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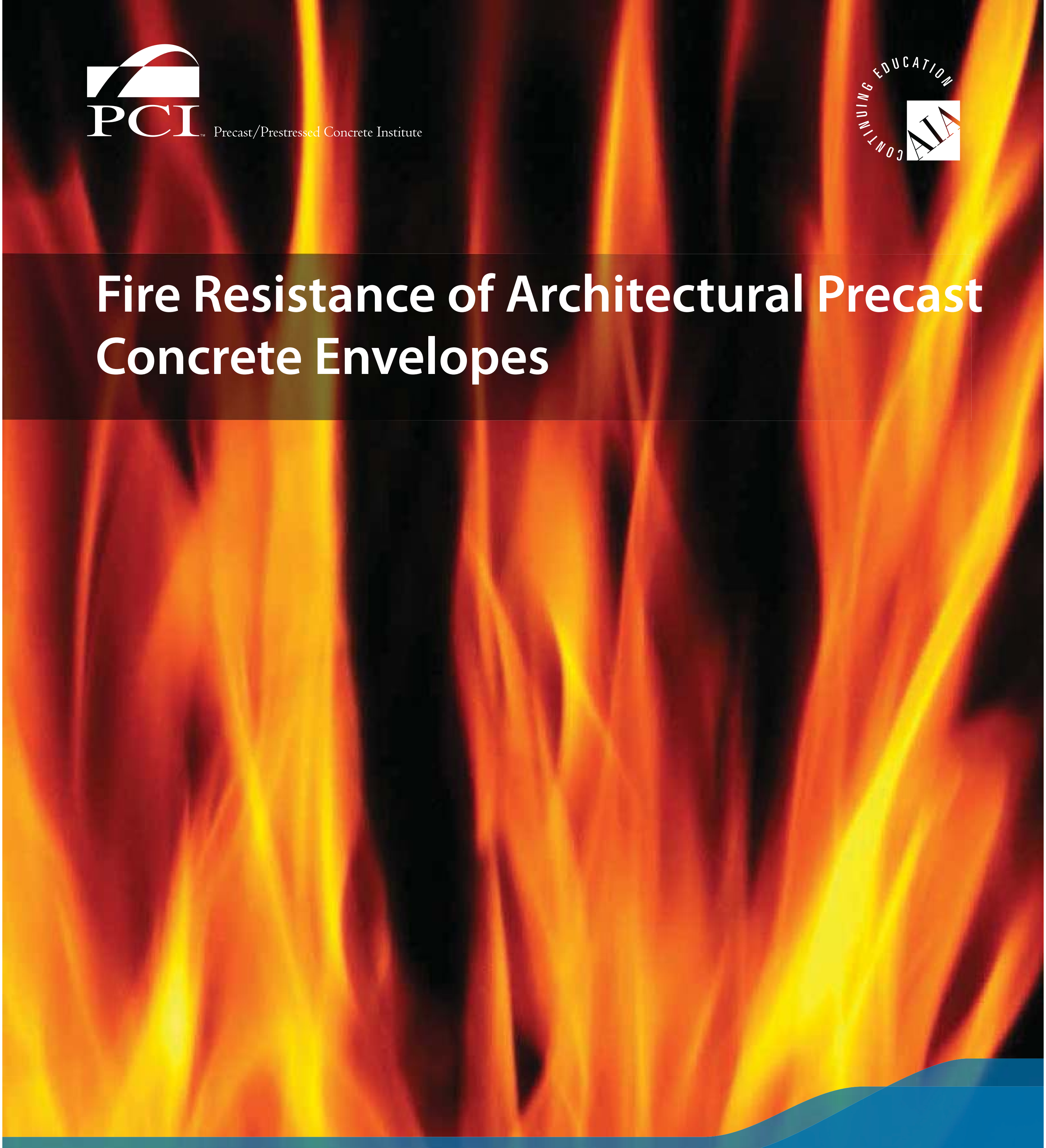
Fire Resistance of Architectural Precast Concrete Envelopes



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FIRE RESISTANCE OF ARCHITECTURAL PRECAST CONCRETE ENVELOPES

In the interest of life safety and property protection, building codes require that resistance to fire be considered in the design of buildings. The degree of fire resistance required depends on the type of occupancy, the size of the building, its location (proximity to property lines and within established fire zones), and in some cases, the amount and type of fire detection and extinguishing equipment available in the structure. Precast concrete members are inherently noncombustible and can be designed to meet any degree of fire resistance that may be required by building codes, insurance companies, and other authorities.

