

FIRE RESISTANCE OF EXPOSED WOOD MEMBERS

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Abstract

Fire resistance data on exposed wood beams and columns are plentiful, but few studies have been done on exposed wood members in tension and in decks. To provide data to verify the application of a new calculation procedure, a limited series of fire resistance tests were conducted on wood members loaded in tension and on exposed wood decks.

Key words: wood, fire resistance, decks, tension

INTRODUCTION

In the United States, large exposed wood members were traditionally used in a type of construction known as heavy timber construction. In U. S. building codes, such buildings are required to have concrete or masonry exterior walls and wood members of specified minimum dimensions. With minimum dimensions specified, no fire resistance ratings are required for large wood members. As the demand for large wood members in other types of construction increased, the U.S. wood industry promulgated a calculation procedure for determining the fire resistance rating of exposed wood beams and columns (American Institute of Timber Construction 1984, National Evaluation Board 1984). This procedure was based on the equations of T. T. Lie (Lie 1977) that had previously been adopted in Canada. While T. T. Lie's design equations provided for simple calculation of the fire rating of beams and columns based on their dimensions and the load factor, the "black box" nature of the design equations prevented any adjustment for other member types, loading conditions, or fire exposures. The column equations were also based on separate equations for short and long columns. With the introduction of a single column equation in the National Design Specifications (NDS) for Wood Construction, new procedures were developed by the American Forest & Paper Association (AF&PA) for calculating fire resistance of exposed wood members and incorporated within the 2001 NDS (AF&PA 2001). The new mechanics-based design method, or NDS method, is discussed in Technical Report 10 of AF&PA (2003) and an article by Douglas (1999). The NDS procedure is similar to the simplified effective cross-section method in the European Committee for Standardization (CEN) Eurocode 5 (CEN 1994, White 2002). With explicit equations for the residual fire resistance of wood members, these equations can be applied to other member types and loading conditions, and the charring rate can be adjusted for specific wood products or fire scenarios. To gain acceptance of the new procedures for tensile members, the USDA Forest Service Forest Products Laboratory (FPL) conducted a series of fire resistance tests of exposed wood members loaded in tension.

The fire resistance ratings of heavy timber decks must often be established. Such information is often requested from architects and builders involved in renovating old mill construction buildings, particularly on the east coast of the United States. The renovations often involve mixed occupancies or other changes that result in fire-rated walls and floors being required. Two non-load-bearing heavy timber decks were tested as part of an initial effort to verify procedures for establishing fire resistance ratings of heavy timber decks.

CALCULATION PROCEDURES

For an exposed wood member, the fire resistance rating is the time for structural failure when subjected to the standard fire exposure. In the United States, the standard fire resistance test is ASTM E 119 (ASTM 2000). The ASTM E 119 test method is similar to the ISO 834 test standard of the International Organization for Standardization (ISO 1999). Differences include the method of measuring fire exposure temperatures and specifications for the furnace pressure. As the wood member is exposed to fire, charring reduces the cross section of the member. The residual structural capacity is also affected by the elevated temperature gradient within the uncharred wood (Janssens and White 1994). As discussed in Eurocode 5 and by White (2002), three general procedures can be used for calculating the residual structural capacity of a fire-exposed structural member.

The most general and complicated approach is to assume that the uncharred region of the member consists of layers or elements with different strength and stiffness properties based on their temperatures and moisture contents. In one simplified approach, the entire residual cross section is assumed to have strength and stiffness values that are fractions of their room temperature values. In a second simplified approach, the residual cross section is further reduced beyond that of the expected actual char depth. In this effective cross-sectional area method, the residual structural capacity of this reduced section is calculated using room-temperature property values. In Eurocode 5, char depth is increased by 7 mm. In their fire endurance model for glued laminated beams (Bender and others 1985), Schaffer and others (1986) used an equivalent zero-strength layer thickness of 7.6 mm (0.3 in.). This effective cross-sectional area method is used in the new NDS methodology (AF&PA 2001, 2003).

The NDS method uses strength values at ambient temperatures and an increased char rate to account for reduced strength and stiffness properties and accelerated charring at the corners. The increase in the char depth is 20 % over that experimentally observed in ASTM E 119 fire tests. Thus, the effective char rate is given by

$$\beta_{\text{eff}} = \frac{1.2\beta_n}{t^{0.187}} \quad (1)$$

where β_{eff} is effective char rate adjusted for exposure time t ,
 β_n nominal char rate, linear char rate based on 1-h exposure, and
 t exposure time.

