Structural Concrete in Fire Exposures

By Stephen Szoke, P.E.

Initiated by the September 11, 2001 attacks, the U.S. building industry has an elevated interest in the performance of high-rise and high-occupancy buildings in fire scenarios. Questions have arisen as to the adequacy of current building structural design procedures, the option to design for "real world" fires as opposed to using prescriptive requirements based on standard fire test of building elements, and the ability of buildings to resist total burnout without collapse.

Codes and Standards

The intent of the International Code Council's *International Building Code* (IBC) is described as "…to establish the minimum requirements to safeguard the public health, safety and general welfare through structural strength, means of egress facilities, stability… and safety to life and property from fire and other hazards attributed to the built environment and to provide safety to fire fighters and emergency responders during emergency operations." A similar purpose is provided in the National Fire Protection Association *Building Construction and Safety Code.* Currently, the maximum fire-resistance rating prescribed by the model building codes for structural members is three hours. This is applicable to both structural frames and bearing walls. For some construction, the IBC allows for a 1-hour reduction in the fire-resistance rating of structural frame members and interior bearing walls that only support the roof.

Design standards, referenced in building codes, have been developed and are maintained by Committee 216, jointly sponsored by the American Concrete Institute (ACI) and the Masonry Society (TMS). The *Standard Method for Determining Fire Resistance of Concrete and Masonry Construction Assemblies* contains provisions for determining the fire resistance of structural concrete members: columns, beams, floors, roofs, and walls.

As concrete technology changes, new provisions continue to be developed based on ASTM E 119 tests. For example, the latest revision of ACI/TMS 216 includes provisions for minimum column dimensions and tie configurations for concrete having a specified compressive strength in excess of 12,000 psi (83 MPa). The basis for these new provisions is fire research conducted at the National Research Center in Canada.

> An "endpoint criteria" is that condition which, when reached during a fire test, is considered to be the time at which the tested element no longer is capable of serving its intended function as a fire resistive element.

Test Methods and Prediction Models

The endpoint criteria of a fire test is provided by ASTM's *Standard Method for Fire Tests of Building Construction and Materials* (E 119). One endpoint criteria for all structural members is the ability to support the maximum load condition for the duration of the fire exposure. For bearing walls, the load must also be sustained during the hose stream test. For barrier elements, such as walls, slabs, and roof assemblies, the endpoint criteria also includes maximum temperature rise on the unexposed surface of 250 degrees (F) (139 degrees C) and the penetration by flame or gases hot enough to ignite cotton waste.

The ASTM E 119 standard prescribes a standard time-temperature test curve. The curve was not intended to be representative of a real fire scenario, but instead it is an envelope representative of the maximum fire that may occur in buildings. Several time-temperature curves from actual fires are shown plotted with the ASTM E 119 time-temperature curve in *Figure 1*. The data for the actual fires shown are from "actual fire" tests conducted by the National Bureau of Standards (NBS), now the National Institute of Standards and Technology (NIST). Although in some instances the temperature rise is more rapid or rises above the ASTM E 119 curve, the standard curve serves as an appropriate envelope for various fire load scenarios. Magnusson and Thelandersson also demonstrated the appropriateness of the ASTM E 119 curve as a maximum fire exposure. Curves similar to that of ASTM E 119 are used in National Fire Protection Association, Underwriters' Laboratories, and International Organization for Standardization (ISO) standards.

Three of the six fire scenarios shown in *Figure 1* have combustible loads of 14 psf, and were intended to be representative of fires in office buildings. Different distribution of loads resulted in dramatic variations of the time-temperature curves. Other variables, such as changes in ventilation, influence the severity of any specific fire. These variations strongly support the continued use of a curve that defines the maximum fire severity

