# CALCULATION METHODS FOR STRUCTURAL FIRE PROTECTION

## INTRODUCTION

Building codes require walls and structural elements to have a fire resistance rating for hazard separation, occupancy separation, heights and areas increases, and reduced distances to property lines. When the building is being built, obtaining fire resistance rating is easy since the plans and information are readily available. To determine the fire resistance rating of an assembly after the building had been built can be done in a few different ways. One way is to make an exemplar of the assembly and test it to a fire endurance test such as ASTM E119, ISO 834-1, EN 1363-1, and AS/NZ 1530. Another way is to determine the materials used and calculate the fire resistance rating.

The methods covered here are only a part of ASCE 29, to calculate the assemblies not covered here please refer to ASCE 29. Other manuals such Chapter 2 in Section 19 of the NFPA *Handbook* covers calculating the fire resistive rating of various materials.

## POSITION

### Plain or reinforced concrete

#### Walls

These calculations apply to concrete walls made with cementitious materials, aggregate, and admixtures such as accelerators, retarders, air entrainments, plasticizers, pigments, corrosion inhibitors, and bonding agents as permitted by ACI 318. The specific strength of the concrete does not exceed 10,000 psi (69 MPa). The walls are either cast in place with a non-composite steel form or tilt-up panels. The walls can be either load bearing or non-load bearing.

There are different types of aggregate that are used to make concrete. The main types used for construction are carbonate, lightweight, sand-lightweight, and siliceous.

Carbonate aggregate – mainly consisting of calcium or magnesium carbonate such as limestone or dolomite.

Lightweight aggregate – mainly consisting of expanded clay, shale, slag, or slate with a dry weight between 85 to 115 lb per $ft^3$ (1362 to 1842 $kg/m^3$).

Sand-lightweight aggregate – mainly consisting of sand and lightweight aggregate. The dry weight is between 105 and 120 lb per $ft^3$ (1682 to 1922 $kg/m^3$).

Siliceous aggregate - mainly consisting of silica.

The fire resistance rating of a concrete wall is based on the wall thickness and type of aggregate in the concrete. The equivalent thickness of the wall is determined by the profile of the wall. If the wall is solid and flat, then the equivalent thickness is the minimum thickness of the wall.

If the concrete wall is a flat, hollow core wall the equivalent thickness equals the net cross section divided by the panel width (see Figure 1). If the hollow core is filled with loose fill such as expanded clay, sand, shale, slag, slate, perlite, vermiculate, or grout then the equivalent thickness is calculated as if the wall were a solid wall. The equivalent thickness will be the minimum thickness of the wall.

For example: If the panel is constructed of siliceous concrete measuring 10 ft wide by 8 in. thick (3 m wide by 200 mm thick) and the core opening is 9 ½ ft by 1¾ in. (2.9 m by 45 mm), the net cross sectional area is 732 in.² (455,000 mm²). The equivalent thickness is 760.5/120 = 6.3 in. (469,500/3000 = 156.5 mm). From Table 1 the equivalent thickness for a siliceous aggregate with a 3 h fire resistance rating is 6.1 in. (155 mm), this wall would be a minimum 3 h fire wall.

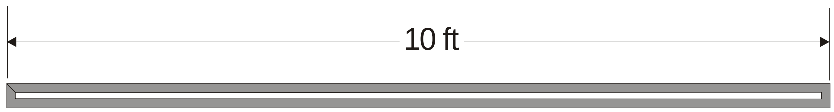



**Figure 1:** Hollow Core Panel Equivalent Thickness

For flanged wall panels the equivalent thickness is the thickness measured at the point on the taper equal to either two times the minimum thickness or 6 in. (152 mm) whichever is smaller (see Figure 2). If *A* is less than 3 in. (75 mm) then measure the thickness at 2*A* in from the edge otherwise measure the thickness 6 in. (150 mm) in from the edge.


