise left the impact floors. An upper limit of the duration of the jet fuel was provided by assuming that the fuel formed a pool. The mass burning rate for liquid fuels is on the order of 50 g/m^2-s.[4] Assuming that the fuel spread throughout one floor with an area of 3,980 m^2, the duration of burning for the remaining 11,000 liters of jet fuel would be less than one minute. Actually, the fuel was probably dispersed over the office furnishings present on the floor (thereby increasing the fuel surface area) and served as an igniter for the mix of office furnishings present on the impact floors. Some of the jet fuel may also have formed small pools in sections of wing tanks that survived the effects of the impact. The jet fuel may have burned in these small sections of the building for several additional minutes.

Consequently, for the majority of the duration that the fires burned in WTC 1 and 2, the fires involved the office furnishings present in the buildings. Rehm, et al., at NIST conducted an analysis of the fire behavior in the towers using FDS.[5] Their analysis was based on matching the rise of the smoke plume from videotapes and photographs with that provided by the computer simulation. Input for the model involved estimating the size of the hole(s) created by the aircraft impact and ambient weather data. The size of the holes was estimated based on photographic evidence. Weather data were reported from three departing aircraft from nearby LaGuardia and Newark airports between 7:15 a.m. and 9:00 a.m. at heights comparable to the floor levels of the impact. The wind speeds were 16 to 32 km/hr. and the ambient temperature was 20°C to 21°C

The peak heat release rate estimated by Rehm, et al., in the towers was likely to be approximately 1.0 to 1.5 GW. Temperatures within the floor areas were also predicted to vary greatly, being as high as 900°C to 1,000°C in some areas, while being 400°C to 800°C in others. This range of temperatures is attributed to the changed geometry and fuel loading in the space as a result of the aircraft entry into the building. The range in fire behavior is evident in the photographic evidence where flame projections from openings are visible in some areas and not others. In addition, in some areas where the exterior columns and glass remained intact, flames are visible, while in other areas they are not. As such, the well-stirred reactor view of fully-developed fires does not appear to apply to this situation.

PROBABLE COLLAPSE MECHANISMS

In both WTC 1 and 2, the collapse of the buildings is attributed to the combined effects of the damage caused by the aircraft and the weakening of the steel as a result of the fire. The damage caused by the aircraft included:

- Destruction of some exterior and interior columns, resulting in some of the remaining columns becoming highly stressed.
- Destruction of some portions of the floor framing and slab, at least in the vicinity of the impact areas. Floor slabs under the collapsed areas were required to support additional loads associated with the damaged aircraft and thus were more heavily stressed.
- The force of the impact and the trajectory of the components of the aircraft through the space resulted in some dislodgement of fireproofing material from the bar joists and core columns.

Unfortunately, eyewitness accounts of the damage caused by the aircraft on the impact floors are unavailable.

Three probable failure mechanisms include:

1. As the temperature of the bar joists increased, they lost rigidity and sagged into catenary action. As catenary action continued, stresses on connections to framing elements and exterior columns increased until the connections failed. As a portion of the floor assembly failed and fell to the floor below, the lower floor became overloaded, causing its connections to fail. This sequence continued with the progressive collapse of all of the lower floors.

2. The susceptibility of the columns to buckling failure increases as the modulus of elasticity decreased with an increase in temperature of the fire-exposed steel columns. Further, as portions of floors collapsed, some support for the columns may have been removed, resulting in an increase in the unsupported length of the columns.

3. Following the aircraft impact, the Vierendeel truss at the roof was a principal component in transferring load between the interior and exterior columns. As the strength of the columns further decreased as a result of increasing temperature, the stresses in the truss elements increased. When these elements reached their load capacity, the truss failed and load transfer could no longer be accomplished, leading to interior columns being overwhelmed.[6]

WTC 5

WTC 5 was a nine-story, steel frame building. The overall dimensions of the L-shaped building were approximately 100 m x 128 m, with an approximate floor area of 11,150 m^2 per floor. The moment-frame design consisted of a composite floor system with wide flange steel beams connected to a lightweight concrete fill on metal deck floor. The columns in the building were wide flange steel sections. A pair of wide flange beams was provided from each column line to provide support for the cantilevered floor slabs (4.6 m).

The fire resistance designs of the structure were believed to have included three-hour columns and two-hour floor-ceiling assemblies. Fire resistance was provided by a mineral fiber SFRM. As with WTC 1 and 2, the stairwell and elevator shaft walls consisted of two layers of Type X gypsum wallboard on each side of steel studs.

There was some localized collapse as a result of the impact of debris from one or both of the towers, including a penetration of the roof in one area and segments of the southern edge of the building from floors 3 to 9. Fires were initiated as a result of impacts by debris from the collapse of WTC 1 or 2. The fires burned without any significant suppression effort, either by the automatic sprinkler system or the fire department. The inaction by the sprinkler system was probably due to a loss of pressure

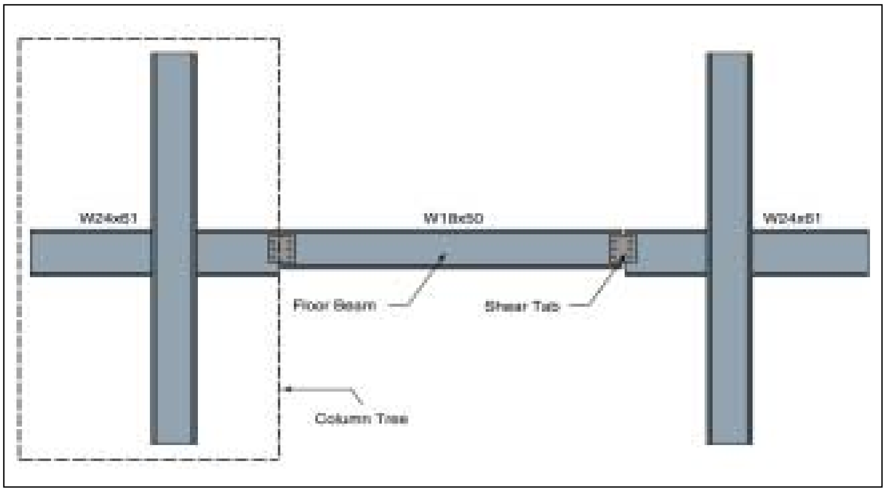


Figure 6. Schematic Diagram of Framing for WTC 5

in the water mains following the collapse of WTC 1. As a result, significant fire damage was evident on floors 4 to 9, with the greatest destruction evident nearest the windows.

Most of the structure responded to the fire in a manner typical of other fire incidents and fire tests.[7,8] As such, significant deflections of beams were observed where tensile membrane action evidently occurred to prevent collapse of the structure. However, the collapse of one area of 3 x 3 bays appeared to be due to fire effects. This collapse was initiated at the 8th floor slab and was arrested at the 5th floor. The collapse is attributed to a failure at the shear tab indicated in Figures 6 and 7. The shear tab was evidently unable to resist an increase in tensile stresses induced following the deflection of the beam.

WTC 7

WTC 7 was a 47-story, steel frame building located across Vesey St. from the remainder of the World Trade Center Complex. The building was an air-rights building, being constructed over a Con Ed substation located on the lower four floors. The next three levels contained switchgear and emergency generators. A total of 91,000 liters of diesel fuel was stored below grade to supply the generators. The top 40 stories contained office space, including space for New York City's Office of Emergency Management on the 23rd floor.

On the 8th floor and above, a moment-frame design was utilized with wide flange steel members. Transfer trusses spanned the 5th to 7th floors to transition from the structure for the substation to that for the office floors. The positions of the transfer trusses are indicated in Figure 8.

The fire resistance design was believed to be similar for this building as for WTC 1, 2, and 5, though using a cementitious SFRM for three-hour fire resistance rated column designs and two-hour fire resistance-rated floor-ceiling assemblies. The trusses were presumably protected in a manner similar to that followed for the columns.

Fires were observed on multiple floors in WTC 7 following the collapse of WTC 2.[2] Photographs of the south face of the building indicate fires were located on many of the floors. Fire fighters report that while the fire appeared on several floors throughout the day, it appeared to be located on the 6th floor for the entire duration. A camera from the north of the building recorded light gray, modestly buoyant smoke emanating from the building throughout much of the day. Approximately one hour before the collapse, the smoke became dark gray and appeared to be much more buoyant.

Figure 7. Location of Failed Shear Tab

At 5:20 p.m., the collapse sequence initiated. First, the penthouse on the east side of the roof disappears from view, then about 10 seconds later the penthouse on the west side disappeared. Immediately after the disappearance of the west penthouse, the progressive collapse started, apparently at a low floor. On the videotape record of the collapse from the news media, the upper 30 to 35 stories appear to descend intact, indicating the collapse was initiated on a lower floor. In addition, just prior to collapse, a crack or "kink" (as referred to in the FEMA report[1]) becomes evident on the north wall in the vicinity of the east penthouse.

The east penthouse is located over transfer trusses 1 and 2. One proposed mechanism of the collapse was a failure of transfer truss 1 or 2 due to fire exposure on that level. Fuel loads were reportedly light in the vicinity of the trusses except for pipes carrying diesel fuel to and from the generators. While some fuel was found in the underground tanks once they were recovered, the role of the diesel fuel was questioned by the BPAT.

OTHER OBSERVATIONS

The FEMA report[1] was intended to provide a compilation of the facts, as could be best accumulated during the seven-month period. The FEMA report did not recommend any immediate code changes based on the limited analysis conducted in the BPS. Certainly, as research continues to identify probable collapse mechanisms in WTC 1, 2, 5, and 7 as well as to understand why collapse was arrested in WTC 5, possible

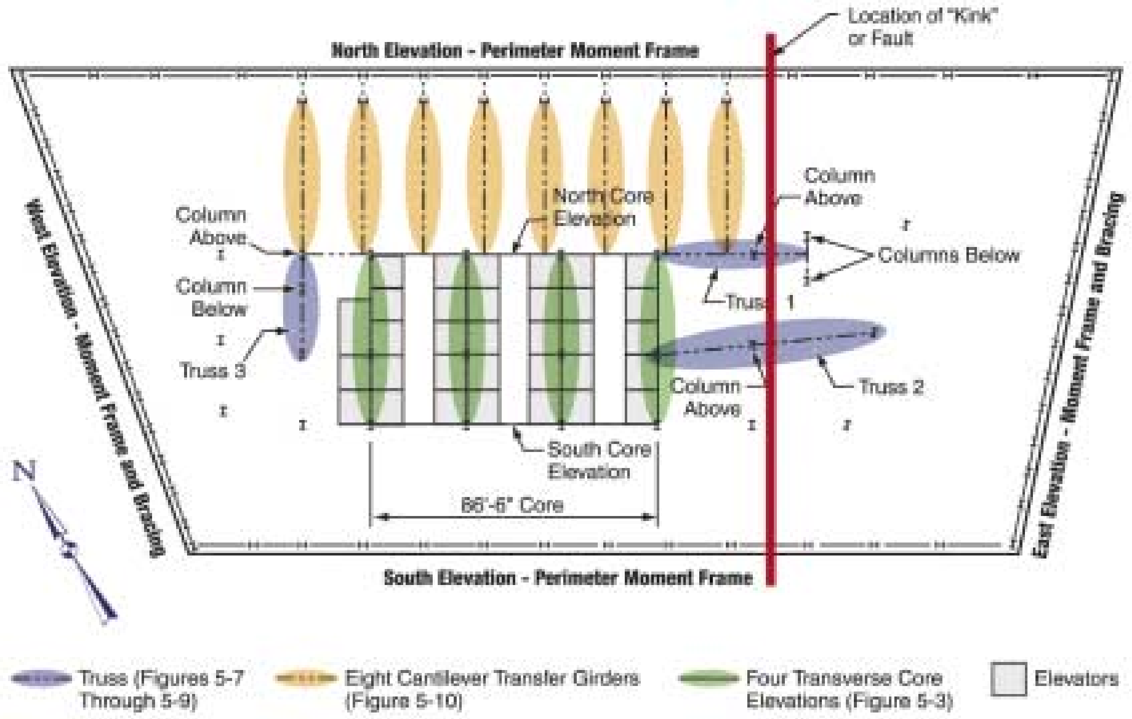


Figure 8. Position of Transfer Trusses in WTC 7

recommendations for code changes could become apparent.

Areas recommended for further study include:

• Are there details of the structural design of WTC 1, 2, 5, and 7 that made them more susceptible to collapse? Are there subtle changes in the design that could have prevented the collapse of these buildings?

• What is the role of connections in fire-resistant assemblies? Connections are not included in standard fire resistance tests. Thus, protection of connections is often done simply by continuing the same protection as for the connected structural member.

• Can the durability of fireproofing materials to impact loads be improved?

• Critical elements whose failure would lead to progressive collapse need to be identified. Such is reportedly common practice in the U.K., but not the U.S. Policy needs to be established on how such critical elements should be protected, *i.e.*, is additional fire resistance needed, should special inspection programs be established to confirm proper protection of such elements?

• Tools to predict performance of buildings to actual fires need to be developed, including the role of connections (results from standard fire resistance tests cannot be used to predict performance). Such tools are needed for conducting performance-based design of structural fire protection systems and would be essential in providing real-time information for fire service officers directing emergency operations in high-rise buildings subjected to serious fires. ▲

James Milke is with the University of Maryland.

REFERENCES

1 *World Trade Center Building Performance Study: Data Collection, Preliminary Observations, and Recommendations*, FEMA Report 403, Federal Emergency Management Agency, Washington, D.C., 2002.