A nominal char rate $\beta_n = 38$ mm/h (1.5 in/h, 0.635 mm/min) is normally assumed. Thus, the effective char depth at 1 h is 46 mm (1.8 in.), and the equivalent zero-strength layer thickness is 8 mm (0.3 in.). Equation (1) also incorporates the nonlinear charring model of White and Nordheim (1992). The charring of composite wood products for this nonlinear model is discussed by White (2000). In the Eurocode 5, the char depth is adjusted only for times less than 20 min.

Using Equation (1), the dimensions of the members are reduced for surfaces that are exposed to the standard fire exposure. Based on the reduced sections, the ultimate residual strength properties of the charred member at time t are calculated using room-temperature allowable design stress values adjusted by average ultimate strength adjustment factors. The failure time is the time when the applied load exceeds the calculated average ultimate residual strength of the charred member for time t .

The AF&PA documents (AF&PA 2001, 2003) address only structural requirements for fire resistance of timber decks. Butt-jointed decking is designed as a series of beams that have reduced charring on the partially protected sides and normal charring on the exposed bottom surface. The char rate for the sides is one-third the normal effective char rate. Decks have a specified thickness of at least 51 mm (2 in.). Tongue-and-groove (T&G) decking is assumed to have charring only on the bottom face (AF&PA 2003).

Janssens (1997) applied a transformed section analysis of a timber deck and the Eurocode 5 effective cross-section method to develop a simplified design equation (thickness and load factor as variables) for timber decks that was similar to the T. T. Lie equations that were being used for fire design of beams and columns.

In addition to the requirement of structural stability, the fire resistance rating of a timber deck also depends on requirements for thermal protection. Thermal protection criteria provide for excessive temperature rise on the unexposed surface and flame penetration. In ASTM E 119, the excessive temperature criteria are temperature increases of 139°C average or 181°C maximum. In small-scale tests of composite rim boards without joints (White 2003), equations for times as a function of thickness were developed for the 139°C/181°C criteria on the back of the board and for 300°C (base of char layer) within the semi-infinite slab. The times for 300°C were 3% faster than the 60 min for 38 mm normally assumed for wood. The calculated board thickness needed for 139°C at 60 min was 47 mm. A 49-mm-thick plywood panel failed the 139°C/181°C criteria at 56 min. In the Eurocode 5, the temperature gradient within the charred wood slab is described by

$$T = T_i + (T_p - T_i) \left(1 - \frac{x}{a} \right) \quad (2)$$

where T is temperature (°C),

T_i initial temperature (°C),

T_p char front temperature (300°C),

x distance from char front (mm), and

a thermal penetration depth (40 mm).

Inserting $T = 139$ °C, $T_i = 20$ °C, $T_p = 300$ °C, and $a = 40$ mm, the distance from char front for the 139 °C criteria is 23 mm, or 61 mm total thickness for char depth of 38 mm. The application of Equation (2) to the data of White and Nordheim (1992) resulted in estimates of 31 to 35 mm for thermal penetration depth a (Janssens and White 1994). For $a = 35$ mm, the estimated thickness for 139 °C at 60 min is 58 mm. For a solid timber with a characteristic density of ≥ 290 kg/m³ and a minimum thickness of 35 mm, the thickness calculated from Eurocode 5 provisions for wood floor without joints is 51 mm for 60 min ($\beta_0 = 0.8$ mm/min, eq. (3.7) of Eurocode 5).

In most decks, there will be joints in the timber planks that make up the deck. Flame penetration through the joints needs to be prevented for the duration of the fire resistance rating. Section C3.1 on wood and wood-based panels of Eurocode 5 provides some guidance for joints in decks. The failure times near the panel joints in floors exposed to fire from below is given by

$$t_{pr} = \xi \frac{t_p}{\beta_0} \quad (3)$$

where t_{pr} is failure times of wood and wood-based panels,

ξ reduction coefficient for increased charring at joints,

t_p thickness of wood or wood-based panel cladding, and

β_0 design charring rate (Sec. 3.1 of Eurocode 5).