Although life safety is of paramount importance, casualty insurance companies and owners are also concerned with the damage that might be inflicted upon the building and its contents during a fire. This means that both fire resistance and containment must be considered. Insurance rates are usually substantially lower for buildings with higher fire-resistance designs incorporating containment features. Building codes commonly assign fire resistance ratings on the basis of results of standard fire tests. However, in recent years, there has been a trend toward calculating the fire endurance of building components, rather than relying entirely on fire tests. Much research work has been conducted on the behavior of materials and building components in fires. This article summarizes the available information on the behavior of architectural precast concrete under fire conditions. The article is based on the PCI "***Design for Fire Resistance of Precast/Prestressed Concrete***" 3rd Edition, (MNL-124-11). MNL-124 is referenced in the International Building Code (IBC). It can also be accepted as an alternate method to what is specified in IBC or UBC Section 703.3 based on ICC-ES Evaluation Report, ESR-1997.

Fire resistance ratings of building components are measured and specified in accordance with ASTM E119. Fire endurance is defined as the period of time elapsed before a prescribed condition of failure or end point is reached during a standard fire test. The major "end points" used to evaluate performance in a fire test include:

1. Structural End Point. Collapse of loadbearing specimens (structural end point).
2. Flame Passage End Point. Formation of holes, cracks, or fissures through which flames or gases hot enough to ignite cotton waste may pass.
3. Heat Transmission End Point. Temperature increase of the unexposed surface of floors, roofs, or walls reaching an average of 250 °F (122 °C) or a maximum of 325 °F (163 °C) at any one point.
4. Hose Stream Test. Collapse of walls and partitions during a hose-stream test or inability to support twice the super-imposed load following the hose stream test.

A fire-resistance rating (sometimes called a fire rating, a fire-resistance classification, or an hourly rating) is a legal term defined in building codes, usually based on fire endurance. Building codes specify required fire-resistance ratings depending on the construction classification, occupancy, and fire separation distance. In IBC

2012, Table 601 defines the required fire-resistance rating based on type of construction and Table 602 defines the required fire-resistance rating based on separation distance. The more restrictive would apply. Performance is defined by the authorities (regulatory and insurance) as the time for which each component would reach its controlling end point if it were subjected to a standard test.

Fire Endurance of Exterior Walls

The fire endurances of precast concrete walls, as determined by fire tests, are almost universally governed by the ASTM E119 criteria for heat transmission (temperature rise of the unexposed surface) rather than by structural behavior during fire tests. This is probably due to the low level of stresses, even in concrete bearing walls, and the fact that reinforcement generally does not perform a primary structural function. Concrete cover as specified in ACI 318 for durability will be sufficient for fire ratings up to 4-hr.

Most of the information on heat transmission was derived from fire tests of assemblies tested in a horizontal position simulating floors or roofs. The data is slightly conservative for assemblies tested vertically, such as walls. Nevertheless, it is suggested that no correction be made unless more specific data derived from fire tests of walls are used.

For concrete wall panels, the temperature rise of the unexposed surface depends mainly on the thickness and aggregate type in the concrete mixture. Other less important factors include unit weight, moisture condition, air content, and maximum aggregate size. Within the usual ranges, water-cement ratio, strength, and age have insignificant effects.

Table 1. Fire Endurances for Single-Mixture Concrete Panel.

Aggregate	Thickness for fire endurance, in.			
	1 hr	2 hr	3 hr	4 hr
All lightweight	2.5	3.6	4.4	5.1
Sand-lightweight	2.7	3.8	4.6	5.4
Carbonate	3.2	4.6	5.7	6.6
Siliceous	3.5	5.0	6.2	7.0

From information that has been developed from fire tests, it is possible to accurately estimate the thickness of many types of single-course and multicourse (face and backup mixtures) walls that will provide fire endurances of 1, 2, 3, or 4 hours, based on the temperature rise of the unexposed surface. Based on fire test data, the thicknesses shown in Fig. 1 and Tables 1 and 2 can be expected to provide the fire endurances indicated for single-course and two-course walls. Figure 1 shows the fire endurance (heat transmission) of concrete as influenced by aggregate type and thickness. Interpolation of varying concrete unit weights is acceptable in this figure. Table 1 provides the thickness (in inches) of solid concrete wall panels for various fire endurances, while Table 2 provides the same for two-course panels. Table 3 provides reduced required thickness when $^{5}/_{8}$ in. thick Type X gypsum wallboard covers the fire-exposed surface.

