Practical Design: A Supplement to Academics

New Engineers Under Fire

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Despite concrete's inherent fire-resistive properties, concrete structures must still be designed with due consideration for fire effects. In this article, we'll take an introductory look at how fire affects concrete and masonry structures, as well as how to determine if a structure meets building code requirements for fire endurance. As we will see, member sizes are not simply functions of load, span, and formwork costs, but they can also be functions of requirements for fire safety. Fire considerations must, therefore, be part of the preliminary design stages.

THE BASICS

As you probably know, the architect works directly with the owner to define the functional and aesthetic requirements for a building. You may not know, however, that the architect (either directly or through consultants) is also responsible for ensuring that the building and its various components meet minimum fire resistance requirements. These requirements are normally defined by the building code and will be a function of the building use (for example, assembly, business, or educational), floor areas, number of stories, property line setbacks, and the presence or lack of automatic fire sprinklers. For this article, we'll only focus on concrete structures, but keep in mind that other structural materials will have similar requirements.

MATERIAL CONSIDERATIONS

As shown in Fig. 1, the effect of temperature on the compressive strength of concrete varies depending on the type of coarse aggregate used. Concrete containing lightweight aggregates (expanded clay, shale, or slate) and carbonate aggregates (limestone or dolomite) retain most of their compressive strength up to about 1200 °F (650 °C). The strength retention of concrete containing siliceous aggregate begins to drop off at about 800 °F (430 °C). Because of its superior insulating properties, lightweight concrete also transfers heat more slowly than normalweight concrete with the same thickness, and therefore generally provides increased fire resistance.

Reinforcing steel is much more sensitive to high temperatures than concrete. As indicated in Fig. 2, hot-rolled steels (reinforcing bars) retain much of their yield strength up to about 800 °F (430 °C), while cold-drawn steels (prestressing strands) begin to lose strength at about 500 °F (260 °C). Fire resistance ratings therefore vary between prestressed and nonprestressed elements, as well as for different types of concrete.

Boundary conditions also influence the fire rating of a structural component. Most concrete construction provides resistance to thermal expansion and is therefore

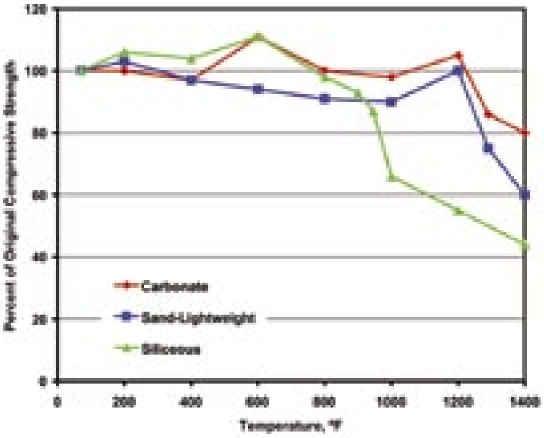

Fig. 1: Compressive strength of concrete at high temperatures.[1] The values shown are for concrete that was stressed to approximately 0.4f'_c during heating and then tested to failure while still hot. Tests of unstressed concrete and concrete that is cooled before testing exhibit even lower strength retention

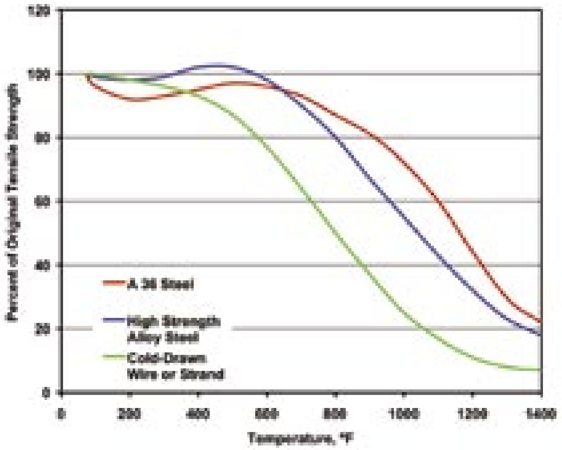

Fig. 2: Strength of flexural reinforcement steel bar and strand at high temperatures[2]

classified as restrained. However, single spans, simply-supported end spans of multiple bays in bearing wall buildings, and end spans in flat slab construction, among others, are generally classified as unrestrained.

