# AITC TECHNICAL NOTE 7

## FIRE RESISTANCE OF EXPOSED GLUED LAMINATED TIMBERS

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## Introduction

Fire safety is one of the primary considerations for the design and use of buildings. The primary focus of fire-safe design is to ensure that a building's occupants can exit safely in the event of a fire. A structure should also permit rescue activities without disproportionately endangering the lives of the firefighters. As such, building codes typically require increased fire resistance for large structures, for structures intended for large groups of people, and structures with high fire hazard. The building code requirements are based on historical experience, research, and judgment.

Combustibility of the building's structural materials is only one factor when considering fire safety. No structural material is immune to the effects of fire: wood burns, steel softens and buckles, concrete spalls, etc. The duration of time that the structure will continue to function, allowing egress and rescue activities is much more important than the type of building materials or mode of failure. The height and area limitations in the building codes are prescribed with this in mind.

### *Performance of Wood in Fire*

Wood will ignite and burn at temperatures above approximately 500 °F. The residue created by the combustion of wood is referred to as "char." As wood burns, char develops at a rate of approximately 1.5 inches per hour [1]. The growing char layer acts as an insulator, greatly reducing the temperature of the underlying wood surface and protecting the wood beneath the char layer. A typical building fire will reach temperatures of 1290 – 1650 °F, but the interface between the char and the wood will be reduced to approximately 550 °F. Due to the insulating nature of the wood itself, the temperature drops to 360 °F [2] at a distance of ¼ in. ahead of the char front and drops to 210 °F at ½ in. ahead of the char front. The core of the timber remains relatively cool and maintains its ability to carry loads. The capacity of the member is reduced only as the outer layer of material is lost due to the charring.

Although wood burns, large timbers perform well in fires and are recognized for such in the building codes. *Heavy timber construction* (with exposed timbers) is permitted for buildings of larger heights and areas than for Type $II_B$ (unrated, noncombustible construction), and is permitted for similar size buildings as those of Type $II_A$ (one-hour fire-rated, noncombustible construction). Exposed timbers can also be designed for one-hour fire-resistance ratings where required in Types $III_A$ and $V_A$ fire-resistance-rated construction.

### *Heavy Timber Construction*

The inclusion of Heavy Timber Construction in the building codes is based on excellent historical performance in building fires. While individual members do not necessarily meet the requirements for one-hour fire-rated construction, the system as a whole (including the exclusion of concealed spaces and minimum timber sizes) performs very well. Based on its excellent record, *Heavy timber construction* roof systems are permitted to be used in all construction types that otherwise require a 1-hour or less fire-resistance-rated roof (IBC Table 601, Footnote c and 603.1.18 [3]).

Structural glued laminated timber is permitted to be used in *heavy timber construction*. Equivalent net finished widths and depths for glulam members corresponding to the minimum nominal widths and depths of solid sawn lumber are tabulated in the IBC [3]. These minimum dimensions were selected based on comparable dimensions and equivalent cross-sectional areas. The values in the table reflect the fact that glulam dimensions do not generally match the dimensions of solid-sawn timbers.

### *Fire-Resistance-Rated Construction*

Fire-resistance-rated construction requires structural components and assemblies to meet defined fire performance standards. Rather than prescribing minimum sizes and eliminating concealed spaces, structural elements are assigned a specific fire-resistance rating based on approved tests or analysis procedures based on tests. IBC 2009 [3] defines *fire-resistance rating* as “The period of time a building element, component or assembly maintains the ability to confine a fire, continues to perform a given structural function, or both, as determined by the tests, or the methods based on tests, prescribed in Section 703.”

For a structural beam or column, a fire-resistance rating of one hour means that the member is expected to support its loads for at least an hour during a fire event. For a non-load-bearing partition wall, a fire-resistance rating of one hour means that a fire should not breach the wall for at least one hour. One-hour-rated load-bearing walls and floors should support their loads *and* prevent passage of fire for at least one hour.

## Fire-Resistance-Rating of Unprotected Timber Members

Unprotected timber members can be used in fire-resistance-rated construction. Provisions for designing fire-resistance-rated timber members are included in the *National Design Specification® (NDS®) for Wood Construction* [4]. The *NDS®* procedure includes provisions for 1-1/2-hour and 2-hour fire-rated members. Development of the *NDS®* procedure is detailed in AWC Technical Report 10 *Calculating the Fire Resistance of Exposed Wood Members* [1].

### *Section Loss*

When a timber member is exposed to fire, material is lost from the surfaces due to charring (**Figure 1**). The strength of the heated wood just ahead of the char front is also reduced. The net effect of the charring and heat is a reduction in the effective section properties (area, section modulus, moment of inertia) of the member. The rate of material loss can be adequately predicted, so the capacity of the remaining section can be calculated based on the member's required fire-resistance rating. The thickness lost to charring and heating of the wood is referred to as the *effective char layer thickness* and is illustrated in **Figure 2** for timbers exposed on three or four sides to fire.