2 Smith, D., *Report from Ground Zero: The Story of the Rescue Efforts at the World Trade Center*, Putnam Publishing Group, 2002.

3 Zalosh, R., "Explosion Protection," *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, P.J. DiNenno, (Ed.), NFPA: Quincy, MA, 2002.

4 Babrauskas, V., "Heat Release Rates," *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, P.J. DiNenno, (Ed.), NFPA: Quincy, MA, 2002.

5 Rehm, R., "Modeling Fires In the World Trade Center Towers," *Fire Risk & Hazard Assessment Research Application Symposium*, Fire Protection Research Foundation, Baltimore, MD, 2002.

6 Clifton, G., "Collapse of the World Trade Center Towers," *Structures in Fire '02*, University of Canterbury, New Zealand, 2002.

7 Routley, J., Jennings, C., and Chubb, M., "High-Rise Office Building Fire, One Meridian Plaza, Philadelphia, Pennsylvania," FEMA Report 049, Federal Emergency Management Agency. Washington, D.C., 1991.

8 Kirby, B., "Large Scale Fire Tests: The British Steel European Collaborative Research Programme on the Building Research Establishment 8-storey Frame." *Fire Safety Science – Proceedings of the 5th Intl Symposium*, International Association for Fire Safety Science, Melbourne, Australia, 1997.

Restructuring Confidence in the Fire Safety of Buildings

By Robert Berhinig, P.E.

The attack on the World Trade Center (WTC) in New York City has raised concerns regarding the fire safety of high-rise structures. Until Sept. 11, 2001, few people envisioned the total collapse of a high-rise building except under controlled conditions such as an implosion for demolition purposes. Today, the public's concerns are heightened.

These concerns can be reduced by recognizing that the Sept. 11 attack on the WTC was an extreme act of terrorism. Also, fires in high-rise structures are not unexpected events. Fire-testing procedures are in place to determine a building assembly's ability to resist structural collapse when exposed to fire. Structures that consist of fire-resistive building assemblies have functioned well under severe fire conditions. In fact, the Federal Emergency Management Agency (FEMA) report, "World Trade Center Building Performance Study,"[1] states the collapse of these structures is particularly significant in that, prior to these events, no protected steel-frame structure, the most common form of large commercial construction in the United States, had ever experienced a fire-induced collapse. The overall performance of structures during fires is a credit to the entire fire-protection community, which includes engineers, product designers, architects, testing organizations, code bodies, inspection agencies, and the fire services.

HOW ARE FIRE-TESTING METHODS USED?

The nationally recognized standard used to conduct tests in the United States is the American Society for Testing and Materials *Standard Fire Test Methods of Building Constructions and Materials*,[2] also known as ASTM E119. It is used to generate data to measure the integrity of building assemblies subjected to fire exposure. The first edition of this standard was published in 1918, with the most recent edition published in 2000. Throughout the world, similar fire-test methods are published by international organizations such as the International Organization for Standardization (ISO). These basic fire-test standards are the foundation for many other test methods that focus upon fire containment within building structures. Technical committees with membership extending throughout the global fire-protection community develop these test standards, which are consistently reviewed and updated as technology changes. While today's test is similar to the test devised in 1918, the quantity and the accuracy of the data obtained during the tests have advanced greatly. It is important to keep in mind that the testing chamber that is used in the fire test is only a tool – it is used to determine that a fire will be contained by fire-resistance building assemblies within a laboratory environment.

Several published stories have questioned the reliability of the ASTM E119 fire test standard in light of the WTC terrorist attacks. It is implied that because the standard was originally developed 80 years ago and because relatively "low-tech" equipment such as kiln-type furnaces is used for the test, the resulting data may be inadequate.

At the heart of this debate is the time-temperature curve that controls the temperature conditions within the test chamber. The time-temperature curve is intended to represent an intense, fully developed fire within a building. Does the time-temperature curve perfectly represent every fully developed fire in every location? No. The actual heat and temperature conditions generated from a fire in a particular location is dependent upon many variables such as building contents, materials of construction, and ventilation conditions.

The value of the time-temperature curve in ASTM E119 is its reproducibility and its relationship to the previously referenced variables. This standardization enables the building code community to specify a minimum fire-resistive rating for the performance of these building assemblies.

In recent years, some fire conditions have been identified as sufficiently different from those represented by the time-temperature curve in ASTM E119, thus meriting an additional time-temperature curve. As a result, several fire test standards, including UL 1709, *Standard for Rapid Rise Fire Tests of Protection Materials for Structural Steel*,[3] specify fire test-chamber temperatures that rise at a quicker rate than those specified in ASTM E119. The time-temperature curve in UL 1709 represents the conditions associated with burning pools of hydrocarbon fuels. At the other end of the spectrum, discussions have cited the need for a time-temperature curve that has a slower rate of rise than specified in ASTM E119.

The ASTM fire-test standard is a living document that undergoes constant review by the ASTM technical committee responsible for its content. Discussions regarding the merits of the ASTM standard among fire science professionals are similar to the discussions among professionals in other sciences on topics in their specialized field. It is telling to note that, in the FEMA report,[1] an observation on the condition of the structural steel in WTC 5 states that the structural damage due to the fires closely resemble that commonly observed in test assemblies exposed to the ASTM E119 Standard Fire Test.

ARE BUILDINGS SAFE FROM FIRE TODAY?

This is an appropriate question to raise as a result of the collapse of the buildings at the WTC site. The FEMA report has taken the initial step in focusing upon opportunities to enhance high-rise building safety. Items cited in the report include:

- the durability of materials used in passive fire-protection systems,
- the lack of data on the performance of structural connections when exposed to fire, and
- a need for additional data describing the physical characteristics of materials used in passive fire-protection systems.

These material characteristics are required for a broad temperature range.

Since fires do occur in high-rise buildings, building codes typically require a combination of both active systems (smoke alarms and sprinklers) and passive systems (building assemblies with hourly fire-endurance ratings) as a means to protect public buildings. The construction of the WTC and all typical high-rise buildings is based upon requirements in the applicable building codes. The WTC was exposed to conditions far beyond the scope of the building codes. Yet, at the WTC, the FEMA report[1] states that almost everyone below the points of impact was able to safely evacuate the buildings. More than 30,000 people evacuated the WTC.

CAN BUILDINGS BE SAFER IN THE FUTURE?

As with any engineering challenge, the resulting solution depends heavily upon the assumptions made during the evaluation process. With respect to the WTC, does one assume the fire origin will be the result of careless housekeeping or the deliberate impact of a highly combustible object such as an airplane? Each scenario requires a different fire-protection solution.

In the area of passive fire protection, the FEMA report[1] focuses upon three items where action is recommended:

- Develop additional data on the fire resistance of structural connections.
- Improve the durability of fire-resistant materials.
- Develop data describing the characteristics of materials used in passive fire-protection systems.

The fire resistance of structural connections is not within the current scope of ASTM E119. This does not mean that data on the fire resistance of structural connections could not be obtained using existing test equipment.

With respect to the durability of fire-resistive materials, the ASTM E119 standard test method assumes that the systems tested are located within environmentally controlled areas of a building. By contrast, for more than 20 years, UL has certified fire-resistive materials intended for exterior use. Before a fire test, samples of the materials intended for exterior applications are subjected to various exposures, which include accelerated aging, wet-freeze-dry cycling, high humidity, salt spray, and ultraviolet light.

Furthermore, all intumescent-type materials certified by UL for use in fire-resistive assemblies have been subjected to adverse conditions to measure their durability. These conditions include exposure to accelerated aging and high humidity. These durability tests on intumescent materials are conducted to evaluate the ability of these products to perform as intended after being exposed to harsh environmental conditions.

Similar types of requirements can be developed for all types of fire-resistive materials for which a higher degree of durability is desired. Another consideration could be the expanded use of a hose stream test that is part of the ASTM E119 standard. The hose stream test subjects fire-resistive assemblies to impact and erosion effects. An alternate method of applying the hose stream test, or establishing new acceptance criteria intended for highly durable materials, might be a desirable approach to enhance the level of safety for these products and systems.

As in almost all fields, the growth of computer-related applications has been enormous since the WTC was constructed. The application of computer models in fire protection engineering is an example of this growth. Today, computer models are available that will predict temperatures of building materials, such as structural steel, during a fire. Computer models that will predict the performance of multistory structures under varying temperature conditions are also available. These computer programs are available to the fire protection engineering community. However, the input data required for these programs to function are not readily available for most fire-resistive materials.

As stated in the FEMA report,[1] standardized test methods are needed for fire-resistive materials to determine their physical characteristics such as density, conductivity, and specific heat for temperature ranging from 70°F to 2,000°F (20°C-1100°C). The material properties are known for common construction materials such as concrete and steel but not for most proprietary materials. In addition to the need for material properties, the results from computer models require validation. Today's computer models cannot predict the physical performance of fire-resistive materials. This includes items such as the adhesion of coatings to structural steel, the securement of gypsum board, and the performance of an acoustical ceiling system with respect to the acoustical panels remaining within the steel suspension system.

Data from full-scale fire tests, such as ASTM E119, provide this type of physical performance information. Data from full-scale fire tests may also be used to validate the accuracy of the computer models for the material properties and fire conditions provided as input to the model. This can be accomplished only because of the reproducibility of the ASTM E119 fire test chamber conditions. ▲

Robert Berhinig is with Underwriters Laboratories, Inc.

REFERENCES

1 "World Tracde Center Building Performance Study: Data Collection, Preliminary Observations, and Recommendations." FEMA 403, Federal Emergency Management Agency, May, 2002.

2 ASTM E-119, "Standard Test Methods for Fire Tests of Building Construction and Materials," American Society for Testing and Materials, West Conshohocken, PA, 2002.

3 UL 1709, "Standard for Rapid-Rise Fire Tests of Protection Materials for Structural Steel," Underwriters Laboratories, Northbrook, IL, 1994.

Consequences of Imperfect Insulation – Numerical Modeling

Figure 1: View of the Building

Figure 2: The Protected Steel Columns

By Jean-Marc Franssen, Ph.D.

A 13-story high-rise office building in Germany was undergoing refurbishment (see Figure 1). In order to enlarge the area of some individual offices, some load-bearing concrete walls were being replaced with steel frames consisting of one steel beam and two steel columns. This modification extended from the second floor to the top of the building, with 24 steel columns at each floor.

In order to achieve the required fire resistance time of 90 minutes to the standard ISO 834 fire curve, the columns were thermally protected by a box protection made of gypsum-type fire protection boards (see Figure 2).


Figure 3: Imperfect Detailing


Figure 4: One "Repaired" Column

After the work was completed, the thermal protection did not totally cover the horizontal steel plates upon which the columns were placed; some 40 mm or 50 mm of this steel plate was exposed and could be susceptible to fire attack (see Figure 3).

The control authority questioned whether the exposed steel could significantly reduce the fire resistance of the columns. Figure 4 shows one of the columns that underwent a tentative repair.

The University of Liege was commissioned to investigate potential fire exposures to the bottom region of the columns.

DATA AND HYPOTHESES

Each column is made of a hot rolled H profile of the heavy HEM 160 type (166 mm x 180 mm x 76.2 kg/m). It is placed on a 330 mm x 300 mm x 35 mm steel plate. The steel plate comes on a 140 mm thick concrete slab, with a 35 mm intermediate layer of mortar. Steel is assumed to have the thermal properties of Eurocode 3.[1]

The thermal insulation is made of 25 mm boards a density of 900 kg/m^3; a specific heat of 1700 J/kg-K, and a thermal conductivity of 0.20 W/m-K. The high value of the specific heat accounts for the energy absorbed by the evaporation of the moisture and for the endothermic chemical reactions of the gypsum-type board.

A 70 mm topping layer was added on the concrete slab. The concrete of the slab, the topping, and the mortar layer are assumed to have the thermal properties of Eurocode 2[2] with a density of 2,300 kg/m^3 and a moisture content of 46 kg/m^3.

This heat transfer involves not only conduction, but also radiation in the chambers of the H profile created by the box insulation. Different materials are involved, with nonlinear temperature-dependent properties, and a transient situation has to be taken into account. Strictly speaking, this was a 3D problem. The software SAFIR,[3,4] established at the University of Liege for the analysis of structures subjected to fire, can treat 3D conductive problems. Internal cavities with radiation inside can be taken into account, but only in 2D sections. This is because the algorithms for evaluating the view factors in the cavity are quite complex, even in 2D, particularly if the cavity is a complex shape, if there is partial visibility within the cavity, or if there are objects within the cavity. The possibility of internal cavities in 3D structures has thus not been programmed in the code. In order to have an indication of the solution, it was decided to treat the problem as a series of uncoupled 2D problems and then to exercise some engineering judgment in order to reach a conclusion.

It is assumed in the analyses that no contact resistance exists at the interface between two adjacent different materials.

The heat flux from the fire environment to the boundaries of the column is calculated accorded to the recommendation of Eurocode I:[5] see equation 1.

$$\dot{q}'' = \alpha_c \left(T_g - T_m\right) + \sigma \varepsilon_{res} \left(T_g^4 - T_m^4\right) \qquad (1)$$

where

$\dot{q}''$ heat flux at the boundary, W/m^2
h_c coefficient of convection, 25 W/m^2-K
T_g gas temperature according to the ISO 834 standard fire curve, K
T_m temperature at the surface of the material, K
σ Stefan-Boltzman constant, 5.67 10^{-8} W/m^2K^4
ε_{res} resultant emissivity, 0.56

RESULTS OF THE MODELS

Simple calculation model

Eurocode 3, and many other textbooks, gives a simple differential equation that allows calculating the temperature evolution in a protected steel profile on the hypothesis of uniform temperatures of both the steel profile and surrounding gases. With the thermal massivity of the box-protected profile being equal to 71.3 m^{-1}, this equation yields temperatures in the profile of:

127 °C after 30 minutes,
263 °C after 60 minutes,
383 °C after 90 minutes.