As used in this article, concrete aggregates are designated as lightweight, sand-lightweight, carbonate, or siliceous.

Table 2. Thickness of Wythes to Provide Various Fire Endurances for Panels with Facing and Backup Materials.

Fire Endurance, hr	Backup Material / Inside Wythe Material (Fire-Exposed Side)	Siliceous Aggregate Concrete, in. (Facing Material)			Sand-Lightweight Concrete, in. (Facing Material)		
		$1^1/_2$	2	3	$1^1/_2$	2	3
1	Carbonate aggregate concrete*	1.9	1.4	0.45	1.7	1.0	0
1	Siliceous aggregate concrete	2.0	1.48	0.48	1.7	1.0	0
1	Lightweight aggregate concrete	1.5	1.2	0.25	1.13	0.63	0
2	Carbonate aggregate concrete*	3.25	2.8	1.9	3.2	2.6	1.25
2	Siliceous aggregate concrete	3.5	3.0	2.0	3.3	2.7	1.3
2	Lightweight aggregate concrete	2.5	2.1	1.4	2.26	1.76	0.76
3	Carbonate aggregate concrete*	4.4	3.9	3.0	4.2	3.7	2.4
3	Siliceous aggregate concrete	4.65	4.15	3.15	4.4	3.8	2.5
3	Lightweight aggregate concrete	3.4	3.1	2.4	3.12	2.62	1.62
4	Carbonate aggregate concrete*	5.15	4.8	3.85	5.2	4.7	3.5
4	Siliceous aggregate concrete	5.55	5.05	4.05	5.5	4.9	3.7
4	Lightweight aggregate concrete	4.2	3.8	3.0	3.87	3.37	2.37

*Tabulated values for thickness of inside wythe are conservative for carbonate aggregate concrete.
Note: 1. NA = not applicable; that is, a thicker facing material is needed.
2. To obtain thickness of concrete for a specific fire endurance, read across and then up. For example, a 2 hr fire endurance for a 2 in. siliceous facing and carbonate backup requires 4.8 in. of concrete.

1. Lightweight aggregates include expanded clay, shale, slate, and sintered fly ash. These materials produce concretes having unit weights of about 90 to 105 pcf (1520 to 1680 kg/m^3) without sand replacement.

2. Lightweight concretes in which sand is used as part of or all of the fine aggregate, and unit weight of 105 to 120 pcf (1680 to 1920 kg/m^3), are designated as sand-lightweight.

Table 3. Use of $^5/_8$ in. thick type X gypsum wallboard required to provide fire endurances of 2 hr and 3 hr.

Aggregate	Thickness of concrete panel, in., for fire endurance of 2 hr and 3 hr	
	2 hr	3 hr
Sand-lightweight	2.5	3.6
Carbonate	2.8	4.0
Siliceous	2.9	4.2

3. Carbonate aggregates include limestone and dolomite (minerals consisting mainly of calcium and/or magnesium carbonate).

4. Siliceous aggregates include quartzite, granite, basalt, and most rocks other than limestone and dolomite.

Ribbed panel heat transmission is influenced by both the thinnest portion of the panel and by the panel's "equivalent thickness." Here, equivalent thickness is defined as the net cross-sectional area of the panel divided by the width of the cross-section. In calculating the net cross-sectional area of the panel, portions of ribs that project beyond twice the minimum thickness should be neglected (Fig. 2).

The fire endurance (as defined by the heat transmission end point) can be governed by either the thinnest section, the average thickness, or a combination of the two. The following rule-of-thumb expressions describe the conditions under which each set of criteria governs.

Let t = minimum thickness, in.

t_e = equivalent thickness of panel, in.

s = rib spacing, in.

If $t \leq s/4$, fire endurance, R, is governed by t and is equal to R_t.

If $t \geq s/2$, fire endurance, R, is governed by t_e and is equal to R_{te}.