**Figure 2:** Flanged Wall Panel Equivalent Thickness

For ribbed or undulating concrete panels the equivalent thickness is determined based on the distances between ribs or undulations (see Figure 3). Where the distance between ribs or undulations is equal to or greater than four time the minimum thickness of the panel, the equivalent thickness is the minimum thickness of the panel. Where the distance between ribs or undulations is equal to or less than two times the minimum thickness, the equivalent thickness equals the net cross-sectional area divided by the panel width.

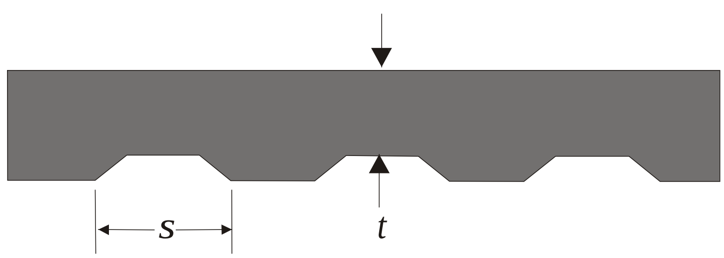



**Figure 3:** Ribbed Or Undulating Wall Panel Equivalent Thickness

Where the distance between ribs or undulations exceeds two time the thickness but is less than four times the thickness the equivalent thickness is calculated using the following formula:

$$T_e = t + [((4t/s) - 1)(t_e - t)]$$

Where

$t$ = minimum thickness

$s$ = distance between ribs or undulations

$t_e$ = net cross-sectional area / panel width

For example: In Figure 3, a siliceous concrete panel has a minimum thickness ($t$) of 4 in. (100 mm), a width of 10 ft (3 m), and a net cross-sectional area of 600 in.² (387,000 mm²).

- If the spacing ($s$) between ribs is 36 in. (915 mm) ($s$ is > 4$t$ or 16 in. (400 mm)) then the equivalent thickness is 4 in. (100 mm) and from Table 1 the fire resistance rating is 1 h.
- If the spacing ($s$) between ribs is 6 in. (150 mm) ($s$ is < 2$t$ or 8 in. (200 mm)) then the equivalent thickness is 5 in. (125 mm) and from Table 1 the fire resistance rating is 2 h.
- If the spacing ($s$) between ribs is 12 in. (300 mm) ($s$ is > 2$t$ but <4$t$ ) then the equivalent thickness is 4.45 in. (109.67 mm) and from Table 1 the fire resistance rating is 1½ h as derived by the formula.

$$T_e = t + [((4t/s) - 1)(t_e - t)]$$

$$T_e = 4 + [((4 \times 4/12) - 1)(600/120 - 4)] = 4.45$$

$$T_e = 100 + [((4 \times 100/300) - 1)(387000/300 - 100)] = 109.67$$

The fire resistance rating of the concrete wall is shown in Table 1 depending on the aggregate and the equivalent thickness

**TABLE 1**
**Fire Resistance of Concrete Walls, Floors, and Roofs**

| Aggregate | Equivalent Thickness (in.) | | | | |
|---|---|---|---|---|---|
| | 1 h | 1 ½ h | 2 h | 3 h | 4 h |
| Carbonate | 3.2 | 4.0 | 4.6 | 5.7 | 6.6 |
| Lightweight | 2.5 | 3.1 | 3.6 | 4.4 | 5.1 |
| Sand-Lightweight | 2.7 | 3.3 | 3.8 | 4.6 | 5.4 |
| Siliceous | 3.5 | 4.3 | 5.0 | 6.2 | 7.0 |

SI Units: 1 in. = 25 mm

## Joints

Joints are required between panels for expansion and earthquake protection and are typically ⅜ in. (10 mm) to 1 in. (25 mm) wide. Include joints between panels in the calculation for the fire resistance rating. Unprotected joints on exterior walls are to be included in the calculation of allowable openings per the building codes. Do not include the area of a protected joints in interior walls in the maximum wall opening calculations. Protected joints are those joints between ⅜ in. (10 mm) and 1 in. (25 mm) wide filled with mineral wool insulation material to the thickness from Figure 4. The mineral wool insulation material is made of alumina-silica fibers and having a density of 4 lb per ft³ to 8 lb per ft³ (5 kg per m³ to 130 kg per m³). For joints widths between the ⅜ in. (10 mm) and 1 in. (25 mm), interpolate the required insulation thickness from the two curves.

