Summary

In 2001, a new mechanics-based design procedure for calculating the fire resistance of exposed wood members was adopted in the National Design Specification® for Wood Construction (NDS®). This new procedure, based on information contained in AF&PA’s Technical Report 10: Calculating the Fire Resistance of Exposed Wood Members, utilizes actual mechanical and physical properties of wood in the calculation of member capacities for a given period of time. Section properties are computed assuming an effective char rate, $\beta_{\text{eff}}$, 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 procedures used to calculate design properties and engineering procedures found in the NDS for allowable stress design. A summary of Technical Report 10 and design provisions in the NDS are presented.

1. Introduction

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 timber members are now commonly used where large sections and long spans are needed and 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.

2. 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 initial 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 285°C. The remaining wood section is heated over a narrow region that extends approximately 38 mm 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 ($L_e/D = 0$) 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 ($L_e/D = \infty$) stressed in compression during fire exposure, failure occurs when critical buckling capacity is exceeded due to the reduction in the moment of inertia, $I$. In the U.S., current code-accepted design procedures in the NDS contain a single column equation used to approximate the column capacity for all slenderness ratios based on the calculated interaction of theoretical short and long column capacities.

3. Mechanics-based Design Method

For many years, the fire resistance of exposed wood members in North America was estimated using an empirical method developed by T.T. Lie at the National Research Council of Canada in the 1970's (Lie, 1977). Lie’s method was based on actual fire test results and engineering mechanics. However, the final prediction equations were based on empirical solutions fit to beam and column test data; therefore, application of Lie’s method was 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.

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, $\beta_{eff}$, 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.

### 3.1 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:

\[
\beta_{\text{eff}} = \frac{1.2 \beta_n}{t^{0.187}} \tag{1}
\]

Where;
\[
\begin{align*}
\beta_{\text{eff}} & = \text{Effective char rate (mm/hr), adjusted for exposure time, } t \\
\beta_n & = \text{Nominal char rate (mm/hr), linear char rate based on 1-hour exposure} \\
t & = \text{Exposure time (hrs)}
\end{align*}
\]

A nominal char rate, \( \beta_n \), of 38 mm/hour is commonly assumed for solid-sawn and glued-laminated softwood members. For \( \beta_n = 38 \text{ mm/hour} \), the effective char rates, \( \beta_{\text{eff}} \), and effective char layer thicknesses, \( a_{\text{char}} \), for each exposed surface are:

#### Effective Char Rates and Char Layer Thicknesses (for \( \beta_n = 38 \text{ mm/hour} \))

<table>
<thead>
<tr>
<th>Required Fire Endurance (hr)</th>
<th>Effective Char Rate, ( B_{\text{eff}} ) (mm/hr)</th>
<th>Effective Char Layer Thickness, ( a_{\text{char}} ) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-Hour</td>
<td>46</td>
<td>46</td>
</tr>
<tr>
<td>1½-Hour</td>
<td>42</td>
<td>64</td>
</tr>
<tr>
<td>2-Hour</td>
<td>40</td>
<td>81</td>
</tr>
</tbody>
</table>

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, \( a_{\text{char}} \), for each exposed surface exposed to fire.

### 3.2 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. In the U.S., the average member capacity for solid-sawn and glued-laminated wood members can be approximated by multiplying the allowable design capacity, \( R \), by the following factors, \( K \):

<table>
<thead>
<tr>
<th>Member Capacity</th>
<th>( K )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bending Moment Capacity, in-lbs.</td>
<td>2.85</td>
</tr>
<tr>
<td>Tensile Capacity, lbs.</td>
<td>2.85</td>
</tr>
</tbody>
</table>
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.

3.3 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 nominal design capacity to avg. ultimate capacity

3.4 Special Design Provisions for Glued Laminated Timber Beams

For glued laminated timber bending members rated for 1-hour fire resistance, an outer tension lamination should be substituted for a core lamination on the tension side for unbalanced beams and on both sides for balanced beams. For glued laminated timber bending members rated for 1½ or 2-hour fire resistance, two outer tension laminations should be substituted for two core laminations on the tension side for unbalanced beams and on both sides for balanced beams.

3.5 Special Design Procedures for Timber Decks

In the U.S, timber decks consist of planks that are at least 50 mm 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 120°C above ambient temperature over the entire surface area, or 165°C 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 fully-exposed on one face.
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.

3.6 Connections

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.

4. Verification of Mechanics-Based Design Model

Given the theoretical derivation of the new mechanics-based design method, existing test results from fire tests of exposed, large wood members were compared against the model predictions. International, as well as North American, test data were reviewed. The results are summarized in the following sections.

4.1 Wood Beams

A total of seven full-size beam tests were reviewed. Beam dimensions and load ratios resulted in fire resistance times ranging from 53 to 147 minutes. Figure 2 provides a graphical comparison of the calculated and observed fire resistance times. A detailed report of the test results are provided in Technical Report 10.

Fig 2 Model Predictions for Exposed Wood Beams

4.2 Wood Columns

A total of sixty-three full-size column tests were reviewed. These columns ranged from highly loaded short columns to lightly loaded slender columns. Column dimensions and load ratios resulted in fire resistance times ranging 42 to 124 minutes. Figure 3 provides a graphical comparison of the calculated and observed fire resistance times. A detailed report of the test
results are provided in Technical Report 10.

Fig 3  Model Predictions for Exposed Wood Columns

### 4.3 Wood Tension Members

A total of three full-size tension member tests were reviewed. Member dimensions and load ratios resulted in fire resistance times ranging 42 to 124 minutes. Figure 4 provides a graphical comparison of the calculated and observed fire resistance times. A detailed report of the test results are provided in Technical Report 10.

Fig 4  Model Predictions for Exposed Wood Tension Members

### 4.4 Wood Decking

A total of six full-size deck tests were reviewed. Decking dimensions and load ratios resulted in fire resistance times ranging 18 to 62 minutes. Figure 5 provides a graphical comparison of the calculated and observed fire resistance times. A detailed report of the test results are provided in Technical Report 10.

Fig 5  Model Predictions for Exposed Wood Decking

5. Conclusion
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 addressed by the empirical design procedure used in North America. 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, $\beta_{\text{eff}}$, 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 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.

6. References