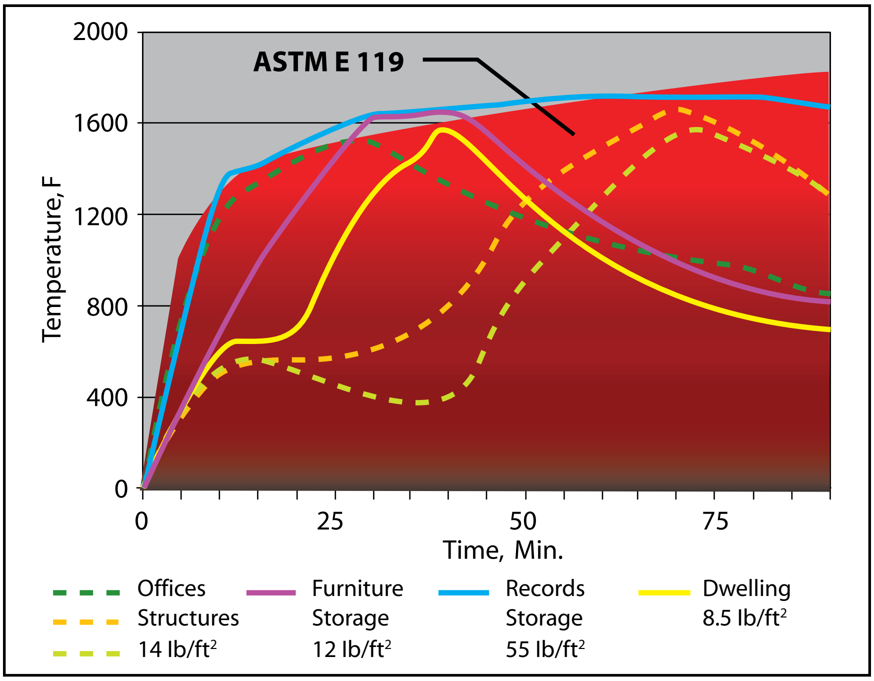

Figure 1: Time Temperature Curves.

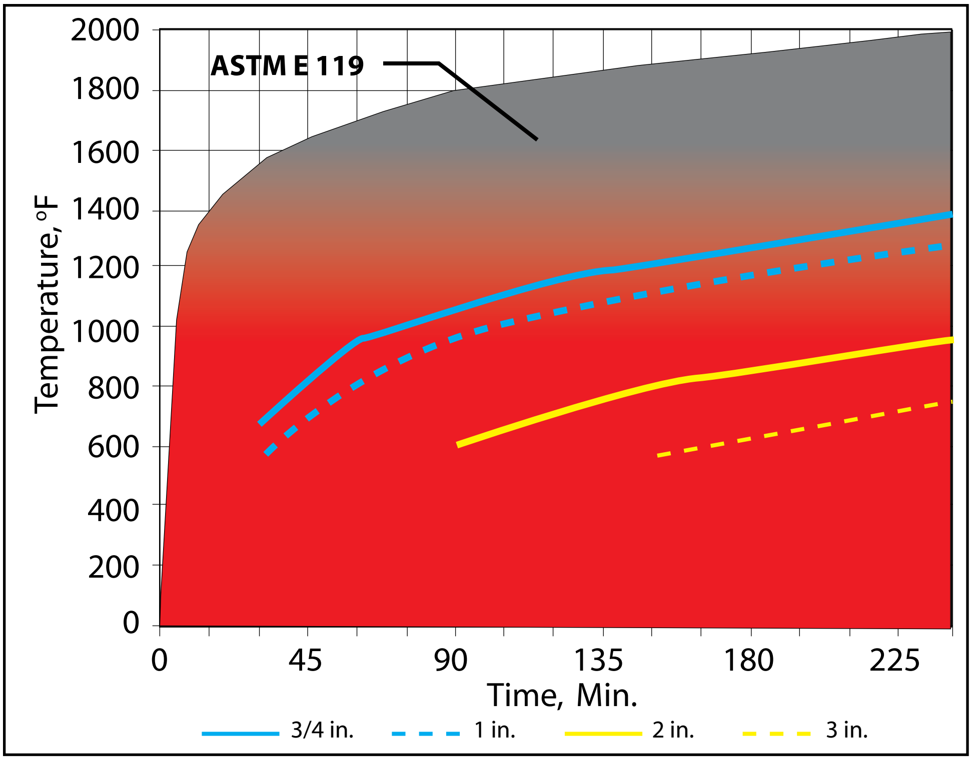

Figure 2: Temperature Gradient for Slabs Made of Carbonate Aggregate Concrete.

due to changes that may occur during the life of a building. Different occupants, even within the same occupancy group, may have different needs for ventilation and different quantities and arrangements of combustible materials. Also, in severe fires, the fire load tends not to be that of the average fire load but of a much higher fire load. While the average fire load for records storage has been approximated to be about 55 psf, the load at the Military Personnel Records Center, discussed later, was approximately 200 psf. Caro and Milke identified the average fuel load for a modern office to be approximately 14 psf. However, the maximum load identified in their study was nearly 22 psf. Since loads may often exceed the average, it may be important to consider the anticipated maximum fire load over the life of the structure.

