United States
Department of
Agriculture

Forest Service

Forest
Products
Laboratory

Research
Paper
FPL–RP–633

# Fire Resistance of Structural Composite Lumber Products

Robert H. White

## Abstract

Use of structural composite lumber products is increasing. In applications requiring a fire resistance rating, calculation procedures are used to obtain the fire resistance rating of exposed structural wood products. A critical factor in the calculation procedures is char rate for ASTM E 119 fire exposure. In this study, we tested 14 structural composite lumber products to determine char rate when subjected to the fire exposure of the standard fire resistance test. Char rate tests on 10 of the composite lumber products were also conducted in an intermediate-scale horizontal furnace. The National Design Specification/Technical Report 10 design procedure for calculating fire resistance ratings of exposed wood members can be used to predict failure times for members loaded in tension. Thirteen tests were conducted in which composite lumber products were loaded in tension as they were subjected to the standard fire exposure of ASTM E 119. Charring rates, observed failure times in tension tests, and deviations from predicted failure times of the structural composite lumber products were within expected range of results for sawn lumber and glued laminated timbers.

Keywords: structural composite lumber, LVL, fire resistance, char rate

April 2006

White, Robert H. 2006. Fire resistance of structural composite lumber products. Research Paper FPL-RP-633. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 28 p.

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The Forest Products Laboratory is maintained in cooperation with the University of Wisconsin.



## Acknowledgments

This study was suggested by Rodney McPhee of the Canadian Wood Council (CWC). Funds for this study were provided by the CWC. The following manufacturers provided the structural composite lumber (SCL) test materials: Boise Cascade, Georgia–Pacific, Louisiana–Pacific, Trus Joist MacMillan (now Trus Joist, a Weyerhaeuser Business), and Willamette Industries (now part of Weyerhaeuser Company). Advice and suggestions were provided by the members of the CWC/FPL SCL Charring Rate Study task group of the Wood I-Joist Manufacturers Association. This task group was chaired by Bruce Craig. Comazel Caldwell of the FPL fire research work unit made the specimens and conducted the tests. The author greatly appreciates the support, assistance, and patience from the parties involved.

## Contents

# Fire Resistance of Structural Composite Lumber Products

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## Introduction

Production and use of structural composite lumber (SCL) products are increasing (McKeever 1997, Schuler and others 2001). Such products include laminated veneer lumber (LVL), parallel strand lumber (PSL), laminated strand lumber (LSL), and oriented strand lumber (OSL) (Green and Hernandez 1998, Moody and others 1999, ASTM International 2005) (Fig. 1). Introduction of composite lumber products started in the 1970s with LVL and continued with introduction of PSL in the 1980s and LSL in the 1990s (Yeh 2003). Oriented strand lumber is the latest of these products. For each of these products, adhesives are utilized to manufacture the composite product from veneers or strands of wood. Questions are sometimes raised about the performance of the adhesive when exposed to elevated temperature. The code and market acceptance of products depends on documentation of acceptable performance.

Code acceptance of calculation procedures for determining fire resistance ratings of exposed wood beams and columns permitted their use in applications requiring structural members to have specified fire resistance ratings. As a result, the potential market for such wood products increased. This report provides test data on the charring rate of three types of composite lumber products (LVL, LSL, and PSL) and their performance when loaded in tension and subjected to the fire exposure specified in the standard fire resistance test. Several species of composite lumber products were included in testing. In the first two phases of this project, we documented charring rates of composite lumber products. Fire tests conducted in the first two phases of this project did not include any load being applied to the member. Results of Phase One were initially published in a conference proceedings article, "Charring Rate of Composite Timber Products" (White 2000). These one-dimensional charring experiments were conducted in the small vertical-furnace at the USDA Forest Products Laboratory (FPL), Madison, Wisconsin. In the second phase, we measured temperatures in the interior of a non-loaded beam subjected to the ASTM E 119 (ASTM International 2000) fire exposure in an intermediate-scale horizontal furnace. Charring rates determined in the two furnaces were compared. In the third and final phase of the study, a series of SCL test specimens were subjected to ASTM E 119 fire exposure while loaded in tension.

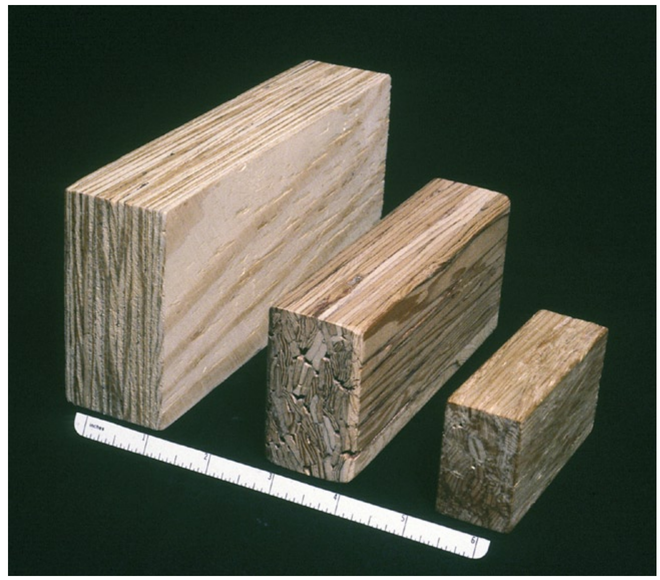


**Figure 1. Examples of types of composite lumber products tested in this study: (left to right) laminated veneer lumber, parallel strand lumber, and laminated strand lumber.**

## Background

### Fire Resistance Calculations

Fire resistance ratings of structural members are normally determined by conducting the full-scale test described in specifications of ASTM E 119 or similar standards. Calculation procedures for determining fire resistance rating of wood members have code acceptance (White 2002). Lie (1977) developed the first procedure to gain code acceptance in the United States and Canada for wood beams and columns (American Institute of Timber Construction 1984, Canadian Wood Council 1997, American Forest & Paper Association 2000, 2003). A more recent calculation procedure, the National Design Specification (NDS) method, was developed by the American Wood Council (AWC) of the American Forest & Paper Association. It was included in the NDS (American Forest & Paper Association 2001) starting with the 2001 edition. This new, more explicit procedure is applicable to other structural members besides beams and columns. Per NDS, the fire design procedure is applicable to all wood structural members and connections covered under NDS. These include wood members of solid-sawn lumber, structural glued-laminated timber, and structural composite lumber. Methodology and supporting data for solid-sawn lumber and structural glued-laminated timber are fully discussed in “Calculating the fire resistance of exposed wood members,” Technical Report 10 (TR 10) of the American Forest & Paper Association (2003).

Tests of three glued-laminated specimens were conducted to verify calculation procedures for determining the fire resistance rating of axially loaded wood tension members contained in TR 10 (White 2004). Tests were conducted using the horizontal furnace and tension apparatus at the FPL. Glued-laminated specimens were exposed to an ASTM E 119 fire exposure while loaded in tension for the full duration of the test.

Other options for analytical methods for determining fire resistance of timber members are reviewed by White (2002). Analytical methods in the updated Eurocode 5 document of Europe are discussed by König (2005).

A critical parameter in calculation procedures is charring rate of the member while directly subjected to fire exposure of the time–temperature curve specified in ASTM E 119.

## Char Rate of Wood

Parameters affecting charring rate for solid wood have been extensively studied at the FPL (Schaffer 1967, White and Nordheim 1992, White and Tran 1996) and elsewhere (White 1988, White 2002). For solid wood and glued-laminated members, the value for charring rate generally used in the United States and Canada is 0.635 mm/min. The 0.60 mm/min value was used in developing calculation procedures for large wood members (Lie 1977).

The following time–location models for the time needed to obtain a char depth ($x_c$) were considered by White and Nordheim (1992) and White (1988):

$$t = m_1 x_c \tag{1}$$

$$t = m_2 x_c - b \tag{2}$$

$$t = m_3 x_c^a \tag{3}$$

or its linear form

$$\ln t = \ln m_3 + a \ln x_c \tag{4}$$

and

$$t = m_5 x_c^{1.23} \tag{5}$$

Equation (1) is the simple linear single parameter ($m_1$) model (zero-intercept) that is generally reported for the charring rate of wood products. Equation (1) is also the one-parameter model assumed when charring rate is calculated from residual section and duration of fire exposure. The value of $m_1$ for the conventional 0.635-mm/min charring rate is 1.575 min/mm. Equation (2) is a two-parameter model ($m_2$ and $b$) that allows a fast initial char rate followed by a slower linear char rate. Equation (3) is a nonlinear charring model with two parameters ($m_3$ and $a$). Equation (4) is the linear form of Equation (3). Results for Equation (3) can be obtained by linear regression of Equation (4). The model of Equation (5) was developed by White and Nordheim (1992). This nonlinear model was used in the methodology of TR 10. The value of $m_5$ for the conventional 38-mm char depth at 1 h is 0.682 min/mm$^{1.23}$.

Charring data on composite lumber products in the public domain have been limited. In a series of cone calorimeter tests of sawn lumber and wood composites, Mikkola (1990, 1991) tested a 37-mm-thick laminated veneer lumber product with a density of 520 kg/m$^3$. For an external exposure of 50 kW/m$^2$, char rates were 1.05, 0.82, and 0.68 mm/min for moisture contents of 0%, 10%, and 20%, respectively. For the 38-mm-thick spruce sawn lumber with density of 490 kg/m$^3$, char rates were 1.06, 0.80, and 0.60 mm/min for moisture contents of 0%, 10%, and 20%, respectively. Ignition properties and char rates from cone calorimeter tests of radiata pine were reported by Lane and others (2004). Getto and Ishihara (1998) found that fire resistance of untreated wood or fire-retardant-treated wood was improved by compression of the board. Fire resistance of lathed-veneer laminated boards was greater than that of the solid-sawn board. In a study of LVL with different types of joints, Uesugi and others (1999) obtained charring rate of 0.6 to 0.7 mm/min in tests of Douglas-fir and larch LVL and concluded that these materials showed the same performance in fire as heavy timber. Subyakto and others (2001) investigated fire resistance of a LVL–metal plate connection and its improvement with graphite phenolic sphere sheeting. Experimental results for parameters of both Equations (1) and (5) for six wood composite rim board products were reported by White (2003). The six products included three oriented strandboards (OSB), a plywood, an LVL, and a com-ply product. In addition to data for the exposed rim boards, White (2003) also provided parameter estimates for rim boards protected with gypsum board. More recently, fire resistance of LVL was investigated at the University of Canterbury in New Zealand (Lane and others 2004). In a report on variability of wood charring rates, Hietaniemi (2005) included unpublished data for Kertopuu LVL specimens obtained from private communication with T. Oksansen. For LVL data obtained from T. Oksansen, Hietaniemi (2005) reported mean charring rates of 0.60 and 0.76 mm/min for charring perpendicular and parallel to the veneers, respectively. For each direction, coefficients of variation were 8% to 9%.

Charring tests in the small vertical-furnace included in this report were previously discussed by White (2000). Results for the composite lumber products were comparable to those for solid-sawn lumber. As with solid-sawn lumber, charring rate of a specific composite lumber product would depend on density, moisture content, and species.