If $s/2 > t > s/4$:

$R = R_t + (4t/s - 1)(R_{te} - R_t)$
(Eq. 1)

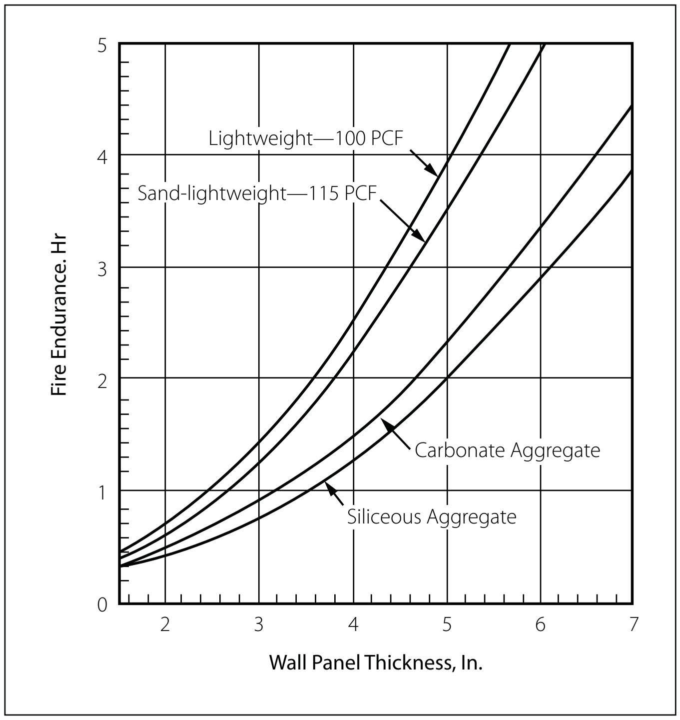

Figure 1 Fire endurance (heat transmision) as a function of panel thickness.

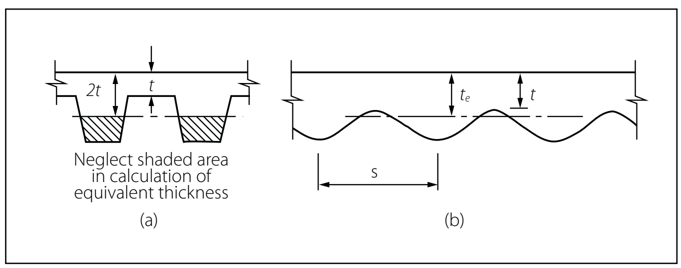

Figure 2 Cross-section of ribbed wall panels.

where R is the fire endurance of a concrete panel and subscripts t and t_e relate the corresponding R values to a concrete slab of thicknesses t and t_e, respectively.

These expressions apply to ribbed and corrugated panels, but they give excessively low results for panels with widely spaced grooves or rustications. Consequently, engineering judgment must be used when applying these expressions.

Insulated precast concrete panels have insulating materials between the two wythes of concrete. Exterior walls of buildings of Type I, II, III, or IV construction of any height must comply with IBC Sections 2603.5.1

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through 2603.5.7. Insulated precast concrete panels are Type I and II. Exterior walls of cold storage buildings required to be constructed of noncombustible materials, where the building is more than one story in height, must also comply with the provisions of Sections 2603.5.1 through 2603.5.7.

The exterior wall assembly must be tested in accordance with and comply with the acceptance criteria of NFPA 285 with the following exceptions:

1. One-story buildings complying with (2012) IBC Section 2603.4.1.4.
2. The 2015 IBC in Section 2603.5.5 includes the following additional exceptions. Wall assemblies where the foam plastic insulation is covered on each face by a minimum of 1-inch (25 mm) thickness of concrete or masonry and meeting one of the following:
    a. There is no air space between the insulation and the concrete or masonry; or
    b. The insulation has a flame spread index of not more than 25 as determined in accordance with ASTM E 84 or UL 723 and the maximum air space between the insulation and the concrete or masonry is not more than 1-inch (25 mm).

It should be noted that cellular plastics melt and are consumed at about 400 to 600° F (205 to 316° C). Thus, thickness of cellular plastics greater than 1.0 in. (25 mm) or changes in composition probably have only a minor affect on the fire endurance of insulated precast concrete panels. The danger of toxic fumes caused by the burning of cellular plastics is practically eliminated when the plastics are completely encased within the two concrete withes.

It is possible to calculate the thicknesses of various materials in an insulated precast concrete panel required to achieve a given fire rating using Equation 2.