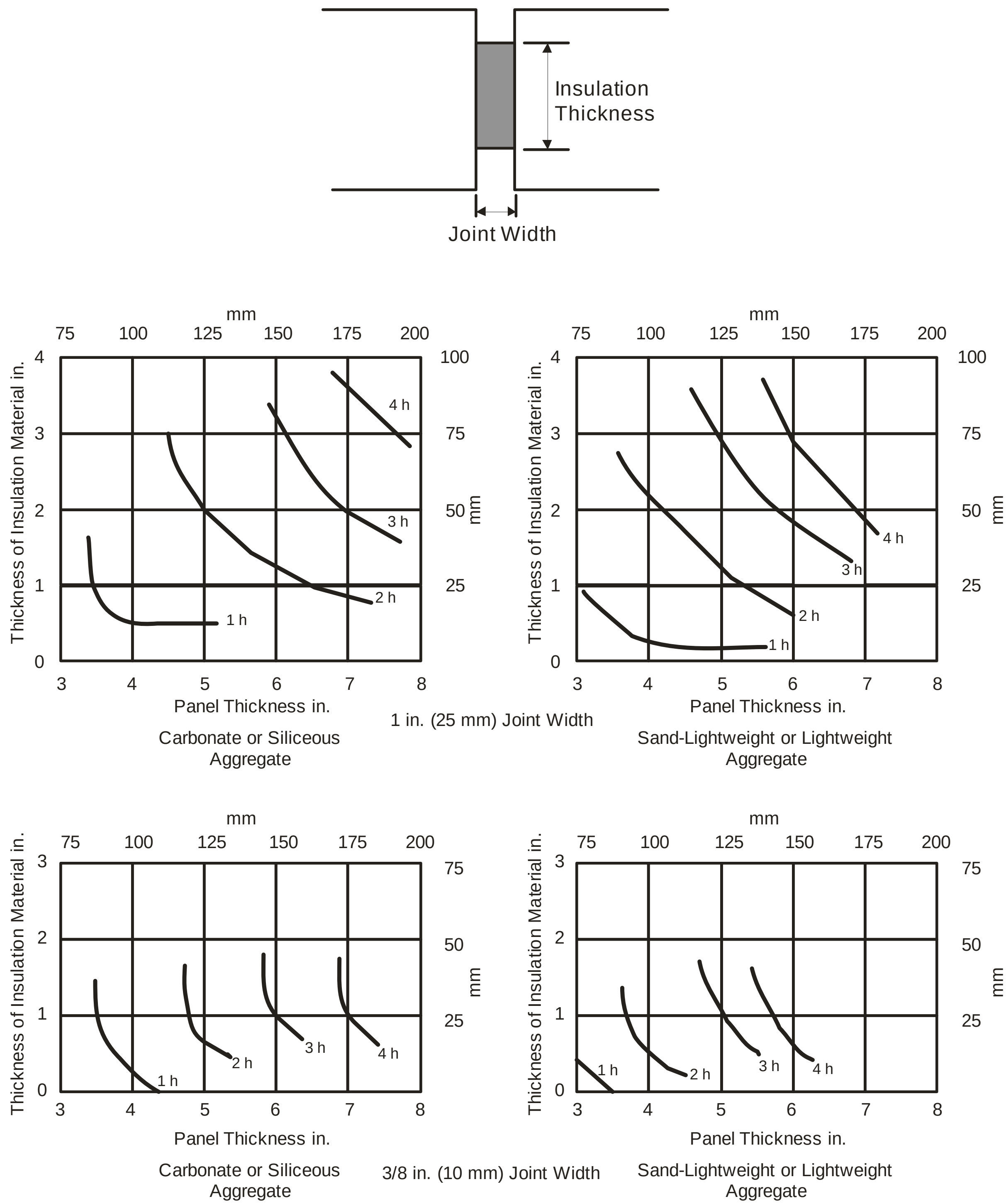



**Figure 4:** Joint Thickness

For example, siliceous concrete panels have a thickness (*t*) of 5 in. (125 mm), a width of 10 ft (3 m), and 1 in. (25 mm) wide joints with 3 in. (75 mm) thick insulation in the joints, fire resistant rating would be 2 hr.