This uniform temperature is an approximation of the situation prevailing at mid-level of the column, *i.e.*, far away from the perturbation existing at the bottom. It can be used as a comparison with other results obtained by numerical methods.

2D numerical model at mid-level

At mid-level, the situation is purely 2D and the “exact” solution can be obtained numerically using the discretization shown on Figure 5. Only one-fourth of the section is analyzed owing to symmetry.

The isotherms after 90 minutes of fire are shown on Figure 6. This Figure indeed confirms that, in this well-protected profile, the temperature distribution in the steel is nearly perfectly uniform. Minimum and maximum steel temperatures at that time are 337 °C in the center of the web (node 1) and 349 °C in the corner of the profile (node 105).

The average temperature obtained by the numerical model is 40 °C cooler than the uniform temperature given by the simple model. This difference can be attributed to the two simplifying hypotheses made in the simple model:

1. The heat transfer between the hot gases and the section is neglected in the simple model; it is assumed that the temperature at the edge of the section is equal to the temperature of the gas, and this is not exactly the case.

2. The thermal massivity is calculated with the inside surface of the insulating box as the surface of heat transfer. In the present case, the thickness of the insulation board is not small compared to the dimensions of the profile. If, for example, the external surface of the insulating box is taken into account, this yields a thermal massivity of 91.9 $m^{-1,}$ and the uniform temperature calculated by the simple model after 90 minutes is then 435 °C. The value obtained by the numerical analysis is between the two extreme values given by the simple method, which gives some confidence in the results of the numerical analysis.

2D discretisation perpendicular to the web

A 2D analysis is then performed in a vertical plane passing through the center of the section and perpendicular to the plane of the web (A-A' on Figure 5). The discretization is shown on Figure 7. The first material is the concrete slab; material 2 is the mortar layer; material 3 is the concrete topping; material 4 is the steel of the web and of the horizontal plate (with 42 mm exposed to the fire); and material 5 is the insulation board. Figure 7 is a zone near the bottom of the column; a 1.040 m height of the column was modeled. A 450 mm width of the slab is represented because the thermal field through the slab becomes uniaxial at greater distance from the column. An axis of symmetry exists on the left edge of the section.

Figure 8 shows the isotherms in the section after 90 minutes of the ISO 834 fire. The temperature in the web is nearly uniform from the bottom to the top. It is slightly colder at the bottom than in the current section, 416 °C versus 420 °C, because the heat flux to the web is higher due to radiation from the insulation rather than due to conduction via the horizontal steel plate. During the first minutes of the fire, the contrary situation prevails: The temperature increases faster at the bottom of the web than in the current section. This is because the temperature wave needs some time to travel through the insulation before it can attack the web by radiation (as a function of the fourth power of the temperature in the inside of the insulation), whereas the heat transfer through the plate by conduction is more a linear function of the temperature difference. The linear function has a steeper slope at the beginning, but at the end, the fourth power function prevails.

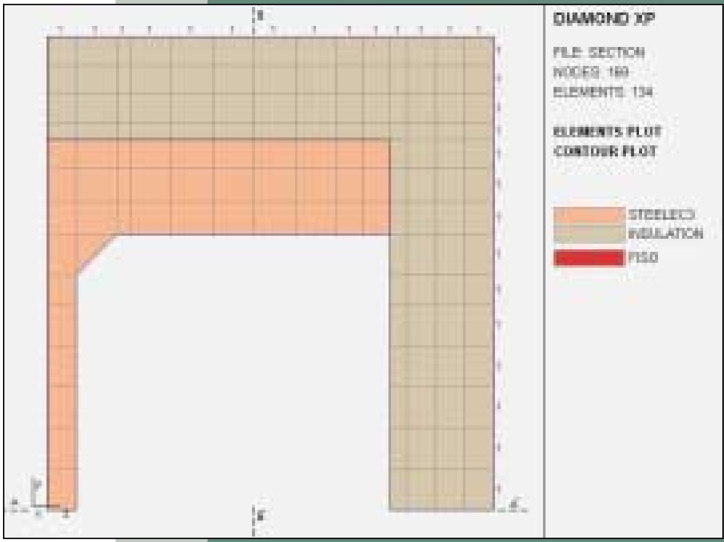


Figure 5: Discretization of the Section

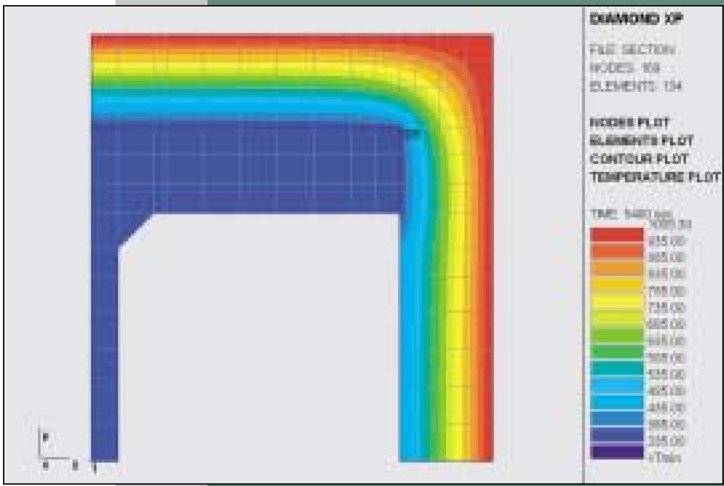


Figure 6: Isotherms After 90 Minutes

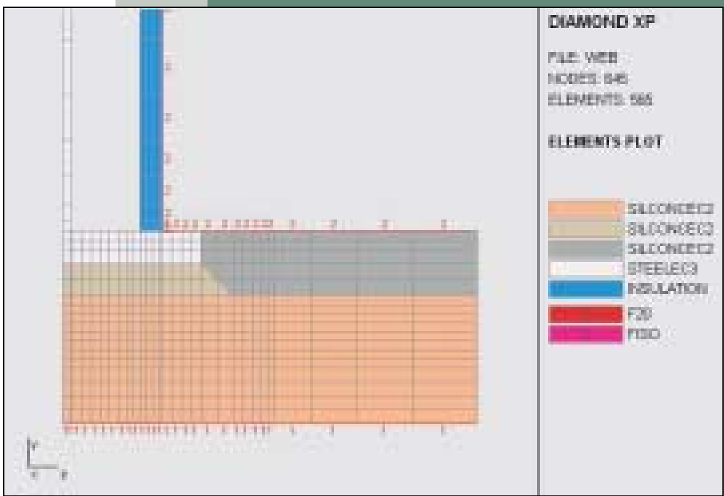


Figure 7: Discretization Perpendicular to the We

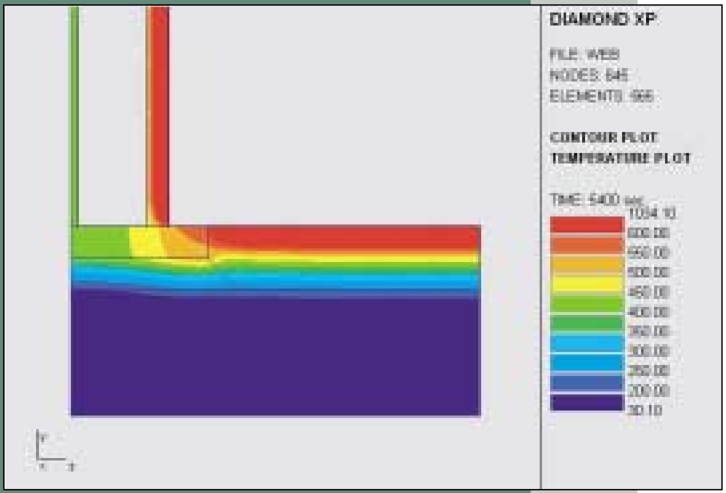


Figure 8: Isotherms in the Section Perpendicular to the Web

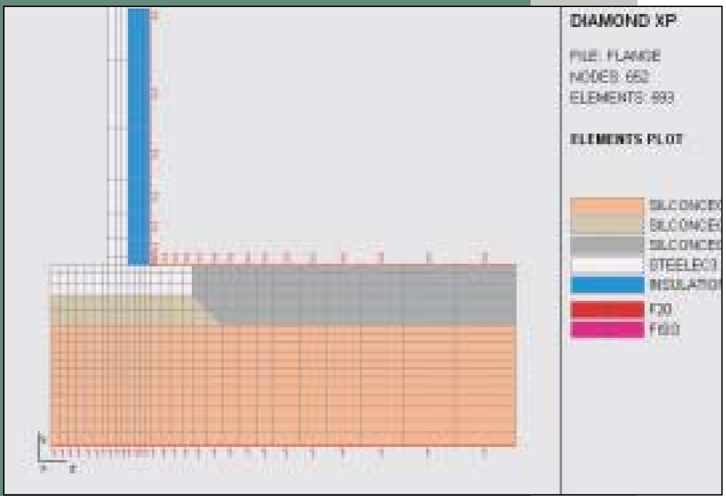


Figure 9: Discretization Parallel to the Web

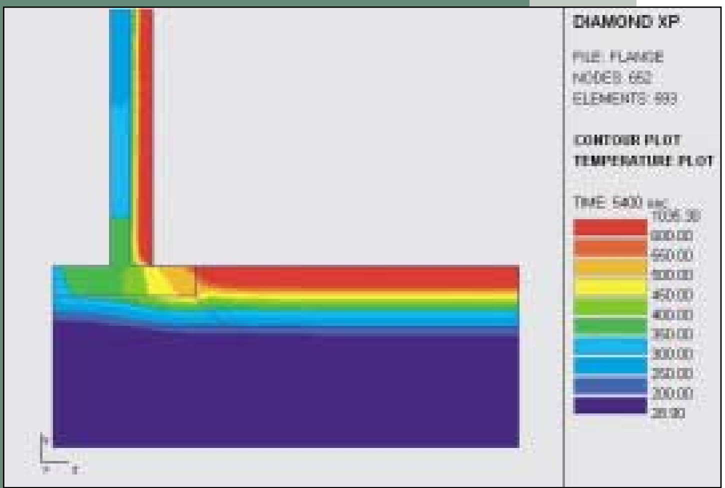


Figure 10: Isotherms in the Section Parallel to the Web

2D discretization through the web

A 2D analysis is then performed in a vertical plane parallel to the plane of the web and passing at one-fourth or three-fourths of the width of the section (B-B' on Figure 5). The discretization is shown on Figure 9.
50 mm of the horizontal steel plate are exposed to the fire. The insulating board is in contact with the flange of the profile that is visible on this Figure.

Figure 10 shows the isotherms in the section after 90 minutes of the ISO 834 fire. In the flange, the temperature is somewhat higher at the bottom of the column than in the current section (392 °C versus 356 °C). This is not because a bigger surface of the horizontal plate is exposed to the fire, but more likely because the flange is located closer to the exposed surface. The length for conduction through the plate has been reduced, and this overwhelms the fact that the radiation resistance has disappeared between the insulation and the flange.

This temperature increase has yet a limited extension along the height of the column. Figure 11 shows that the affected zone does not extend further than 400 mm above the slab after 90 minutes of fire.

CONCLUSIONS

Two main observations emerge from the analyses.

1. The local temperature at the foot of the column is slightly higher than the average uniform temperature that can be calculated by the simple method of Eurocode 3. The difference increases in time but is limited to 35 °C in the web and to 10 °C in the flange after 90 minutes of ISO fire.
2. The region that is influenced by the local effect has a very limited extension, in the order of 400 mm after 90 minutes of fire.

Because the local temperatures at the bottom of the column hardly exceed 400 °C, the temperature at which the yield strength of steel starts to decrease according to the Eurocode model, a failure by local crushing of the section is not likely.

The Young's modulus of steel starts decreasing at temperatures as low as 100 °C. There will thus be a local decrease of the stiffness of the column, but this decrease acts over too short a distance to increase significantly the buckling length of the column.

As a consequence, it was judged that the consequences of the apparently improper detailing could be neglected. Although the software SAFIR is able to perform a mechanical analysis of the column under a transient and nonuniform temperature distribution, it was estimated that such a nonlinear structural analysis was not necessary. ▲

Jean-Marc Franssen is with National Fund for Scientific Research Belgium.