### National Design Specification Technical Report 10 Procedure

The NDS method described in TR 10 (American Forest & Paper Association 2003) is a reduced-section method for calculating fire resistance of an individual structural wood member (White 2002). For each surface of the member subjected to fire exposure, charring reduces the cross-sectional area of the member. In TR 10, a form of Equation (5) is used to calculate char depth at time $t$. A nominal char rate, $\beta_n$ (mm/min or in/h), is initially assumed. This is a linear char rate based on char depth for 1-h exposure, and in most cases a value of 38 mm at 60 min is used. As noted in the NDS (American Forest & Paper Association 2001), this nominal char rate of 38 mm/h is commonly assumed for solid-sawn and structural glued-laminated softwood members. The char depth, $x_c$, at time $t$ is calculated from

$$x_c = \beta_n t^{0.813} \tag{6}$$

To account for loss of strength from elevated temperatures within the residual cross-sectional area of the member and rounding the corners of a rectangular member, the cross-sectional area is further reduced to an effective cross-sectional area. In the TR 10 procedure, additional reduction in dimensions is 20% of char depth. Thus, the effective char rate used to calculate section properties of the charred member at time $t$ is

$$\beta_{\text{eff}} = 1.2\beta_n / t^{0.187} \tag{7}$$

For the nominal char rate of 38 mm at 1 h, the effective char rates are 46 mm/h, 42 mm/h, and 40 mm/h for 60, 90, and 120 min, respectively. For a rectangular member with dimensions of $B$ and $D$ and all four sides exposed to the fire, the area of the cross section at time $t$, $A(t)$, is

$$A(t) = (B - 2\beta_{\text{eff}}t)(D - 2\beta_{\text{eff}}t) \tag{8}$$

With this effective reduced cross-sectional area, the ultimate load bearing capacity of the member at time $t$ is calculated using normal room temperature assumptions. The failure criteria for tension members are

$$D + L \le KR_{\text{ASD}} \le KF_t A_f \tag{9}$$

where

| | | |
|---|---|---|
| $D$ | is | design dead load, |
| $L$ | | design live load, |
| $K$ | | factor to adjust from nominal design capacity to average ultimate capacity, |
| $R_{\text{ASD}}$ | | nominal allowable design capacity or $F_t A_f$, |
| $F_t$ | | tabulated tension parallel-to-grain design value, and |
| $A_f$ | | area of cross section using cross-section dimensions reduced from fire exposure that will result in failure of the tension member. |

For a member in tension, the allowable design stress to average ultimate strength adjustment factor, $K$, is 2.85 (American Forest & Paper Association 2003). For the fire design procedure in the NDS, this value for design stress to member strength factor is considered valid for solid-sawn, glued-laminated timber, and structural-composite lumber wood members (American Forest & Paper Association 2003). Calculated failure time or fire resistance rating is the time for which the effective cross-sectional area has been reduced to $A_f$ per the failure criteria of Equation (9).

## Char Rate Experiments

This project included the determination of charring rate of composite lumber products in two fire resistance furnaces at the FPL. The small vertical-furnace was used to obtain the one-dimensional charring rates for the widest range of products and included replicates for statistical comparison. Tests in the intermediate-scale horizontal furnace provided verification that data obtained in the smaller furnace would likely be valid for the even larger test furnaces specified in ASTM E 119.

### Materials

Fourteen different materials were tested in the small vertical-furnace experiments of Phase 1 (Table 1). Ten of the fourteen materials were tested in horizontal-furnace tests of Phase 2 (Table 2). Three general types of products were tested: LVL, PSL, and LSL. No OSL product was tested. Species included two aspen products, four Douglas-fir products, three Southern Pine products, four yellow-poplar products, and one eucalyptus product (Table 1). Except for Material Number 7 (Table 1), the products tested were those commercially available. The eucalyptus LVL (Material Number 7) was a prototype sample of the product.

Laminated strand lumber is made of strands of wood that are glued together such that strands are parallel to the longitudinal or axial direction of the lumber product. Laminated veneer lumber is a composite made by laminating sheets of veneer with an adhesive so the longitudinal grain of the majority of veneers is parallel to the longitudinal or axial direction of the lumber product. The veneers are end-jointed with a lap, butt, or scarf joint. In typical applications, the glue lines are vertical. Parallel strand lumber is made of strands obtained by clipping sheets of veneer with strands aligned parallel to the longitudinal axis. The wide face of the strands is parallel to the tangential direction and perpendicular to the radial direction of the wood itself. Aligned strands are pressed together with adhesive.

Information on adhesives used in the products (Tables 1 and 2) was provided by the manufacturers. Exterior-type

**Table 1. Composite lumber products tested**

| Material number | Type | Species | Adhesive[a] | Density[b] (kg/m$^3$) | Material number in White (2000) |
|---|---|---|---|---|---|
| 1 | LSL | Aspen | MDI | 674 | 1 |
| 2 | LSL | Yellow-poplar | MDI | 678 | 9 |
| 3 | LVL | Aspen | PF | 464 | – |
| 4 | LVL | Douglas-fir | PF | 529 | 2 |
| 5 | LVL | Douglas-fir | PF | 535 | 4 |
| 6 | LVL | Douglas-fir | PF | 552 | 3 |
| 7 | LVL | Eucalyptus | PF[c] | 586 | – |
| 8 | LVL | Southern Pine | PF[c] | 652 | 6 |
| 9 | LVL | Southern Pine | PF | 635 | 7 |
| 10 | LVL | Yellow-poplar | PF | 536 | 11 |
| 11 | LVL | Yellow-poplar | PF | 554 | 10 |
| 12 | PSL | Douglas-fir | PF | 610 | 5 |
| 13 | PSL | Southern Pine | PF | 728 | 8 |
| 14 | PSL | Yellow-poplar | PF | 628 | 12 |

[a]PF, phenol–formaldehyde.
MDI, methylene diphenyl diisocyanate.
[b]Density calculated from oven-dried mass and volume as tested.
[c]Hot setting phenol–resorcinol–formaldehyde adhesive is used to glue 1/10-in.-thick veneers into 7/8-in. panels in plywood press. These panels are finger-jointed with a cold setting PRF adhesive and pressed into final product using a cold setting isocyanurate adhesive.

**Table 2. Tests of unloaded specimens in horizontal furnace**

| Test number | Material number[a] | Species | Composite type | Width (mm) | Height (mm) | Range of char depth[b] (mm) | Max. time[c] (min) | FPL test number |
|---|---|---|---|---|---|---|---|---|
| 1 | 1 | Aspen | LSL | 175 [d] | 356 | 14–57 | 95 | 2110 |
| 2 | 4 | Douglas-fir | LVL | 180 | 455 | 13–60 | 91 | 2112 |
| 3 | 5 | Douglas-fir | LVL | 44 | 352 | 3–13 | 16 | 2117 |
| 4 | 5 | Douglas-fir | LVL | 83 | 351 | 12–28 | 45 | 2108 |
| 5 | 5 | Douglas-fir | LVL | 167 [d] | 352 | 12–60 | 85 | 2113 |
| 6 | 6 | Douglas-fir | LVL | 179 [e] | 352 | 14–57 | 86 | 2118 |
| 7 | 8 | Southern Pine | LVL | 169 [e] | 407 | 13–57 | 63 | 2120 |
| 8 | 9 | Southern Pine | LVL | 173 [e] | 352 | 13–58 | 76 | 2115 |
| 9 | 10 | Yellow-poplar | LVL | 170 [e] | 353 | 12–59 | 76 | 2111 |
| 10 | 11 | Yellow-poplar | LVL | 85 [d] | 403 | 12–27 | 34 | 2109 |
| 11 | 11 | Yellow-poplar | LVL | 170 [e] | 405 | 13–59 | 82 | 2119 |
| 12 | 12 | Douglas-fir | PSL | 177 | 357 | 12–57 | 86 | 2116 |
| 13 | 13 | Southern Pine | PSL | 176 | 355 | 12–60 | 92 | 2114 |

[a]Numbers correspond to those listed in Table 1.
[b]Range of char depths used in the regression calculations of the charring rates (Tables 8 and 9).
[c]Maximum time for the data used in the regression calculations of the charring rates (Tables 8 and 9).
[d]Thickness obtained by FPL gluing two of the manufactured products together with phenol–resorcinol glue.
[e]Thickness obtained by FPL gluing four of the manufactured products together with phenol–resorcinol glue.

adhesives typically were phenol–formaldehyde-based adhesives. Other adhesives included isocyanate-based adhesives (MDI, or methylene diphenyl diisocyanate).

Individual pieces of test materials were glued together to make test specimens for the small vertical-furnace tests. For some of the horizontal-furnace charring tests of Phase 2, FPL researchers glued manufactured products together with a phenol–resorcinol adhesive to obtain a thicker specimen (Table 2).

All specimens were conditioned at 23ºC, 50% relative humidity prior to testing as specified in ASTM E 119. Moisture contents were 6% to 8%.

## Small Vertical-Furnace Tests

### Test method

In the small vertical-furnace tests, the specimens of the structural composite lumber products were inserted in the 510-mm-square opening of the small gas-fired vertical-furnace (Fig. 2) to obtain the one-dimensional charring rates. The procedures were similar to those used to determine char rate for eight species of solid lumber (White 1988, White and Nordheim 1992). Natural gas supply was controlled so the temperature determined with a thermocouple in an iron-capped pipe near the exposed surface of the specimen followed the ASTM E 119 time–temperature curve (Fig. 2a). A single center thermocouple was used to


**Figure 2. Opening of small vertical furnace (a) without and (b) with a test specimen in place.**

control the furnace, but there are four additional thermocouples at the centers of the quadrants.

Specimens were 510 mm wide and 89 mm deep. The 250- or 264-mm-high specimens were constructed by gluing five 50-mm-thick pieces (or six 44-mm-thick pieces) together with phenol–resorcinol adhesive (Fig. 2b). Which of the two setups was used depended on available dimensions of the lumber product. Charring occurred in the 89-mm direction.

Because of their construction, products are anisotropic. We obtained charring rates for both transverse directions (perpendicular to wood grain). No tests were conducted for charring in the longitudinal direction (parallel to wood grain). The LVL specimens were tested with the direction of charring either parallel or perpendicular to the plane of veneer laminates. We tested PSL and LSL specimens with the direction of charring either perpendicular or parallel to the wide face of the original beam that was cut to obtain pieces for the specimens. Two replicates of each specimen type and transverse direction were tested. For test materials that were only provided with a width of 44 mm, we glued two pieces together to get the 89-mm dimension in the charring-perpendicular-to-veneer tests.

Temperature measurements were taken within the middle three pieces or layers of the test specimen, where two thermocouples were embedded at each of four distances from the exposed surface, 13, 25, 38, and 51 mm (Fig. 3). For each test, specimens 250 or 264 mm high were placed at mid-height in the 510-mm-square furnace opening so that they were opposite the center control furnace thermocouple (Fig. 2). Thermocouples were made from Type K (chromel-alumel), 30-gauge (0.254-mm-diameter) insulated thermocouple wire. Thermocouple data were collected on a personal computer data acquisition system. Data acquisition scans in these small vertical-furnace tests occurred every 3 or 5 s.

Tests were terminated when the last of the six thermocouples at 51-mm depth reached 300°C. The 300°C criterion for the base of the char layer was used to calculate charring rate. This criterion of 300°C or the criterion of 288°C were successfully used in earlier charring studies (Schaffer 1967, White 1988). The 288°C is the exact conversion of 550°F used in the early studies. Because temperatures are rapidly increasing at that point of the test, we consider the difference in times for the 288°C and 300°C criteria not to be significant. In a study of composite-rim boards, White (2003) found the average times for the 300°C criteria to be less than 1% greater than for the 288°C criteria.

## Test results

As just explained, charring was assumed to have occurred when thermocouples embedded in the specimen recorded a temperature in excess of 300°C. Visual observations of char depths after the tests were consistent with depths calculated from the 300°C criterion.

For each specimen, 24 pairs of time $t$ and char depth ($x_c$) were used to calculate char rates for each test (Fig. 4). These 24 pairs are for char depths of 13, 25, 38, and 51 mm from the fire-exposed surface. We obtained estimates for char rate parameters for Equations (1) and (5) discussed previously.