THE "STANDARD FIRE"

Fire ratings are defined as the amount of time that an assembly (roof, floor, beam, wall, or column) can endure a "standard fire" as defined in ASTM E 119.[3] Although the idea of a "standard fire" may seem nonsensical, it's necessary to have some way of quantitatively comparing the fire endurance of various systems and materials. This fire is defined by a time-versus-temperature relationship that is equivalent to burning about 10 lb of wood for each square foot of exposed floor surface area each hour and produces a temperature of 1700 °F (927 °C) in the first hour.

It is interesting to note that, because of concrete's large heat capacity, test furnaces actually use more energy when testing assemblies constructed of concrete than when testing assemblies constructed of other materials.[1] In addition, when combustible assemblies are fire tested, less outside energy is used because burning of the combustible material also contributes heat.

END POINTS

For an assembly, fire endurance is judged mainly by satisfaction of three conditions (end points) defined in ASTM E 119. The flame passage end point is reached when a roof, floor, or wall assembly fails to stop the passage of flame or gases hot enough to ignite cotton waste. The heat transmission end point is when the surface temperature of a roof, floor, or wall assembly increases by 250 °F (139 °C) on the side opposite the fire. The structural end point for load-bearing assemblies occurs when the assembly fails to support the applied loads, if any, that are included in the test. The applied load is often the maximum service load expected for the assembly.

In addition, ASTM E 119 limits the temperature of tension reinforcement in beams of concrete floor and roof assemblies spaced more than 4 ft (1.2 m) on center to 800 and 1100 °F (427 and 593 °C) for cold-drawn prestressing steel and hot-rolled steel bars, respectively. The period of time that the steel temperature must remain below these limits depends on whether the assembly is restrained or unrestrained. The first end point to be reached determines the fire resistance rating of the assembly.

Walls and partitions are also required to pass a hose stream test. In many cases, a duplicate specimen is exposed to the standard fire for a minimum of 1 h or half the rated exposure time. It's then sprayed with a stream of water from a firefighter's hose. The assembly fails this test if any openings develop that allow the stream to pass beyond the unexposed surface of the wall. Wall assemblies incorporating gypsum wallboard are normally tested using this procedure. In contrast, concrete and masonry walls are generally subjected to the hose stream test after the full fire test duration (no duplicate specimen is tested). Although this is a more severe test, the robustness of concrete allows the wall to easily withstand the hose stream.

CODE REQUIREMENTS

The governing building code for any project will include provisions required to achieve a specific fire rating. However, the client may require that your design comply with additional requirements, such as finance or insurance company standards. Be aware that these requirements may be stricter than those found in the building code.

Many building assemblies comprise proprietary systems of various materials. Building codes require these assemblies to be tested and listed as rated assemblies by certified testing agencies. The results are specific to the manufactured components and therefore can't be described in a generic or prescriptive manner.

One well-known testing agency is Underwriters Laboratories, Inc. (UL). Fire ratings for assemblies composed of various building materials can be found in the UL Fire Resistance Directory,[4] which can also be viewed on the Internet (go to **www.ul.com/regulators/QuickGuide.pdf** for a guide to viewing the online directory). Numerous floor and roof assemblies that use precast concrete components are listed. However, very few listed assemblies incorporate cast-in-place concrete because concrete is not a proprietary material.

The 2003 International Building Code (IBC)[5] contains prescriptive requirements for building elements in Section 720. This section contains tables describing various assemblies of building materials and finishes that meet specific fire ratings. If your specific assembly is not included in the tables, IBC Section 721 contains methods and design values to calculate the fire rating that are based on data from decades of fire testing. This section also allows calculations per ACI 216.1/TMS 0216.1,[2] which is in general agreement with the IBC provisions.

The calculation method in ACI 216.1/TMS 0216.1 is by far the most commonly used in typical design situations. Although testing according to ASTM E 119 is probably the most reliable method, the time and expense required to build and test the assemblies makes this method impractical and unnecessary for most situations. The fire resistance (based on the heat transmission end point) of a concrete or masonry assembly is found by calculating the equivalent thickness for the assembly and then finding the corresponding rating in the charts and tables provided in ACI 216.1/TMS 0216.1. The equivalent thickness of solid walls and slabs with flat surfaces is the actual thickness. The equivalent thickness of walls and slabs that have voids, undulations, ribs, or multiple layers of various materials (for example, a sandwich of concrete, insulation, and concrete) must be calculated using equations found in ACI 216.1/TMS 0216.1.

Once you've established that your assembly has enough equivalent thickness to satisfy the heat transmission end point, you must also determine whether there is enough cover on the reinforcing steel to prevent excessive heat from reducing the yield strength to the point where it can no longer carry the loads (remember the structural end point?). The cover requirements for slabs are functions of the required fire rating, aggregate type, restrained or unrestrained construction, and prestressed or non-prestressed reinforcement.

