codes & standards

Calculating the Fire Resistance of Exposed Wood Members

By Bradford K. Douglas, P.E.

Large wood members have long been recognized for their ability to maintain structural integrity while exposed to fire. Early mill construction from the 19th century utilized massive timbers to carry large loads and to resist structural failure from fire. Exposed wood structural members are popular with architects and designers of modern buildings because they have a pleasing appearance, are economical and easy to use, and provide necessary fire endurance. Glued laminated (glulam) members are now commonly used where large sections and long spans are needed. Glulam members offer the same fire performance advantages as large solid sawn members.

The superior fire performance of heavy timbers can be attributed to the charring effect of wood. As wood members are exposed to fire, an insulating char layer is formed that protects the core. Thus, beams and columns can be designed so that a sufficient cross section of wood remains to sustain the design loads for the required duration of fire exposure. A standard fire exposure is used for design purposes.

Concepts of Heavy Timber Fire Design

At fire exposure time *t*, the initial breadth, *B*, and depth, *D*, of a member are reduced to *b* and *d*, respectively. This is illustrated in *Figure 1* for a section of a beam exposed on three sides. The original section is rectangular. However, since the corners are subject to heat transfer from two directions, charring is faster at these corners. This has the effect of rounding the corners; therefore, shortly after ignition, the remaining cross section is no longer rectangular. The boundary between the char layer and the remaining wood section is quite distinct, and corresponds to a temperature of approximately 550˚F. The remaining wood section is heated over a narrow region that extends approximately 1.5-inches from the char front. The inner core of the remaining wood section is at ambient (or initial) temperature. A section smaller than the original section is capable of supporting the design load because of the safety margin provided in cold design. The original section is stressed only to a fraction of the maximum capacity. Failure occurs when the remaining cross section is stressed beyond the maximum capacity.

For members stressed in bending during fire exposure, failure occurs when bending capacity is exceeded due to the reduction in section modulus, *S*. For members stressed in tension parallel-to-grain during fire exposure, failure occurs when tension capacity is exceeded due to the reduction in cross-sectional area, *A*.

For members stressed in compression parallel-to-grain during fire exposure, the failure mode is a function of the column slenderness ratio, (L_e/D). The column slenderness ratio changes with exposure time. For short column members ($L_e/D \approx 0$) stressed in compression during fire exposure, failure occurs when compressive capacity is exceeded due to the reduction in cross-sectional area, *A*. For long column members ($L_e/D \approx \infty$) stressed in compression during fire exposure, failure occurs when critical buckling capacity is exceeded due to the reduction in the moment of inertia, *I*. Current code-accepted design procedures in the *2001 National Design Specification® (NDS®) for Wood Construction* (AF&PA, 2001) and the *1996 Standard for Load and Resistance Factor Design (LRFD) for Engineered Wood Construction* (ASCE, 1996) contain a single column equation which is used to calculate a stability factor, C_p, which approximates the column capacity for all slenderness ratios based on the calculated interaction of theoretical short and long column capacities.