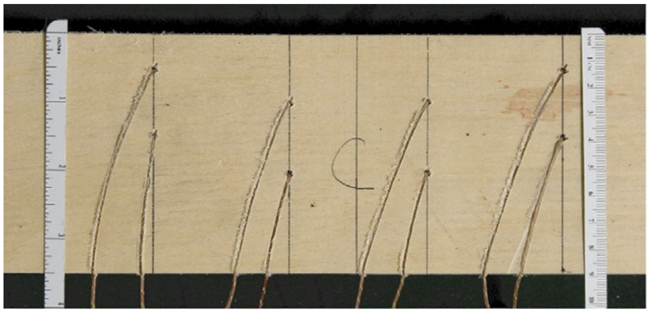


**Figure 3. Location of thermocouples in one of the laminates that was glued together to make the specimen for small vertical-furnace tests. With thermocouples in three laminates, a total of six thermocouples was at each of the four distances (13, 25, 38, and 51 mm) from the fire-exposed surface.**

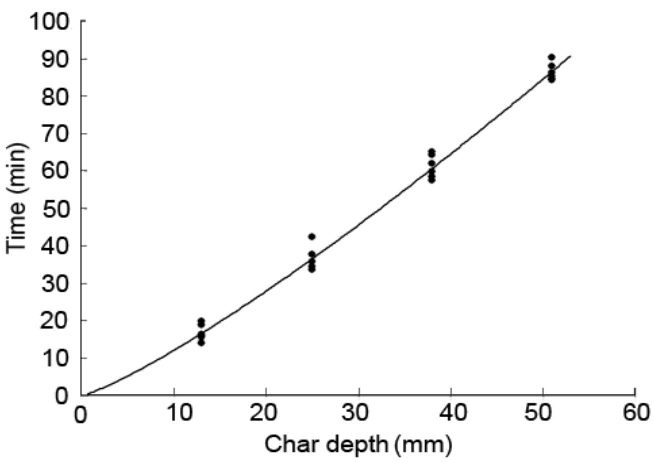



**Figure 4. Example of the time–location data for one small vertical-furnace test. The data were obtained from 24 thermocouples located at different depths in a specimen. The curve is a power function.**

These time–location models are

$$t = m_1 x_c \tag{1}$$

and

$$t = m_5 x_c^{1.23} \tag{5}$$

Results for linear regression of data for each small vertical-furnace test are given in the Appendix. A total of 58 small vertical-furnace tests were conducted. Individual thermocouples of a test specimen were in one of three different layers of the test specimen. A full model includes as a variable the height of the thermocouple in the specimen. In this model (White 1988), overall coefficients of variation of predicted values were 6.6% for $m_1$ and 6.2 % for $m_5$. Individual parameter estimates for each individual layer are included in the Appendix. Results for each layer provide an indictor of the variability of char rate determinations. For the reduced model (Eqs. (1) and (5)) that considers only distance from the exposed surface, $x_c$, the overall coefficients of variation of predicted values were 7.1% for $m_1$ and 6.7% for $m_5$. Results presented in this paper are for the reduced model.

In Tables 3 and 4, data for individual tests were combined for linear regressions to obtain parameter estimates. For each material (Table 1), estimates of the parameter $m_1$ (Table 3) are provided for charring parallel and perpendicular to the plane of veneers for LVL or the plane of the normal vertical surface of LSL or PSL. Equation (1) is the simple linear one-parameter model most often used to define charring rate of wood when subjected to standard fire exposure. There were two replicates for each direction for all but one case. For Material Number 8, three replicates for each direction were tested. Table 3 gives the number $N$ of pairs of time for 300°C and corresponding depth of thermocouple used in linear regressions to obtain estimates. The conventional 0.635 mm/min charring rate corresponds to $m_1$ of 1.575 min/mm. Also in Table 3 are estimates for $m_1$ when all data for a material are combined. For each estimate of the mean for the parameter $m_1$, the standard error of estimate is listed in Table 3. Likewise, the coefficient of variation of predicted times for the Equation (1) model is listed. These measurements of variability were obtained by using individual pairs of times for 300°C and char depth for the data set. In Table 4, data for similar materials were combined for linear regressions to obtain parameter estimates of a more generic nature. Format and information listed in Table 4 are similar to those in Table 3. If the 38 individual $m_1$ results for LVL tests are used for the data set, standard error and coefficient of variation for the $m_1$ mean of 1.50 min/mm are 0.02 min/mm and 8%, respectively. Regression of all data for different composite lumber products produced $m_1$ of 1.54 min/mm (Table 4). If the 58 individual $m_1$ results for all tests are used for the data set, standard error and coefficient of variation for the $m_1$ mean of 1.54 min/mm are 0.01 min/mm and 7.1%, respectively.

Tables 5 and 6 are similar to Tables 3 and 4 except the data are for parameter $m_5$ of Equation (5). The one-parameter model of Equation (5) is used in the fire resistance calculation procedures of TR 10. If the 38 individual $m_5$ results for LVL tests are used for the data set, standard error, and coefficient of variation for the $m_5$ mean of 0.638 min/mm$^{1.23}$ are 0.008 min/mm$^{1.23}$ and 8%, respectively. For a char depth of 38 mm at 60 min, $m_5$ is 0.682 min/mm$^{1.23}$. Regression of all composite lumber data together produced a value for $m_5$ of 0.652. min/mm$^{1.23}$ (Table 6). If the 58 individual $m_5$ results for all tests are used for the data set, standard error, and coefficient of variation for the $m_5$ mean of 0.653 min/mm$^{1.23}$ are 0.006 min/mm$^{1.23}$ and 7.1%, respectively.

In Equation (5), the exponent of the nonlinear model has a value of 1.23. For Equations (3) and (4), in which the exponent $a$ is a second variable, regression of all data together produced a mean estimate for $a$ of 1.151 and a standard error of the estimate of 0.006.

**Table 3. Estimates for parameter $m_1$ of Equation (1) for the 14 materials tested in the small vertical furnace**

| | | | $m_1$ of Equation (1) | | | | $m_1$ of Equation (1) for both directions[g] | | |
|---|---|---|---|---|---|---|---|---|---|
| Material number[a] | Species composite type | Direction[b] | $N$[c] | Mean[d] (min/mm) | Standard error[e] (min/mm) | Predicted COV[f] (%) | Mean[d] (min/mm) | Standard error[e] (min/mm) | Predicted COV[f] (%) |
| 1 | Aspen LSL | Parallel | 48 | 1.601 | 0.013 | 6.4 | 1.579 | 0.009 | 6.5 |
| | | Perpendicular | 47 | 1.557 | 0.013 | 6.2 | | | |
| 2 | Yellow-poplar LSL | Parallel | 47 | 1.586 | 0.016 | 7.7 | 1.589 | 0.011 | 7.9 |
| | | Perpendicular | 48 | 1.593 | 0.017 | 8.2 | | | |
| 3 | Aspen LVL | Parallel | 48 | 1.511 | 0.020 | 10.4 | 1.480 | 0.012 | 9.1 |
| | | Perpendicular | 47 | 1.448 | 0.012 | 6.4 | | | |
| 4 | Douglas-fir LVL | Parallel | 48 | 1.531 | 0.012 | 6.0 | 1.529 | 0.008 | 5.8 |
| | | Perpendicular | 48 | 1.526 | 0.011 | 5.6 | | | |
| 5 | Douglas-fir LVL | Parallel | 48 | 1.660 | 0.015 | 7.2 | 1.610 | 0.012 | 8.1 |
| | | Perpendicular | 48 | 1.559 | 0.015 | 7.5 | | | |
| 6 | Douglas-fir LVL | Parallel | 48 | 1.626 | 0.014 | 6.6 | 1.623 | 0.010 | 6.6 |
| | | Perpendicular | 48 | 1.620 | 0.014 | 6.7 | | | |
| 7 | Eucalyptus LVL | Parallel | 44 | 1.674 | 0.027 | 11.9 | 1.667 | 0.016 | 10.2 |
| | | Perpendicular | 46 | 1.661 | 0.018 | 8.4 | | | |
| 8 | Southern Pine LVL | Parallel | 72 | 1.446 | 0.010 | 6.4 | 1.422 | 0.008 | 8.0 |
| | | Perpendicular | 71 | 1.401 | 0.014 | 9.2 | | | |
| 9 | Southern Pine LVL | Parallel | 48 | 1.552 | 0.013 | 6.6 | 1.480 | 0.012 | 9.1 |
| | | Perpendicular | 48 | 1.409 | 0.015 | 8.2 | | | |
| 10 | Yellow-poplar LVL | Parallel | 48 | 1.452 | 0.011 | 5.7 | 1.387 | 0.011 | 8.8 |
| | | Perpendicular | 48 | 1.323 | 0.014 | 8.5 | | | |
| 11 | Yellow-poplar LVL | Parallel | 48 | 1.421 | 0.011 | 6.2 | 1.372 | 0.013 | 10.1 |
| | | Perpendicular | 47 | 1.323 | 0.020 | 12.0 | | | |
| 12 | Douglas-fir PSL | Parallel | 47 | 1.625 | 0.016 | 7.7 | 1.624 | 0.010 | 6.7 |
| | | Perpendicular | 48 | 1.623 | 0.012 | 5.7 | | | |
| 13 | Southern Pine PSL | Parallel | 48 | 1.623 | 0.017 | 8.3 | 1.627 | 0.011 | 7.4 |
| | | Perpendicular | 48 | 1.630 | 0.014 | 6.4 | | | |
| 14 | Yellow-poplar PSL | Parallel | 38 | 1.556 | 0.015 | 6.9 | 1.570 | 0.010 | 6.4 |
| | | Perpendicular | 48 | 1.579 | 0.012 | 6.0 | | | |

[a]Numbers correspond to those listed in Table 1.
[b]Direction of charring relative to the plane of veneers in the laminated veneer lumber (LVL) or normal vertical surface of the laminated strand lumber (LSL) or parallel strand lumber (PSL).
[c]Number of pairs of time for 300°C and corresponding depth of thermocouples used in linear regression to obtain estimate of parameter.
[d]Mean estimate of the parameter $m_1$ in Equation (1).
[e]Standard error of estimate for the parameter $m_1$ in Equation (1).
[f]Coefficient of variation of the predictions from Equation (1).
[g]Data for both charring directions relative to the plane of the veneers are combined for these results.