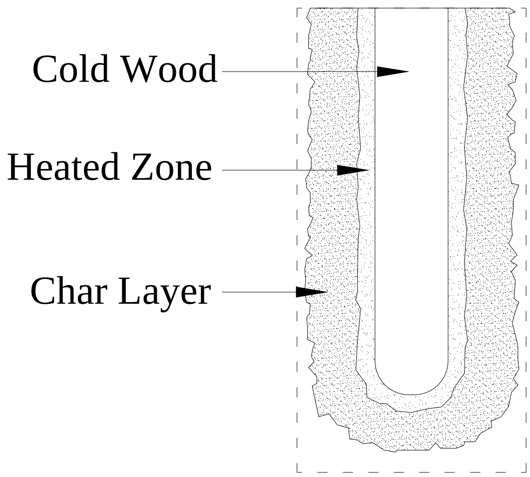



**Figure 1.** Charring of a wood member exposed to fire on three sides.

The effective char layer thickness for fires of 1-hour, 1½-hours, and 2 hours from the NDS are given in **Table 1**. These values were calculated based on a nominal char rate of 1½ in. per hour and account for some damage from heat ahead of the actual char front.

**Table 1** Effective Char Layer Thicknesses

| **Required Fire-Resistance Rating (hr)** | **Effective Char Layer Thickness, $a_{char}$ (in.)** |
|---|---|
| 1-hour | 1.8 |
| 1½-hour | 2.5 |
| 2-hour | 3.2 |

For three-sided fire exposure the dimensions at the end of the fire are estimated using Equations 1 and 2.

$$b_{fire} = b - 2a_{char} \quad (1)$$

$$d_{fire} = d - a_{char} \quad (2)$$

For four-sided fire exposure, the dimensions at the end of the fire are estimated using Equations 3 and 4.

$$b_{fire} = b - 2a_{char} \quad (3)$$

$$d_{fire} = d - 2a_{char} \quad (4)$$

The section properties at the end of the fire are calculated using Equations 5 through 7.

$$A_{fire} = b_{fire} d_{fire} \tag{5}$$

$$S_{fire} = \frac{b_{fire} d_{fire}^2}{6} \tag{6}$$

$$I_{fire} = \frac{b_{fire} d_{fire}^3}{12} \tag{7}$$

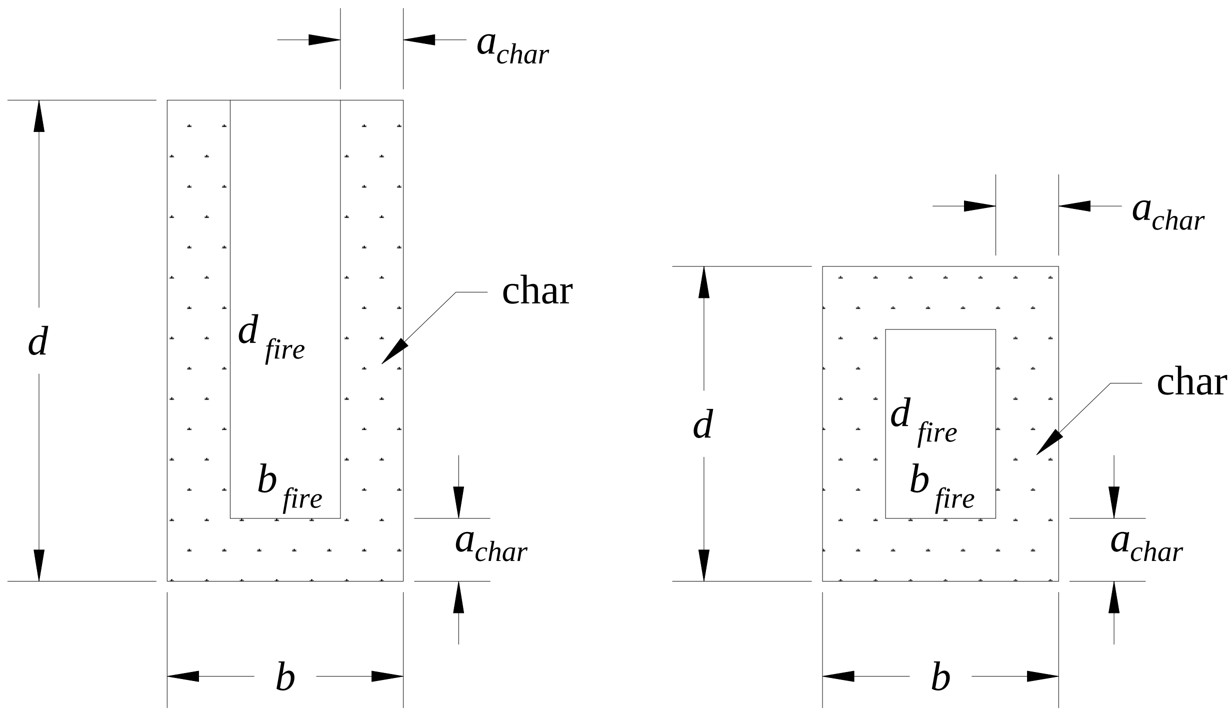



**Figure 2** Effective dimensions of members exposed to fire: prior to fire ($b, d$), after fire ($b_{fire}, d_{fire}$).

***Design Values***

Published design values for timber design (cold) include factors of safety and adjustment to 10-year (normal) load duration. As such, the average ultimate strength of glulam beams in testing is significantly higher than the published design value. The average ultimate strength of glulam can be estimated as 2.95 times the published (ASD) reference design value for bending [5]. Due to higher variability in sawn timbers, the expected average ultimate strength is more than three times the published ASD reference design value.