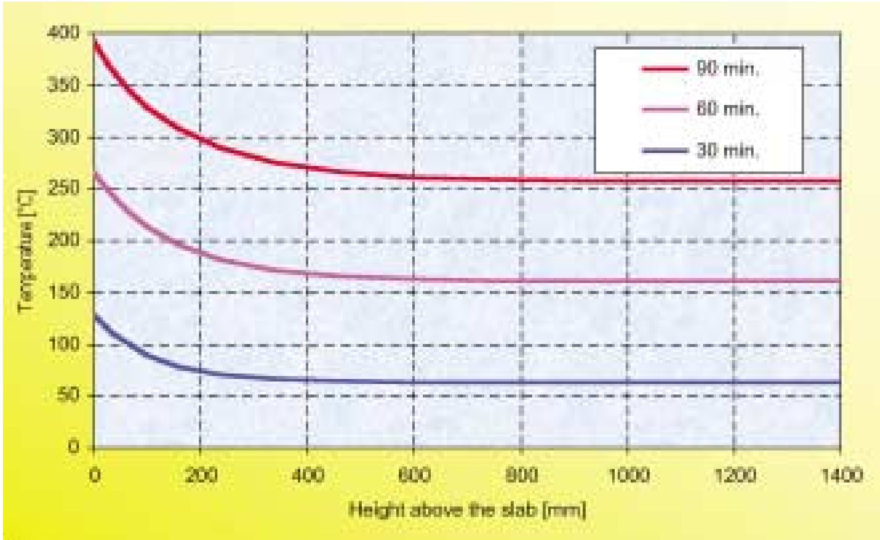


Figure 11: Evolution of the Temperature Along the Height of the Flange

Note: A free demonstration version of the SAFIR software can be ordered on the FTP site *msmpc27.gciv.ulg.ac.be*; userid and password: SAFIR

REFERENCES

1 Eurocode 3: Design of steel structures. Part 1.2: General rules. Structural fire design. ENV 1993-1-2, CEN, Brussels, 1995.

2 Eurocode 2: Design of concrete structures. Part 1.2: General rules. Structural fire design. ENV 1992-1-2, CEN, Brussels, 1995.

3 Nwosu, D. I., Kodur, V. K. R., Franssen, J. M., and Hum, J. K., User Manual for SAFIR. A Computer Program for Analysis of Structures at Elevated Temperature Conditions, National Research Council Canada, int. Report 782, 1999.

4 Franssen, J. M., Kodur, V. K. R., and Mason, J., User's Manual for SAFIR 2002. A Computer Program for Analysis of Structures subjected to fire, Univ. of Liege, Dpt M&S, 2002.

5 Eurocode 1: Basis of design and actions on structures – Part 2-2: Actions on structures – Actions on structures exposed to fire. ENV 1991-2-2, CEN, Brussels, 1995.

Accuracy, Precision, Resolution, and Uncertainty in FIRE PROTECTION ENGINEERING

Much of the work done by fire protection engineers involves computations using data gathered during experiments. Those data were gathered by making measurements, and there is always some uncertainty when making a measurement. Therefore, there is uncertainty in any computations using that data. This article offers a brief refresher on accuracy, precision, resolution, and uncertainty, and challenges the fire protection community to take the next great step for an evolving discipline: recognition and public reporting of our uncertainty. Whether a model or a calculation method is accurate or not requires careful analysis and study, and is beyond the scope of this article, which is intended to focus on how to properly report data and the results of calculations.

"In physical science, the first essential step in the direction of learning any subject is to find principles of numerical reckoning and practicable methods for measuring some quality connected with it. I often say that when you can measure what you are speaking about and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely in your thoughts advanced to the state of Science, whatever the matter may be." Lord Kelvin, 1824 – 1907 (Sir William Thomson, Baron Kelvin of Largs)

Many fire protection engineers and scientists use fire models. Calculations are made using data whose uncertainty is unknown – or at least not reported. Clients and courts are given results by experts that imply the work has a degree of accuracy and precision that it may not have. The experimenter must determine and report the uncertainty interval for measured data, and the engineer that uses the data in calculations or models is responsible for informing their audience of the uncertainties inherent in the analysis[†].

DEFINITIONS

Accuracy: How close a measurement or statement is to the true value. Of course, when measuring something, the true value can never be known.

Precision: The degree of agreement between individual measurements of a set of measurements. This is the most common use of the term. Sometimes, precision or the word "precise" is used when describing the resolution of an instrument.

Resolution: The smallest interval that an instrument can actually measure. A meter stick with 1 mm gradations has a resolution of 1 mm even though accepted practice is to estimate one additional significant figure.

Uncertainty: An interval around a measured value such that repeated measurements will lie within this interval.

Repeatability: Close agreement between the results of successive measurements carried out under the same conditions of measurement.[1] Repeatability conditions include:

- the same measurement procedure;
- the same observer;
- the same measuring instrument, used under the same conditions;
- the same location; and
- repetition over a short period of time.

Reproducibility: Close agreement between the results of measurements carried out under changed conditions of measurement.[1] The changed conditions may include:

- principle of measurement;
- method of measurement;
- observer;
- measuring instrument;
- reference standard;
- location;
- conditions of use; and
- time.

Significant Figures: The number of digits needed to express the number to within the uncertainty of the measurement. Only figures or digits which are actually measured are said to be significant. Significant figures include the uncertain digit that is estimated when a measurement is made (observed). For example, when a scale is graduated in grams and the display shows that the value lies between 5 and 6 grams, we may estimate the value to be 5.2, 5.5, or 5.9 grams. Thus, the last digit is uncertain but is significant.

Numbers other than measured values also have significant digits. These include integers, such as the number of smoke detectors used in a battery calculation. With defined numbers such as π, square roots, or unit conversions, every digit you choose to use is significant.

Determining the number of significant figures in a number can be tricky. For example, if you are told that the temperature is 20°C, does that number have one or two significant figures? Our experience tells us that most thermometers are graduated in single degrees, not 10-degree increments. So it would be safe to say that the resolution is one degree, and that our uncertainty is one degree and the number of significant digits is two. However, if you are given heat release rate datum such as 2,579 kW you should question whether that datum really has four significant figures as reported. Was it really measured (or calculated) with that level of resolution? Similarly, if the datum is listed as 2,000 kW, is it really only certain to within 1,000 kW or is it better reported as 2.0×10^3 kW, thereby confirming two significant digits?

Most engineers are familiar with the rules for rounding to the correct number of significant figures after making a calculation using multiple pieces of data. However, recent work shows that the standard rule for rounding after multiplication and division can result in errors and the loss of data.[2, 3]

The standard rule for addition and subtraction is that the number of significant figures is determined by the smallest resolution or uncertainty (lowest precision) of all the quantities involved. For example, 1.413 + 9.2 = 10.613 and should be rounded to 10.6. The standard rule for multiplication and division states that the results should be written using the same number of significant digits as the least precisely known number used in the computation. For example, 5.60 x 3.7524 = 21.01344 should be reported as 21.0 since 5.60 has only three significant digits. The alternate rule states that the results should be reported using one more significant figure than the standard rule.[2] Thus, for this example, the results would be reported as 21.01.

When combining addition, subtraction, multiplication, and division, determining the number of significant digits in the final result is more difficult. The proper method, which preserves the integrity of the data, is to apply the rules at each step. For example:

$$X = 5.60(1.413 + 9.2)3.7524$$
$$X = 5.60(10.6)3.7524$$
$$X = 222.706$$
$$X = 222.7 \quad \text{by the alternate rule}$$
$$X = 223 \quad \text{by the standard rule}$$

However, using a calculator, spreadsheet, or computer model, intermediate results are not rounded, and the user (or the person who wrote the spreadsheet or program) must determine how to present the results. For the above example, the following results might be displayed:

$$X = 5.60(1.413 + 9.2)3.7524$$
$$X = 223.01564$$

How should this be rounded? If the least number of significant digits in the data (two) is used, it would be written as 220 without a decimal point. If the least level of precision is used, it would be written as 223.0. Neither matches the most reliable answer, 222.7, which is found by intermediate rounding using the alternate rule*. Nor do they match the next most reliable answer, 223, reached using the standard rounding rules. Wherever possible, models should use intermediate rounding. If this is not possible, the easiest method is to round using either the lowest precision or the least number of significant digits plus one, whichever results in the least number of digits. This would cause the results to be reported as 223 or 2.23 x 10^2.

What is the uncertainty associated with our results? It depends on the uncertainty of the data used to get the results. When making measurements to obtain data, it is best to make several measurements and calculate the mean and the average deviation. For example, the following table lists many measurements made of the length of a sample:[4]

Length (cm)	Deviation from mean
15.39	0.012
15.37	0.008
15.37	0.008
15.39	0.012
15.38	0.002
15.37	0.008
15.37	0.008
15.38	0.002

The mean is calculated to be 123.02/8=15.378 cm. The average deviation is 0.060/8=0.008 cm. The results, including uncertainty, would be reported as 15.378 +/- 0.008 cm. A simpler approach is to make only one measurement and to apply the general rule for uncertainty, which is to use one-half the smallest scale division of the measuring instrument as the uncertainty. For this example, assume the scale is in mm and that last digit in the data is the observer's estimate. If they measured 15.38, it should be reported as 15.38 +/- 0.05. Consult the references for how uncertainties propagate through calculations.

This article has only touched on a few of the issues related to accuracy, precision, resolution, and uncertainty. It is incumbent on the engineering practitioner to be both accurate and precise, as well as honest in their work. For example, a calculation may indicate that the time to egress a space is 2 min., 30 seconds, and the minimum time for untenability, based on a series of realistic design fires is 3 minutes. It is insufficient, even dangerous, to say that a protection plan is good if the egress time includes a detection component with an uncertainty of 1 minute.

It is only through careful, disciplined practice that the fire protection community will correctly present its work to peers and other more established disciplines, and gain recognition and respect for its engineering and scientific efforts.

† This article address only measurement uncertainty. Chapter 5-4, "Uncertainty," by Dr. Kathy Notarianni, in the *SFPE Handbook of Fire Protection Engineering*, 3rd ed., addresses other types of uncertainty that are important for honest and complete reporting of engineering analyses.

* Here, "reliable" is used to mean a result that is least likely to contain an error or to lose data when a rounding rule is applied. For more information on the reliability of the standard rule and the alternate rule, see references 2 and 3, which can accessed at http://www.angelfire.com/oh/cmulliss/.

REFERENCES

1 Taylor, B.N., and Kuyatt, C.E., "Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results," NIST Technical Note 1297, U.S. Government Printing Office, Washington, DC, 1994.

2 Mulliss, C., and Lee,W., "On the Standard Rounding Rule for Multiplication and Division", *Chinese Journal of Physics*, 1998, 36(3), 479-487.

3 Lee,W., Mulliss, C., and Chiu,H., "On the Standard Rounding Rule for Addition and Subtraction", *Chinese Journal of Physics*, 2000, 38(1), 36-41.

4 Example from Bellevue Community Collage Physics Department Web site, *http://scidiv.bcc.ctc.edu/Physics/Measure&sigfigs/Measure&sigfigsintro.html*.

Additional Information:

ISO, *Guide to the Expression of Uncertainty in Measurement, International Organization for Standardization*, Geneva, Switzerland, 1993.

Eric W. Weisstein, Wolfram Research, Inc.: *http://mathworld.wolfram.com/S/SignificantDigits.html*

Purdue University, Chemistry primer on Significant Digits: *http://chemed.chem.purdue.edu/genchem/topicreview/bp/ch1/sigfigs.html*

World of Chemistry: The Home Page of Ralph Logan: *http://members.aol.com/profchm/sig_fig.html*

Interactive (JAVA) site to test your knowledge of significant digits: *http://brad.tcimet.net/java_samples/sigfigs/autogen_SigFigs.html*

Significant Figures, by Timothy C.K. Su, Professor, Chemistry Department, UMass Dartmouth: *http://www.umassd.edu/1Academic/CArtsandSciences/Chemistry/Catalyst/sf.html*

Editor's Note – About This Article

This is a continuing series of articles that is supported by the National Electrical Manufacturer's Association (NEMA), Signaling Protection and Communications Section, and is intended to provide fire alarm industry-related information to members of the fire protection engineering profession.

CALCULATING STRUCTURAL RESPONSE TO FIRE

By Robert H. Iding, Ph.D.[1]

INTRODUCTION

A performance-based approach to designing structures for fire resistance is gradually gaining favor as an alternative to traditional prescriptive requirements such as hourly ratings and tables of required fireproofing thicknesses. The basic concept underlying performance-based fire analysis is that a building should be designed for the fire severity that might actually occur in the building rather than for a code-specified "one-size-fits-all" fire such as ASTM E-119. Using factors such as fuel load and ventilation, the maximum credible fire in different locations in the building is calculated, and the structural response to these fires is calculated.

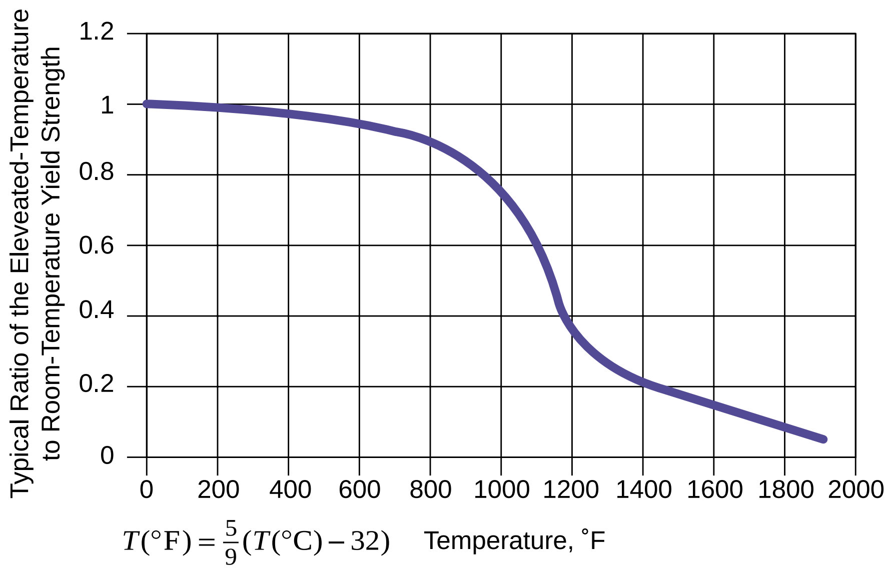


Figure 1. Effect of Temperature on the Yield Strength of Steel[3]

Calculating a structure's response to fire is a three step process:

1. Fire Hazards Analysis to identify all credible fire scenarios and determine the impact of each scenario on adjacent structural members.
2. Thermal Analysis to calculate temperature history in each member.
3. Structural Analysis to determine forces and stresses in each member and whether local or progressive structural collapse would occur during any of the fire hazard scenarios.