Values for the reduction coefficients are 0.2 for a butt joint, 0.3 for a lap joint, 0.4 for a single T&G joint, and 0.6 for a double T&G joint. The gaps are limited to 1 mm or less. The lap joint is 30 mm long. The tongue and groove of the T&G joints are 15 mm long.

Based on a series of tests of timber decks, Richardson and Batista (2001) obtained reduction coefficients of 0.10 for simple butt joints, 0.40 for single T&G joints, and 0.40 for double T&G boards. The specification for the gaps between boards was 2 mm or less. For a gap of = 1mm, the tests suggested a reduction coefficient of 0.3 for simple butt joints. Decks with additional wood flooring or panel products on top of the timber deck and gypsum board on the bottom of the deck were also tested. Paneling on top of the decks provided the most benefits to the fire resistance of decks when the butt joints had 4-mm gaps, compared with decks of T&G joints or narrower gaps.

FPL FURNACE

The decks and tension members were tested in the FPL intermediate-scale furnace. The overall dimensions of the furnace are 2.2 by 1.3 m. The furnace is lined with mineral fiber blankets and heated by eight diffusion-flame natural gas burners. Furnace temperatures are measured using six protected thermocouples. For the horizontal decks, the thermocouples were 305 mm below the exposed surface of the deck, which was placed on the top of the furnace. The furnace is not the full size specified in ASTM E 119, but it is unique in that it is located in the middle of a tension apparatus. For tension members, we placed three furnace thermocouples 152 mm from the surface down the length of each of the two sides of the member (at mid-height.) Natural gas flow to the burners was controlled so that the furnace temperatures followed the time–temperature curve specified in ASTM E 119.

TENSION TESTS

Fire resistance tests were conducted on exposed wood members loaded in tension. Initial tests on nominal 2- by 4-in. (standard 38- by 89-mm) (hereafter referred to as “2 by 4”) lumber were conducted as part of a study on metal-plate-connected wood trusses (White and others 1993, White 1996). A nominal 4- by 6-in. (standard 89- by 140-mm) solid lumber member was used in a preliminary test prior to three tests of glued laminated specimens. The glued laminated specimens were tested for AF&PA.

Materials

The 2 by 4 lumber specimens were No. 1 Dense Southern Pine lumber. The total length of these specimens was 4.9 m. Eleven specimens were tested. The 4 by 6 lumber specimen was Douglas-fir, visually determined to be No. 2 grade. The structural glued laminated specimens of Douglas-fir were combination symbol 5 (six laminates). Dimensions are given in Table 1. Grades are in accordance with the National Design Specification for Wood Construction (AF&PA 2001).

Methodology

The specimens were loaded in tension in a specially made tension apparatus that is part of the FPL intermediate-scale furnace. Each end of the furnace has an opening 229 mm wide and 508 mm deep for the test specimen. The length of the tensile test specimen exposed to the furnace temperatures was 1.8 m. The specimen was oriented such that the wider side was vertical. The mid-height of the test specimen is 305 mm from the ceiling of the furnace. The tension apparatus uses an electric-powered hydraulic loading system and wedge gripping system. Load is measured with an electronic load cell force-measuring system. The wedge gripping system was used for the 2 by 4 lumber tests (tests 1 and 2 of Table 1). The wedge gripping system allows only for specimen thickness of 19, 38, and 64 mm. Special grips were made to test the wider specimens. Steel plates were used to grip the timbers. Eight 25-m (1-in.) bolts were used at each end (six for the smaller specimen). The holes in steel plates were oversized by 1.6 mm (1/16 in.). A 64-mm (2.5-in.) pin was used to connect the two grip plates to another plate that was inserted into the wedge gripping system of the tension apparatus.

In tests 1 through 5, a constant load was applied to the test specimen prior to the initiation of the furnace (Table 1). The furnace was controlled to follow the ASTM E 119 time–temperature curve. Failure was recorded when the specimen could no longer support the load. In test 6, a constant load of 26.7 kN (6,000 lb) was applied, and then the furnace was initiated. After 120 min of ASTM E 119 exposure, the load was increased until failure occurred. The limitations of the bolted connections limited the loads to values less than the full allowable loads of the wood specimen (Table 1). For test 6, the TR10 model predicts a failure load of 96 kN at 123.7 min.