For fire endurance calculations, design stresses are increased to a level close to the expected average ultimate strength. Equations 8 through 13 show the design strengths used to calculate the fire endurance of timber members. Note that load duration effects are already included in the factors, therefore, the load duration factor is not applied separately for fire design.

$$F'_{bx\ fire} = 2.85F_{bx}\left(C_v \text{ or } C_L\right) \quad (8)$$

$$F'_{by\ fire} = 2.85F_{by}\left(C_{fu} \text{ or } C_L\right) \quad (9)$$

$$F'_{t\ fire} = 2.85F_t \quad (10)$$

$$F'_{c\ fire} = 2.58F_c C_P \quad (11)$$

$$F'_{bE\ fire} = 2.03F_{bE\ fire} \quad (12)$$

$$F'_{cE\ fire} = 2.03F_{cE\ fire} \quad (13)$$

where: $C_V$ and $C_{fu}$ are calculated based on pre-fire dimensions
$C_L$ and $C_P$ are calculated based on post-fire dimensions
$F_{bE\ fire}$ and $F_{cE\ fire}$ are calculated based on post-fire dimensions

***Member Capacity***

The expected member capacities in bending, tension and compression at the end of the fire event are calculated using Equations 14 through 17.

$$M'_{x\ fire} = F'_{bx\ fire} S_{x\ fire} = 2.85F_{bx}\left(C_v \text{ or } C_L\right)\frac{b_{fire} d_{fire}^2}{6} \quad (14)$$

$$M'_{y\ fire} = F'_{by\ fire} S_{y\ fire} = 2.85F_{by}\left(C_{fu} \text{ or } C_L\right)\frac{d_{fire} b_{fire}^2}{6} \quad (15)$$

$$T'_{fire} = F'_{t\ fire} A_{fire} = 2.85F_t b_{fire} d_{fire} \quad (16)$$

$$P'_{fire} = F'_{c\ fire} A_{fire} = 2.58F_c C_P b_{fire} d_{fire} \quad (17)$$

***Glulam Lay-up Modifications***

Structural glued laminated timber members are commonly manufactured with the highest quality laminations placed at the outer surfaces and with decreasing quality permitted as the laminations get closer to the core. In the event of a fire, the outer laminations are destroyed first. To prevent a loss of design strength, such members require lay-up modifications.

For a one-hour fire-resistance-rated member, one nominal two-inch thick lamination is removed from the core of the beam (lowest grade zone) and another nominal two-inch thickness surface-quality lamination is placed at the surface that will be exposed to fire (**Figure 3**) [6]. For timbers that will be exposed to fire on all four sides, two core laminations are removed and additional high-grade laminations are placed at both surfaces (i.e. top and bottom). For 1-1/2 or 2-hour rated beams, two additional high-quality laminations are added to each top or bottom face that will be exposed to fire, with the same number of lower grade laminations removed from the core (**Figure 3**).

Timbers that have been appropriately modified are marked by the manufacturer with the appropriate fire-resistance rating. Lay-up modifications are not required for glulam timbers used to meet the prescriptive requirements of *heavy timber construction*.

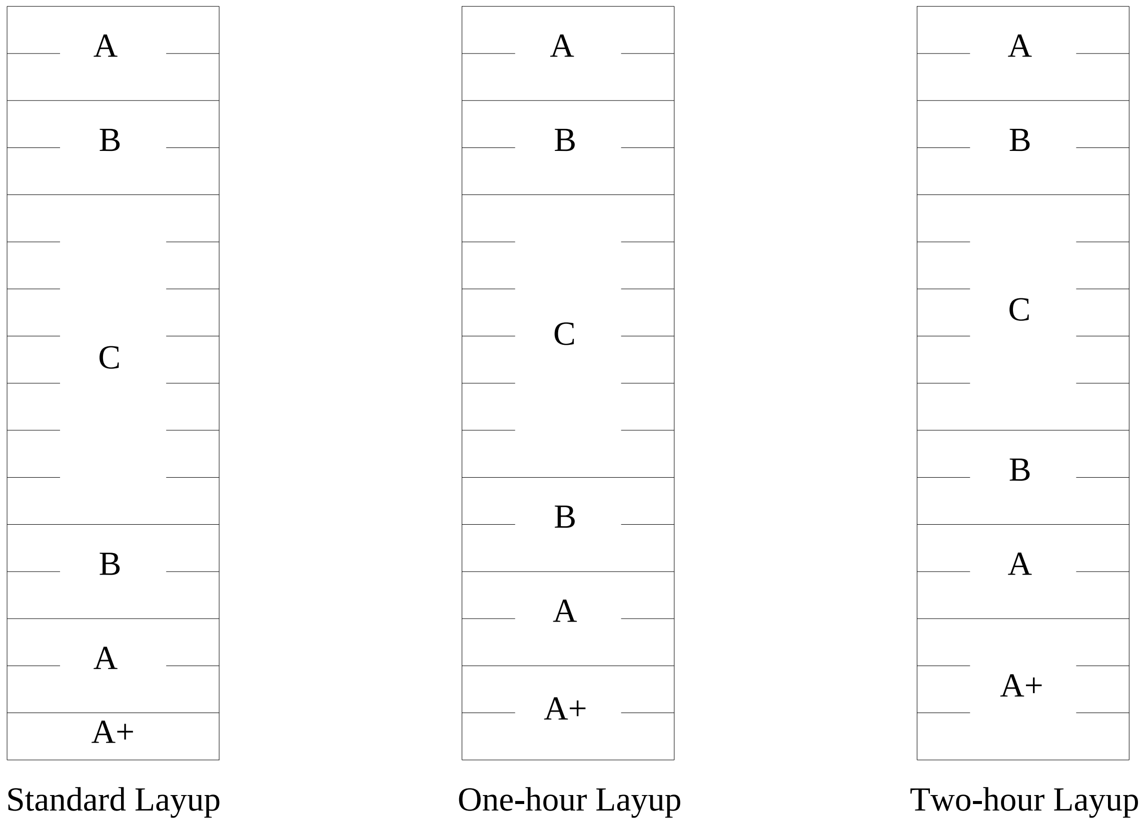



**Figure 3.** Lay-up modifications for fire-resistance-rated beams (fire on three sides). Letters represent relative quality of laminations with C as the lowest; they are not actual grade designations.

