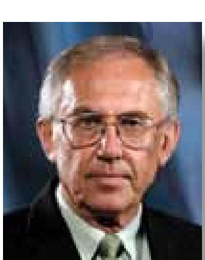
The Current State of Fire Design

— By Roger Becker, P.E., S.E.

Many decisions in building design hinge on the code requirements for fire-resistive construction. While the fire-resistance ratings required by the codes may be modified with new code editions, the technology of fire resistance has changed very little in the past 50 years. Early in the development of the precast/prestressed concrete industry, fire resistance was considered an important attribute of precast concrete construction, so significant resources were dedicated to fire research. The results of that research are still the basis for much of what is known about the fire performance of structural concrete elements today.

What has changed over the years is an increased reliance on detection and suppression of fires, with a corresponding decrease in attention to fire containment within the building. The International Building Code[1] (IBC) now allows substantial building areas and heights to be constructed (up to 70 ft. high and over 250,000 square feet of building area for B occupancies) entirely out of Type V construction where an approved automatic sprinkler system is provided. Type V construction consists of wood or light-gage steel framing with as little as one hour of protection for many building elements. This shift in emphasis toward an increased reliance on fire protection systems as the primary life-safety component in fire-protective design ignores the issue of functional resiliency and facility durability.



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Functional resilience is the ability of a building to resist damage and return to usefulness from the effects of natural and man-made disasters. For architects increasingly focused on the demands of owners for designing high performing buildings, functional resilience may well become a key guiding principle in designing buildings that not only meet the code, but limit fire and sprinkler damage, facility downtime, and the costs and carbon impact of restoring the building to full operation following a disaster.

Insurers are increasingly becoming involved in the fire-resistive construction of major facilities. For specific occupancies, such as retail, office, and other facilities, the owner may require the architect to comply with Factory Mutual (FM) design requirements, and obtain review and approval of FM for insurance purposes. FM conducts its own testing of building products and fire assemblies and their requirements may exceed the minimum building code requirements.

Designing for Fire

Accounting for fire requirements involves two tasks. The first task is to establish the required rating for various building elements. This is accomplished by defining the use and occupancy category for the building, selecting the construction type based on the height and area of the building, and then identifying the required fire resistance rating for the various building components based on the construction type. The process is clearly more complex than this as special features of a building are considered.

The second task is to select construction materials that will provide the fire resistance determined from the code review. Most jurisdictions today have adopted some edition of the IBC perhaps with local modifications. As codes have evolved, the required fire-resistance ratings have been tweaked. However, from the 2000 IBC through the 2012 IBC, other than section number changes, the means by which fire resistance is provided by various construction materials has not changed.

Providing Fire Resistive Construction

The American Society for Testing and Materials (ASTM) standard E119, Standard Test Methods for Fire Tests of Building Construction and Materials[2], is the primary document that has been used to establish fire resistance in the United States and dates back to first adoption in 1918. A fundamental component of the standard is the time-temperature curve. For any fire test, this curve defines the temperatures that must be achieved and the rate of temperature gain. The curve is reproduced in **Figure 1.** This standard also defines the acceptability criteria to establish the endpoint for a fire test. Those criteria include:

- Structural endpoint, which is defined by collapse of the element.
- Heat transmission endpoint, which is defined by the average or peak temperature on the opposite side from the fire.
- Flame endpoint, which is defined by the passage of flames or gases hot enough to ignite cotton waste on the opposite side from the fire.
- A hose stream test, which the walls must withstand.

The standard further defines how various construction elements are to be tested. For example, floor and roof specimens shall not be less than 180 square feet in area and neither plan dimension shall be less than 12 feet. Since most test furnaces do not exceed the minimum specified dimensions by very much, it is clear that fire tests are not representative of practical construction. However, the same rules are applied to all materials, so there is a basis for comparison.

One of the important concepts contained in the ASTM E119 standard is the differentiation between restrained and unrestrained fire ratings that are applied to floors and roofs. As a structural element is heated in a fire, the material naturally needs to expand. If the surrounding construction is stiff enough and strong enough to restrain this expansion, the assembly is considered restrained. If the element can freely expand as it is heated in a fire because there is no surrounding structure or because the surrounding structure is not adequate to restrain the expansion, the assembly is considered unrestrained. The issue of restraint is an important consideration as decisions are made in developing a building concept and some examples are provided in Appendix X3 of the ASTM E119 standard.