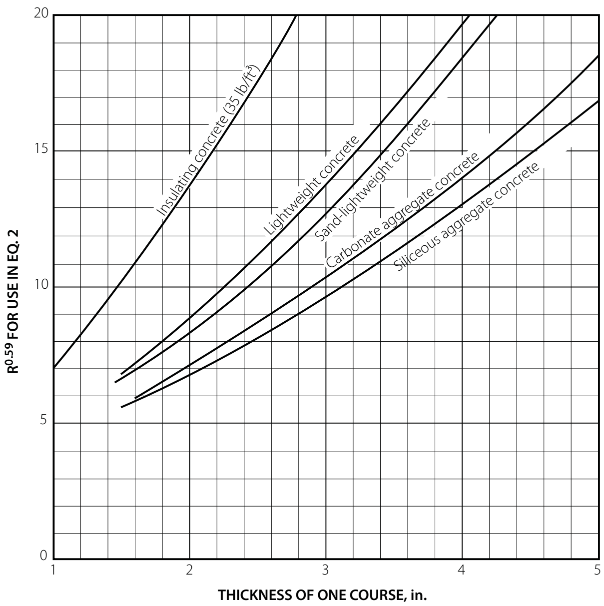
$$R^{0.59} = R_1^{0.59} + R_2^{0.59} \dots R_n^{0.59} \qquad \text{(Eq. 2)}$$

where R = fire endurance of the composite assembly in minutes and R_1, R_2, and R_n = fire endurance of each of the individual courses in minutes.

A design graph for solving the equation is provided in Fig. 3.

Table 4 lists fire endurances for insulated precast concrete panels with either cellular plastic, glass fiber board used as the insulating material. The values were obtained using Eq. 2.

Walls that have windows and are required to be fire resistive have limits imposed on the area of window openings by the building code. Openings in exterior walls must comply with Section 705.8 (2012 IBC). These limits are based on the construction classification, occupancy, fire separation distance, and use of sprinklers. For example, Table 705.8 of the IBC permits no openings in exterior walls when the fire separation distance is less than 3 ft (0.9 m). Where protected openings are allowed 2012 IBC Tables 716.5 and 716.6 provide the rating required for fire doors and windows in the exterior wall. For example, exterior walls with a 1-hour rating require fire doors and window assemblies with a 45-minute rating. For 2- and 3-hour rated exterior walls, door and



R, Minutes	$R^{0.59}$
60	11.20
120	16.85
180	21.41
240	25.37
Material	**$R^{0.59}$**
Cellular plastic (i in. or thicker)	2.57
$^3/_4$ in. thick glass fiber board	4.03
$1^1/_2$ in. thick glass fiber board	8.57
Continuous air space	3.33
Two continuous air spaces	6.67

Figure 3 Design aid for use in solving Eq. 2.

window openings must have a 90-minute rating.

For buildings that are more than three stories in height, openings in exterior walls in adjacent stories are to be separated vertically to protect against fire spread on the exterior of the buildings where the openings are within 5 ft (1.5 m) of each other horizontally and the opening in the lower story is not a protected opening with not less than $^3/_4$ hr. rating. Such openings are to be separated vertically by at least 3 ft (1 m) by spandrel girders, exterior walls, or other similar assemblies that have a fire-resistance rating of at least 1 hour or by flame barriers having a fire-resistance rating of at least 1 hour that extends horizontally at least 30 in. (762 mm) beyond the exterior wall.

Requirements for various occupancies differ somewhat but generally follow the same pattern and certain exceptions often apply. The IBC code relates fire separation distance and maximum area of openings to the area of the exposed building face. Percentages of opening areas are then tabulated in the code for various percentages of area of the exterior wall per story and fire separation distance. The percentage of openings permitted increases as the fire separation distance increases.

Where the allowable area of protected openings is not limited or the allowable area of protected openings is limited and the equivalent area from Eq. 3 satisfies the limit, the heat transmission end point for the exterior wall does not apply. The equivalent opening factor is a function of the temperature on the unexposed surface of the wall and the fire rating of the wall.

Table 4. Fire Endurance of Insulated Precast Concrete Panels.

Inside Wythe, in.	Insulation, in.	Outside Wythe, in.	Fire Endurance, hr: min
$1^1/_2$ Sil	1 CP	$1^1/_2$ Sil	1:23
$1^1/_2$ Carb.	1 CP	$1^1/_2$ Carb.	1:23
$1^1/_2$ SLW	1 CP	$1^1/_2$ SLW	1:45
2 Sil	1 CP	2 Sil	1:50
2 Carb.	1 CP	2 Carb	2:00
2 SLW	1 CP	2 SLW	2:32
3 Sil	1 CP	3 Sil	3:07
$1^1/_2$ Sil	$^3/_4$ GFB	$1^1/_2$ Sil	1:39
2 Sil	$^3/_4$ GFB	2 Sil	2:07
2 SLW	$^3/_4$ GFB	2 SLW	2:52
2 Sil	$^3/_4$ GFB	3 SLW	3:10
$1^1/_2$ Sil	$1^1/_2$ GFB	$1^1/_2$ Sil	2:35
2 Sil	$1^1/_2$ GFB	2 Sil	3:08
2 SLW	$1^1/_2$ GFB	2 SLW	4:00

Note: Carb = carbonate aggregate concrete; Sil = siliceous aggregate concrete; SLW = sand-lightweight concrete (115 pcf maximum); CP = cellular plastic (polystyrene or polyurethane); GFB = glass fiber board.

$$A_c = A + A_t F_{eo} \qquad \text{(Eq. 3)}$$

where

A_c = equivalent area of protected openings.