### *Loads for Fire Design*

Traditionally, engineers have applied the full allowable stress design gravity load when designing for fire-resistance ratings. Members and assemblies are tested under full allowable design load, while exposed to standardized fire conditions. Members or systems that can support their full design load throughout the required time period have been “deemed to comply” for fire-resistance ratings of the same or lesser time.

Recently, however, load combinations for extraordinary events, such as fire, have been developed and published in ASCE 7 [7]. These load combinations were developed based on a probabilistic analysis similar to that used to develop other LRFD load combinations. Additionally, there is a trend toward better defining the fire behavior of structures. It is expected that new design procedures will be developed for fire design of timber members using the load combinations for extraordinary events, however, such procedures are not currently available.

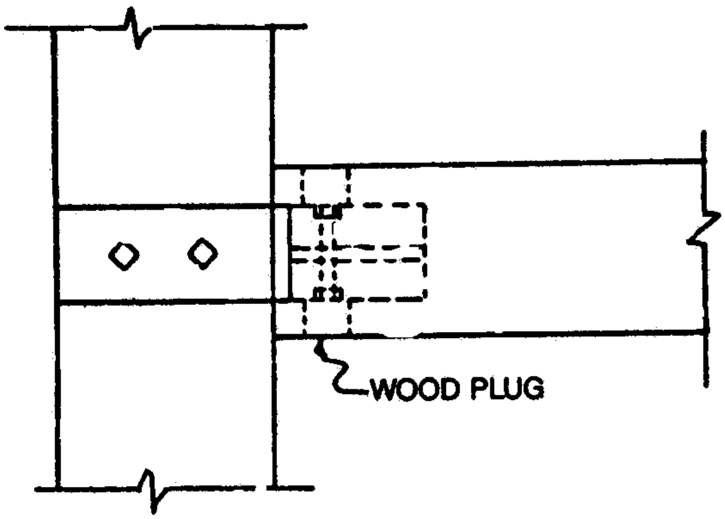
### *Use of Standard Glulam Beams in Fire Rated Construction*

At times, the designer may be called upon to evaluate the fire-resistance-rating of a glulam member with a standard or stock layup (not modified for fire exposure). Members manufactured without the modified lay-up are subject to lesser post-fire design values due to the un-replaced loss of high grade material. The reduced design stress for a standard or stock glulam beam with one lamination notionally removed (i.e. resulting from a one-hour fire) from the bottom of the beam can be estimated as 70% of the original design stress of the member. This reduced design stress should be used when evaluating the fire resistance rating of off-the-shelf or stock glulam beams. This procedure is limited to fire-resistance ratings of one-hour or less and fire exposure from the bottom (three-sides) only. Due to the reduction in design strength, stock lay-ups are necessarily less efficient than beams that have been specifically modified for one-hour fire resistance.

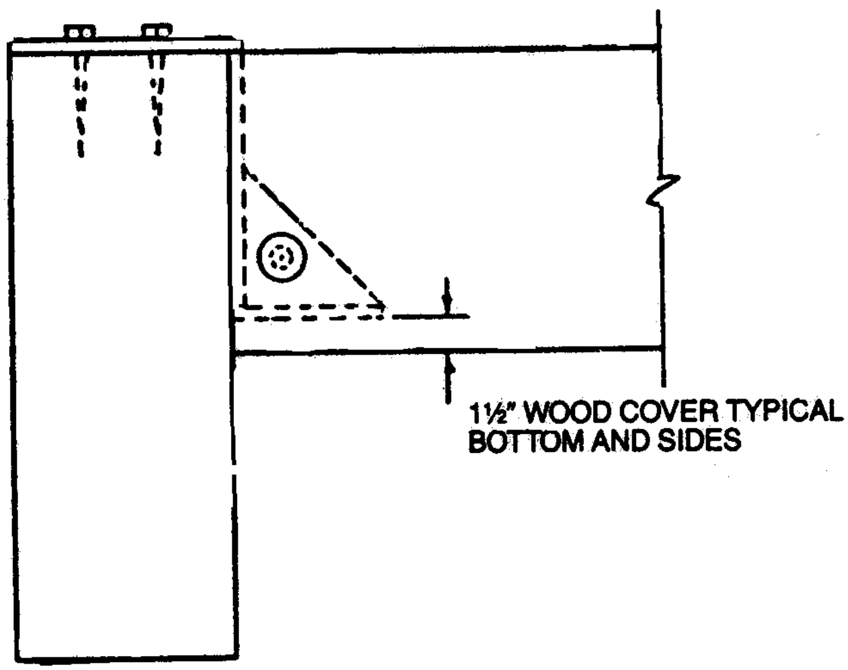
### *Protection of Metal Fasteners*

For fire-resistance-rated construction, both the members and the fasteners must be designed and constructed to achieve the required fire-resistance rating. Where minimum 1-hour fire resistance is required, connectors and fasteners must be protected from fire exposure by 1½ inches of wood, or other approved covering or coating for a 1-hour rating as shown in **Figures 4 through 9**.