THERMAL ANALYSIS

Structural members exposed to hot gases from fires gradually heat up and can reach very high temperatures. The temperature rise always lags the fire temperature because of the thermal inertia inherent in the material and the tendency for heat to flow to cooler material adjacent to the heated area. Insulation can greatly slow the temperature rise in protected members. When the fire starts to cool, the temperature drop in a structural member will lag the falling gas temperature, again because of thermal inertia and insulation.

Basic heat conduction theory can predict temperature history in fire-exposed structures when thermal material properties of concrete, steel, and insulation are known. The heat conduction field equation for a three-dimensional body is:

$$\rho C_p \frac{\partial T}{\partial t} + K\nabla^2 T = \dot{Q}$$

where

- ρ = density of material
- C_p = specific heat capacity of material
- T = temperature distribution in member
- t = time
- K = heat conductivity of material
- = heat input into member per unit time

$$\nabla^2(\,) = \frac{\partial^2(\,)}{\partial x^2} + \frac{\partial^2(\,)}{\partial y^2} + \frac{\partial^2(\,)}{\partial z^2}$$

Heat input is due to a combination of convection and radiation into the fire-exposed surfaces. This heat flow can be calculated using the equation:

$$\dot{Q} = A\left[h(T_f - T_s)^N + V\sigma\left(\alpha\varepsilon_f T_f^{\,4} - \varepsilon_s T_s^{\,4}\right)\right]$$

where

- A = surface exposed to fire
- h = convection coefficient
- N = convection power factor
- V = radiation view factor
- σ = Stefan-Boltzmann constant
- α = absorption of surface
- ε_f = emissivity of the flame associated with fire
- ε_s = surface emissivity
- T_f = fire exposure temperature
- T_s = surface temperature

There are a number of finite element computer codes that solve the heat conduction field equation with this fire-boundary condition. Two of the most commonly used are FIRES-T3[1] and TASEF[2]. All of these codes discretize the field equations into a set of linear equations expressed by the matrix relationship:

$$[C]\{T\} + [K]\{T\} = \{Q\}$$

where

- $[C]$ = capacity matrix (temperature-dependent)
- $[K]$ = conductivity matrix (temperature-dependent)
- $\{Q\}$ = external heat flow vector (depends on exothermic reactions and fire-boundary conditions)
- $\{T\}$ = temperature vector (time-dependent)

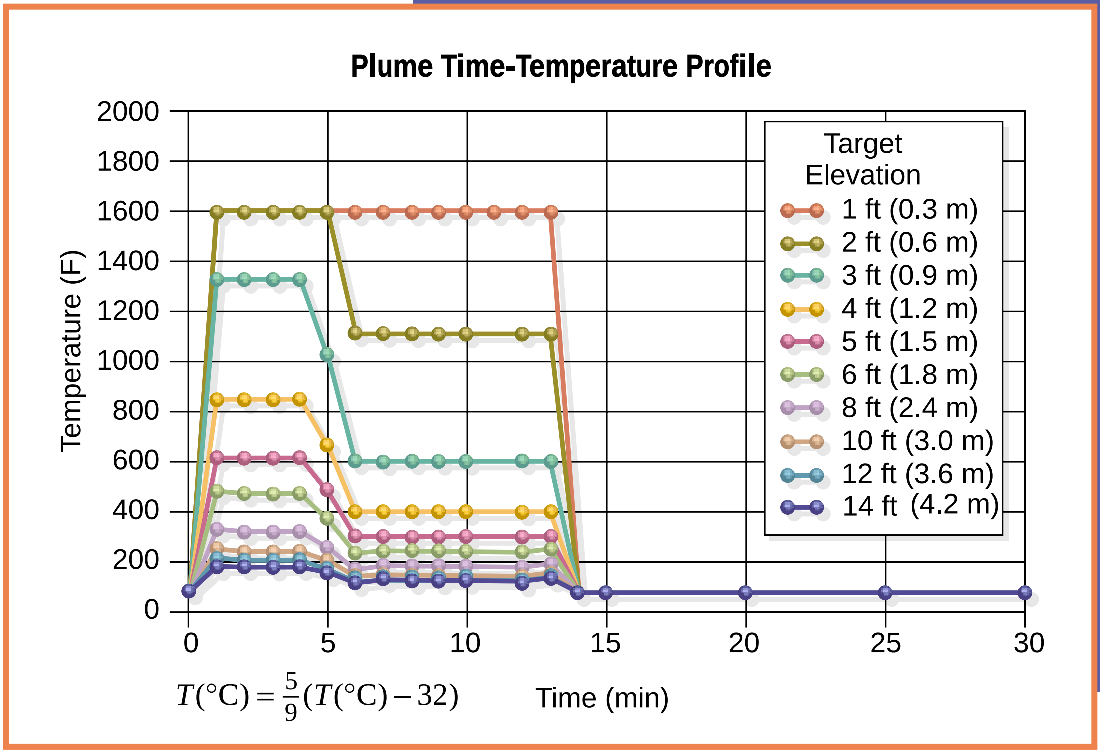


Figure 2. Column Exposure Temperatures from Maintenance Refuse Fire.[9]

All thermal analyses start with discretizing the structural members into finite elements and defining boundary conditions, both fire-exposure boundaries and other boundaries where heat may escape from the member into adjoining parts of the structure or into the environment. The thermal material properties are defined for all components of the model, and the time-dependent fire curve (gas temperature T_f) from the particular fire scenario to be considered is specified. The equations are then solved to obtain the temperature history in all parts of the structural member during the fire. Such temperatures form the basis for a structural analysis of each member and the structure as a whole.

STRUCTURAL ANALYSIS

Once the maximum temperature loading in each structural member is known, calculations to determine the structural response of these members to the fire can be made, particularly to determine whether any member will fail during the fire. Standard structural analysis methods and computer models can be used, but they must take into account the special characteristics of materials at high temperatures:

- Thermal expansion (coefficient of expansion multiplied by temperature change), which can be very large in a fire. When there is restraint acting, very large stresses can be generated by this thermal expansion.
- Effect of temperature on material properties, such as modulus of elasticity, yield point, and ultimate strength. For example, when steel becomes hot enough, the yield point can drop so much that the member cannot support gravity loads during the fire and collapse will occur. The degradation of yield strength with temperature for A36 mild steel is shown in Figure 1.[3] It can be seen that between 1000°F and 1100°F (500°C-600°C) the yield point has fallen to only 60 percent of its room-temperature value. Typical maximum design loads produce about 60 percent of yield stress, so collapse of a fully loaded member could occur once this temperature is reached, although most steel structures would be much

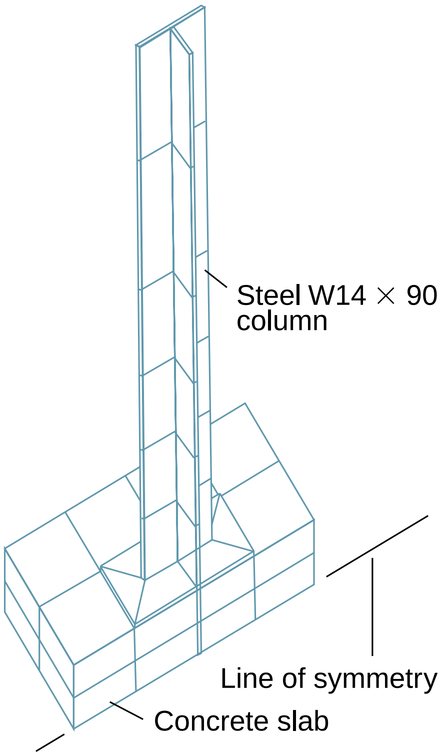


Figure 3. Column, Adjacent Base Plate, and Floor Slab Discretized into Finite Element Mesh.

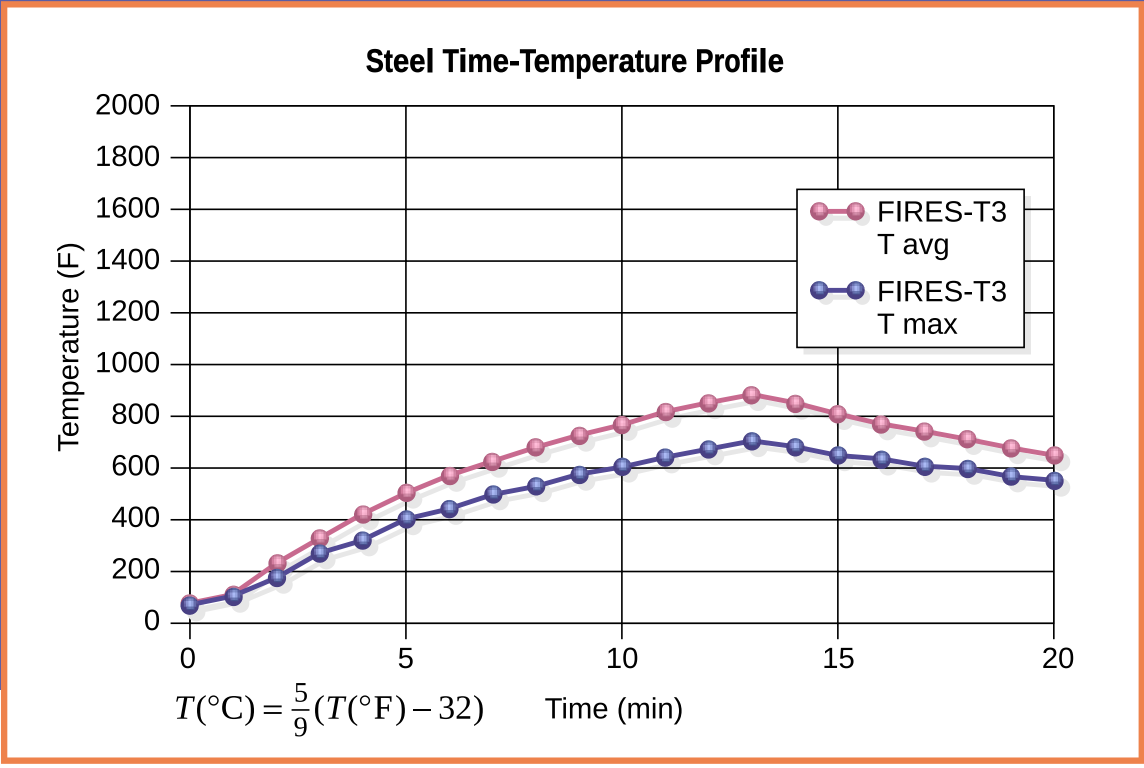


Figure 4. Steel Temperature History for Maintenance Refuse Fire.

more lightly loaded during a fire and would fail at higher temperatures. Concrete loses strength more slowly at elevated temperatures than steel does,[3] but it is susceptible to spalling, which may expose reinforcing steel to fire and loss of strength.

- Nonlinear behavior. Structural response during a severe fire can quickly lead to high stresses, yielding, creep, and local or general failure. A complete analysis must take these nonlinear effects into account.

Several computer models were specifically designed to model these special high-temperature phenomena, including FIRES-RC II,[4] FASBUS II[5,6] and SAFIR.[7] Other nonlinear structural programs such as ABAQUS and DIANA have been modified and utilized for fire analysis.[8] General-purpose linear programs can sometimes also be used, particularly if member temperatures are not very high or if there is little restraint to thermal expansion. When using a linear program, the analyst must account for any yielding or other nonlinear behavior by modifying material properties as the analysis proceeds.

Simplified approaches are also possible. For example, in relatively unrestrained steel members, a temperature threshold can be set (typically 800°F-1000°F [400°C-500°C]) at which the yield point is well above the stresses the member must carry during the fire, and the member can be considered acceptable. This is the type of acceptance criterion used in ASTM E-119 furnace tests when assemblies are not loaded during the test.

The emphasis of a structural analysis should be on examining the fire safety of the building as a whole. The response of each member is calculated, and local failures are identified. But then it is important to continue the calculations in order to determine whether these local failures could lead to progressive collapse of the entire building. Increasing structural redundancy in the fire-affected area may be necessary if analysis indicates progressive collapse is likely. This is one way structural engineers can make an important contribution to fire safety.

EXAMPLE – TRANSIENT TRASH FIRE IN POWER PLANT

The particular fire hazard to be examined here is a transient trash, or refuse, fire in a large steel-framed power plant. This is an important scenario to consider since there are many places in such a structure that could be impacted by a fire of this type. If the refuse is placed directly against an unfireproofed steel column, and the fire were large enough, the structural integrity of that column might be affected.

The first step in the analysis is to conservatively estimate the quantity of transient material that could be adjacent to a column. The fuel package selected is typical maintenance refuse composed of a cardboard box, Kimwipes™, acetone, and a plastic wash bottle. The burning characteristics of this fuel package (about 120 kW heat release rate) were calculated, from which the gas temperatures of the fire plume impacting the surface of the column were also calculated,[9] as shown in

Figure 2. Note that for this fuel load, the fire duration is about 13 minutes and the peak plume temperature is 1600°F (870°C). Also note in Figure 2 that the temperature of the gas enveloping the column decreases at higher elevations above the fire, so that only the first few feet of column above the refuse pile are exposed to very high temperatures.