A = actual area of protected openings

A_t = area of exterior wall surface in the story under consideration exclusive of openings, on which the temperature limitation of the standard fire test is exceeded.

Equation 3 can be rearranged to solve for F_{eo} from which a panel thickness can be determined from Figure 4.

Pockets into the thickness of a panel may be required for many reasons. The concrete thickness outside the pocket must be considered in determining the fire resistance of the wall. One approach is to consider the reduction in wall thickness the same as an opening which would occur with complete through penetration.

If the wall is close to the property line, within 5 ft (1.5 m), then openings may not be allowed. This could require restoring the pocket to its original fire rating by applying a fire-resistive spray, inserting various fire-retardant materials, or during design moving the pocket to the opposite wall or using a corbel or ledge instead of a pocket.

Detailing Precautions

If precast concrete wall panels could be designed and installed such that no space exists between the wall panel and floor, a fire below the floor could not pass through the joint between the floor and wall. However, all exterior panels are designed such that a space does exist, a space referred to as a "safe-off" area.

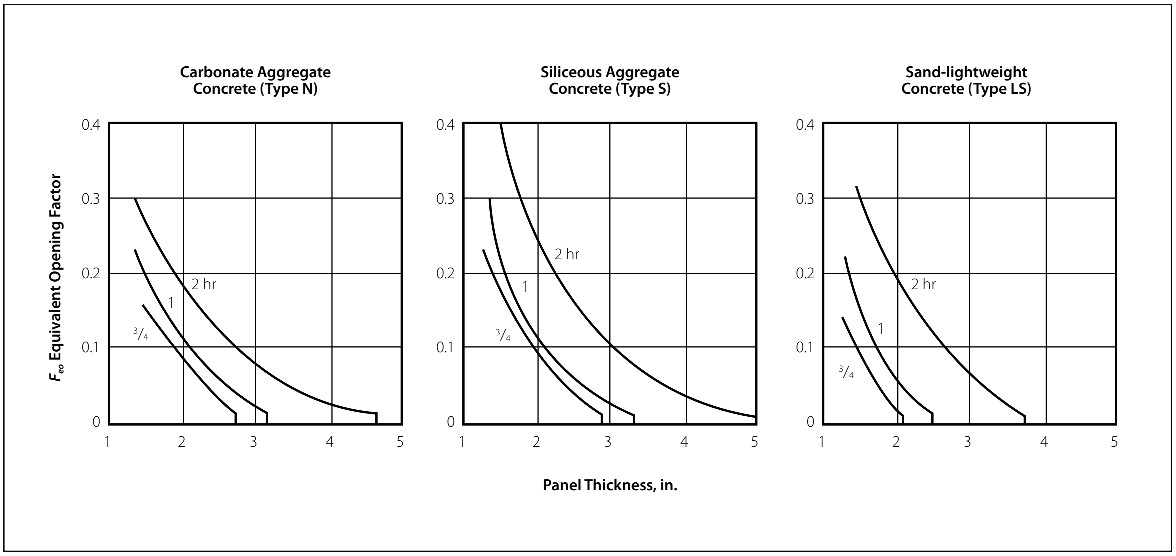


Figure 4 Equivalent opening factor, F_{eo}.

Figure 5 shows a method of fire stopping such safe-off areas. Safing is supported on a steel angle, with or without Z-shaped impaling pins, depending on gauge of steel angle. Safing insulation is available as mineral fiber mats of varying dimensions and densities.

The mineral fiber should be sealed with a sprayed-on firestop caulk. Care must be taken during installation to ensure that the entire safe-off area is sealed. The safing insulation provides an adequate firestop and accommodates differential movement between the wall panel and the floor.