Where the designer does not want to encase the steel connections with wood or otherwise conceal them, intumescent paints may be permitted for use as protection for structural steel members subject to approval by the building official. These paints foam when subjected to the high heat of fires, providing insulation to the metal components. Information regarding the appropriate coating thickness should be obtained from the coating manufacturer.




PLAN VIEW




ELEVATION

**Figure 4.** Concealed beam-to-girder connection..

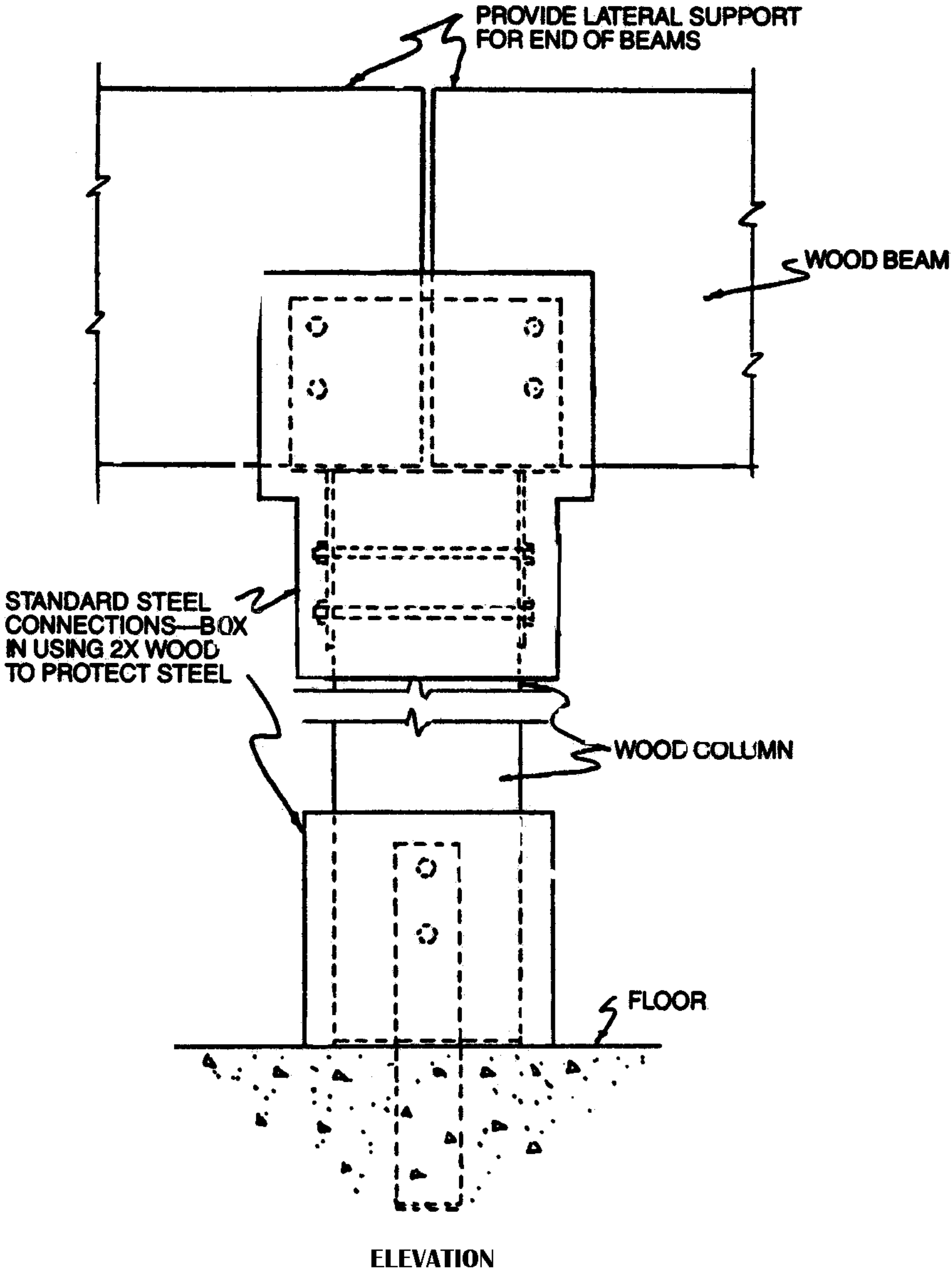



**Figure 5.** Covered column connection.

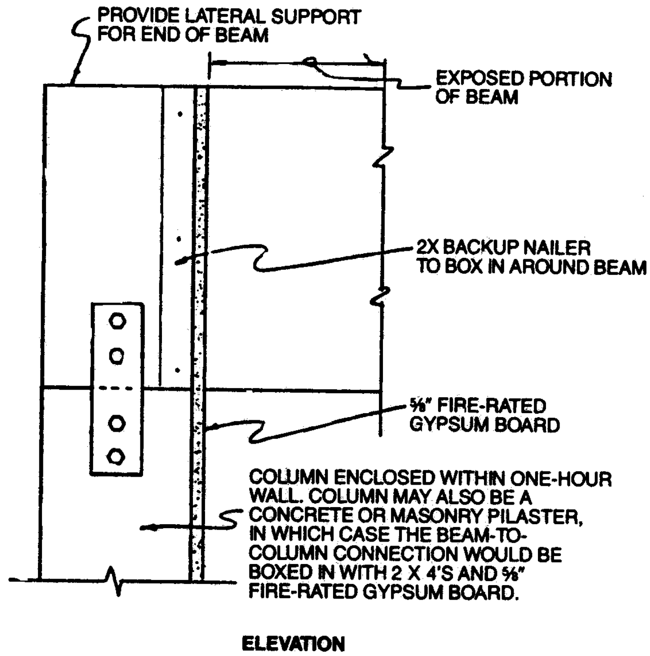



**Figure 6.** Beam-to-column connection with connection protected by wall membrane.

**FIGURE 6**

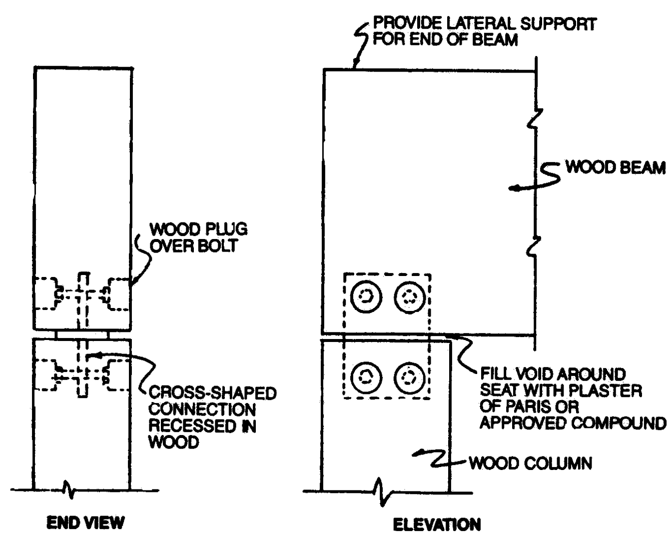