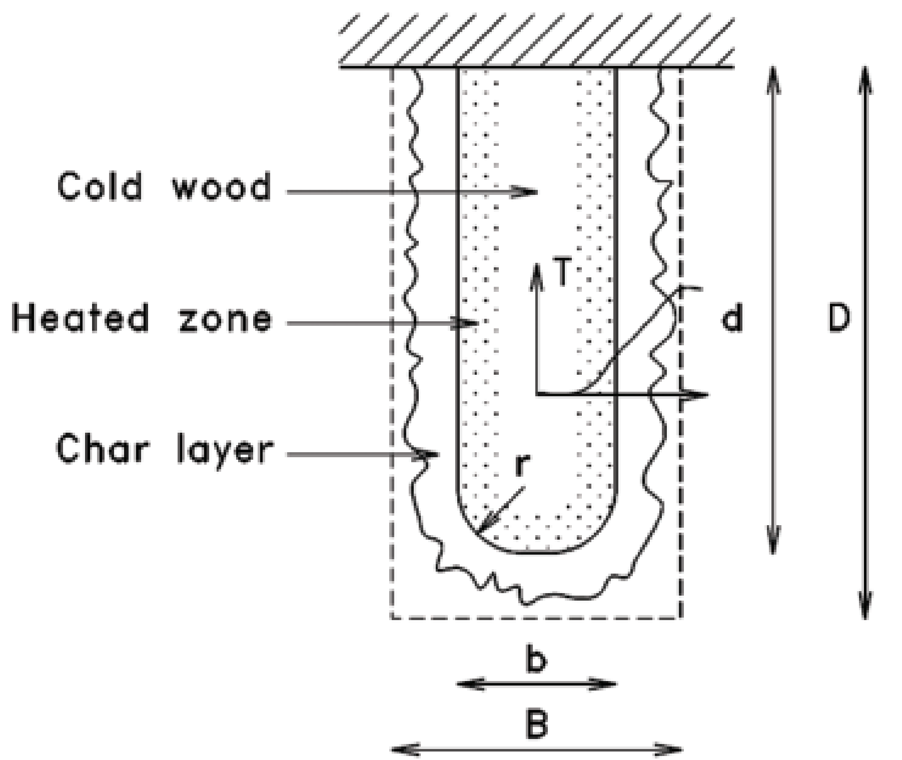

Figure 1: Wood member exposed from 3 sides

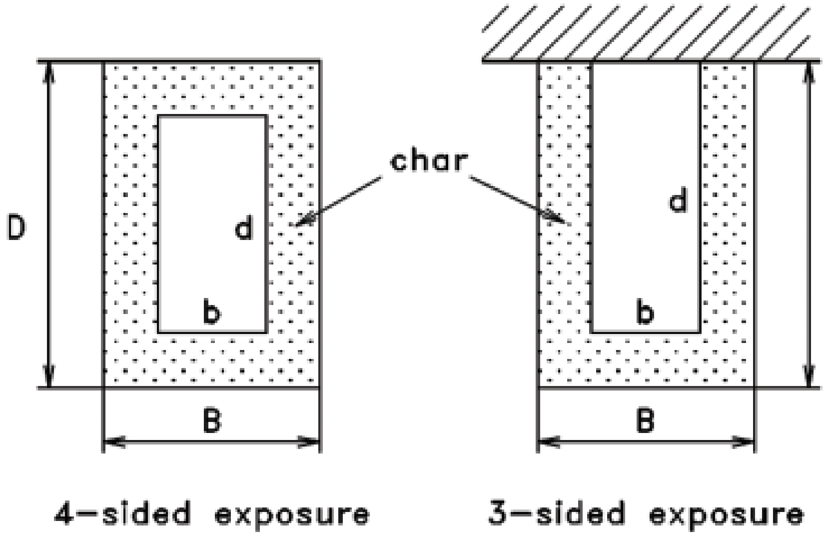

Figure 2: Symbols for cross-sectional dimensions

Current Empirical Design Method

The current building code-accepted design method for fire-resistive exposed wood members used in North America is based on analysis conducted by T.T. Lie at the National Research Council of Canada in the 1970's (Lie, 1977). The empirical method was first recognized by the U.S. model building codes in 1984 through a Council of American Building Official (CABO) National Evaluation Board Report (NEB, 1984). In subsequent years, the method was adopted directly into the building codes by the three model code organizations, allowing engineers and architects to include fire-rated heavy timber members in their projects without conducting expensive standard fire resistance tests.

Lie assumed a charring rate of 1.42 in/hr, and accounted for a reduction in strength and stiffness due to heating of a small zone progressing approximately 1.5 in. ahead of the char front. Lie reported that studies showed that the ultimate strength and stiffness of various woods, at temperatures that uncharred wood normally reaches in fires, reduces to about 0.85-0.90 of the original strength and stiffness. To account for this effect, reductions to strength and stiffness properties were implemented by uniformly reducing strength and stiffness values over the remaining cross section by a factor α. Furthermore, a factor k was introduced to account for the ratio of design strength to ultimate strength. To obtain conservative estimates, Lie recommended a k factor of 0.33 based on a safety factor of 3, and an α factor of 0.8 to account for strength and stiffness reductions.

Lie ignored increased rate of charring at the corners, and assumed that the remaining section is rectangular. With this assumption, initial breadth B and depth D of a member after t minutes of fire exposure are reduced to b and d respectively, as shown in *Figure 2*. Both b and d are a function of exposure time, t, and charring rate, β.

New Mechanics-based Design Method

The method for calculating the fire endurance of exposed, large wood members, developed by Lie, is based on actual fire test results and sound engineering. However, the final prediction equations are based on empirical solutions fit to beam and column test data; therefore, application of the current method is limited. A new mechanics-based design method was deemed necessary to permit the calculation of fire endurance for exposed, large wood members for other loading conditions and fire exposures not considered by Lie. As a result, a new mechanics-based design method has been developed and verified in a publication entitled *Technical Report 10: Calculating the Fire Resistance of Exposed Wood Members* (AF&PA, 2003).

The new mechanics-based design procedure calculates the capacity of exposed wood members using basic wood engineering mechanics. Actual mechanical and physical properties of the wood are used and member capacity is directly calculated for a given period of time. Section properties are computed assuming an effective char rate, β_{eff}, at a given time, t. Reductions of strength and stiffness of wood directly adjacent to the char layer are addressed by accelerating the char rate 20%. Average member strength properties are approximated from existing accepted procedures used to calculate design properties. Finally, wood members are designed using accepted engineering procedures found in *NDS* for allowable stress design.

Char Rate - The effective char rate to be used in this procedure can be estimated from published nominal one-hour char rate data using the following equation:

$$\beta_{eff} = \frac{1.2\beta_n}{t^{0.187}}$$

Where;

β_{eff} = Effective char rate (in/hr), adjusted for exposure time, t

β_n = Nominal char rate (in/hr), linear char rate based on 1-hour exposure

t = Exposure time (hrs)

A nominal char rate, β_n, of 1.5 inches/hour is commonly assumed for solid-sawn and glued-laminated softwood members. For β_n = 1.5 inches/hour, the effective char rates, β_{eff}, and effective char layer thicknesses, a_{char}, for each exposed surface are shown in *Figure 3*.