Table 1. Tension tests

Test no.	Specimen	Width (mm)	Height (mm)	Load (kN)	Load as percentage of full allowable ^a	Predicted failure time (min)	Observed failure time (min)
1	2 by 4 lumber	38	89	14.6	50	14	13 ^b
2	2 by 4 lumber	38	89	29.2	100	9	10 ^c
3	4 by 6 lumber	86	135	13.4	22	44	42
4	Glulam	217	222	103.8 ^e	20	22	96 ^d
5	Glulam	128	224	153.0 ^e	48	60	58
6	Glulam	217	222	87.1 ^f	16	126	124 ^f

^a Applied load as percentage of full allowable structural calculated using National Design Specification for Wood Construction (AF&PA 2001).

^b Average of six specimens, coefficient of variation was 17 %.

^c Average of five specimens, coefficient of variation was 17 %.

^d Unintended load eccentricity due to bolted connection not accounted for in predicted failure time.

^e Constant load applied, load reported is the average recorded 30 s prior to failure.

^f A load of 26.7 kN was initially applied. Starting at 120 min, the load was increased until failure of the member occurred at the stated load and time.

Results and Discussion

With the exception of test 4, the predicted times of failure were -15.1% to $+5.9\%$ of the observed failure times. In test 4, the predicted time was 21% greater than the observed failure time. In tests 3 and 4, the nuts of the bolts in the connections of the specimen to the tension apparatus were tight, and the specimen and grips were not perfectly straight. As a result, there was an unintended eccentricity in the application of the load. The smaller dimensions of the specimen in test 3 reduced the impact of this eccentricity on the results. In tests 5 and 6, the nuts on the bolts were not fully tightened, so the specimen and the grips straightened when the load was applied. Thus, there was no eccentricity to cause a moment load to be applied to the specimen. In these two tests, the predicted failure times were 3.1% and 1.9% greater than the observed failure times, respectively. An ultimate strength to allowable ratio of 2.85 was used in the calculations of predicted failure times.

DECKS TESTS

Two tests of decks constructed from laminated decking were conducted. The purpose of these initial tests was to learn whether the Eurocode reduction factors for the joints are overly conservative and whether a more extensive set of tests is warranted and feasible for FPL to conduct. It should be noted that ASTM E 119 provides only for the testing of floors that are much larger than the decks tested.

Materials

The laminated decking material was an appearance-grade decking product consisting of three 18-mm-thick laminates. This decking material was manufactured so the middle laminate of the decking provided the tongue and the other two laminates formed the groove. Total thickness of the decking was 55 mm. Outer laminates were 131 mm wide. The 129-mm-wide center laminate resulted in an 18-mm tongue and a 20-mm deep groove. The edges of the tongue and groove were beveled. The second deck was constructed from material with the tongue and groove removed, so the deck consisted of butt edge joints. Dimensions were 55 mm thick and 124 mm wide. The boards were of mixed species that included spruce, Douglas-fir, and true firs. Moisture meter readings of the decks were 11% to 12%.

Methodology

The decks were tested on top of the FPL tension furnace. The decks were 1.32 m wide and 2.44 m long. At each end, the 2.44-m-long boards were nailed to a piece of nominal 4- by 4-in. (standard 89- by 89-mm) lumber with two nails. They were also toe-nailed at 760-mm intervals along the come of the decking. There were no end joints within the specimen. The 4 by 4's at the ends of the decks were allowed to hang over the sides of the furnace. Exposed surface area was 2.08 by 0.94 m.

Results and Discussion

Visual observations of flame penetration at the joints occurred at 44.4 min for the T&G deck and at 64 min for the butt-joint deck. In the T&G test, the temperatures for the unexposed surface were 78°C average and 98°C maximum just before flame penetration failure (43.4 min.). In the butt-joint test, the temperatures for the unexposed surface were 144°C average and 187°C maximum just before flame penetration failure (63 min.). These are less than the excessive temperature rise failure criteria (+139°C average, +181°C maximum) of ASTM E 119 (i.e., 161°C average, 203°C maximum). In the butt-joint test, an average temperature of 76°C was obtained at 44.6 min., which is consistent with the T&G test (43.3 min.). These tests confirmed the importance of joints in evaluating the fire resistance of a solid wood barrier. Assuming a constant charring rate of 0.65 mm/min, the predicted failure time (300°C) for a solid 55-mm-thick slab is 85 min. Using the equations of White (2003) for composite rim boards, the estimated failure times for the 55-mm-thick solid wood deck are 72 min for the +139°C criteria and 77 min for the 300°C criteria.