**Figure 7.** Concealed beam-to-column connection.

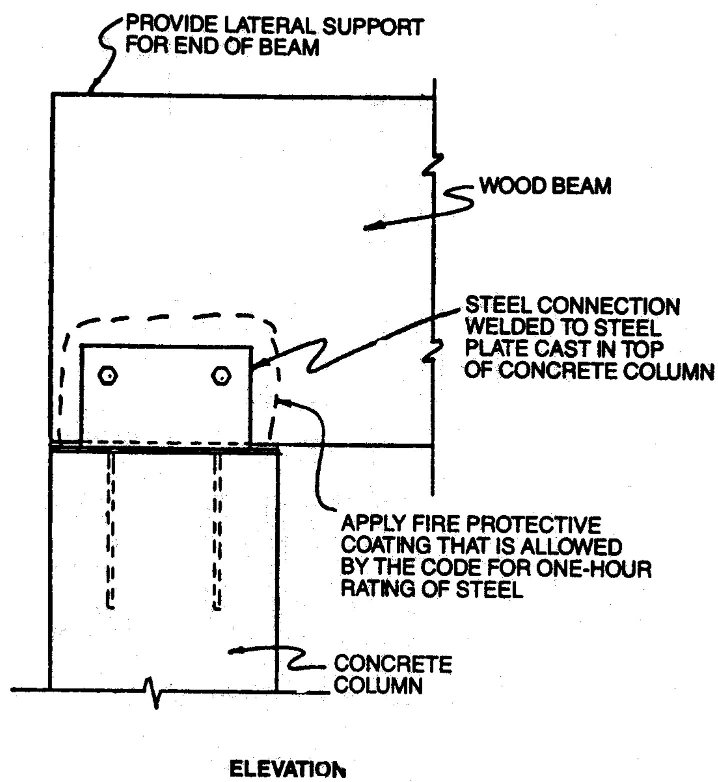



**Figure 8.** Beam-to-column connection where steel has fire-protective coating.

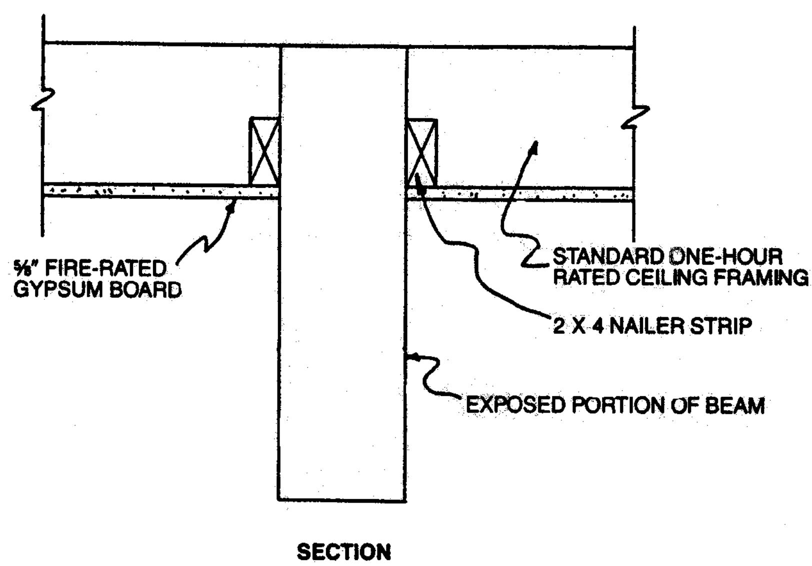



**Figure 9.** Glulam beam supporting one-hour rated ceiling.

## Example 1: Analysis of Glulam Beam for One-Hour-Fire Rating

**<u>Given</u>:** A 6-3/4 in. x 13-1/2 in. 24F-V4 DF simply-supported glulam beam spans 20 ft and supports a one-hour-fire-resistance-rated floor assembly. The attachment to the floor above provides lateral support to the top of the beam. The layup of the beam has been modified, and the beam has been marked for a one-hour fire-resistance rating. The beam will be exposed to fire on 3 sides.