The next step in the analysis is to determine the temperature rise in the steel column itself during the trash fire. A three-dimensional heat conduction analysis using FIRES-T3 was performed for a typical uninsulated W14 x 90 column, which is the smallest size column in the steel frame and, therefore, would be most severely affected by the trash fire. Also modeled is the base plate and adjacent concrete slab. It is assumed that the trash is piled at ground level against one side of the column's web and adjacent flanges, thereby exposing these surfaces to the full radiation from the fire. The finite element model is shown in Figure 3 and makes use of the symmetry of the fire and associated heat flow.

Calculated temperatures within the hottest cross-section of the column (about 18 inches [460 mm] from the floor) are plotted in Figure 4. Maximum steel surface temperature of 900°F (500 °C) is reached after 13 minutes of fire exposure, after which the fire begins to cool. Average temperature within the hottest steel cross-section peaks at 715°F (380°C), also at 13 minutes of fire exposure.

The final step in the analysis is a structural evaluation of the ability of the steel column to support superposed load when subjected to these temperatures. In this case, temperatures are so low that complex nonlinear failure analysis is not needed. At 715°F (380°C), the A36 steel columns retain more than 90% of their room-temperature yield strength (Figure 1), so there can be no significant weakening of the frame from this fire scenario. In addition, the configuration of this frame and its connections will not offer much restraint to the thermal expansion in the columns, and thermal stresses would not be important. Therefore, these columns will continue to support full design loading demands at these steel temperatures.

The performance-based analysis for this typical transient trash fire shows that such fires are too small to significantly affect the load-bearing capacity of columns anywhere in the steel frame, even if they are uninsulated. Therefore, spray-on insulation is not necessary for this fire hazard.

THE FUTURE

Performance-based fire codes and associated analysis will eventually find universal acceptance, but not as quickly and easily as other types of performance-based codes have in the past. For example, earthquake codes and seismic structural analysis were quickly accepted since they arose unrestrained by previous practice. Buildings had essentially not been designed specifically for earthquakes, and engineers, architects, and building officials gratefully adopted the new methods as they found their way into engineering literature and the building codes. Performance-based fire analysis methods, however, find the field already occupied by a long-established prescriptive code based on a hundred years of furnace tests and engineering practice. The new methods must be highly developed, extensively verified, and carefully peer-reviewed before they can supplement or replace the traditional methods. The following types of efforts would aid in this process:

* Development of peer-review protocols for the transitional period when performance-based analysis is first being presented to building officials.

* More exposure of engineering students and practitioners to the basics of structural fire performance and analytical methods to predict it. Sponsorship of workshops and seminars for non-specialists.

* Some sort of codification of methods to calculate fire curves for the most common fire scenarios so design engineers do not have to engage a specialist for routine structural design. An effort in this area is currently being made by SFPE and ASCE.

* Incorporation into commercial structural computer codes the basic capabilities to conduct fire analysis, especially as nonlinear programs come into greater use. Ideally, fire should be treated as an additional design load case, just as other infrequent loading conditions such as wind or earthquake are. ▲

Robert H. Iding is with Wiss, Janney, Elstner Associates.

REFERENCES

1 Iding, R.H., Bresler, B., and Nizamuddin, Z., "FIRES-T3-A Computer Program for the Fire Response of Structures-Thermal (Three-Dimensional)," UCB-FRG Report 77-15, Fire Research Group, Department of Civil Engineering, University of California, Berkeley, October 1977.

2 Sterner, E., and Wickström, U., "TASEF - Temperature Analysis of Structures Exposed to Fire," SP Report 1990:05, Swedish National Testing and Research Institute, Borås, 1990.

3 ASCE/SFPE 29 "Standard Calculation Methods for Structural Fire Protection," 1999.

4 Iding, R.H., Bresler, B., and Nizamuddin, Z., "FIRES-RC II – Structural Analysis Program for the Fire Response of Reinforced Concrete Frames," UCB-FRG Report 77-8, Fire Research Group, Department of Civil Engineering, University of California, Berkeley, July 1977.

5 Iding, R.H., and Bresler, B., "FASBUS II User's Manual" prepared for the American Iron and Steel Institute, Wiss, Janney, Elstner Associates, Inc., April 30, 1987.

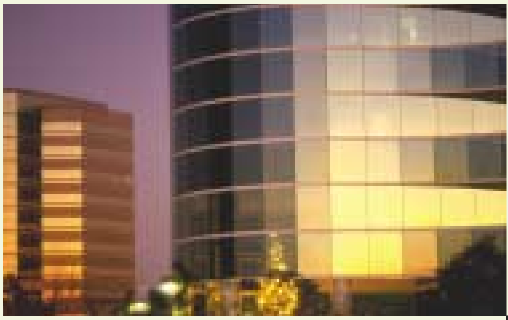
6 Iding, R.H., and Bresler, B., "Effect of Restraint Conditions on Fire Endurance of Steel-Framed Construction," *Proceedings of the 1990 National Steel Construction Conference*, AISC, Chicago IL, March 14, 1990.

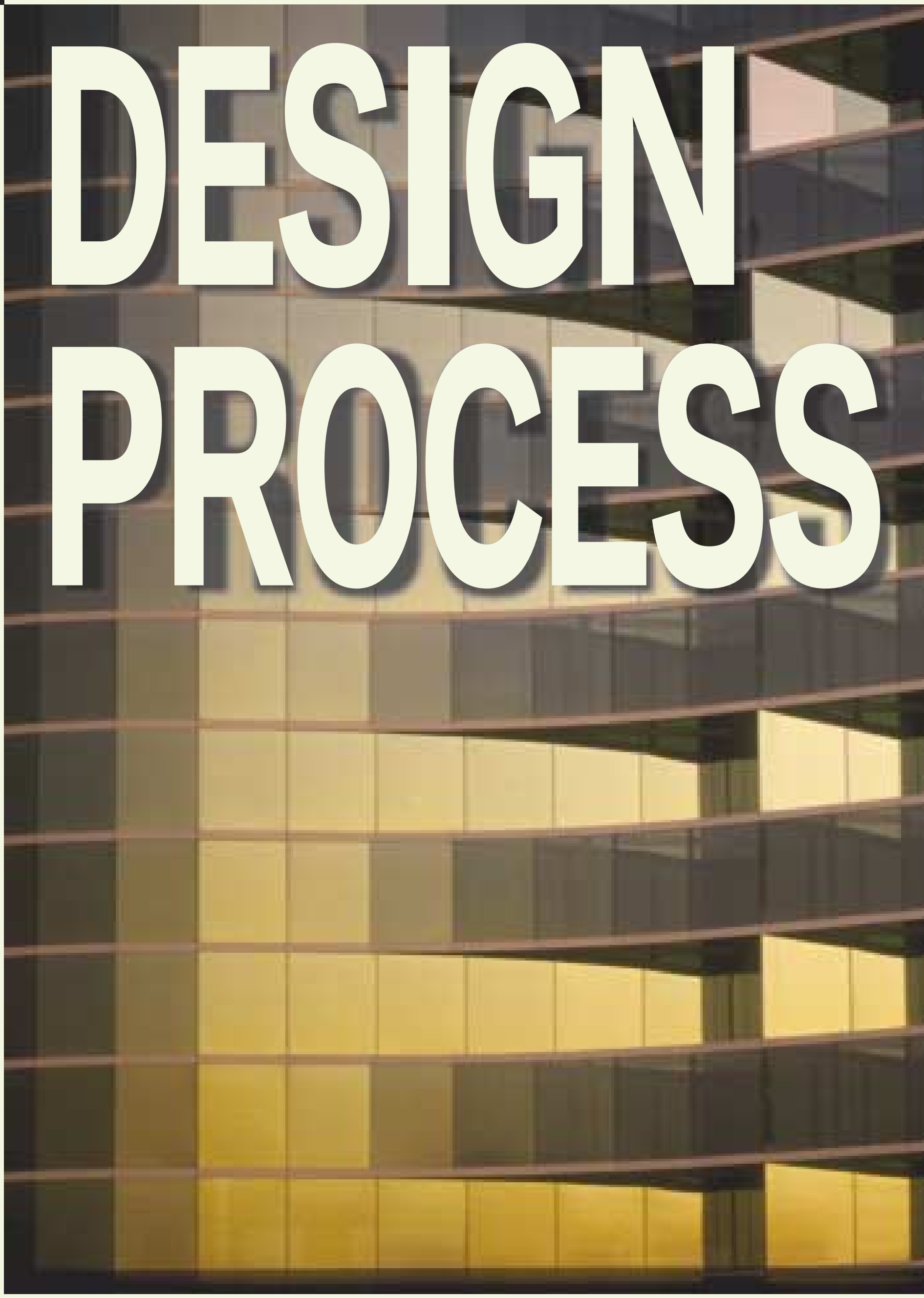
7 Nwosu, D.I., Kodur, V.K.R., Franssen, J.M., and Hum, J.K., "User Manual for SAFIR: A Computer Program for Analysis of Structures at Elevated Temperature Conditions," National Research Council Canada, int. Report 782, 1999.

8 Sanad, A.M., Rotter, J.M., Usmani, A.S., and O'Connor, M.A., "Finite Element Modeling of Fire Tests on the Cardington Composite Building," *Proceedings of Interflam* '99, Interscience Communications, London, 1999.

9 Lee, John A., et alia, "Fire Hazards Analysis and Fire Structural Analysis of the Healy Clean Coal Plant-Technical Report to Stone and Webster Engineering Corporation," SAIC Corporation, February 1996.

INTEGRATING STRUCTURAL FIRE PROTECTION INTO THE DESIGN PROCESS





By Harold A. Locke, P.Eng.

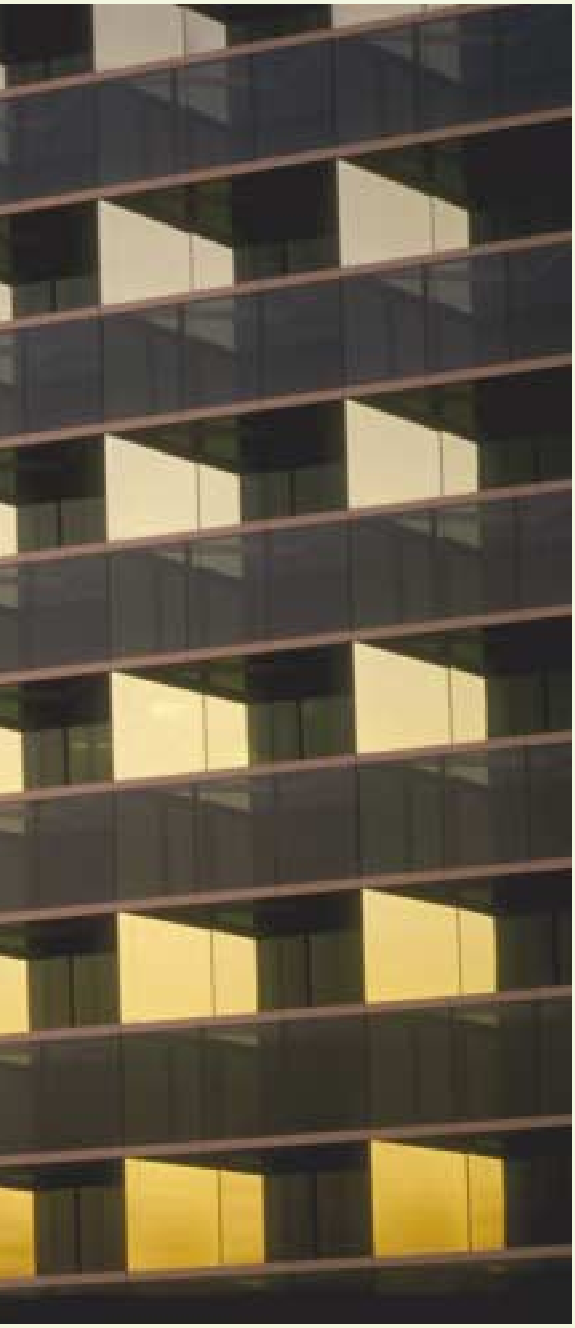
The building design process has become more complex with the introduction of new technologies and materials. This has impacted the architectural profession, but as well, many new tools have been made available to the engineering profession.

Fire protection engineering has made great strides in recent years, which has enabled building designers to provide greater fire safety in buildings. However, this presupposes that the design team avails itself of the most current technical information applicable to the building design.

BUILDING CODES

The starting process of any building design is guided by the requirements of the local building code. Any building design is influenced by a number of factors. In the first place, the architect has to capture the purpose's of the building together with the owner's needs, and interpret them architecturally. This usually occurs during the initial planning process or schematic design phase. It is also usual at this time for the preliminary design to be subject to review by a Planning Board. This review process may also ultimately have an impact on the form of the building in "fitting" into the built environment. Site conditions may also be a factor in dictating the need for a different approach for fire department access and evacuation of the building occupants.

Building codes contain requirements that typically are considered to represent a minimum level of performance necessary for the health and safety of the building occupants and emergency responders, and public welfare. The requirements generally are based on a combination of factors, including the hazard represented by the uses and occupancy types, the type of construction materials, fire department access, and the building exposure.



Modern building codes address public health, safety, and welfare under many hazard conditions, including structural stability under various load conditions, in addition to addressing fire hazards through regulating fire endurance, flammability of surface finishes, safety within floor areas, exiting, fire department access, special measures to address high-rise buildings, and building exposure. In the area of structural design, reliability-based performance design has been introduced, particularly for wind and earthquake design. The typical design team would be comprised of the architect and other key professionals representing structural, mechanical, electrical, and geotechnical expertise. Encouragingly, the fire protection engineer is being included more frequently as one of the key professionals on the design team, which is essential to ensure that protecting the building structure from fire exposure becomes an integral part of the design process.