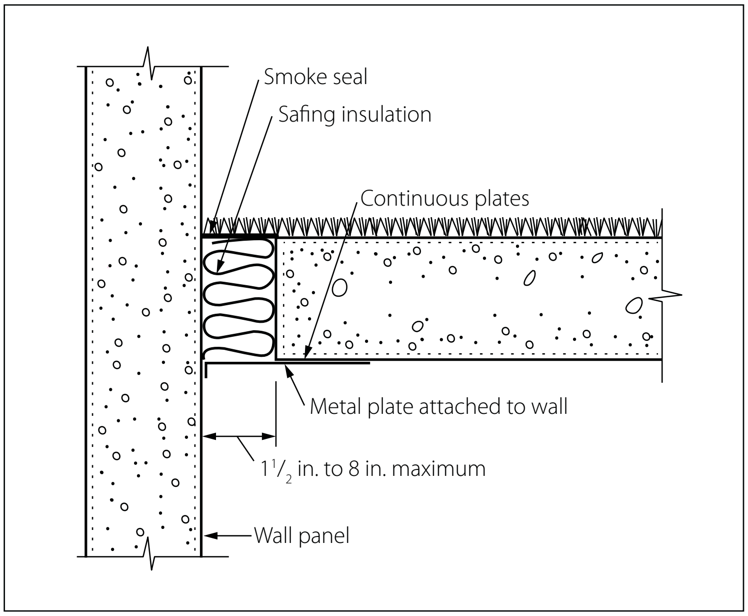


Figure 5 Methods of installing safing insulation.

Columns and Column Covers

Reinforced precast concrete columns have for many years served as the standard for fire-resistive construction. Indeed, the performance of concrete columns in actual fires has been excellent.

Table 5. Minimum sizes of concrete columns.

	Minimum column size for fire resistance rating, in.				
Aggregate Type	**1 hr**	**$1^1/_2$ hr**	**2 hr**	**3 hr**	**4 hr**
Siliceous	8	9	10	12	14
Carbonate	8	9	10	11	12
Sand-lightweight	8	$8^1/_2$	9	$10^1/_2$	12

The inherent fire resistance of concrete columns results from three factors:

1. Minimum size of a structural column is generally such that the inner core of the column retains much of its strength even after long periods of fire exposure.
2. Concrete cover to the primary reinforcing bars is generally $1^7/_8$ in. or more, thus providing considerable fire protection for the reinforcement.
3. Ties or spirals contain the concrete within the core.

Table 5 shows typical building code requirements for reinforced concrete columns, and the values shown apply to both precast and cast-in-place concrete columns with concrete strength less than or equal to 12,000 psi. In addition, they apply to cast-in-place concrete columns clad with precast concrete column covers, whether the covers serve merely as cladding or as forms for the cast-in-place column.

The IBC Code in Section 722.2.4.2 states that regardless of the type of aggregate used in the concrete and the specified compressive strength, the minimum thickness of concrete cover to the main longitudinal reinforcement shall not be less than 1 in. (25 mm) times the number of hours of required fire resistance, or 2 in. (50 mm), whichever is less.

Precast concrete column covers are often used to clad steel columns for architectural reasons. Such covers also provide fire protection for the columns. Figure 6 shows the relationship between the thickness of a concrete column cover and the fire endurance for various steel column sections. The fire endurances shown are based on an empirical relationship. It was also found that the air space between the steel core and the column cover has only a minor affect on the fire endurance. An air space will probably increase the fire endurance but by an insignificant amount.

Most precast concrete column covers are 3 in. (75 mm) or more in thickness, but some are as thin as $2^1/_2$ in. (63 mm). From Fig. 6, it can be seen that such column covers provide fire endurances of at least 2.5 hours and usually more than 3 hours. For steel column sections other than those shown, including shapes other than wide flange beams, interpolation between the curves on the basis of weight per foot will generally give reasonable results.

For example, the fire endurance afforded by a 3 in. thick (75mm) column cover of normalweight concrete for an 8 x 8 x $^1/_2$ in. (200 x 200 x 13 mm) steel tube column will be about 3 hours 20 minutes (the weight of the section is 47.35 lb/ft [691 N/m]).