**<u>Wanted</u>:** Determine the maximum load that the beam can be expected to support for the duration of the one-hour design fire.

**<u>Solution</u>:**

**Post-fire dimensions – 3 sided exposure (Equations 1 and 2):**

$$b_{fire} = b - 2a_{char}$$

$$b_{fire} = 6.75\text{ in} - 2(1.8\text{ in}) = 3.15\text{ in}$$

$$d_{fire} = d - a_{char}$$

$$d_{fire} = 13.5\text{ in} - (1.8\text{ in}) = 11.7\text{ in}$$

**Beam stability factor:**

The beam will be assumed to be laterally braced along the compression edge through the fire while supporting the floor, so, $C_L = 1.0$.

**Volume factor (pre-fire dimensions):**

$$C_V = \left(\frac{5.125\text{ in}}{6.75\text{ in}}\right)^{\frac{1}{10}} \left(\frac{12\text{ in}}{13.5\text{ in}}\right)^{\frac{1}{10}} \left(\frac{21\text{ ft}}{19\text{ ft}}\right)^{\frac{1}{10}} = 0.971$$

**Post-fire bending capacity (Equation 14):**

$$M'_{x\,fire} = F'_{bx\,fire} S_{x\,fire} = 2.85 F_{bx} \left(C_v \text{ or } C_L\right) \frac{b_{fire} d_{fire}^2}{6}$$

$$M'_{x\,fire} = 2.85(2400\text{ psi})(0.971) \frac{(3.15\text{ in})(11.7\text{ in})^2}{6}$$

$$M'_{x\,fire} = 477{,}300\text{ in-lb}$$

**Maximum load at end of one-hour fire:**

$$\omega = \frac{8M_{x\,fire}}{L^2} = \frac{8(477{,}300\text{ in} - \text{lb})}{(240\text{ in})^2} = 66.3\ \frac{\text{lb}}{\text{in}} = 796\ \frac{\text{lb}}{\text{ft}}$$

**<u>Result</u>:** The glulam beam is expected to support a load of 796 lb/ft throughout a one-hour design fire, provided that the beam is manufactured with a one-hour-fire lay-up.

## Example 2: Analysis of Stock Glulam Beam for One-Hour-Fire Rating

**Given:** A 6-3/4 in. x 17-7/8 in. 24F-V3 SP simply-supported glulam beam spans 27 ft and supports a one-hour-fire-resistance-rated floor assembly. The attachment to the floor above provides lateral support to the top of the beam. The layup of the beam has *not* been modified, and the beam has *not* been marked for a one-hour fire-resistance rating. The beam will be exposed to fire on 3 sides.

**Wanted:** Determine the maximum load that the beam can be expected to support for the duration of the one-hour fire.

**Solution:**

**Post-fire dimensions – 3 sided exposure (Equations 1 and 2):**

$$b_{fire} = b - 2a_{char}$$

$$b_{fire} = 6.75\text{ in} - 2(1.8\text{ in}) = 3.15\text{ in}$$

$$d_{fire} = d - a_{char}$$

$$d_{fire} = 17.875\text{ in} - (1.8\text{ in}) = 16.1\text{ in}$$

**Beam stability factor:**

The beam will be assumed to be laterally braced along the compression edge through the fire while supporting the floor, so, $C_L = 1.0$.

**Volume factor (pre-fire dimensions):**

$$C_V = \left(\frac{5.125\text{ in}}{6.75\text{ in}}\right)^{\frac{1}{20}} \left(\frac{12\text{ in}}{17.875\text{ in}}\right)^{\frac{1}{20}} \left(\frac{21\text{ ft}}{27\text{ ft}}\right)^{\frac{1}{20}} = 0.955$$

**Post-fire bending capacity (Equation 14):**

$$M'_{x\ fire} = F'_{bx\ fire} S_{x\ fire} = 2.85 F_{bx} \left(C_v \text{ or } C_L\right) \frac{b_{fire} d_{fire}^2}{6}$$

$$M'_{x\ fire} = 2.85(0.7)(2400\text{ psi})(0.955)\frac{(3.15\text{ in})(16.1\text{ in})^2}{6}$$

$$M'_{x\ fire} = 622,300\text{ in-lb}$$

**Maximum load at end of one-hour fire:**

$$\omega = \frac{8M_{x\ fire}}{L^2} = \frac{8(622,300\text{ in} - \text{lb})}{(324\text{ in})^2} = 47.4\ \frac{\text{lb}}{\text{in}} = 569\ \frac{\text{lb}}{\text{ft}}$$

**Result:** The stock glulam beam is expected to support a load of 569 lb/ft throughout a one-hour fire.

## Example 3: Analysis of Glulam Column for One-Hour-Fire Rating

**<u>Given</u>:** A 8-1/2 in. x 8-1/4 in., Combination 47 SP column with an effective length of 14 ft supports a one-hour-fire-resistance-rated floor assembly. The column will be exposed to fire on all four sides.