The endpoints noted for the ASTM E119 acceptance criteria are logical whether or not a test is conducted. During a fire, the material strengths will be reduced at elevated temperatures. If the material strength diminishes to the point where the element strength is less than the load demand, collapse will occur. The primary mechanism for improving resistance for the structural endpoint for concrete elements is to increase the amount of concrete cover over the reinforcement. Additional concrete will protect the steel reinforcement and reduce the temperature of the steel during a fire. The steel will then maintain a higher percentage of its room temperature strength. When the concrete cover is increased to improve fire resistance, the effective depth of the reinforcement is decreased. In this case, additional reinforcement will be required to resist normal loads at room temperature.

The objective of the heat transmission endpoint is to protect combustible contents on the opposite side of the element from the fire. This endpoint is a function of the type and mass of concrete available. For example, the required fire resistance rating may govern the thickness of a wall or floor slab based on the heat transmission endpoint. **Table 1**, which can be found in many references, summarizes minimum wall and slab thicknesses required for various fire resistance ratings. Note, for example, a 6 inch thick slab might be ideal for building dimensions and structural adequacy, but it would not be sufficient for a three hour fire rating based on heat transmission if it were constructed of siliceous aggregate concrete.

Underwriters Laboratories, Inc. (UL) has conducted countless fire tests on structural assemblies using ASTM E119 as the standard. Many construction assemblies received fire resistance ratings as a result of UL testing. UL assemblies have been popular with architects and code officials because they are easy to understand and readily acceptable. An assembly built in conformance to the rated assembly construction automatically gets the UL fire resistance rating. However, this also illustrates one of the difficulties with a UL fire rated assembly. For the fire resistance rating to be achieved, the actual construction must duplicate the tested assembly. Most assemblies are also product specific. The challenge becomes using more modern materials and techniques that do not substitute directly into the UL assemblies.

The International Building Code has simplified the whole issue of fire resistance for structural elements. While the IBC allows use of tested assemblies, such as those provided by UL, there is no requirement that a construction must be one of those assemblies. A UL designation is not required by code.

The IBC provides alternate methods for establishing fire resistance and the provisions are located in Chapter 7 of the IBC. Using the 2012 IBC as the reference, the first method provided is in Section 721 entitled Prescriptive Fire Resistance. The resource provided in that section is Table 721.1 where various structural elements are described and the re-

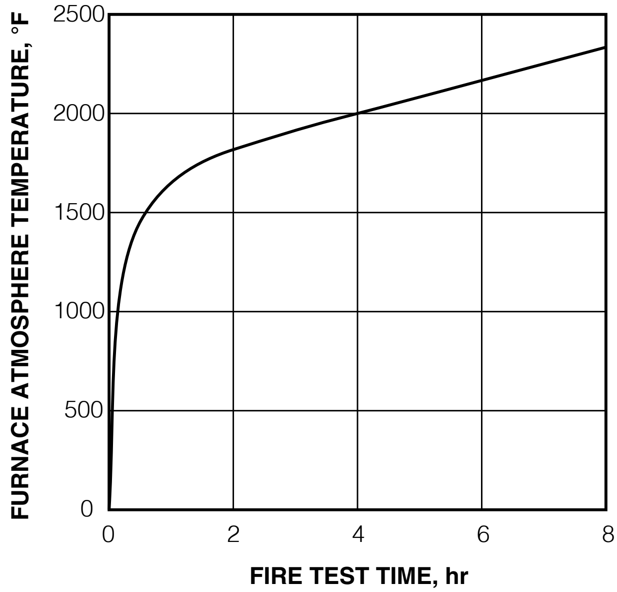

Figure 1. Time-temperature curve from ASTM E119.

Table 1. Minimum wall or slab thickness (in.) based on heat transmission.