If there are multiple wythe (multiple layers), calculate the fire resistance rating based on the following:

$$R = \left(R_1^{0.59} + R_2^{0.59} + R_3^{0.59} + \ldots.. + R_n^{0.59}\right)^{1.7}$$

Where

$R$ = fire resistance rating of total wall assembly

$R_1$, $R_2$, $R_n$ = fire resistance rating of each wall

**Floor/Ceiling and Roof Systems**

Determine the fire resistance rating of floor/ceiling and roof panels the same as wall panels. If the floor/ceiling or roof panel is covered with at least 1 in. (25 mm) of concrete, the joints between panels can be ignored. If the panels are not covered or covered with less than 1 in. (25 mm) of concrete the joint need to be grouted to at least ⅓ the panel thickness but not less that 1 in. (25 mm) or a listed joint assembly is used.

If the floor/ceiling panels are covered with terrazzo, the thickness of the terrazzo need to be converted to an equivalent thickness. The equivalent thickness depends on the thickness of the terrazzo and the type of concrete. If the terrazzo covers a siliceous or carbonate concrete, the equivalent thickness is the thickness of the terrazzo. If the terrazzo covers a sand-lightweight or lightweight concrete, the equivalent thickness is ¾ the thickness of the terrazzo. The fire resistance rating is the based on the equivalent thickness of the concrete plus the equivalent thickness of the terrazzo.

If the roof panels are covered with gypsum board, the thickness of the gypsum board need to be converted to an equivalent thickness. The equivalent thickness depends on the thickness of the gypsum board and the type of concrete. If the gypsum board covers a siliceous or carbonate concrete, the equivalent thickness is three (3) times the thickness of the gypsum board. If the gypsum board covers a sand-lightweight or lightweight concrete, the equivalent thickness is two and a quarter (2 ¼) times the thickness of the gypsum board. The fire resistance rating is the based on the equivalent thickness of the concrete plus the equivalent thickness of the gypsum board.

If the roof panels are covered with an insulating concrete such as cellular, perlite, or vermiculite concrete or mineral or glass fiber boards consult the curves in ASCE 29.

## Masonry walls

This section will cover the two types of masonry units, clay masonry and units concrete masonry units. Clay masonry units are larger than a brick and made of either clay or shale. Clay units are categorized by grade either NW, MW or SW and type FBA, FBS and FBX. Concrete masonry units vary in size from 2 in. (50 mm) deep by 8 in. (200 mm) high by 16 in. (400 mm) wide to 14 in. (350 mm) deep 8 in. (200 mm) high by 16 in. (400 mm) wide made of different aggregate. Typical aggregate includes calcareous gravel, cinders, expanded clay, expanded slag, limestone, pumice, shale, slag, slate, and siliceous gravel. The walls can be either load bearing or non-load bearing.

Determine the fire resistance rating of masonry block based on the aggregate type, equivalent thickness and cavity fill. The equivalent thickness of the masonry unit is determined by dividing the net volume by the surface area of the unit. With the equivalent thickness use Table 2 to determine the fire resistance rating.

$$T_e = V_n / LH$$

For example, if a block is 8 in. (200 mm) x 8 in. (200 mm) x 16 in. (400 mm) made of calcareous gravel and the volume of the voids in the block is 346 in³ (5,671 cm³) the fire resistance rating would be 3 h.