The internal temperatures obtained in the two tests were consistent. Using the times for 300°C at depths of 12.7 and 19.05 mm, the calculated char rate was 1.543 min/mm (zero intercept) for the T&G test and 1.539 min/mm for the butt joint test. This 1.54-min/mm char rate corresponds to 0.65 mm/min (1.534 in/h), which compares favorably with the 1.5-in/h charring rate normally assumed for ASTM E 119 fire exposure. Charring rates cited in the Eurocode 5 are 0.64 mm/min for glued laminated timber and 0.67 mm/min for solid timber (coniferous, characteristic density of 290 kg/m³ or greater).

Using the deck thickness of 55 mm, design charring rate of 0.8 mm/min, and the Eurocode 5 reduction coefficients, the calculated failure times from Equation (3) are 27.5 min for the T&G deck and 13.8 min for the butt-joint deck. If the actual charring rate (0.65 mm/min) is used in Equation (3), the calculated failure times are 33.8 min for the T&G deck and 16.9 min for the butt-joint deck. The calculated times are less than the observed failure times of 44.4 min for the T&G deck and 64 min for the butt-joint deck. The experimental data likely reflect the tightness of the joints in these tests, particularly for the butt joint deck. The Eurocode 5 allows for a gap of 1 mm. The tests of Richardson and Batista (2001) illustrated the effect of increasing the thickness of gaps, particularly with butt joints.

The biggest surprise in these tests was the greater time for the butt-joint deck compared with the T&G joint deck. This was likely due to gaps in the tongue-and-groove joints and the tightness of the butt joints. The gap between the end of the tongue and the bottom of the groove was about 2 mm. While the product was a high quality product, its design does not include a snug fit of the tongue-and-groove joint. The fit is sufficiently tight to provide its intended structural integrity along the edge. Smaller tolerance in the design would likely cause problems in installation when moisture content changes result in dimensional changes in the wood after manufacture. Assuming the observed charring rate (0.65 mm/min), the exposed laminate would have been gone in 28 min ($= 18/0.65$). If one assumes that failure occurred when both of the outer laminates charred with no contribution from the middle laminate, the predicted failure time with no reduction factor is 55 min ($= 2(18)/0.65$). With the gaps around the tongue of the joint, the observed failure at 44 min is reasonable.

In contrast, the butt joint was a very tight joint along its entire 55-mm thickness. The increase in humidity after the construction of the deck likely made it even tighter. The observed failure time was 25 % less than the 85 min calculated using the observed charring rate and the full 55-mm

thickness. This result seems reasonable given the tightness of the butt joint. While the butt joint did better than the T&G joint in these two tests, the time for a worst-case butt joint is no doubt less than the endurance time for a worst case T&G joint.

Given the limited ability to control gaps between deck boards over time, panel products on top of the heavy timber decks are probably the best method to address the joint issue. In unpublished small-scale tests, cement boards were effective barriers for the joints when placed on the unexposed side of the wood boards. Due to their high thermal conductivity, cement boards benefit from having the insulative wood between the panel and the fire exposure.

CONCLUSIONS

Fire resistance tests of loaded wood members in tension supported the validity of the NDS methodology described in Technical Report No. 10 (AF&PA 2003) and the NDS (AF&PA 2001) for calculating the fire endurance of axially loaded tension members in the standard fire resistance test. Two decks were tested in a small horizontal furnace that provides for the fire exposure specified in ASTM E 119. The tests support the view that joints in a heavy timber deck are critical to its fire endurance times and that the reduction factors specified in Eurocode 5 are conservative for tight joints. The unexpected result of greater time for the butt-joint deck compared with the tongue-and-groove deck supports the view that “tightness” of the joints affects the actual performance of any given deck. In particular, the gap between the tongue and the groove of T&G decks needs to be considered when evaluating fire resistance of such decking. Given the uncertainty of gaps, the best solution is likely the addition of sheathing over the top of the decking.

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