Building codes seldom require fire ratings of slabs to be greater than 2 h. As shown in Table 1, a 2 h fire rating can be achieved with only 3/4 in. (20 mm) of cover (the minimum allowed by ACI 318[6] for slabs) for all restrained conditions and in all unrestrained conditions except where siliceous aggregate concrete is used. The cover requirements for unrestrained prestressed slabs are higher due to the more detrimental effect of heat on cold-drawn strands (Fig. 2). These increased values are most prevalent in prestressed flat slab construction, where the end spans are considered unrestrained because there is not sufficient stiffness or end fixity to create a restrained condition.[7]

The cover requirements for beams are also tabulated, but because the bars in the corners are exposed to high temperatures on two sides, a weighted average cover must be used. For interior bars, the cover is the actual minimum cover. For the bars in the corners, the cover

TABLE 1:
MINIMUM COVER FOR CONCRETE FLOOR AND ROOF SLABS[2]

	Cover for corresponding fire resistance, in.					
	Restrained	Unrestrained				
Aggregate type	4 or less	1 h	1-1/2 h	2 h	3 h	4 h
Nonprestressed						
Siliceous	3/4	3/4	3/4	1	1-1/4	1-5/8
Carbonate	3/4	3/4	3/4	3/4	1-1/4	1-1/4
Semi-lightweight	3/4	3/4	3/4	3/4	1-1/4	1-1/4
Lightweight	3/4	3/4	3/4	3/4	1-1/4	1-1/4
Prestressed						
Siliceous	3/4	1-1/8	1-1/2	1-3/4	2-3/8	2-3/4
Carbonate	3/4	1	1-3/8	1-5/8	2-1/8	2-1/4
Semi-lightweight	3/4	1	1-3/8	1-1/2	2	2-1/4
Lightweight	3/4	1	1-3/8	1-1/2	2	2-1/4

Note: 1 in. = 25.4 mm.

used is half of the actual minimum cover. The weighted average is obtained by summing the covers for each individual bar and dividing by the total number of bars. None of the bars in the beam should have an actual cover less than half of the tabulated cover values or 3/4 in. (20 mm), whichever is greater. As with slabs, substantial fire ratings can be achieved in beams using ACI 318 minimum cover requirements.

A separate analytical method of calculating fire resistance for flexural members is also contained in ACI 216.1/TMS 0216.1. This method may be the most interesting because it involves estimating the actual temperatures of the concrete and reinforcing steel and using the properties of the materials at those temperatures in the analysis. The method takes into account the fact that the bottom, positive moment steel will reach elevated temperatures and begin to weaken before the top concrete and reinforcement. This allows the moment in the member to be redistributed from the weaker, positive moment region to the negative moment region where little reduction in strength will have occurred.

A precise analysis of this behavior would be quite complex, but the document contains equations and procedures that are fairly easy to follow and simplify the analysis. Also, because a factor of safety is already built into the fire rating, the full nominal moment capacity M_n is compared to the service load moments (no load factors).

Obviously, this procedure will take a considerable amount of design time, so keep your boss happy and use it only when necessary (for example, in evaluating an existing structure for a change in use, it may not be possible to use simple cover checks to show the structure meets the required fire rating). If the analytical procedure is used, however, be aware that the redistribution of moments will cause a shift in the moment diagram. Top bar cutoff points must therefore be carefully checked to be sure that the bars are adequately developed and meet ACI 318 requirements.

JUST A FEW MINUTES

We hope you now have a basic understanding of the effects of fire on concrete structures and how to determine fire ratings. As we have seen, determining fire ratings can vary in complexity from a simple table lookup to a fairly sophisticated structural analysis. Often, other requirements (such as strength or constructibility) will govern your design. You will therefore find that a little design time near the beginning of a project reviewing the tables, charts, and text of some of the documents mentioned in this article will be all the time you need to properly protect your structure in the event of a fire.

Do you have another topic that might be worthy of an article? As a young engineer, is there something that you find confusing? Seasoned engineers—do you remember back when you were a new designer—the problems you had? Please send in your ideas—suggestions for additional topics are welcome.

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6. ACI Committee 318, "Building Code Requirements for Structural Concrete (ACI 318-05) and Commentary (318R-05)," American Concrete Institute, Farmington Hills, MI, 2005, 430 pp.

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Selected for reader interest by the editor.

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