$V_{gross}$ = 8 x 8 x 16 = 1024 in.³ (200 x 200 x 400 = 16,000 cm³)

$V_n$ = 1024 – 346 = 678 in.³ (16,000 – 5671 = 10,329 cm³)

$T_e$ = 678 / (8)(16) = 5.3 in. (10,329,000 / (200)(400) = 129.1 mm)

**TABLE 2**
**Fire Resistance of Masonry Units**

| Concrete Masonry Aggregate | Equivalent Thickness (in.) 1 h | 1 ½ h | 2 h | 3 h | 4 h |
|---|---|---|---|---|---|
| Calcareous or siliceous gravel | 2.8 | 3.6 | 4.2 | 5.3 | 6.2 |
| Expanded clay, shale or slate | 2.6 | 3.3 | 3.6 | 4.4 | 5.1 |
| Expanded slag or pumice | 2.1 | 2.7 | 3.2 | 4.0 | 4.7 |
| Limestone, cinders or slag | 2.7 | 3.4 | 4.0 | 5.0 | 5.9 |
| **Clay Masonry** | | | | | |
| Clay or shale – unfilled | 2.3 | 2.85 | 3.4 | 4.3 | 5.0 |
| Clay or shale – filled with expanded shale, perlite, or vermiculite | 3.0 | 3.7 | 4.4 | 5.5 | 6.6 |

SI Units: 1 in. = 25 mm

Linear interpolation between hours based on the equivalent thickness of the same a masonry unit type is allowed. For example if the equivalent thickness of a calcareous gravel masonry unit is 4.475 in. (111.875 mm) the rating would be 2¼ h.

If the masonry unit is filled with sand, pea stone, crushed stone, slag, pumice, expanded shale, expanded clay, expanded slate, expanded slag, cinders, perlite or vermiculite the equivalent thickness is the thickness of the unit.

If there are multiple wythe (multiple layers), calculate the fire resistance rating based on the following:

$$R = \left(R_1^{0.59} + R_2^{0.59} + R_3^{0.59} + ..... + R_n^{0.59}\right)^{1.7}$$

Where

$R$ = fire resistance rating of total wall assembly

$R_1, R_2, R_n$ = fire resistance rating of each wall

If the wythe are of different material such as concrete and concrete masonry, determine the of each material then calculate the rating.

## Structural steel

### Columns

Unprotected normal weight structural steel has only a few minutes of fire resistance. Large, heavy unprotected structural steel can display some fire resistance depending on the size of the column. To determine the fire resistance rating of unprotected structural steel use the following formula depending on the *W/D* of the column.

$$R = 10.3\left(\frac{W}{D}\right)^{0.7} \text{ for columns with } \frac{W}{D} < 10$$

$$R = 8.3\left(\frac{W}{D}\right)^{0.8} \text{ for columns with } \frac{W}{D} \geq 10$$

SI Units

$$R = 75.1\left(\frac{W}{D}\right)^{0.7} \text{ for columns with } \frac{W}{D} < 171$$

$$R = 60.5\left(\frac{W}{D}\right)^{0.8} \text{ for columns with } \frac{W}{D} \geq 171$$

Where

$R$ = fire resistance period (min)

$W$ = weight per length (lb/ft kg/m)

$D$ = heated perimeter of the wide-flanged columns (in. mm)

Structural steel can be protected in different ways, spray-on fire proofing, encapsulating with concrete, gypsum, or masonry units or filling the hollow steel columns with concrete. To determine the rating basic information about the steel is necessary, the weight of the steel (*W*) usually given in weight per length, lb/linear ft, or kg/m and the heated perimeter (*D*) usually given in in. or mm. To calculate the heated perimeter (*D*) for various types of protection and columns see Figure 5.