**Table 4. Estimates for parameter $m_1$ of Equation (1) for combinations of the 14 materials tested in small vertical furnace**

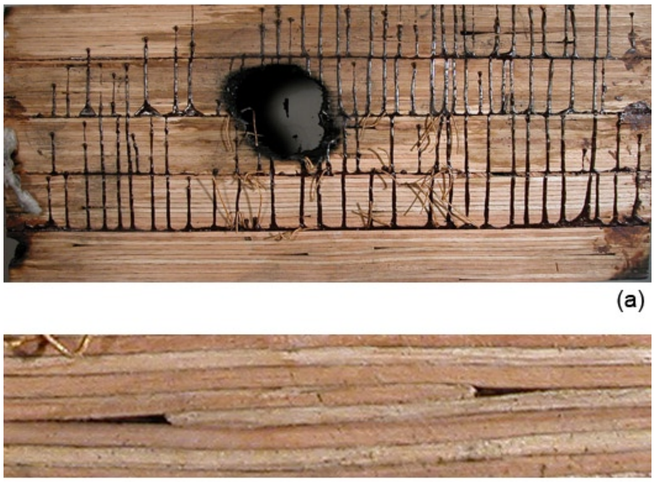
| Material numbers[a] | Species composite type | Direction[b] | $N$[c] | $m_1$ of Equation (1) Mean[d] (min/mm) | Standard error[e] (min/mm) | Predicted COV[f] (%) | $m_1$ of Equation (1) for both directions[g] Mean[d] (min/mm) | Standard error[e] (min/mm) | Predicted COV[f] (%) |
|---|---|---|---|---|---|---|---|---|---|
| 4, 5 ,6 | Douglas-fir LVL | Parallel | 144 | 1.606 | 0.009 | 7.6 | 1.587 | 0.006 | 7.5 |
| | | Perpendicular | 144 | 1.568 | 0.008 | 7.2 | | | |
| 8.9 | Southern Pine LVL | Parallel | 120 | 1.487 | 0.009 | 7.6 | 1.446 | 0.007 | 8.7 |
| | | Perpendicular | 119 | 1.404 | 0.010 | 8.8 | | | |
| 10, 11 | Yellow-poplar LVL | Parallel | 96 | 1.436 | 0.008 | 6.0 | 1.380 | 0.008 | 9.4 |
| | | Perpendicular | 95 | 1.323 | 0.012 | 10.3 | | | |
| 1, 3 | Aspen | Parallel | 96 | 1.556 | 0.013 | 9.1 | 1.530 | 0.008 | 8.6 |
| | | Perpendicular | 94 | 1.503 | 0.010 | 7.5 | | | |
| 4, 5 ,6 ,12 | Douglas-fir | Parallel | 191 | 1.611 | 0.008 | 7.6 | 1.596 | 0.005 | 7.4 |
| | | Perpendicular | 192 | 1.582 | 0.007 | 7.0 | | | |
| 8, 9, 13 | Southern Pine | Parallel | 168 | 1.526 | 0.009 | 9.0 | 1.498 | 0.008 | 10.3 |
| | | Perpendicular | 167 | 1.469 | 0.011 | 11.2 | | | |
| 2, 10, 11, 14 | Yellow-poplar | Parallel | 181 | 1.497 | 0.008 | 8.5 | 1.475 | 0.008 | 11.3 |
| | | Perpendicular | 191 | 1.455 | 0.012 | 13.3 | | | |
| 1, 2 | LSL | Parallel | 95 | 1.594 | 0.010 | 7.1 | 1.584 | 0.007 | 7.2 |
| | | Perpendicular | 95 | 1.574 | 0.010 | 7.3 | | | |
| 3–11 | LVL | Parallel | 452 | 1.534 | 0.006 | 10.0 | 1.502 | 0.005 | 11.2 |
| | | Perpendicular | 451 | 1.470 | 0.007 | 11.9 | | | |
| 12–14 | PSL | Parallel | 133 | 1.608 | 0.010 | 8.0 | 1.609 | 0.006 | 7.1 |
| | | Perpendicular | 144 | 1.610 | 0.007 | 6.2 | | | |
| 1–14 | All data | Parallel | 680 | 1.556 | 0.005 | 9.5 | 1.535 | 0.004 | 10.4 |
| | | Perpendicular | 690 | 1.514 | 0.006 | 11.1 | | | |

[a]Numbers correspond to those listed in Table 1.
[b]Direction of charring relative to the plane of the veneers in the laminated veneer lumber (LVL) or normal vertical surface of the laminated strand lumber (LSL) or parallel strand lumber (PSL).
[c]Number of pairs of time for 300°C and corresponding depth of thermocouples used in linear regression to obtain estimate of parameter.
[d]Mean estimate of the parameter $m_1$ in Equation (1).
[e]Standard error of estimate for the parameter $m_1$ in Equation (1).
[f]Coefficient of variation of the predictions from Equation (1).
[g]Data for both charring directions relative to the plane of the laminates are combined for these results.

**Table 5. Estimates for parameter $m_5$ of Equation (5) for the 14 materials tested in small vertical furnace**

| | | | $m_5$ of Equation (5) | | | $m_5$ of Equation (5) for both directions[f] | | |
|---|---|---|---|---|---|---|---|---|
| Material number[a] | Species composite type | Direction[b] | Mean[c] (min/mm$^{1.23}$) | Standard error[d] (min/mm$^{1.23}$) | Predicted COV[e] (%) | Mean[c] (min/mm$^{1.23}$) | Standard error[d] (min/mm$^{1.23}$) | Predicted COV[e] (%) |
| 1 | Aspen LSL | Parallel | 0.6796 | 0.0052 | 5.9 | 0.6698 | 0.0040 | 6.4 |
| | | Perpendicular | 0.6599 | 0.0057 | 6.6 | | | |
| 2 | Yellow-poplar LSL | Parallel | 0.6753 | 0.0051 | 5.8 | 0.6759 | 0.0039 | 6.3 |
| | | Perpendicular | 0.6765 | 0.0059 | 6.8 | | | |
| 3 | Aspen LVL | Parallel | 0.6411 | 0.0088 | 10.6 | 0.6281 | 0.0049 | 8.5 |
| | | Perpendicular | 0.6147 | 0.0033 | 4.1 | | | |
| 4 | Douglas-fir LVL | Parallel | 0.6499 | 0.0052 | 6.1 | 0.6486 | 0.0039 | 6.5 |
| | | Perpendicular | 0.6473 | 0.0058 | 6.9 | | | |
| 5 | Douglas-fir LVL | Parallel | 0.7046 | 0.0069 | 7.5 | 0.6827 | 0.0059 | 9.3 |
| | | Perpendicular | 0.6607 | 0.0084 | 9.7 | | | |
| 6 | Douglas-fir LVL | Parallel | 0.6894 | 0.0075 | 8.3 | 0.6880 | 0.0053 | 8.4 |
| | | Perpendicular | 0.6866 | 0.0077 | 8.5 | | | |
| 7 | Eucalyptus LVL | Parallel | 0.7106 | 0.0134 | 13.8 | 0.7073 | 0.0072 | 10.8 |
| | | Perpendicular | 0.7043 | 0.0064 | 7.0 | | | |
| 8 | Southern Pine LVL | Parallel | 0.6126 | 0.0045 | 6.9 | 0.6039 | 0.0033 | 7.2 |
| | | Perpendicular | 0.5951 | 0.0046 | 7.3 | | | |
| 9 | Southern Pine LVL | Parallel | 0.6588 | 0.0050 | 5.9 | 0.6286 | 0.0047 | 8.2 |
| | | Perpendicular | 0.5985 | 0.0051 | 6.7 | | | |
| 10 | Yellow-poplar LVL | Parallel | 0.6160 | 0.0049 | 6.1 | 0.5892 | 0.0041 | 7.7 |
| | | Perpendicular | 0.5624 | 0.0038 | 5.3 | | | |
| 11 | Yellow-poplar LVL | Parallel | 0.6032 | 0.0043 | 5.6 | 0.5831 | 0.0044 | 8.3 |
| | | Perpendicular | 0.5626 | 0.0065 | 9.0 | | | |
| 12 | Douglas-fir PSL | Parallel | 0.6920 | 0.0054 | 6.0 | 0.6900 | 0.0042 | 6.6 |
| | | Perpendicular | 0.6881 | 0.0065 | 7.2 | | | |
| 13 | Southern Pine PSL | Parallel | 0.6902 | 0.0041 | 4.7 | 0.6911 | 0.0034 | 5.3 |
| | | Perpendicular | 0.6919 | 0.0053 | 6.0 | | | |
| 14 | Yellow-poplar PSL | Parallel | 0.6727 | 0.0056 | 5.9 | 0.6712 | 0.0034 | 5.2 |
| | | Perpendicular | 0.6703 | 0.0042 | 4.8 | | | |

[a]Numbers correspond to those listed in Table 1.
[b]Direction of charring relative to the plane of the veneers in laminated veneer lumber (LVL) or normal vertical surface of laminated strand lumber (LSL) or parallel strand lumber (PSL).
[c]Mean estimate of the parameter $m_5$ in Equation (5).
[d]Standard error of estimate for the parameter $m_5$ in Equation (5).
[e]Coefficient of variation of the predictions from Equation (5).
[f]Data for both charring directions relative to the plane of the laminates are combined for these results.



(a)

(b)

**Figure 5. Example of (a) the hole burned though the eucalyptus specimen after a small vertical-furnace test in which charring was parallel to the plane of laminated veneer and (b) gaps formed in the manufacture of laminated veneer lumber.**

In these small vertical-furnace tests, the residual char surface was a fairly consistent vertical plane. The exceptions were tests of the eucalyptus LVL specimens, in which specimen orientation was such that the intended direction of charring was parallel to the plane of the laminated veneers. The charring of these eucalyptus LVL specimens caused holes to appear on the back surface. In some cases, smaller holes merged to form a larger hole at the end of the test (Fig. 5a). In an LVL, gaps are formed by termination of a veneer within the product and the veneer above and below being pressed together (Fig. 5b). These gaps went completely through the test specimens. Unlike the other test specimens, this test material was a prototype sample of the product. We concluded that these gaps allowed three-dimensional charring at that point and the resulting rapid flame penetration through the specimen. On the fire-exposed surface, a physical hole was formed in the char layer. The magnitude of the gaps in these prototype samples would not occur in the commercial products for non-fire reasons. In commercial products, the ends of veneers were tapered or otherwise constructed to reduce the size of any physical gap being created. The early penetration of test specimen or holes in the charred surface was not observed in the tests of other products. In most applications of LVL, the potential fire exposure would be perpendicular to the plane of the veneers.

## Horizontal-Furnace Tests

### Test methods

The 13 intermediate-scale tests in the horizontal furnace included 10 different materials (Table 2). Width of the test specimens ranged from 44 to 180 mm (Table 2). Heights ranged from 351 to 455 mm.

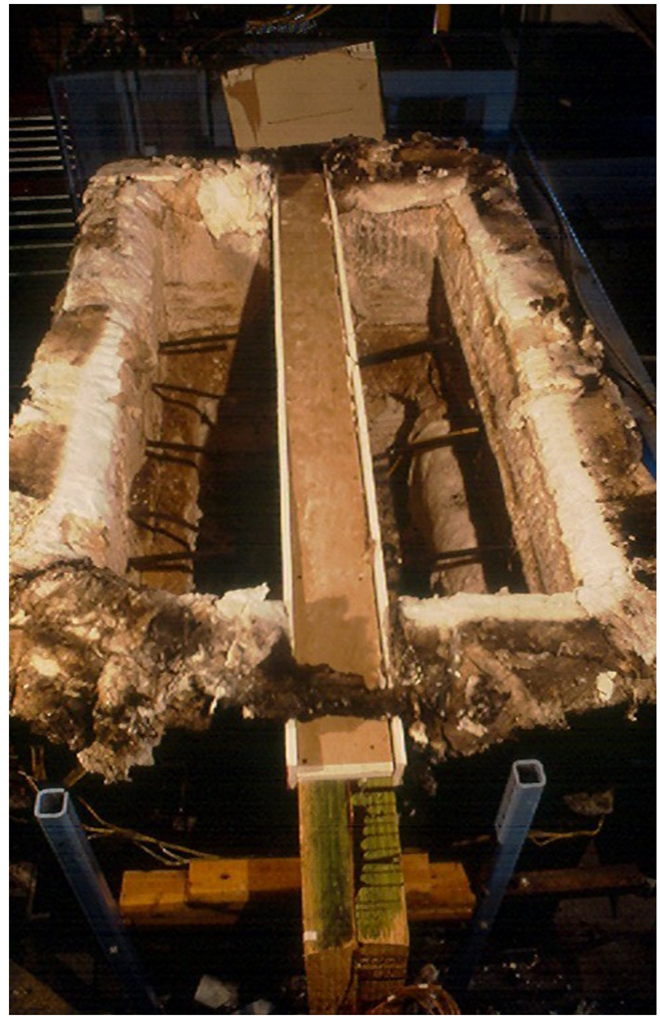


**Figure 6. Unloaded specimen in horizontal-furnace test.**

The intermediate-scale horizontal furnace was a metal box lined with ceramic/mineral fiber blankets and heated by eight diffusion-flame natural gas burners on the floor of the furnace (Fig. 6). The central 1.8 m of a specimen was exposed to furnace temperatures. The interior dimensions of the furnace were 1.83 m long, 0.99 m wide, and 1.22 m high. On each end of the furnace was an opening 229 mm wide and 508 mm deep for the test specimen. The ceramic fiber-lined metal cover for the furnace was removable from the top of the furnace. All air for combustion was provided by natural draft through vents at the bottom of the furnace.