Figure 7 displays some of the various shapes of precast concrete column covers, including (a) two L-shaped

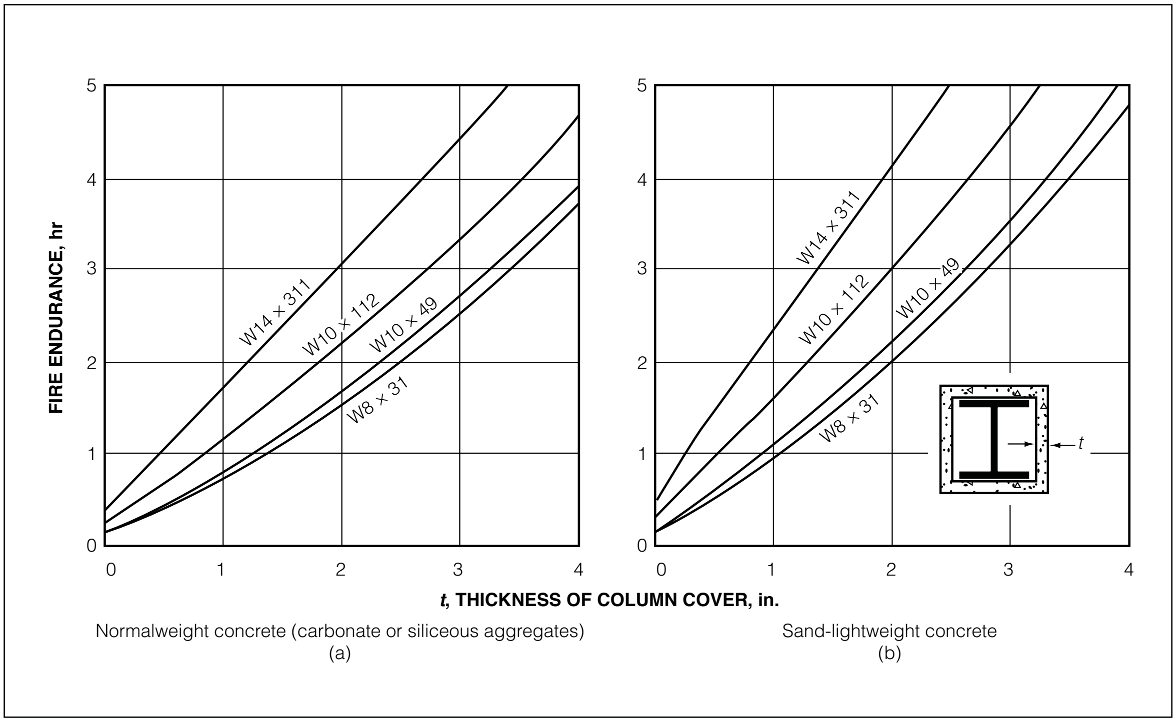


Figure 6 Fire endurance of steel columns afforded protection by concrete column covers.

units, (b) two mitered units, and (c) two U-shaped units. There are, of course, many other combinations that may be used to accommodate isolated columns, corner columns, and columns in walls.

To be fully effective, the column covers must remain in place without severe distortion. Many types of connections are used to hold the column covers in place. Some connections consist of bolted or welded clip angles attached to the tops and bottoms of the covers. Others consist of steel plates embedded in the covers that are welded to angles, plates, or other shapes which are, in turn, welded or bolted to the steel column. In any case, these connections are used primarily to position the column covers and as such, are not highly stressed. As a result, temperature limits do not need to be applied to the steel in most column cover connections.

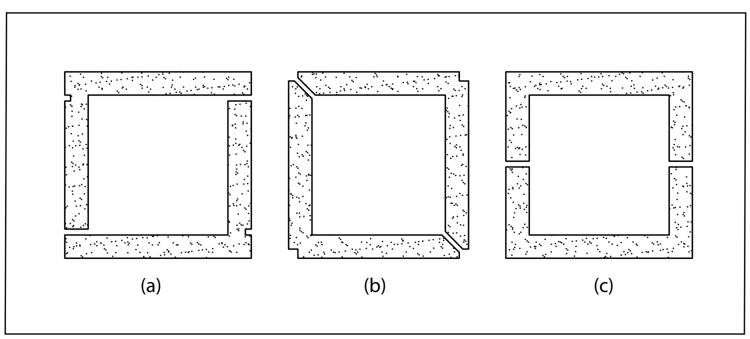


Figure 7 Types of column covers.

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Review the learning objectives below.

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Complete the online test. You will need to answer at least 80% of the questions correctly to receive the 1.0 HSW Learning Units associated with this educational program.

Learning Objectives:

1. Discuss behavior of precast concrete under fire conditions.
2. Determine fire endurance of precast concrete walls.
3. Describe fire code requirements for sandwich wall panels and window walls.
4. Explain the necessary fire protection of reinforcing steel and connections as well as treatment of joints.

Questions: contact Education Dept. - Alex Morales, (312) 786-0300 Email amorales@pci.org