Rational Structural Engineering Approach

The ASTM E 119 curve is seen by some as an actual fire with a safety factor that is not quantified. While having a safety factor in the standard test is arguably not ideal, there is little documentation for a quantifiable safety factor when designing for actual fires that might occur in a specific occupancy group. For the more exacting dead and live gravity loads, ASCE 7 provides load factors for use in various load combinations. In addition, strength reduction factors are prescribed for structural elements in ACI 318. For relatively precise gravity loads and time-proven design methods, the safety factor even for the simplest of load combinations is often approximately 1.5 and may in some instances exceed 2.0. Currently, load factors and strength reduction factors are not prescribed in building codes for the rational design to resist fire loads, nor are there provisions for safety factors for "real world" fires. In addition to maximum fire loads, appropriate safety factors for various fire scenarios need to be developed.

A better understanding of the fire performance of individual building members and whole structural systems in various fire scenarios may also be needed. The temperature gradient within concrete elements for specific design fire scenarios is difficult to develop and incorporate into the structural design process. While there is data indicating the temperature within concrete elements from research, most data only exists for full-scale elements tested using the ASTM E 119 curve. The temperature gradient may vary for other fire exposures. Abrams and Gustaferro show the rapid drop in temperature inside concrete slabs tested in accordance with ASTM E 119 (*Figure 2*). Another consideration is that when some elements are weakened by fire, alternative load paths will be developed. Appropriate design tools should account for the ability of loads to be transferred to other elements within a building.

Performance in Actual Fires

Large building fires in mid- and high-rise buildings in the United States strongly suggest that the current design practice for the structural performance of concrete buildings is adequate. Jim Arnold reported on building fires between 1836 and 2004 – excluding the disasters on September 11, 2001 – that resulted in building code changes. Of the 62 fires, 23 were in the United States, and of those, only five were in buildings over five stories in height. While many fires cited had tragic loss of life and injuries, there were no reports of major structural collapse of mid- and high-rise concrete buildings in the United States since the adoption of modern building codes. Only one of the all the U.S. fires reported involved collapse of any structural concrete members.

Events Involving Collapse

There have been two fire events in the United States that led to the collapse of multiple structural concrete elements. One was at the Military Personnel Records Center in Overland, Missouri in 1973. The other was at the Pentagon on September 11, 2001.

The 6-story concrete frame Military Personnel Records Center was designed and constructed for storage of records in metal file cabinets. The storage of the building was changed to paper files in cardboard boxes on metal shelves in 1960, and although sprinklers were considered for the new storage type, they were not installed. The fire started on the top floor of the building and burned for over 20 hours before it was under control. All of the significant structural damage was reported to be on the sixth floor and the roof. Culver and Crist reported that damage to the structural system below that level was relatively minor. Aerial photography showed that even after 10 to 12 hours of burning there was no structural collapse of the roof. Sometime after that, approximately 30 per-cent of the roof collapsed onto the 6th floor. The roof collapse was concentrated in the area of origin of the fire. "Visual examination

Occupancy	Automatic Extinguishing Systems 1985	Automatic Extinguishing Systems 1998	Fire Detection Systems 1985	Fire Detection Systems 1998	Fire Resistive Construction 1985	Fire Resistive Construction 1998
Apartments	12%	36%	61%	84%	61%	47%
Hotel and motel	51%	77%	74%	87%	57%	54%
Office	46%	63%	60%	76%	60%	46%
Facilities that care for the sick	61%	80%	82%	92%	73%	49%

Table 1: Percent of Buildings Using Fire Protection Strategies

of the underside of the sixth floor showed minor cracking of the slab, in a crack pattern that was consistent with uniform loading on the floor system." Slab integrity was noted by water leakage being limited to areas around floor slab penetrations for pipes and ducts. Residual displacement at the roof edge was nearly two feet at one location. Fire design for the new fire load, compartmentation, and the use of fire sprinklers may have resulted in improved building performance. The 4-hour fire resistance-rated concrete construction endured for more than 12 hours without collapse. The fire load, which far exceeded the fire-resistance rating, clearly indicates the ability of concrete to satisfy the intent of the building code. Abrams reported that the 200 psf fire load would be equivalent to a minimum 20-hour standard fire. The rest of the structure retained its integrity, so the 6th floor was removed and the structure became a 5-story building.