Three capped furnace thermocouples were 152 mm from the exposed specimen surface down the length of each of the two sides of the test specimen. These six thermocouples were located 305 mm from the top of the furnace interior. The gas was controlled so temperatures of the capped thermocouples followed the time–temperature curve in ASTM E 119. The ASTM E 119 specifies a distance of 305 mm for the capped pipe from the exposed surface in tests of floors and columns and 152 mm for tests of walls and partitions.

**Table 6. Estimates for parameter $m_5$ of Equation (5) for combinations of the 14 materials tested in small vertical furnace**

| | | | $m_5$ of Equation (5) | | | $m_5$ of Equation (5) for both directions[f] | | |
|---|---|---|---|---|---|---|---|---|
| Material number[a] | Species composite type | Direction[b] | Mean[c] (min/mm$^{1.23}$) | Standard error[d] (min/mm$^{1.23}$) | Predicted COV[e] (%) | Mean[c] (min/mm$^{1.23}$) | Standard error[d] (min/mm$^{1.23}$) | Predicted COV[e] (%) |
| 4, 5, 6 | Douglas-fir LVL | Parallel | 0.6813 | 0.0042 | 8.3 | 0.6731 | 0.0031 | 8.7 |
| | | Perpendicular | 0.6649 | 0.0044 | 8.9 | | | |
| 8, 9 | Southern Pine LVL | Parallel | 0.6311 | 0.0039 | 7.6 | 0.6139 | 0.0028 | 8.0 |
| | | Perpendicular | 0.5965 | 0.0034 | 7.0 | | | |
| 10, 11 | Yellow-poplar LVL | Parallel | 0.6096 | 0.0033 | 5.9 | 0.5862 | 0.0030 | 8.0 |
| | | Perpendicular | 0.5625 | 0.0037 | 7.3 | | | |
| 1, 3 | Aspen | Parallel | 0.6604 | 0.0055 | 9.0 | 0.6490 | 0.0035 | 8.3 |
| | | Perpendicular | 0.6375 | 0.0040 | 6.9 | | | |
| 4, 5, 6, 12 | Douglas-fir | Parallel | 0.6838 | 0.0035 | 7.8 | 0.6772 | 0.0026 | 8.3 |
| | | Perpendicular | 0.6707 | 0.0038 | 8.6 | | | |
| 8, 9, 13 | Southern Pine | Parallel | 0.6480 | 0.0037 | 8.2 | 0.6360 | 0.0029 | 9.5 |
| | | Perpendicular | 0.6239 | 0.0044 | 10.2 | | | |
| 2, 10, 11, 14 | Yellow-poplar | Parallel | 0.6380 | 0.0034 | 8.1 | 0.6276 | 0.0030 | 10.4 |
| | | Perpendicular | 0.6183 | 0.0048 | 12.0 | | | |
| 1, 2 | LSL | Parallel | 0.6775 | 0.0036 | 5.9 | 0.6728 | 0.0028 | 6.4 |
| | | Perpendicular | 0.6682 | 0.0042 | 6.8 | | | |
| 3–11 | LVL | Parallel | 0.6511 | 0.0029 | 10.5 | 0.6376 | 0.0021 | 11.1 |
| | | Perpendicular | 0.6242 | 0.0030 | 11.3 | | | |
| 12–14 | PSL | Parallel | 0.6867 | 0.0030 | 5.6 | 0.6850 | 0.0022 | 6.0 |
| | | Perpendicular | 0.6835 | 0.0032 | 6.3 | | | |
| 1–14 | All data | Parallel | 0.6614 | 0.0022 | 9.5 | 0.6518 | 0.0016 | 10.2 |
| | | Perpendicular | 0.6426 | 0.0024 | 10.7 | | | |

[a]Numbers correspond to those listed in Table 1.
[b]Direction of charring relative to the plane of the veneers in laminated veneer lumber (LVL) or normal vertical surface of laminated strand lumber (LSL) or parallel strand lumber (PSL).
[c]Mean estimate of the parameter $m_5$ in Equation (5).
[d]Standard error of estimate for the parameter $m_5$ in Equation (5).
[e]Coefficient of variation of the predictions from Equation (5).
[f]Data for both charring directions relative to the plane of the laminates are combined for these results.

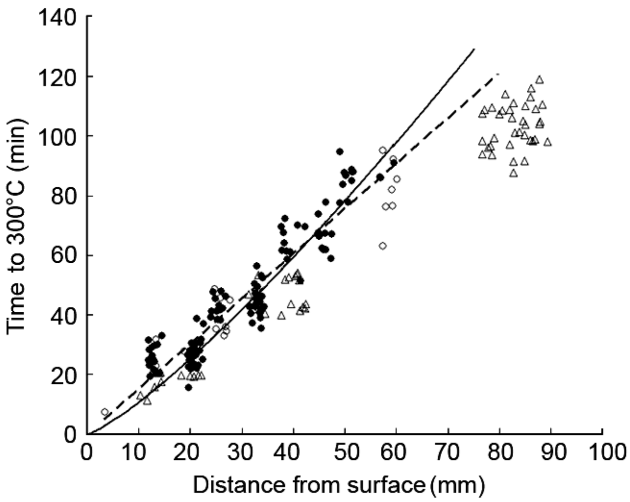



**Figure 7. Plot of experimental data (symbols) and predictions based on $x_c$ model (- - -) and $x_c^{1.23}$ model (—) of data. Solid circles (●) are for locations greater than 13 mm from horizontal center of test specimen. Open circles (○) are data for locations between 13 and 30 mm from the horizontal center of the test specimen. Open triangles (∆) are locations less than 13 mm from the center of the test specimen.**

Horizontal-furnace specimens were subjected to fire exposure on three sides. Specimens were oriented in the furnace with the wider side vertical. The top surface was covered with gypsum board and ceramic fiber (Fig. 6). A strip of gypsum board was also placed along the top edges of the vertical surfaces to ensure no charring of the top surface. The top surface was protected to allow holes for the 16 thermocouples to be drilled from the top surface. Four groups of thermocouples were inserted into a test specimen. Each group of thermocouples included thermocouples at different depths from the sides of the specimen. Four groups of thermocouples were located at different locations along the length of the specimens. Depths of the thermocouples from the top of the specimen also varied between the groups. In the furnace, the length of the specimen was in an east–west direction. The four groups of thermocouples were as follows:

a. Group one consisted of five thermocouples at 50-mm intervals from 350 to 500 mm east of mid-span of the test specimen. Four thermocouples were placed at different distances from the north surface of the test specimen and one was at mid-width of the specimen. Design depths from the vertical surface were 13, 25, 38, and 51 mm, but actual depths varied depending on the width of the test specimen. The ends of the thermocouples were 175 mm from the top of the specimen. For most specimens, this represented approximately the mid-height of the test specimen (Table 2).

b. Group two consisted of three thermocouples at a 50-mm interval along the specimen length 75 to 175 mm east of mid-span. Design depths were two thermocouples at 13 mm and 25 mm from the north surface and one at the mid-width of the test specimen. Thermocouples were 270 mm from the top of the specimen.

c. Group three was likewise three thermocouples 75 to 175 mm west of mid-span. Design depths from the vertical surface for two thermocouples were 13 mm and 25 mm from the north surface and one at the mid-width of the test specimen. Thermocouples were located 80 mm from the top of the specimen.

d. Group four was similar to group one but located 350 mm to 550 mm west of mid-span and at depths from the south surface of the test specimen.

To install the thermocouples, we drilled 3.2-mm-diameter holes from the top of the test specimen at thermocouple locations so we could insert wood dowels. A groove was made on the side of each wood dowel for thermocouple wire. Placement of the dowel in the hole was such that the groove with the thermocouple was on the side of the nearest fire-exposed surface. Thermocouples were made from Type K (chromel-alumel), 30-gauge (0.254-mm-diameter) insulated thermocouple wire. This procedure was used because the depths of the thermocouple holes made it impractical to use a drill bit comparable to the diameter of the thermocouple wire.

Thermocouple data were collected on a personal computer data acquisition system. The scan rates of data acquisition in these horizontal-furnace tests were a reading every 15 s.

### Test results

As with data from small vertical-furnace tests, pairs of time for 300°C and thermocouple depth from the horizontal-furnace tests (Table 2) were used to calculate char rate parameters of Equations (1) and (5). Models of Equations (1) and (5) are for a semi-infinite slab. Char rates reported for small vertical-furnace tests are for a semi-infinite slab, because the last times for 300°C were obtained prior to any significant temperature increase on the unexposed or back surface of test specimens. In horizontal-furnace tests (Fig. 7), data at or near the mid-width of a test specimen deviated from models of Equations (1) and (5). Data indicated a very rapid charring of the test specimen as temperature at the center of the specimen increased. This is consistent with a slab insulated on the back or an unexposed surface. The center of a specimen fire exposed to both sides is often represented as an insulated boundary condition that prevents heat loss out the back surface. In Figure 7, data from locations less than 13 mm from the center of the test specimen are represented by open triangles. Open circles represent locations between 13 and 30 mm from the horizontal center. Data from locations 13 mm or closer to the horizontal center of the test specimen from linear regressions were excluded from the data set to obtain parameter estimates

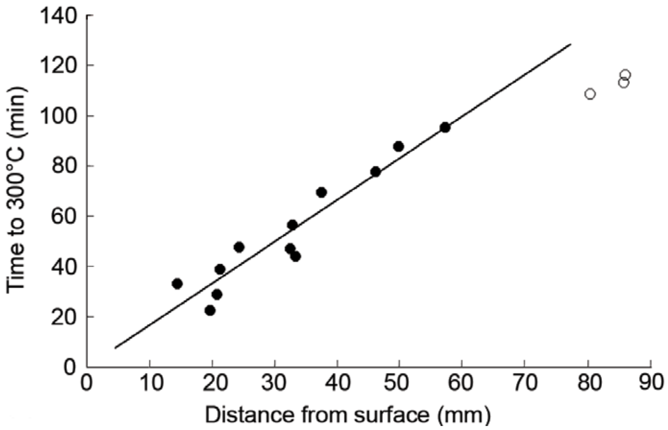



**Figure 8. Experimental times to 300°C plotted against distance from fire-exposed surface for horizontal-furnace Test Number 1 of aspen laminated strand lumber (LSL, Material 1). Line is the linear $m_1$ model using data for locations greater than 13 mm from the horizontal center of test specimen (●). Open circles (○) are data for locations less than 13 mm from the horizontal center of the test specimen. The left edge of the graph corresponds to the horizontal center of the test specimen.**

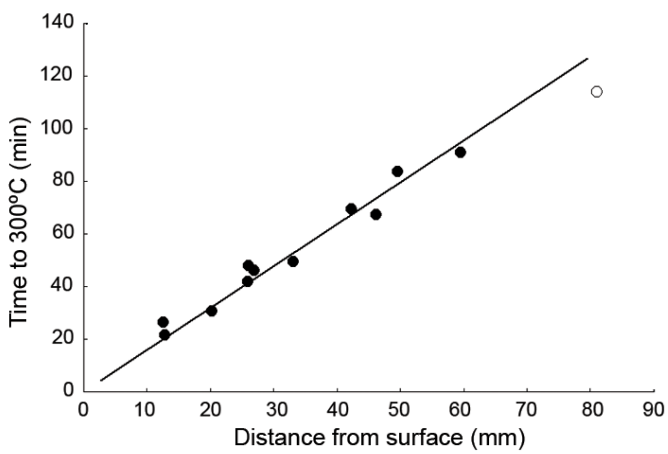



**Figure 9. Experimental times to 300°C plotted against distance from fire-exposed surface for horizontal-furnace Test Number 2 of Douglas-fir laminated veneer lumber (LVL, Material 4). Line is the linear $m_1$ model using data for locations greater than 13 mm from the horizontal center of test specimen (●). Open circles are data (○) for locations less than 13 mm from the horizontal center of the test specimen. The left edge of the graph corresponds to the horizontal center of the test specimen.**

(Tables 7 and 8). For Test Number 3, data closer than 9 mm were excluded since the width of the specimen was only 44 mm. Widths of the 13 horizontal-furnace specimens ranged from 44 to 179 mm (Table 2). Range of char depth data and maximum time for the 300°C recorded varied depending on the width of the test specimen (Table 2).