**<u>Wanted</u>:** Determine the maximum load that the column can be expected to support for the duration of the one-hour design fire.

**<u>Solution</u>:**

**Post-fire dimensions – 4 sided exposure (Equations 3 and 4):**

$$b_{fire} = b - 2a_{char}$$

$$b_{fire} = 8.5 \text{ in} - 2(1.8 \text{ in}) = 4.9 \text{ in}$$

$$d_{fire} = d - 2a_{char}$$

$$d_{fire} = 8.25 \text{ in} - 2(1.8 \text{ in}) = 4.65 \text{ in}$$

**Critical buckling design value – post-fire dimensions (Equation 13):**

$$F'_{cE\text{ fire}} = 2.03\left(\frac{0.822E_{\min}}{\left(L_e/d_{fire}\right)^2}\right) = \frac{(2.03)0.822\left(0.74\left(10^6\right)\text{ psi}\right)}{\left((168\text{ in})/(4.65\text{ in})\right)^2} = 1280\text{ psi}$$

$$F^*_{c\,fire} = 2.58F_c = 2.58(1900\text{ psi}) = 4900\text{ psi}$$

**Column Stability Factor:**

$$C_P = \frac{1+\left(F'_{cE}/F_{c\,fire}\right)}{2c} - \sqrt{\left[\frac{1+\left(F'_{cE}/F_{c\,fire}\right)}{2c}\right]^2 - \frac{F'_{cE}/F_{c\,fire}}{c}}$$

$$C_P = \frac{1+\left(\frac{1280\text{ psi}}{4900\text{ psi}}\right)}{2(0.9)} - \sqrt{\left[\frac{1+\left(\frac{1280\text{ psi}}{4900\text{ psi}}\right)}{2(0.9)}\right]^2 - \frac{\frac{1280\text{ psi}}{4900\text{ psi}}}{(0.9)}}$$

$$C_P = 0.253$$

**Post-fire compression capacity:**

$$P'_{fire} = F'_{c\,fire}A_{fire}$$

$$P'_{fire} = 2.58F_cC_Pb_{fire}d_{fire}$$

$$P'_{fire} = 2.58(1900\text{ psi})(0.253)(4.9\text{ in})(4.65\text{ in})$$

$$P'_{fire} = 34{,}300\text{ lb}$$

**<u>Result</u>:** The glulam column can support a load of 34,300 lb for a one-hour fire.

## Example 4: Analysis of Glulam Column for One-Hour-Fire Rating

**<u>Given</u>:** A 10-3/4 in. x 12 in., Combination 2 DF column with an effective length of 20 ft supports a one-hour-fire-resistance-rated roof assembly. The column will be exposed to fire on all four sides.

**<u>Wanted</u>:** Determine the maximum load that the column can be expected to support for the duration of the one-hour design fire.

**<u>Solution</u>:**

**Post-fire dimensions – 4 sided exposure (Equations 3 and 4):**

$$b_{fire} = b - 2a_{char}$$

$$b_{fire} = 10.75\text{ in} - 2(1.8\text{ in}) = 7.15\text{ in}$$

$$d_{fire} = d - 2a_{char}$$

$$d_{fire} = 12.0\text{ in} - 2(1.8\text{ in}) = 8.40\text{ in}$$

**Critical buckling design value – post-fire dimensions (Equation 13):**

$$F'_{cE\text{ fire}} = 2.03\left(\frac{0.822E_{\min}}{\left(L_e/b_{fire}\right)^2}\right) = \frac{(2.03)0.822\left(0.84\left(10^6\right)\text{ psi}\right)}{\left((240\text{ in})/(7.15\text{ in})\right)^2} = 1240\text{ psi}$$

$$F^*_{c\ fire} = 2.58F_c = 2.58(1950\text{ psi}) = 5030\text{ psi}$$

**Column Stability Factor:**

$$C_P = \frac{1+\left(F'_{cE}/F_{c\ fire}\right)}{2c} - \sqrt{\left[\frac{1+\left(F'_{cE}/F_{c\ fire}\right)}{2c}\right]^2 - \frac{F'_{cE}/F_{c\ fire}}{c}}$$

$$C_P = \frac{1+\left(\dfrac{1240\text{ psi}}{5030\text{ psi}}\right)}{2(0.9)} - \sqrt{\left[\frac{1+\left(\dfrac{1240\text{ psi}}{5030\text{ psi}}\right)}{2(0.9)}\right]^2 - \frac{\dfrac{1240\text{ psi}}{5030\text{ psi}}}{(0.9)}}$$

$$C_P = 0.239$$

**Post-fire compression capacity:**

$$P'_{fire} = F'_{c\ fire}A_{fire}$$

$$P'_{fire} = 2.58F_cC_Pb_{fire}d_{fire}$$

$$P'_{fire} = 2.58(1950\text{ psi})(0.239)(7.15\text{ in})(8.40\text{ in})$$

$$P'_{fire} = 72{,}200\text{ lb}$$

**<u>Result</u>:** The glulam column can support a load of 72,200 lb for a one-hour fire.

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