At the Pentagon, most of the collapse occurred as a result of damage to the reinforced concrete elements due to the direct impact of the aircraft. In *The Pentagon Building Performance Report*, the investigation team determined that: "…the direct impact of the aircraft destroyed the load capacity of about 30 first-floor columns and significantly impaired that of about 20 others along a diagonal path…" This impact may also have destroyed the load capacity of about six second-floor columns adjacent to the exterior wall. While the impact scoured the cover of around 30 other columns, their spiral reinforcement conspicuously preserved some of their load capacity."

"The subsequent fire fed by aircraft fuel, the aircraft contents, and building contents caused damage throughout a very large area of the first story, a significant area of the second, a small part of the third, and only the stairwells above. This fire caused serious spalling of the reinforced-concrete frame only in a few, small isolated areas on the first and second stories." The findings in the report advise that, "Despite the extensive damage on the first floor, the collapse of the floors above was extremely limited."

Trends in High Rise Construction

Combining the inherent fire resistance of concrete construction with smoke detection and automatic fire suppression systems can provide excellent performance of buildings. There is a trend, however, toward an increased reliance on water supply alone for fire suppression and control. Newer buildings without sufficiently robust fire resistive construction may be more prone to collapse than many older buildings when subjected to fires after major natural disasters that affect water supply, such as earthquakes. Hall indicates changes in fire protection and detection systems by occupancy from 1985 to 1998. The percentage of buildings using each of the various fire protection techniques is summarized in *Table 1*.

Future Needs

Efforts to substantiate and incorporate code changes for new concrete mix designs and applications using ASTM E 119 continue. The cost of a fire test is high, however, and the increasing frequency at which concrete technology changes has created a real need for more sophisticated design, analysis, and prediction tools for the performance of concrete in fire scenarios. To meet this goal, several variables will need to be defined. For occupancy-based fire modeling, "design" fires need to be developed with accompanying safety factors. Of course, any new method must be validated with expensive large-scale fire tests. To reduce the financial impact of such validation, defining relationships between large- and small-scale tests might be a prudent first step.

Summary

Concrete and masonry structural members and fire protection continue to demonstrate excellent performance in fires. When the actual fire load is consistent with the fire resistance rating, structural integrity is maintained. With on-going research, the development of new products and construction processes, fire testing of new products, and the continual advancement of codes and standards to recognize these new developments, the concrete industry is confident that it will continue to provide the design community the tools to efficiently and efficiently design concrete structures that will not only meet code requirements, but will perform very well when fires occur.▪

Stephen Szoke, P.E., is the Director of Codes and Standards for the Portland Cement Association located in Skokie, Illinois. He can be reached via email at ***sszoke@cement.org****.*

References

Abrams, M.S. and Gustaferro, A.H. *Fire Endurance of Concrete Slabs as Influenced by Thickness, Aggregate Type and Moisture*, Portland Cement Association, Skokie, IL 1968.

Arnold, J. *Large Building Fires and Subsequent Code Changes*, Department of Development Services, Clark County, Nevada, National Fire Protection Association, Quincy, MA, 2005.

Building Construction and Safety Code, National Fire Protection Association, Quincy, MA, 2003.

Caro, T. Milke, J.A. *A Survey of Fuel Loads in Contemporary Office Buildings*, NIST GCR-96-697, National Institute for Standards and Technology, Gaithersburg, MD, 1996.

Culver, C. and Crist, R. *Military Personnel Records Center Fire*, Fire Journal, Boston 1974.

Fire Protection Handbook, Fourteenth Edition, National Fire Protection Association, Quincy, MA.

Hall, J. R. Jr. *High-Rise Building Fires*, National Fire Protection Association Quincy, MA, 2005.

International Building Code (IBC), International Code Council, Washington, DC, 2006

Magnusson, S.E. and Thelandersson, S. *Temperature-Time Curves of Complete Process of Fire Development*, Civil Engineering and Building Construction Series No. 65, Acto Polytechnica Scandinavica, 1970.

The Pentagon Building Performance Report, American Society of Civil Engineers, Structural Engineering Institute, Reston, 2003