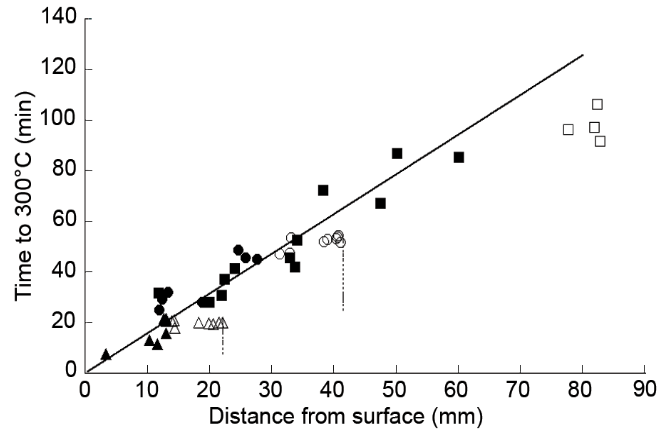



**Figure 10. Experimental times to 300°C plotted against distance from fire-exposed surface for horizontal-furnace Test Numbers 3, 4, and 5 of Douglas-fir laminated veneer lumber (LVL, Material 5). Line is the linear $m_1$ model using data for locations greater than 13 mm from the horizontal center (9 mm for Test 3) of test specimen (solid symbol). Open symbols are data for locations less than 13 mm (9 mm for Test 3) from the horizontal center of the test specimen. Left edge of the graph corresponds to the horizontal center of the widest test specimen. Vertical lines correspond to the horizontal center of the two narrower test specimens. Symbols: ∆, Test 3; ○, Test 4; □, Test 5.**

Data for the four groups of thermocouples within a test specimen were combined to estimate char rate parameters (Figs. 8 to 17). Three horizontal-furnace tests were Douglas-fir LVL of Material Number 5 (Table 2, Fig. 10). Two horizontal-furnace tests were yellow-poplar LVL of Material Number 11 (Table 2, Fig. 15). As with the tables for the small vertical-furnace tests, tables for horizontal-furnace tests include estimates for mean and standard error for char rate parameter $m_1$ (Table 7) and $m_5$ (Table 8) and coefficients of variation for predicted times. Numbers of pairs of data included in the regressions are also listed. Estimates were calculated for each individual test and for combinations of common test material (Tables 7 and 8).

## Discussion

Comparison of small vertical-furnace data for three composite lumber products with earlier data and predictive equations for charring of solid lumber was previously reported (White 2000). In Table 9, average estimates of $m_1$ of Equation (1) for LSL, LVL, and PSL obtained in small vertical-furnace tests are compared with values for $m_1$ from earlier FPL tests of different species of solid lumber.

Compared with the range of averages for four species of aspen, Douglas-fir, Southern Pine, and yellow-poplar ($m_1$ of 1.38 to 1.59 for LVL and $m_1$ of 1.33 to 1.64 for lumber), the range of average values for four types of wood products was less ($m_1$ of 1.50 to 1.61). Species effect on char rate of LVL was comparable to lumber data. Species was less of a factor in char rate of PSL and LSL. On average, char

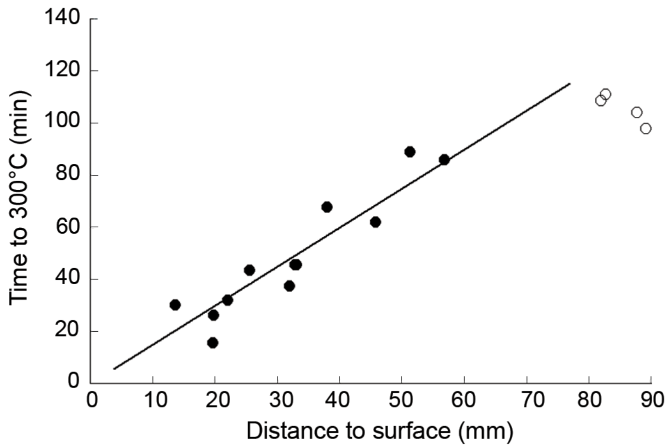



**Figure 11. Experimental times to 300°C plotted against distance from fire-exposed surface for horizontal-furnace Test Number 6 of Douglas-fir laminated veneer lumber (LVL, Material 6). Line is the linear $m_1$ model using data for locations greater than 13 mm from the horizontal center of test specimen (●). Open circles (○) are data for locations less than 13 mm from the horizontal center of the test specimen. The left edge of the graph corresponds to the horizontal center of the test specimen.**

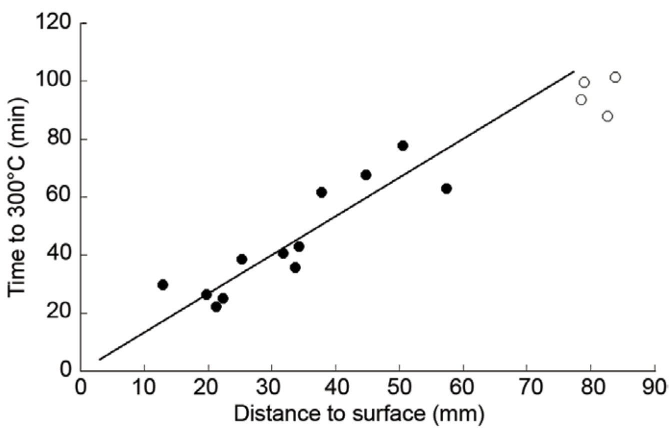



**Figure 12. Experimental times to 300°C plotted against distance from fire-exposed surface for horizontal-furnace Test Number 7 of Southern Pine laminated veneer lumber (LVL, Material 8). Line is the linear $m_1$ model using data for locations greater than 13 mm from the horizontal center of test specimen (●). Open circles (○) are data for locations less than 13 mm from the horizontal center of the test specimen. The left edge of the graph corresponds to the horizontal center of the test specimen.**

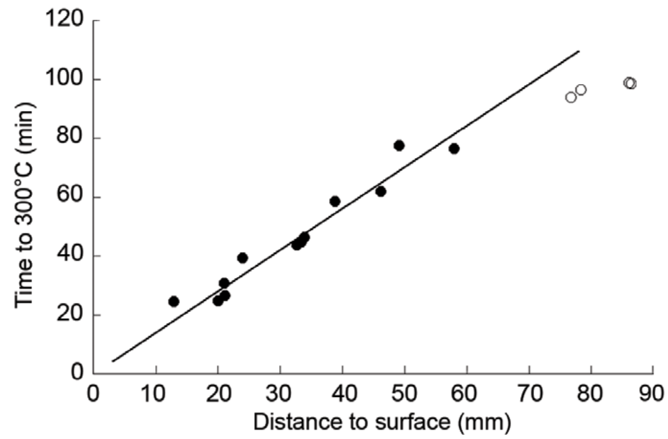



**Figure 13. Experimental times to 300°C plotted against distance from fire-exposed surface for horizontal-furnace Test Number 8 of Southern Pine laminated veneer lumber (LVL, Material 9). Line is the linear $m_1$ model using data for locations greater than 13 mm from the horizontal center of test specimen (●). Open circles (○) are data for locations less than 13 mm from the horizontal center of the test specimen. The left edge of the graph corresponds to the horizontal center of the test specimen.**

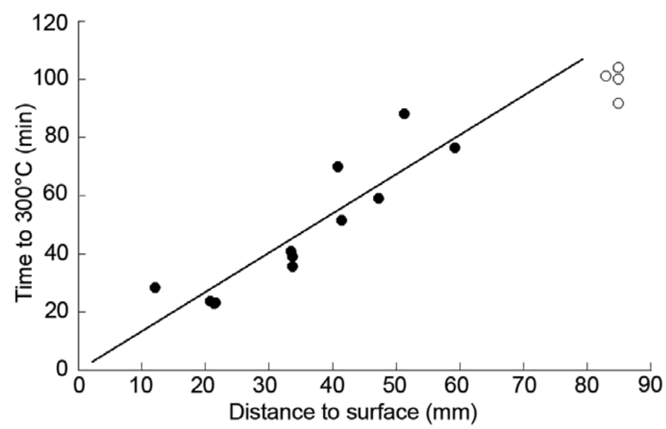



**Figure 14. Experimental times to 300°C plotted against distance from fire-exposed surface for horizontal-furnace Test Number 9 of yellow-poplar laminated veneer lumber (LVL, Material 10). Line is the linear $m_1$ model using data for locations greater than 13 mm from the horizontal center of test specimen (●). Open circles (○) are data for locations less than 13 mm from the horizontal center of the test specimen. The left edge of the graph corresponds to the horizontal center of the test specimen.**

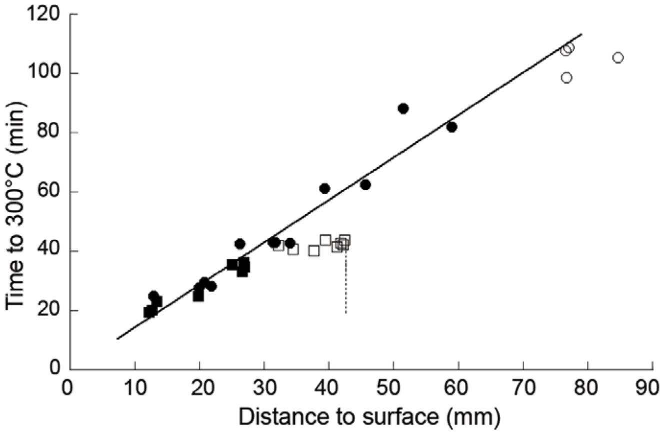



**Figure 15. Experimental times to 300°C plotted against distance from fire-exposed surface for horizontal-furnace Test Number 10 and 11 of yellow-poplar laminated veneer lumber (LVL, Material 11). Line is the linear $m_1$ model using data for locations greater than 13 mm from center of test specimen (solid symbol). Open symbols are data for locations less than 13 mm from the horizontal center of the test specimen. The left edge of the graph corresponds to the horizontal center of the widest test specimen. Vertical lines correspond to the horizontal center of the two narrower test specimens. Symbols: ○, Test Number 4; □, Test Number 5.**