STRUCTURAL STABILITY UNDER FIRE CONDITIONS

The design team has the responsibility to design the building to provide the degree of structural fire resistance required by the building code.

According to ASTM 176, *Standard Terminology of Fire Standards,*[1] fire resistance (endurance) is defined as "the property of a material or assemblage to withstand fires or give protection from it... As applied to elements of a building, it is characterized by the ability to confine a building fire or to continue to perform a given structural function." According to the National Building Code of Canada, fire-resistance ratings must be established by one of two methods, using either a prescriptive determination as outlined in Appendix D of the building code or by physical testing in a calibrated furnace. Appendix D provides a method for the user to develop fire-resistance ratings of generic materials without the need for a fire test.

Fire-resistance testing has been conducted in North America since the 1890s.[2] ASTM adopted a standard time-temperature curve in 1917 that to this date has remained essentially unchanged. The fire test method (e.g., CAN/ULC-S-101-M89[3] or ASTM E119) requires that the structural component or assembly of materials be exposed to a fire condition represented by the standard time-temperature curve for the period for which the fire-resistance rating is required. In the case of a structural member, the rating is based on meeting specific temperature criteria as well as the ability to carry the design load for the specified period.

The standard time-temperature curve, while providing a convenient method for comparing the performance of structural members under standard laboratory conditions, as well as demonstrating compliance with building code requirements, is not representative of "real" fire conditions.[4] It is simply a method of establishing a rank ordering of different assemblies exposed to the same fire conditions, the severity of which is represented by the fire-resistance rating at a point in time on the curve. Nevertheless, the results of such tests provide a source of information helpful to the practitioner in undertaking a fire hazard or risk assessment of a specific end use.

However, the standard fire test has been widely criticized as not being representative of real fires. Although the fire test method was developed to ensure the structural integrity and compartmentation within buildings under post-flashover conditions, this approach is inherently conservative insofar as limiting the flexibility of designs desired by architects and engineers.

Some of the concerns with the fire test method include the following:

- The cost and time required to conduct tests;
- Reproducibility between testing laboratories;
- The testing of single structural elements do not take account of the beneficial effects of adjacent struc-

tural components;

- The size of structural elements is limited by the size of the test furnace;
- The time-temperature curve represents only a fully developed fire;
- The benefits of sprinkler protection are not taken into account in the fire test; and
- The test does not evaluate the durability of fire-protective treatments under anticipated service conditions.

As a result, considerable efforts have been directed towards the development of more rational design approaches for the determination of fire endurance of building elements.[5]

PERFORMANCE-BASED STRUCTURAL FIRE PROTECTION

The involvement of the fire protection engineer early in the design of a project is crucial to the successful introduction of a more rational approach to developing the structural fire protection of a building. Opportunities for developing a fire engineering approach at an early stage may have a profound impact on the feasibility, costs, and architectural design of the building.

All too frequently, the architect will take a simplistic approach to fire safety in a building, assuming that the requirements of the local code will address all of the concerns related to the intended use of the building. This approach fails to recognize that the requirements of the local code are a minimum safety standard. In other cases, the owner may adopt an attitude towards fire as being something that will not happen to them and take comfort from fire insurance and public fire protection.

Thus, to begin with, there has to be a willingness on the part of the owner and the architect, as well as other members of the design team, to recognize that there may be other considerations related to the design or use of a building that warrant consideration beyond the minimum standards of the local building code. With design-build projects in particular, this may not be realized until after the commencement of construction and the ordering of long-term delivery materials, such as structural steel. This often leads to costly delays in the completion of the project as the matter is resolved, which at this stage will not only be a challenge to the fire protection engineer, but at best will likely be a compromise in order make use of the existing design approach as much as possible. Such a compromise may still not be as cost-effective a solution as could have been found had the initial design taken into account the problem encountered or had it been identified during the initial design phase.

The prescriptive approach to developing fire-resistance ratings does not take account of the various factors that influence fire growth. Such factors include the fire load, distribution of the fire load, ceiling heights, ventilation, geometry of the room or space, the inherent fire resistance of the structure, and whether or not the space is protected by an automatic sprinkler system. As a result, the prescriptive approaches for structural fire protection required by codes in North America are the same, for example, regardless of the room size. In reality, fire severity will vary from compartment to compartment and will depend on the factors above. Thus it can be readily seen that simply meeting the code requirement often results in overdesigning the protection of the structural elements of the building and limits design flexibility.

While there are well-established analytical methods for developing fire-resistance ratings of traditional building materials, such as those included in Appendix D to the National Building Code of Canada and the *Guidelines for Determining Fire Resistance Ratings of Building Elements*,[6] the North American regulatory system does not generally recognize the use of a performance-based approach for this purpose, even though the concept of performance-based design has existed for many years.[7] However, relatively new codes such as the *International Performance Code*[8] and NFPA 5000,[9] Chapter 5, hold some promise in this area.

Nevertheless, fire protection engineers are more frequently using a performance-based design approach in order to achieve the design objectives of a building, where it is recognized that it is impractical to comply literally with the prescriptive requirements of the local building code.[10] However, such an approach requires the agreement and participation of the Authority Having Jurisdiction in order to be successful. The starting point in the process is to first identify the applicable prescriptive code requirements. Acknowledging that performance-based design solutions will be necessary, the next step in the process will be to define and agree upon acceptable performance criteria. Obviously, this requires a collaborative effort of all stakeholders to be successful; in some situations it may also be appropriate to appoint peer reviewers as part of the team so that input and feedback can be provided as the performance solutions are developed.

The performance-based design approach will likely consider the desired time for which structural stability is required, consider the likely fire load associated with the use of the building, select a suitable model to model the fire and structural loads, model the thermal response of the structural members, and assess the results against the acceptable performance criteria.

Integrating structural fire protection into the design process at an early stage using a performance-based solution allows for greater flexibility in achieving an optimal design solution. A recent case study[11] demonstrated that such an approach could also provide significant cost savings, both in capital and life-cycle costs, while yielding a more rational basis for the design of the fire and life safety systems.

The traditional approach of specifying fire endurance as an attribute to be specified and achieved independently of structural design can be inefficient. The concept of integrating structural fire endurance into structural limit states design with defined strength and serviceability limits in fire conditions allows for more efficient and reliable building designs, with the potential for more accurate optimization of life-cycle costing. ▲

Harold A. Locke, P.Eng. is with Locke MacKinnon Domingo Gibson & Associates Ltd.

REFERENCES

1 ASTM E-176,Standard Terminology of Fire Standards, American Society for Testing and Materials, West Conshohocken, PA, 2002

2 *The Behaviour of a Multi-storey Steel Framed Building Subjected to Fire Attack-Experimental Data*, British Steel, Swindon Technology, 1998.

3 CAN/ULC-S101, Standard Methods of Fire Endurance Tests of Building Construction and Materials, Underwriters Laboratories of Canada, 1989.

4 Ingberg, S.H., "Tests of the severity of building fires", *NFPA Quarterly*, Vol. 22, No. 1, 1928.

5 Gilvrey, K.R., and Dexter, R. J., "Evaluation of Alternative Methods for Fire Rating Structural Elements", NIST-GCR -97-718.

6 *Guidelines for Determining Fire Resistance Ratings of Building Elements*, Building Officials and Code Administrators, International, Country Club Hills, IL, 2001.

7 Meacham, B. J., *The Evolution of Performance- Based Codes and Fire Safety Design Methods*, Society of Fire Protection Engineers, Bethesda, MD, 1996.

8 *International Performance Code for Buildings and Facilities*, International Code Council, Falls Church, VA: 2003.

9 NFPA 5000, *Building Construction and Safety Code*, National Fire Protection Association, Quincy, MA, 2003.

10 Gibson, G. A. and Locke, H. A., "A Performance-Based Approach to Exiting of the Proposed Vancouver Convention and Exhibition Centre Utilizing Fire Modelling," *Proceedings of the International Conference on Engineered Fire Protection Design*, Society of Fire Protection Engineers, Bethesda, MD, June 2001.

11 Locke, H. A., et al., "Hotel Fire Safety Case Study – A Canadian Approach," *Proceedings of the 4th International Conference on Performance-Based Codes and Fire Safety Design Methods*, Society of Fire Protection Engineers, Bethesda, MD, March 2002.

Resources

Designing Structures for Fire Conference

September 30-October 1, 2003
Radisson Plaza Lord Baltimore Hotel in Baltimore, MD

Intended for:

Provision of appropriate fire resistance to structural members is one of the major safety requirements in building design. However, evaluating fire resistance of a structure is very complex and requires significant effort. While there has been advancements in developing new approaches for evaluating fire resistance, much of this knowledge has been applied by true “fire specialists.” In the aftermath of the September 11 terrorist incidents, resulting in significant damage and destruction to buildings and infrastructure in the WTC vicinity and Pentagon, building performance under fire conditions has received significant attention of the research and engineering community. This conference is aimed at sharing the recent advancements in fire resistance design with researchers, engineers and practitioners. The conference is of particular interest to scientists, fire protection/structural/material engineers, architects and regulators.

Description:

Seminar Themes:

- Current methodology of fire resistance evaluation – merits and drawbacks
- Fire resistance evaluation through testing
- Fire resistance evaluation through numerical modeling
- Fire resistance evaluation through simplified (calculation) methods
- Material performance and properties under fire
- Performance based fire safety engineering
- WTC and Pentagon disaster – fire resistance issues
- Fire resistance case studies of actual buildings
- Integrating fire and aesthetics
- Strategies for complying with fire resistance requirements in codes and standards

For more information visit: *www.sfpe.org*

UPCOMING EVENTS

May 8-10, 2003
Strategies for Performance in the Aftermath of the World Trade Center
Kuala Lampur, Malasia
Info: www.cibklutm.com

May 13-16, 2003
Fire Guangdong 2003
China Foreign Trade Center, Guangzhou China
Info: www.unionft.com

May 18-22, 2003
NFPA World Safety Conference and Exposition
Dallas, TX
Info: www.nfpa.org

June 8-13, 2003
Third Mediterranean Combustion Symposium
Marrakech, Morocco
Info: www.combustioninstitute.it

June 22-25, 2003
13th World Conference on Disaster Management
Toronto, Canada
Info: www.wcdm.org

June 24-27, 2003
Scientific Program of ITEE 2003
The Technical University of Gdansk, Poland
Info: www.icsc-naiso.org/conferences/itee2003

August 20-22, 2003
2nd International Conference in Pedestrian and Evacuation Dynamics (PED)
Greenwich, London
Info: http://fseg.gre.ac.uk/ped2003/

September 8-12, 2003
4th International Seminar on Fire and Explosion Hazards
Northern Ireland, UK
Info: www.engj.ulst.ac.uk/4thisfeh/

September 22-25, 2003
6th Asia-Oceania Symposium on Fire Science and Technology
Info: yhpark@office.hoseo.ac.kr

March 2004
International Fire Safety Engineering Conference
Sydney, Australia
Info: www.sfs.au.com

March 2-4, 2004
Use of Elevators in Fires and Other Emergencies
Atlanta, Georgia
Info: www.asme.org/cns/elevators/cfp.shtml

March 17-19, 2004
Fire & Safety At Sea
Melbourne, Australia
Info: conference@rocarm.com

May 2-7, 2004
CIB World Building Congress 2004
Toronto, Ontario, Canada
www.cibworld.nl

SFPE

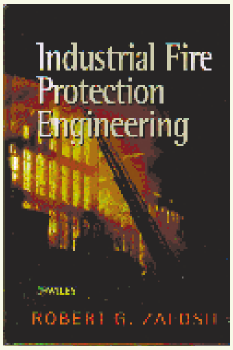
Resources

An Historic Event – SFPE's Annual Meeting Moves to Fall 2003

Mark your calendars for an historic event – the SFPE Annual Meeting and Awards Banquet, September 29 through October 3 at the Radisson Lord Baltimore Hotel, in Baltimore, MD. For the first time, SFPE will combine its Annual Meeting with a series of education programs for the practicing fire protection engineer and will not be meeting in conjunction with the NFPA World Fire Safety Congress. Following in the path of the successful year 2000, 2001 and 2002 Professional Development Week activities in Baltimore, the new Annual Meeting format will include a complimentary one day professional program with the latest updates on the science and practice of fire protection engineering, and the professional issues of concern to the practicing FPE, as well as the familiar ice cream social. This will be followed by the traditional Awards and Honors Banquet, and by four days of education events, including 6 seminars, and an international conference on Design of Structures for Fire.

Visit www.sfpe.org for more information.

Industrial Fire Protection Engineering
Robert G. Zalosh



NEW! This text covers general considerations that relate to the application of all fire protection engineering. The text also examines specific problem areas such as warehousing, storage of flammable liquids and safety of electrical equipment and computers. The text includes a variety of up-to-date and international case studies. References are made to both European and domestic codes and standards. Some of the latest research in the field such as protection of cabling from fire is explored.

Visit www.sfpe.org to order.