Aggregate Type	Fire Resistance Rating, hr				
	1	$1^1/_2$	2	3	4
Siliceous	3.5	4.3	5.0	6.2	7.0
Carbonate	3.2	4.0	4.6	5.7	6.6
Sand-lightweight	2.7	3.3	3.8	4.6	5.4
Lightweight	2.5	3.1	3.6	4.4	5.1

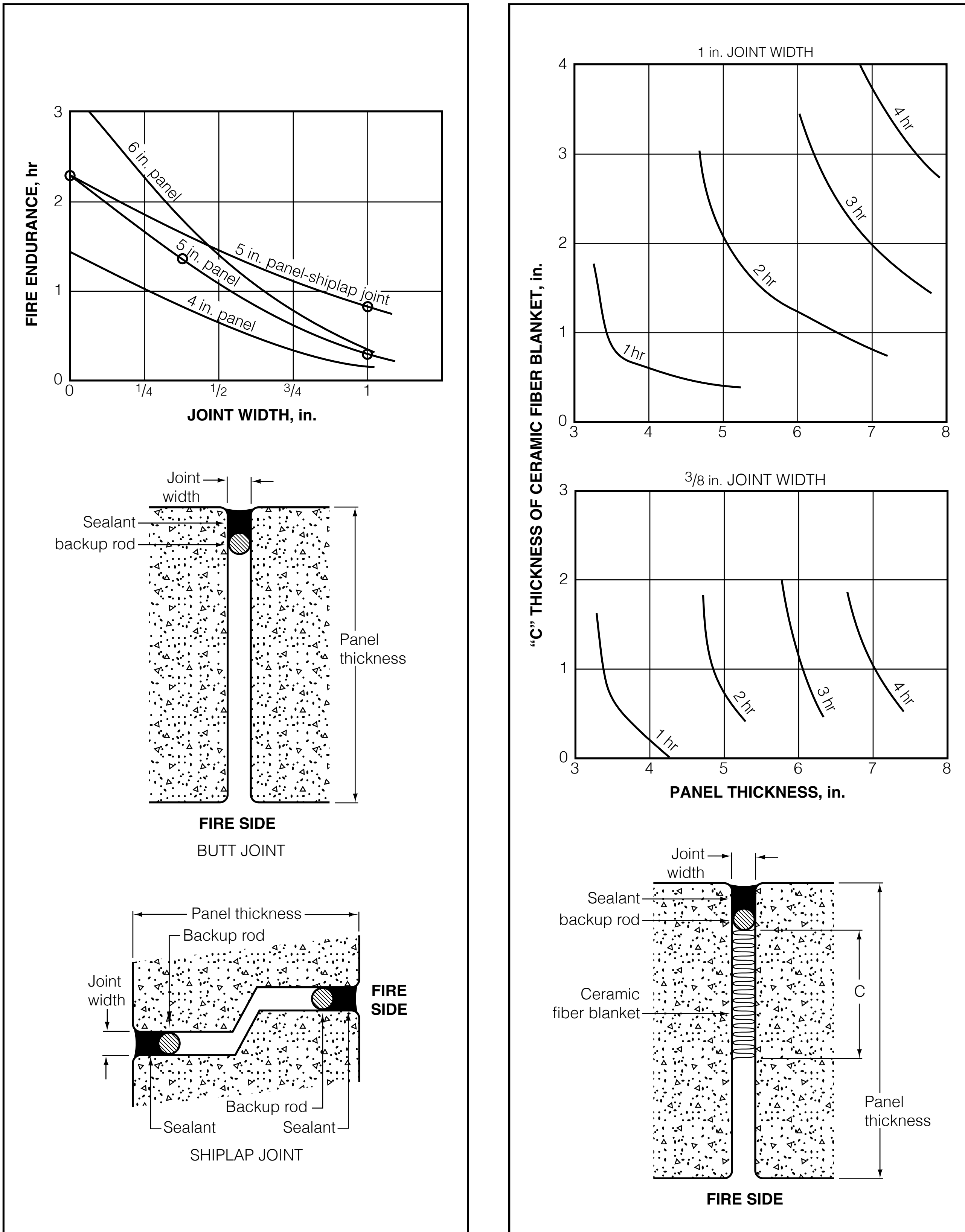

Figure 2. Fire resistance of precast concrete wall joints.

quired element attributes are specified. For example, for concrete slab construction, the minimum concrete cover over reinforcing steel and minimum slab thickness are specified. This is similar to the UL test assembly approach except that all materials are generic.