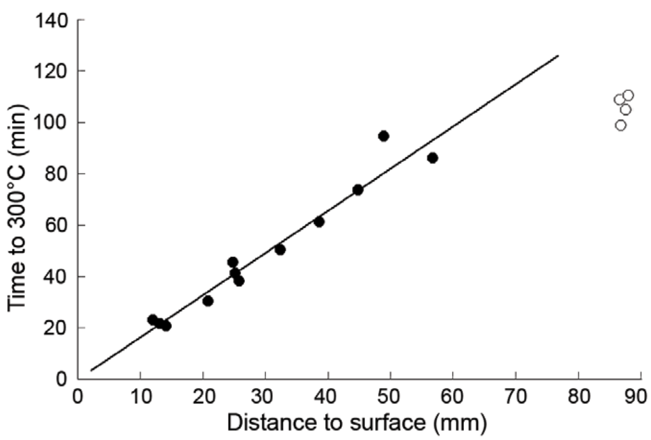



**Figure 16. Experimental times to 300°C plotted against distance from fire-exposed surface for horizontal-furnace Test Number 12 of Douglas-fir parallel strand lumber (PSL, Material 12). Line is the linear $m_1$ model using data for locations greater than 13 mm from the horizontal center of test specimen (●). Open circles (○) are data for locations less than 13 mm from the horizontal center of the test specimen. The left edge of the graph corresponds to the horizontal center of the test specimen.**

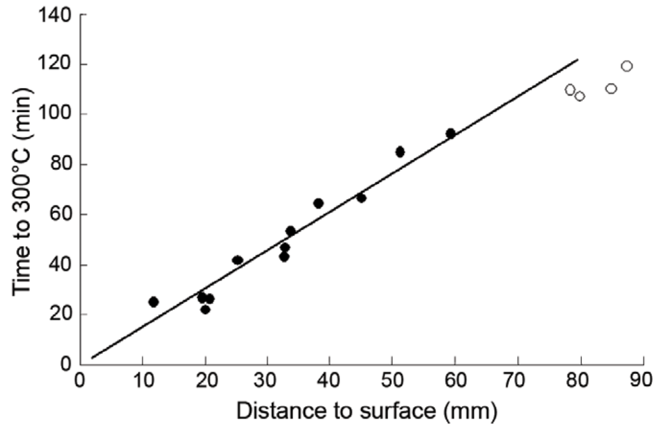



**Figure 17. Experimental times to 300°C plotted against distance from fire-exposed surface for horizontal-furnace Test Number 13 of Southern Pine parallel strand lumber (PSL, Material 13). Line is the linear $m_1$ model using data for locations greater than 13 mm from the horizontal center of test specimen (●). Open circles (○) are data for locations less than 13 mm from the horizontal center of the test specimen. The left edge of the graph corresponds to the horizontal center of the test specimen.**

rates of composite products were comparable to previous data for lumber. Estimates for $m_1$ and $m_5$ for all small vertical-furnace composite lumber tests combined were 1.535 and 0.652 min/mm$^{1.23}$, respectively. For 38 mm of char at 1 h cited in TR 10 and generally assumed for solid lumber, corresponding values are 1.575 min/mm for $m_1$ of Equation (1) and 0.682 min/mm$^{1.23}$ for $m_5$ of Equation (5).

There was considerable scatter in the data from horizontal-furnace tests. Coefficients of variation for predicted times were considerably greater for horizontal-furnace tests (Tables 7 and 8) than for small vertical-furnace tests (Tables 3 and 4). This is not surprising given greater difficulties in placing thermocouples within a horizontal-furnace specimen at a precise location. Two furnaces are considerably different in terms of furnace linings and type and placement of natural gas burners. Despite these differences, a zero-intercept linear regression of average $m_1$ results from two furnaces for 10 materials resulted in a slope of 1.001 (Fig. 18). This suggests that there was not a bias between results for the two furnaces. The 52% $R^2$ of the regression likely reflects high variability in horizontal-furnace results.

## Tension Tests

Fire tests conducted in the first two phases of this project did not include any load applied to the member. The third phase provides data on tensile strength of composite lumber products while subjected to standard fire exposure defined by the time–temperature curve in ASTM E 119 (ASTM International 2000). The intermediate-scale horizontal-furnace used in Phase Two was also used for tension tests. The FPL horizontal furnace is considerably smaller than dimensions specified in ASTM E 119, but the furnace is unique in that

**Table 7. Estimates for parameter $m_1$ of Equation (1) for tests of unloaded specimens in horizontal furnace**

| Test number[a] | Material number[a] | Species | Composite type | Width (mm) | $m_1$ for 300°C (min/mm) Mean[b] | Standard error[c] | COV of predictions[d] | Number of data points[e] | FPL test number |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | Aspen | LSL | 175 | 1.660 | 0.058 | 12.9 | 12 | 2110 |
| 2 | 4 | Douglas-fir | LVL | 180 | 1.593 | 0.037 | 8.3 | 11 | 2112 |
| 3 | 5 | Douglas-fir | LVL | 44 | 1.429 | 0.110 | 21.1 | 7 | 2117 |
| 4 | 5 | Douglas-fir | LVL | 83 | 1.813 | 0.106 | 15.7 | 7 | 2108 |
| 5 | 5 | Douglas-fir | LVL | 167 | 1.533 | 0.064 | 15.4 | 12 | 2113 |
| 6 | 6 | Douglas-fir | LVL | 179 | 1.497 | 0.069 | 17.4 | 12 | 2118 |
| 7 | 8 | Southern Pine | LVL | 169 | 1.336 | 0.071 | 19.4 | 12 | 2120 |
| 8 | 9 | Southern Pine | LVL | 173 | 1.404 | 0.037 | 9.9 | 12 | 2115 |
| 9 | 10 | Yellow-poplar | LVL | 170 | 1.349 | 0.075 | 20.8 | 12 | 2111 |
| 10 | 11 | Yellow-poplar | LVL | 85 | 1.348 | 0.047 | 10.1 | 8 | 2109 |
| 11 | 11 | Yellow-poplar | LVL | 170 | 1.454 | 0.046 | 11.9 | 12 | 2119 |
| 12 | 12 | Douglas-fir | PSL | 177 | 1.641 | 0.048 | 11.3 | 12 | 2116 |
| 13 | 13 | Southern Pine | PSL | 176 | 1.527 | 0.044 | 11.0 | 12 | 2114 |
| 10, 11 | 11 | Yellow-poplar | LVL | 85, 170 | 1.433 | 0.035 | 12.1 | 20 | – |
| 3–5 | 5 | Douglas-fir | LVL | 44, 83, 167 | 1.570 | 0.049 | 18.1 | 26 | – |
| 2–6 | 4–6 | Douglas-fir | LVL | 44–180 | 1.554 | 0.031 | 15.5 | 49 | – |
| 7, 8 | 8, 9 | Southern Pine | LVL | 169, 173 | 1.370 | 0.040 | 15.1 | 24 | – |
| 9–11 | 10, 11 | Yellow-poplar | LVL | 85, 170, 170 | 1.393 | 0.037 | 16.6 | 32 | – |
| 2–11 | 4–11 | All | LVL | 44–180 | 1.455 | 0.022 | 16.9 | 105 | – |
| 12, 13 | 12, 13 | All | PSL | 176, 177 | 1.580 | 0.034 | 11.7 | 24 | – |
| All | All | All | All | 44–180 | 1.497 | 0.019 | 16.3 | 141 | – |

[a]Numbers correspond to those listed in Table 2.
[b]Mean estimate for parameter $m_1$ in Equation (1) for temperature criteria of 300ºC.
[c]Standard error for the mean estimate for parameter $m_1$ in Equation (1) for temperature criteria of 300ºC.
[d]Coefficient of variation for the predicted times from Equation (1).
[e]Number of data points included in the regressions. Excluded data that was for locations 13 mm or closer to the horizontal center of the test specimen. For test 3, excluded data was for locations closer than 9 mm from the horizontal center of the test specimen. The width of the specimen for test 3 was only 44 mm.

**Table 8. Estimates for parameter $m_5$ of Equation (5) for tests of unloaded specimens in horizontal furnace**

| | | | | | $m_5$ for 300°C (min/mm) | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Test number[a] | Material number[a] | Species | Composite type | Width (mm) | Mean[b] | Standard Error[c] | COV of predictions[d] | Number of data points[e] | FPL test number |
| 1 | 1 | Aspen | LSL | 175 | 0.706 | 0.028 | 14.5 | 12 | 2110 |
| 2 | 4 | Douglas-fir | LVL | 180 | 0.667 | 0.027 | 14.5 | 11 | 2112 |
| 3 | 5 | Douglas-fir | LVL | 44 | 0.802 | 0.063 | 21.5 | 7 | 2117 |
| 4 | 5 | Douglas-fir | LVL | 83 | 0.878 | 0.067 | 20.6 | 7 | 2108 |
| 5 | 5 | Douglas-fir | LVL | 167 | 0.645 | 0.033 | 18.9 | 12 | 2113 |
| 6 | 6 | Douglas-fir | LVL | 179 | 0.637 | 0.029 | 17.2 | 12 | 2118 |
| 7 | 8 | Southern Pine | LVL | 169 | 0.566 | 0.034 | 22.0 | 12 | 2120 |
| 8 | 9 | Southern Pine | LVL | 173 | 0.595 | 0.022 | 13.7 | 12 | 2115 |
| 9 | 10 | Yellow-poplar | LVL | 170 | 0.568 | 0.031 | 20.4 | 12 | 2111 |
| 10 | 11 | Yellow-poplar | LVL | 85 | 0.648 | 0.034 | 15.2 | 8 | 2109 |
| 11 | 11 | Yellow-poplar | LVL | 170 | 0.615 | 0.023 | 13.7 | 12 | 2119 |
| 12 | 12 | Douglas-fir | PSL | 177 | 0.698 | 0.026 | 14.1 | 12 | 2116 |
| 13 | 13 | Southern Pine | PSL | 176 | 0.647 | 0.019 | 11.3 | 12 | 2114 |
| 10, 11 | 11 | Yellow-poplar | LVL | 85,170 | 0.620 | 0.018 | 14.3 | 20 | – |
| 3–5 | 5 | Douglas-fir | LVL | 44, 83, 167 | 0.677 | 0.029 | 24.1 | 26 | – |
| 2-6 | 4–6 | Douglas-fir | LVL | 44–180 | 0.660 | 0.018 | 19.0 | 49 | – |
| 7, 8 | 8, 9 | Southern Pine | LVL | 169, 173 | 0.581 | 0.020 | 18.0 | 24 | – |
| 9–11 | 10, 11 | Yellow-poplar | LVL | 85, 170, 170 | 0.595 | 0.017 | 17.6 | 32 | – |
| 2–11 | 4–11 | All | LVL | 44–180 | 0.619 | 0.011 | 19.5 | 105 | – |
| 12, 13 | 12, 13 | All | PSL | 176, 177 | 0.670 | 0.016 | 13.2 | 24 | – |
| All | All | All | All | 44–180 | 0.637 | 0.009 | 22.5 | 141 | – |

[a]Numbers correspond to those listed in Table 2.
[b]Mean estimate for parameter $m_5$ in Equation (5) for temperature criteria of 300ºC.
[c]Standard error for the mean estimate for parameter $m_5$ in Equation (5) for temperature criteria of 300ºC.
[d]Coefficient of variation for the predicted times from Equation (5).
[e]Number of data points included in the regressions. Data that were for locations 13 mm or closer to the horizontal center of the test specimen were excluded. For Test 3, data for locations closer than 9 mm from the horizontal center of the test specimen were excluded. The width of the specimen for Test 3 was only 44 mm.