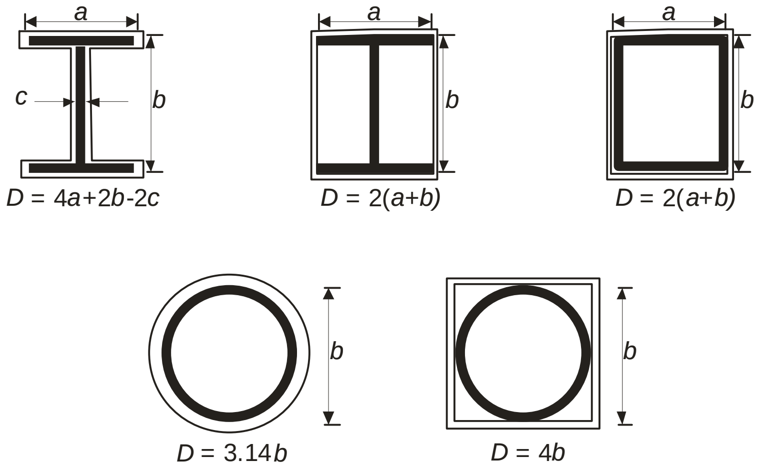



**Figure 5:** *D* Determination for Columns

**Spray-applied materials**

To determine the fire resistance rating of a column protected by spay-applied material you need to know the properties of the spay-applied material and the size and type of the column. The American Iron and Steel Institute (AISI) conducted a series of tests on both wide-flanged and pipe and tubular steel columns protected by cementitious material and mineral fiber material. Those tests determined if the material used is from the UL Design Nos. X701, X704, X722, X723, X801, X807, X818, X821, and X822 the following formula could be used to determine the rating.

$$R = [C_1(W/D) + C_2]h$$

Where

$R$ = fire resistance period (min)

$C_1$ and $C_2$ = are material dependent constants determined by the listing of the material

$W$ = weight per length (lb/ft)

$D$ = heated perimeter of the wide-flanged columns (in.)

$h$ = total thickness of the coating (in.)

SI units

$$R = \left[0.0672 C_1 \left(W/D\right) + 0.039 C_2\right] h$$

Where

*R* = fire resistance period (min)

$C_1$ and $C_2$ = are material dependent constants determined by the listing of the material

*D* = heated perimeter (mm)

*W* = weight per length (kg/m)

*h* = total thickness of the coating (mm)

If the spray applied material is a lightweight cementitious material (13 to 15 lb/ft³ (204 to 240 kg/m³)) and in UL Design Nos. X701, X704, X722, or X723 then $C_1$ = 69 and $C_2$ = 31. If the spray applied material is a lightweight mineral fiber material (13 to 15 lb/ft³ (204 to 240 kg/m³)) and in UL Design Nos. X801, X807, X818, X821, or X822 then $C_1$ = 63 and $C_2$ = 42.

If the spray-applied insulation has a density (*r*) range between 20 to 50 lb/ft³ (302 to 800 kg/m³) and is a mineral fiber, perlite or vermiculite the $C_2$ = 30 and the $C_1$ is calculated using the following formula. If the material is within the density range and contains cement paste or gypsum $C_2$ = 72 and the $C_1$ is calculated using the following formula.

$$C_1 = 1200/r$$

**Gypsum wallboard**

Determination of the fire resistance rating of a steel column of either wide-flanged, pipe or tubular steel covered by Type X gypsum wallboard depends *W/D* ratios of the steel column. The columns must be covered with Type X gypsum board only, regular gypsum wallboard can not be used. For all columns with a *W/D* ratio of 3.65 (0.215) or less the formula is:

$$R = C\left[\frac{h\left(\frac{W'}{D}\right)}{2}\right]^{0.75}$$

$$W' = W + 0.3472hD \quad (W' = W + 0.0008hD)$$

Where

*R* = fire resistance in hours

*C* = 2.17 (1.60)

*h* = total thickness of the gypsum board, in. (mm)

*D* = heated perimeter in. (mm)

*W´* = total weight of structural steel plus gypsum board in lb/ft (kg/m)

*W* = weight per length lb/ft (kg/m)

For all *W/D* ratios greater than 3.65 (0.215), use the properties of a W 14 x 233 (W 360 x 347) column. The *W´* would then be calculated with the following formula:

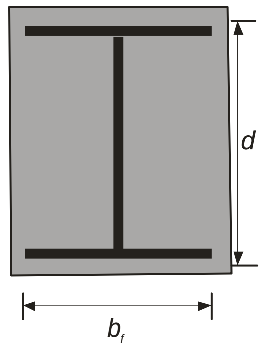
$$W' = 233 + 22.162h \quad (W' = 347 + 1.2976h)$$