The second method is in Section 722 and is entitled Calculated Fire Resistance. Section 722.2 covers concrete assemblies. The term "calculated" is a bit misleading because very few calculations are required to use these provisions. Tables and graphs are provided for various concrete attributes where defining the system is as simple as pulling numbers from a chart. This section does provide information on concrete construction assemblies that are not covered in Section 721. For example, multicourse floors and combinations with finish materials are covered.

The IBC refers to two other standards available for calculated fire resistance. ACI 216.1/TMS 0216, Code Requirements for Determining Fire Resistance of Concrete and Masonry Construction Assemblies[3], essentially repeats the material from IBC Section 722 and provides some analytical methods for determining fire resistance. The IBC also refers to ASCE 29, Standard Calculation Methods for Structural Fire Protection[4], for fire resistance of steel assemblies. That document also includes a chapter on plain and reinforced concrete, which essentially duplicates the material from IBC Section 722. These two documents are applicable for determining fire resistance of precast concrete.

Precast concrete can satisfy everything that has been described to this point. Many precast concrete suppliers have UL numbers for various assemblies. Again, it should be emphasized that a UL designation is not required by code. Either the prescriptive or calculated methods of the IBC may be used with precast and precast/prestressed concrete walls, beams, columns, floors, and roofs.

However, precast concrete has taken fire resistance a step further. PCI publishes MNL 124, Design for Fire Resistance of Precast Prestressed Concrete[5] .It is based on years of fire testing of various components and assemblies of precast concrete. The data obtained from this testing provides for a truly engineered approach to fire resistance. Much of the data from the IBC is included in the manual, but it can also be used to evaluate systems that do not conform to those requirements.

For example, if an existing building were to be modified for a different occupancy requiring a higher fire-resistance rating, the structure could be evaluated by calculation using the data in the manual. Keeping in mind the endpoints defined by ASTM, data are provided to determine the internal steel temperature at the required fire endurance, a reduced steel strength could be calculated, and load capacity could be compared to the demand. For heat transmission, data are provided for the addition of various materials to enhance the insulation capacity of the existing concrete. These procedures have collectively become known as rational design.

For precast concrete walls that must be fire resistive, consideration must be given to the joints between the wall panels. **Figure 2** is taken from MNL 124 to illustrate how wall panel joints can be treated to provide fire resistance ratings to four hours. One last example is floor penetrations. Holes through fire rated floors for power, data, or communication must be protected. Based on fire tests[6], information is provided for detailing such penetrations.

The precast concrete industry has contributed significantly to the understanding of fire performance of concrete construction. Engineers such as Armand Gustaferro, Melvin Abrams, and Walter Prebis distilled fire-test data to develop engineering techniques that are transparent and straightforward in their application. We are grateful that their work allows construction of functional, resilient, and fire safe buildings in precast concrete.

References

1. International Building Code, 2012. International Code Council, Inc., Country Club Hills, Ill.
2. ASTM subcommittee E05.11. Standard Test Methods for Fire Tests of Building Construction and Materials. E119-00a. West Conshohocken, Pa. ASTM International.
3. Joint ACI-TMS Committee 216. 2007. Code Requirements for Determining Fire Resistance of Concrete and Masonry Construction Assemblies (ACI 216.1-07/TMS 0216-07). Farmington Hills, Mich. American Concrete Institute (ACI).
4. American Society of Civil Engineers. 2005. Standard Calculation Methods for Structural Fire Protection (ASCE/SEI/SFPE 29-05). Reston, Va. ASCE.
5. Precast/Prestressed Concrete Institute. 1989. Design for Fire Resistance of Precast Prestressed Concrete. MNL 124-89. Chicago, Ill. PCI.
6. Abrams, M.S., and A.H. Gustaferro. 1971. Fire Tests of Poke-Through Assemblies. Fire Journal (May). ■

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