Figure 3

Effective Char Rates and Char Layer Thicknesses (for β_n = 1.5 inches/hour)

Required Fire Endurance (hr)	Effective Char Rate, β_{eff} (in/hr)	Effective Char Layer Thickness, a_{char} (in)
1-Hour	1.80	1.8
1 1/2-Hour	1.67	2.5
2-Hour	1.58	3.2

Section properties can be calculated using standard equations for area, section modulus and moment of inertia using reduced cross-sectional dimensions. Dimensions are reduced by the effective char layer thickness, a_{char}, for each surface exposed to fire.

Approximation of Member Strength and Capacity - For fire design, the estimated member capacity is evaluated against the loss of cross-section and mechanical properties as a result of fire exposure. While the loss of cross-section and mechanical properties are addressed by reducing the section properties using the effective char layer thickness, the average member strength properties must be determined from published allowable design stresses. The average member capacity of a wood member exposed to fire for a given time, *t*, can be estimated using the average member strength and reduced cross-sectional properties. For solid-sawn and glued-laminated wood members, the average member capacity can be approximated by multiplying the allowable design capacity, *R*, by the following factors, *K*, as shown in *Figure 4*.

Allowable Design Stress to Average Ultimate Strength Adjustment Factor	
Member Capacity	*K*
Bending Moment Capacity, in-lbs.	2.85
Tensile Capacity, lbs.	2.85
Compression Capacity, lbs.	2.58
Beam Buckling Capacity, lbs.	2.03
Column Buckling Capacity, lbs.	2.03

Figure 4

Axial/bending interactions can be calculated using this procedure. All member strength and cross-sectional properties should be adjusted prior to solving the interaction calculations. The interaction calculations should then be conducted in accordance with appropriate *NDS* provisions.

Design of Members - Once member capacity has been determined using effective section properties and member strength approximations, the wood member can be designed using accepted *NDS* design procedures for the following loading condition:

$D + L \leq K\,R_{ASD}$

Where:

D = Design dead load

L = Design live load

R_{ASD} = Nominal allowable design capacity

K = Factor to adjust from nominal design capacity to average ultimate capacity

Design Procedures for Timber Decks - By code, timber decks consist of planks that are at least 2 in. thick. The planks span the distance between supporting beams, and can be arranged in different ways depending on available lengths. Usually, a single or double tongue-and-groove joint is used to connect adjoining planks, but splines or butted joints are also common.

In order to meet requirements for a given fire resistance rating, a timber deck needs to maintain its thermal separation function and load carrying capacity for the specified duration of exposure to standard fire conditions. The thermal separation requirement limits the temperature rise on the unexposed side of the deck to 250˚F above ambient temperature over the entire surface area, or 325˚F above ambient temperature at a single location. When these limits can not be met by decking alone, additional floor coverings can be used to increase the thermal separation time. The calculation procedures in this paper do not address adequacy of thermal separation.

To meet the load carrying capacity requirement, a deck must carry the specified load for the required endurance time. The new mechanics-based design procedure also applies to design of timber decks. Single and double tongue-and-groove (T&G) decking should be designed as an assembly of wood beams fully-exposed on one face. Butt-jointed decking should be designed as an assembly of wood beams partially-exposed on the sides and fully-exposed on one face. To compute the effects of partial exposure on the sides of the decking, the char rate for this limited exposure should be reduced to 33% of the effective char rate.

Application Guidelines for Wood Members - Where fire endurance is required, connectors and fasteners must be protected from fire exposure by wood, fire-rated gypsum board, or any coating approved for the required endurance time.

Glued laminated timber beams should utilize standard laminating combinations, except that a core lamination is removed, the tension zone is moved inward, and the equivalent of an extra nominal 2-inch thick outer tension lamination is added.

Summary

A new mechanics-based design method was developed to permit calculation of fire endurance for exposed, large wood members for loading conditions and fire exposures not recognized by the current code-accepted empirical design procedure. The new procedure calculates the capacity of exposed wood members using basic wood engineering mechanics. Actual mechanical and physical properties of wood are used and the member capacity is directly calculated for a given period of time. Section properties are computed assuming an effective char rate, β_{eff}, at a given time, *t*. Reductions of strength and stiffness of wood directly adjacent to the char layer are addressed by accelerating the char rate 20%. Average member strength properties are approximated from existing accepted procedures used to calculate design properties. Finally, wood members are designed using accepted engineering procedures found in the *National Design Specification for Wood Construction (NDS)* for allowable stress design. This new, verified mechanics-based design method is incorporated in Chapter 16 of the 2001 *NDS* and is described in detail in a publication entitled *Technical Report 10: Calculating the Fire Resistance of Exposed Wood Members*, available for free on the American Wood Council website at **http://www.awc.org/Publications/TR/index.html**.▪

Bradford K. Douglas, P.E., Director of Engineering, American Wood Council, American Forest & Paper Association, Washington, DC.

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