SFPE Invites your Participation in the Corporate 100 Program

Join the leading corporations in the fire protection industry who support SFPE's mission to advance the science and practice of fire protection engineering. The benefits of membership:

Recognition

...through prominent placement on the SFPE website, magazine, annual meeting and exhibit booth

Information and referrals

…free library copies of SFPE Publications
…annual access to the SFPE chapter president contact information
…listing on the referral and recruitment portions of the SFPE Web site
…referrals from phone inquiries to SFPE

Leadership

...through periodic leadership Summits on issues of concern to the industry

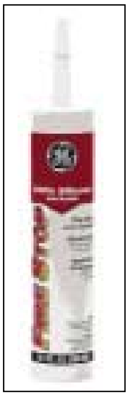
For more information on Corporate 100 membership. Please contact Kathleen Almand at kalmand@sfpe.org

Kathleen H. Almand, P.E.
Executive Director
Society of Fire Protection Engineers
7315 Wisconsin Ave., #1225W
Bethesda, MD 20814

301-718-2910
Fax: 301-718-2242
www.sfpe.org

Products/Literature

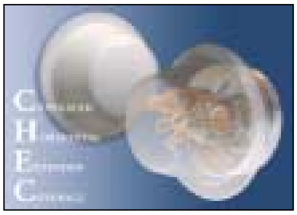
Sealants



New GE Fire Stop™ products include an intumescent water-based sealant (rated for use in 21 UL firestop systems) and a 100% silicone joint sealant (rated for use in 4 UL firestop systems). Designed primarily for multiunit dwellings with firewalls, the products meet stringent ASTM test standards and building code requirements.

www.gesealants.com
—GE Sealants & Adhesives

Unobtrusive Sidewall Sprinklers

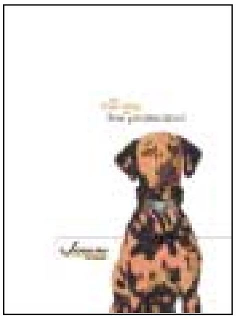


Tyco's new concealed, horizontal, extended coverage (CHEC) sidewall sprinkler is designed to incorporate an unobtrusive, aesthetically pleasing, "push-on, thread-off" cover combined with a horizontal sidewall that is capable of providing a quick-response, extended coverage rating from 16 ft. x 14 ft., to a maximum 16 ft. x 22 ft. area per single sprinkler. Listed for the protection of light hazard occupancies.

www.tyco-fire.com
—Tyco Fire & Building Products

New FP Piping Systems Catalog

Victaulic presents a new catalog for fire protection piping systems. It highlights the company's grooved-end piping system, including IPS carbon steel couplings, fittings, valves, and accessories; FireLock® Automatic Sprinklers and accessories; FireLock Automatic Devices including the Series 745 Fire Pac; IPS carbon steel Pressfit® systems; CPVC FireLock piping products; and more.



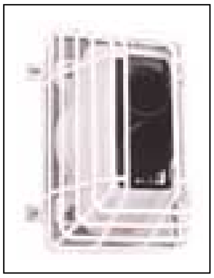
www.victaulic.com
—Victaulic

Flexhead Commercial Ceiling Sprinklers

Flexhead systems, which have been used to protect semiconductor manufacturing facilities including cleanrooms for many years, are now available for commercial markets. Every system begins with stainless steel hose rated up to 300 psi. Hoses are available in 2-ft. to 6-ft. lengths and can be fitted with any standard sprinkler head. Features include easy installation and flexibility.

www.flexhead.com
—Flexhead Industries

Smoke Beam Guards



Available in three sizes, these guards are designed to protect costly sensor units of beam-type smoke detectors from damage leading to misalignment and false alarms in large-area applications such as warehouses and auditoriums. Features include tough construction, resistant coating, easy installation, and lifetime guarantee against breakage in normal use.

www.sti-usa.com
—Safety Technology International, Inc.

Fully Integrated Security Monitoring

The ADPRO® FastTrace™ is a digital recorder with rapid remote access and video alarm verification and control. It is a fully integrated solution for remote storage and protection – an evidential quality digital storage and remote video transmission system. Features include extended duration recording, simultaneous user access, and superior image quality.

www.visionusa.com
—Vision Fire & Security

Gas/Fire Monitoring System

The Vortex multichannel gas and fire monitoring system is available in four configurations. The standard version is a wall-mounted unit in its own enclosure; modular versions may be specified for a variety of specialist enclosures or larger cabinet-based safety systems. All provide up to 12 gas-detection channels (including up to three for fire) and 24 user-configurable relay outputs to drive external alarms and safety equipment.

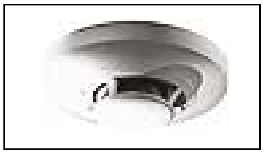
www.crowcon.com
—Crowcon Detection Instruments

Underground Water Tank

Xerxes Corporation provides custom manufactured underground water tanks that are designed to each customer's specific requirements. These tanks are ideal for long-term, watertight storage. Carver County, Minnesota, Public Works new facility: 35,000 gallon underground fiberglass tank to store water for fire protection. Site was too far from city-supplied water, therefore the county's engineer specified this strong, fiberglass tank. Best tank choice for rust-proof, long term storage.

www.xerxescorp.com
—Xerxes Corporation

Photoelectric Smoke Detectors



System Sensor announces six new i3™ Series photoelectric smoke detectors. Available with an 85 dB sounder, a Form C relay, or an isolated thermal sensor, these detectors are ideal for residential, auxiliary control, or other specialty applications. Designed based on i3 principles: installation ease, intelligent features, and instant inspection.

www.systemsensor.com
—System Sensor

Protective Covers Receive UL Listings

UL Hazardous listing has been granted for both STI NEMA 4X-rated protective covers for strobe fire alarm signal units: the STI-1229 Stopper® Dome and the STI-1229HTR Environmental Enclosure for Strobes model with an integral heating system. Both models just add "-HAZ" to the part number to indicate the hazardous model.

www.stopper.com
—Safety Technology International, Inc.

Linear Heat Sensors

The new LHS™ Linear Heat Sensor is a flexible fire detector cable designed to protect a wide range of commercial and industrial fire applications. Typical applications include areas where spot-type heat detectors are not effective such as belt conveyors, tunnels, aircraft hangars, and classified hazardous areas. Available in five alarm temperatures: 155°F, 185°F, 220°F, 350°F, and 465°F.

www.kiddefiresystems.com
—Kidde Fire Systems

Fire Protection Fluid Gets SNAP Approval

3M Performance Materials announces that 3M™ Novec™ 1230 Fire Protection Fluid, a C6-fluoroketone halon alternative, has received Significant New Alternatives Policy (SNAP) approval from the U.S. Environmental Protection Agency. The SNAP approval lists the agent as an acceptable halon 1301 replacement in flooding applications and as an acceptable halon 1211 replacement for nonresidential streaming applications.

www.3M.com/novec1230fluid
—3M

Intelligent Addressable Control Panel

The MS-9200UD intelligent addressable control panel, built upon a platform common to the MS-9200 and MS-9600, features advanced autoprogramming capabilities to help reduce installation time and overall cost. It includes an integral remote upload/download communicator, which allows for reporting of all system activity to a remote monitoring location. Installers may command it to program itself in less than one minute.

www.firelite.com
—Fire-Lite Alarms, Inc.

UV Pigment for Paints and Coatings

New Optically Active Coating System (OACS) uses an ultraviolet light-sensitive pigment, easily added to a wide range of paints and coatings. It allows thorough, timesaving, in-process applications and inspections of coatings, substrate coverage, and structural analysis on metal and nonmetal materials with visual documentation not previously available to the human eye.

www.ncpcoatings.com
—NCP Coatings, Inc.

Self-Contained Fire Suppression

Self-contained Firetrace® automatic fire suppression systems incorporate a flexible polymer tubing that may be installed and routed anywhere within an enclosure where the threat of fire exists to instantly detect and extinguish fires inside equipment, enclosed spaces, or cabinets up to 250 cu.ft. Systems may be customized to dispense specific suppression agents.

www.firetrace.com
—Firetrace International

Network Solutions

NOTIFIER's new eight-page, *Network Solutions* brochure highlights the company's NOTI-FIRE-NET™ fire system network and UniNet™ 2000 facility monitoring network. It illustrates how NOTI-FIRE-NET, a peer-to-peer fire alarm network, allows each fire alarm control panel to maintain its own area of protection, while monitoring and interacting with other nodes. It also outlines how the UniNet 2000 network seamlessly integrates diverse fire and security systems into a single graphics-oriented platform.

www.notifier.com
—NOTIFIER

BRAINTEASER

A train traveling 80 km/h leaves Chicago heading for New York at 8:00 AM. Another train, also headed for New York, leaves Chicago on a parallel track one hour later. If the second train is traveling at 100 km/h, at what time will it pass the first train?

Solution to last issue's brainteaser

Water discharges through an Underwriters Playpipe with a 29 mm diameter nozzle. The playpipe is oriented at a 45° angle to the horizontal. A pitot gauge measures the velocity pressure at the nozzle discharge as 200 kPa. If the playpipe is located on a level surface, how far from the nozzle will the stream land?

The discharge through the playpipe can be calculated by the following formula:[1]

$$Q = 0.0666cd^2\sqrt{p}$$

Where c is the discharge coefficient, d is the inside diameter of the orifice in mm, and p is the velocity pressure in kPa. Using a discharge coefficient of 0.97 for an Underwriters Playpipe,[1] The flow is 768 liters per minute or 0.768 m^3/min.

Since $Q=AV$, this results in a discharge velocity of 1160 m/min or 19.4 m/s. Given that the discharge is oriented at a 45° angle to the horizontal, the vertical component of velocity is 19.4 m/s x sin(45°) = 13.7 m/s. Similarly, the horizontal component of velocity is 19.4 m/s x cos(45°) = 13.7 m/s.

The time that the stream is in the air can be calculated with the following formula:

$$D = V_1 t + \tfrac{1}{2}At^2$$

Where D is the distance traveled, V_1 is the initial velocity, A is the acceleration, and t is the time. Substituting $D = 0$, $A = -9.8$ m/s^2, and solving for t, we obtain values of zero and 2.8 seconds (the calculated time = zero corresponds to the instant the stream leaves the nozzle.)

During the 2.8 seconds that the stream is in the air, the stream travels a horizontal distance of 13.7 m/s x 2.8 s = 38 meters.

1 Linder, K., "Hydraulics for Fire Protection." *Fire Protection Handbook*, 19th Ed. National Fire Protection Association, Quincy, MA, 2003.

Index of Advertisers

Tragedy in Rhode Island

Morgan J. Hurley, P.E.
Technical Director
Society of Fire Protection Engineers

On February 20, 2003, a fire in a Rhode Island nightclub killed almost 100 people, and injured almost twice that many, ranking the fire as one of the deadliest nightclub or social establishment fires in U.S. history. The fire was reportedly caused by pyrotechnic devices inside the nightclub, which ignited expanded thermoplastic sound insulation. The nightclub, which was originally constructed in 1950 as a restaurant, was not required to install sprinklers since it was built before 1974. While a tragedy of monumental proportions, this fire demonstrates some of the challenges that prescriptive codes pose to code writers and regulators, and shows some potential benefits of performance-based codes.

Prescriptive codes typically contain thresholds before certain requirements take effect. For example, according to the National Fire Protection Association's *Life Safety Code*,[1] a door is typically not required to swing in the direction of egress travel if the area served has an occupant load of less than 50. The performance intended by this requirement is to protect against a hazard where opening a closed door could impede egress or could be hindered by egress. Presumably, the writers of this requirement felt that limiting the occupant load served to less than 50 would meet the intended performance while providing a sufficient safety margin and providing for flexibility in areas where it would not be practical to require that a door swing in the direction of egress travel.

Prescriptive codes have the benefit of being easy to apply and enforce. In the previous door example, it would be much more difficult to apply a requirement that stated that "doors shall swing in the direction of egress where necessary to prevent the door from impeding egress travel." While a performance-based requirement such as this and the prescriptive requirement contained in the *Life Safety Code* have the same objective, the prescriptive requirement could either unnecessarily limit flexibility or provide for situations that are unsafe for occupant loads close to 50.

Similarly, the sprinkler provisions in Rhode Island are intended to provide for safe buildings, while not imposing an undue burden on existing buildings. However, prescriptive requirements such as this or the door-swing requirement in the *Life Safety Code* place code writers and legislators in the difficult position of making decisions that have broad impact without a firm basis in engineering or science. Unfortunately, the result is that a door arrangement in a room that serves 49 occupants may be less safe than a door that serves 50 occupants. Similarly, a nightclub built in 1973 in Rhode Island may be less safe than a nightclub built right next door one year later.

Prescriptive requirements are written based on broad classifications of occupancy or building use. They are written such that, for any combination of acceptable features, the resulting building or structure will present an acceptable level of safety. Performance-based requirements, on the other hand, require that the design engineer develop an acceptable solution based on engineering and science.

A goal of the *Life Safety Code* is the protection of occupants who are not intimate with initial fire development. The *Life Safety Code* further elaborates upon this goal through objectives and performance requirements. Thus, any combination of fire protection features and systems that can be shown to meet the goals, objectives, and performance criteria of the *Life Safety Code* would be acceptable. Performance-based codes, such as the performance option in the *Life Safety Code*, allow for the design of buildings which present an acceptable level of safety, allow for the provision of an integrated package of fire protection systems and features based on the hazards that exist within a building or structure, while leaving code writers and legislators free to simply state what constitutes an acceptable level of safety.

There is some degree of hazard or risk present in any activity, and accordingly, accidents will still occur in buildings designed on a performance basis. However, performance-based codes will allow for an increased application of science in the design of buildings and structures, while allowing those responsible for regulating safety to explicitly state what level of safety would be "acceptable."

1 NFPA 101, Life Safety Code. National Fire Protection Association, Quincy, MA, 2000.