If there is a single layer of gypsum wallboard there should be no horizontal joints of the wallboard. If there are multiple layers of wallboard, stagger the joints at least 12 in. (305 mm) and alternate the seams on the corners. For columns to have a 4 h fire resistance rating, cover the gypsum wallboard with a 24 ga (0.06 mm) stainless steel covering. Secure the covering with either a snap lock or

Pittsburgh seam. For columns to have a 3 h fire resistance rating, cover the gypsum wallboard with a 24 ga (0.06 mm) galvanized or stainless steel covering. Secure the covering with either a snap lock or Pittsburgh seam. For columns to have a 2 h or less fire resistance rating, cover the gypsum wallboard with a 23 ga (0.07 mm) galvanized or stainless steel covering. Secure the covering with lap seam and the seam secured with ½ in. (12.7 mm) long No. 8 sheet metal screws spaced 12 in. (305 mm) on center.

**Concrete Encased**

Determination of the fire resistance rating of a structural steel column that is encased by concrete as shown in Figure 6 depends on the type of aggregate used, the cross-sectional area of the column, the flange width and depth of the column.




$D = 2(b_f + d)$

**Figure 6:** Concrete Protected Steel Columns

Use the following formula to determine the fire resistance rating. If lightweight aggregate is used, the density needs to be a minimum of 110 lb/ft³ (1762 kg/m³).

$$R = R_o(1 + 0.03m)$$

Where

$R$ = fire resistance rating at equilibrium moisture conditions in hours

$R_o$ = fire resistance rating at zero moisture conditions in hours

$m$ = equilibrium moisture content of concrete, by volume (%)

$$R_o = 0.17\left(\frac{W}{D}\right)^{0.7} + 0.28\frac{h^{1.6}}{k_c^{\ 0.2}} \times \left[1 + 26\left(\frac{H}{\rho_c c_c (L + h)}\right)\right]^{0.8}$$

$$H = 0.11W + \frac{\rho_c c_c}{144}\left(b_f d - A_s\right)$$

Where

$R_o$ = fire resistance rating at zero moisture conditions in hours

$W$ = weight per length lb/ft

$D$ = heated perimeter in.

$h$ = thickness of the concrete, in.

$k_c$ = ambient temp. thermal conductivity of concrete Btu/h-ft-°F

$H$ = ambient temp. thermal capacity of steel Btu/h-ft-°F

$\rho_c$ = density of concrete lb/ft³

$c_c$ = ambient temp. specific heat of concrete Btu/lb-°F

$L$ = interior dimension of one side of square concrete protection in. $(b_f + d)/2$

$b_f$ = column flange width in.

$d$ = column depth in.

$A_s$ = cross-sectional area of column in.²

SI Units

$$R_o = 1.22\left(\frac{W}{D}\right)^{0.7} + 0.0027\frac{h^{1.6}}{k_c^{\ 0.2}} \times \left[1 + 31{,}000\left(\frac{H}{\rho_c c_c (L+h)}\right)\right]^{0.8}$$

$$H = 0.46W + \frac{\rho_c c_c}{1{,}000{,}000}\left(b_f d - A_s\right)$$

Where

$R_o$ = fire resistance rating at zero moisture conditions in hours

$W$ = weight per length kg/m

$D$ = heated perimeter mm

$h$ = thickness of the concrete mm

$k_c$ = ambient temp. thermal conductivity of concrete W/m-K

$H$ = ambient temp. thermal capacity of steel kJ/m-K

$\rho_c$ = density of concrete kg/m³

$c_c$ = ambient temp. specific heat of concrete kJ/m-K

$L$ = interior dimension of one side of square concrete protection mm $(b_f + d)/2$

$b_f$ = column flange width mm

$d$ = column depth mm

$A_s$ = cross-sectional area of column mm²

The properties of the types of concrete are shown in Table 3.

**TABLE 3**
**Properties of Concrete**

| | Carbonate and Siliceous Aggregate | Lightweight and Sand-Lightweight Aggregate |
|---|---|---|
| Thermal conductivity, $k_c$ | 0.95 Btu/h-ft-°F (1.64 W/m-K) | 0.35 Btu/h-ft-°F (0.61 W/m-K) |
| Specific heat, $c_c$ | 0.20 Btu/lb-°F (0.84 kJ/m-K) | 0.20 Btu/lb-°F (0.84 kJ/m-K) |
| Density, $\rho_c$ | 145 lb/ft³ (2323 kg/m³) | 110 lb/ft³ (1762 kg/m³) |
| Moisture content $m$ | 4 | 5 |

For example, a W 8 x 28 column is encased in carbonate concrete to a thickness of 1½ in (38 mm) the fire resistance rating would be 1.49 h.

$$R = R_o(1 + 0.03m)$$

$$R_o = 0.17\left(\frac{W}{D}\right)^{0.7} + 0.28\frac{h^{1.6}}{k_c^{\ 0.2}} \times \left[1 + 26\left(\frac{H}{\rho_c c_c (L+h)}\right)\right]^{0.8}$$

$$H = 0.11W + \frac{\rho_c c_c}{144}\left(b_f d - A_s\right)$$

Where

$m$ = 4

$W/D$ = 0.67 lb/ft –in.

$A_s$ = 8.25 in.²

$h$ = 1.5 in.

$k_c$ = 0.95 Btu/h-ft-°F

$c_c$ = 0.20 Btu/lb-°F

$\rho_c$ = 145 lb/ft³

$L$ = 7.30 in. $(b_f + d)/2$

$b_f$ = 6.535 in.

$d$ = 8.060 in.

$$H = 0.11 \times 28 + \frac{145 \times 0.2}{144}\left(6.535 \times 8.06 - 8.25\right) = 12.026$$

$$R_o = 0.17\left(0.67\right)^{0.7} + 0.28\frac{1.5^{1.6}}{0.95^{0.2}} \times \left[1 + 26\left(\frac{12.026}{145 \times 0.2\left(7.3 + 1.5\right)}\right)\right]^{0.8} = 1.33$$

$$R = 1.33\left(1 + 0.03 \times 4\right) = 1.49$$

Be careful these equations are for the rating expressed in hours. The constants are different for determining the rating in minutes.

**Beams**

The method for calculating the fire resistance of steel beams is slightly different from columns. The determination of the *D* is different from the column since the top side of the beam will be in contact with the floor/roof assembly. To calculate the heated perimeter (*D*) for two types of protected beam see Figure 7.

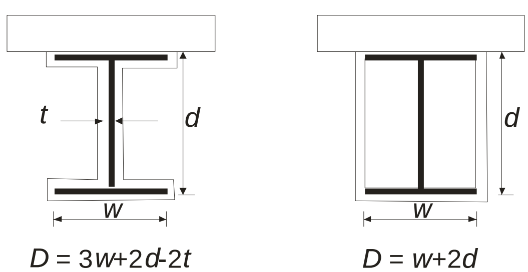



**Figure 7:** *D* Determination for Columns

Beams with larger *W/D* rations can be substituted for a beam listed in a specific tested covering without increasing the required thickness. Beams with different *W/D* ratios can be substituted for a beam listed in a specific tested covering as long as the thickness of the protection is also adjusted using the following formula.

$$h_1 = \left(\frac{W_2/D_2 + 0.6}{W_1/D_1 + 0.6}\right)h_2$$

SI Units

$$h_1 = \left( \frac{W_2/D_2 + 0.036}{W_1/D_1 + 0.036} \right) h_2$$

Where

*W* = weight per length (lb/ft kg/m)

*D* = heated perimeter of the wide-flanged columns (in. mm)

*h* = total thickness of the coating (in.)

Subscript 1 is the substitute beam properties and the required thickness

Subscript 2 is the properties of the listed beam and the listed protection thickness

However the use of this formula has some limitations. They are:

- The *W/D* ratio must be equal to or greater than 0.37 (0.022)
- The *h* thicknesses must be ⅜ in. (9.5 mm) or greater
- Both the restrained and unrestrained beam rating must be at least 1 h.