**Table 9. Comparison of average estimates of $m_1$ in Equation (1) for the different types of wood products[a]**

| Species | $m_1$ for LSL (min/mm) | $m_1$ for LVL (min/mm) | $m_1$ for PSL (min/mm) | $m_1$ for lumber (min/mm) |
|---|---|---|---|---|
| Aspen | 1.579 | 1.480 | – | – |
| Douglas-fir | – | 1.587 | 1.624 | 1.64[b] |
| Southern Pine | – | 1.446 | 1.627 | 1.33[c] |
| Yellow-poplar | 1.589 | 1.380 | 1.570 | 1.36[d] |
| All | 1.584 | 1.502 | 1.609 | 1.575[e] |

[a]All results are for tests in the FPL small vertical furnace and for specimens conditioned at 23°C, 50% relative humidity
[b]Ten tests from Schaffer (1967), White and Schaffer (1981), and White (1988). Average dry density is 457 kg/m$^3$. Standard error for the mean of the 10 tests is 0.051 min/mm.
[c]Five tests from Schaffer (1967), White and Schaffer (1981), and White (1988). Average dry density is 504 kg/m$^3$. Standard error for the mean of the five tests is 0.06 min/mm.
[d]Two tests from White (1988). Average dry density is 484 kg/m$^3$. Standard error for the mean of the two tests is 0.04 min/mm.
[e]The 1.575 min/mm is the generally accepted value for wood charring (1.5 in/h; 0.635 mm/min).

**Table 10. Tension tests conducted in horizontal furnace**

| Test number | Material number[a] | Species composite type | Width (mm) | Height (mm) | Density[b] (kg/m$^3$) | Percentage of full design load[c] | FPL Test number |
|---|---|---|---|---|---|---|---|
| 1 | 2 | Yellow-poplar LSL | 89 | 233 | 668 | 36 | 2138 |
| 2 | 3 | Aspen LVL | 42 | 242 | 464 | 64 | 2134 |
| 3 | 4 | Douglas-fir LVL | 135 | 241 | 523 | 25 | 2140 |
| 4 | 4 | Douglas-fir LVL | 178 | 239 | 513 | 30 | 2142 |
| 5 | 5 | Douglas-fir LVL | 43 | 240 | 575 | 8[d] | 2132 |
| 6 | 5 | Douglas-fir LVL | 90 | 240 | 540 | 33 | 2137 |
| 7 | 5 | Douglas-fir LVL | 128 | 235 | 544 | 24 | 2139 |
| 8 | 6 | Douglas-fir LVL | 178 | 234 | 494 | 33 | 2141 |
| 9 | 7 | Eucalyptus LVL | 41 | 239 | 586 | 28 | 2135 |
| 10 | 8 | Southern Pine LVL | 45 | 239 | 603 | 26 | 2136 |
| 11 | 9 | Southern Pine LVL | 169 | 233 | 589 | 33 | 2143 |
| 12 | 11 | Yellow-poplar LVL | 44 | 230 | 577 | 46 | 2133 |
| 13 | 12 | Douglas-fir PSL | 176 | 251 | 601 | 26 | 2144 |

[a]Material numbers are consistent with those listed in Table 1 for the materials used in the small vertical-furnace tests. Except for Material Numbers 3 and 7, the manufacturer supplied the tension test samples at a later date than the samples used in the small vertical-furnace tests and horizontal-furnace charring tests.
[b]Density calculated using oven-dry mass and volume as tested.
[c]Applied load as a percentage of the full allowable design load. Applied load reported is the average load during last 15 s (5 readings) before rapid drop in load. Allowable load design values obtained from the manufacturer's literature or correspondence.
[d]In this initial test, the member failed in the bolt connection outside the furnace when the load was applied prior to initiation of the fire exposure. Plywood was added to bolted connection and test conducted using the low load reported.

it is located in the middle of a tension apparatus. Testing of tensile members is not specifically addressed in the ASTM E 119 standard. The FPL's furnace test apparatus was previously used to test dimension lumber in tension and metal-plate connections (White and others 1993), glued-laminated specimens (White 2004), and dimension lumber (Lau and others 1998).

## Methods and Materials

In a series of 13 tension tests, 10 of the materials tested for char rate (Table 1) were also tested for fire resistance under load (Table 10). Specimens (Fig. 19a) were loaded in a specially made tension apparatus. In the middle of the tension apparatus is the ceramic-fiber-lined horizontal furnace (Fig. 19d) discussed previously. Test specimens were 2.97 m long. The tension apparatus, Model 403FPL, was a modification of the Model 401 and 402 Tension Proof Testers of Metriguard (Pullman, Washington). It was 5.18 m long, 2.29 m wide, and 1.83 m high. The apparatus was capable of a tensile load of 445 kN. The apparatus used an electric-powered hydraulic loading system (Fig. 19b). The system consisted of two hydraulic cylinders with oil provided by a hydraulic power unit. The manual valve and relief valve limited flow of hydraulic fluid. The load was measured with an electronic load-cell force-measuring system.

The wedge-gripping system of the tension apparatus only allowed for specimen thicknesses of 19, 38, and 64 mm. Special grips were made to test these wider specimens (Fig. 19c). Steel plates were used to grip timbers. Fixed and limited distance between wedge grips of the tension

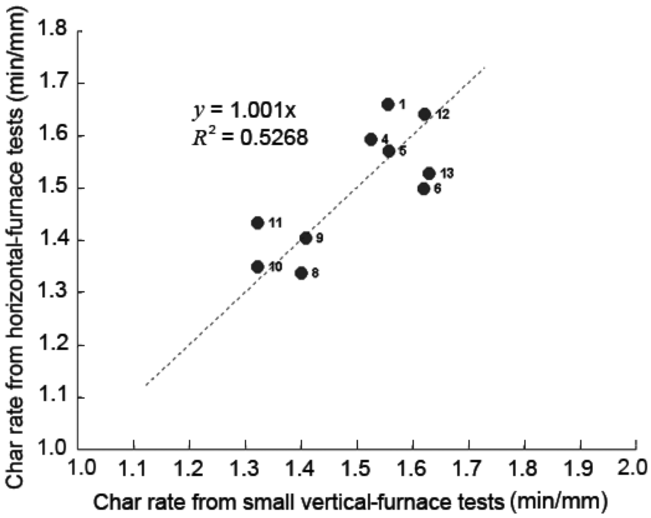



**Figure 18. For the different materials, comparison of charring rates ($m_1$) obtained in the horizontal-furnace tests with those obtained in the small vertical-furnace tests. Labels are the material numbers listed in Table 1.**

apparatus and the edge of the furnace (Fig. 19c) limited the design of the bolted connection and resulting load capacity. Eight 25-mm bolts were used at each end. Holes in the 13-mm-thick steel plates were oversized by 1.6 mm. Nuts on the bolts were not fully tightened to prevent a bending moment from being applied to the specimen. A 64-mm pin was used to connect the two grip plates to another plate that was inserted into the wedge-gripping system of the tension apparatus. Two surfaces of that plate were lined with oak to help ensure a secured gripping system. Prior to application of the load, rollers on support stands provided vertical support to the ends of the member. Application of tensile load lifted the specimen off the vertical support rollers. This was also done to limit any moment load being applied to the specimen during the test.

Selection of the size of test specimens (Table 10) was dictated by limitations of the equipment, desires to obtain certain fire endurance times, and desires to evaluate the validity of fire-endurance models for these materials. Because of


**Figure 19. Test of loaded tension specimen in the intermediate-scale horizontal furnace. (a) Specimens tested in tension apparatus/horizontal furnace in this study were similar to this glued-laminated specimen. (b) Hydraulic loading system of tension apparatus. (c) Steel plates and bolted connections used to apply the tension load. (d) Burning specimen inside the ceramic-fiber-lined furnace after cover was removed at conclusion of a test.**

how the furnace is constructed, specimen size is limited in two ways. Mid-height of the test specimen is 305 mm from the ceiling of the furnace. A 250-mm-high specimen left 180 mm from the top of the specimen to the furnace ceiling. Metal plates used to grip the ends were 190 mm high (Fig. 19). To use all eight bolts to apply the load, the test specimen needed to be at least 235 mm high. The opening at the furnace ends for test specimens was 229 mm wide. To evaluate the range of performance of the model, specimens were approximately 44, 89, 133, and 178 mm thick (Table 10).

Specimens were stored in a 23°C, 50% relative humidity room prior to testing. Test load (Table 11) was applied to the specimen for 10 min prior to initiation of the ASTM E 119 time–temperature exposure. Applied load was limited by load capacity of the bolted connections used to attach specimens to the grips of the tension apparatus (Fig. 19c). Load was a percentage of the full allowable design load (Table 10). Except for Test Number 5, percentage of full design load ranged from 24% to 64% (Table 10). In Test Number 5, initial application of the load resulted in failure of the bolted connections prior to the initiation of fire exposure. Plywood was attached to the specimen in the area of bolted connections and the test specimen was tested with a very low load of 9 kN (8% of the full design load) (Table 11).

Calculation of full allowable tensile design load used allowable design values for tensile load obtained directly from the manufacturer or their literature. If available data required an adjustment for length, values were adjusted for a span of 1.8 m. The furnace was controlled to follow the ASTM E 119 time–temperature curve (Figs. 20 to 32). Furnace thermocouples were 152 mm from sides of the test specimen. Observed failure was recorded when the specimen could no longer support the load. Thermocouples data and load cell data were collected on a personal computer data acquisition system. Data-acquisition scan rates in these horizontal-furnace/tension apparatus tests were every 3 s.

## Failure Times

Observed failure times of the 13 tests listed in Table 10 ranged from 13 to 100 min (Table 11, Figs. 20 to 32). Failure times for the five 44-mm-wide specimens were between 13 and 21 min. Measured widths of the specimens are listed in Table 10. Failure times for the two 89-mm-wide specimens were 35 and 46 min. For the two 127-mm-wide specimens, failure times were 68 and 73 min. Failure times for the four 178-mm-wide specimens ranged from 77 to 100 min. Recorded applied load with time is illustrated in Figures 20 to 32. A problem with the hydraulic loading system in a few tests caused a gradual drop in applied load during fire exposure (Fig. 26). Reported load (Table 11) was the average load recorded during the last 15 s (5 readings) before the rapid drop in load at failure (Figs. 20 to 32).

Recorded furnace temperatures were in compliance with requirements of ASTM E 119 with regard to the area under the time–temperature curve (Figs. 20 to 32). The ASTM E 119 requires deviation from the standard curve calculated using the area under the curve to be within 10%, 7.5%, and 5 % for tests of 1 h or less, 1 to 2 h, and greater than 2 h, respectively. In Test Number 1 of 35-min duration, the recorded curve was 5% greater than the standard curve. For all other tests, deviation in area was less than 5%. In Test Number 1 (Fig. 20), recorded furnace temperature exceeded the standard curve starting at 5 min and ending at 30 min. Because of the construction and size of the horizontal furnace, it can be difficult to adjust the furnace temperature to lower temperatures once higher temperatures have been achieved and a large specimen is burning.

The observed failure times for the five 44-mm-wide specimens were a function of the percentage of design load ($R^2 = 0.982$). Estimated failure times from the regression for these LVL products of five different species were 21.8 min for an unloaded member to 7.1 min for a member loaded to full design load. The variations in percentage design load were not suitable for similar regressions of data for the thicker specimens.

Of the two 89-mm-wide specimens, the yellow-poplar LSL failed in less time (35 min) than the Douglas-fir LVL (46 min). The two 127-mm-thick specimens were both Douglas-fir LVL from different manufacturers. Failure times were similar (68 and 73 min). Load on the four 178-mm-wide specimens was very similar. Of the four, the observed failure time for the Douglas-fir PSL was greater (100 min) than the failure times of the three LVL products (77 to 86 min), which was consistent with its slightly slower char rate in the small vertical tests and the higher allowable design stress (i.e., lower percentage allowable load).

## National Design Specification Model Predictions

National Design Specification methodology (Eqs. (6) to (9)) was used to predict failure times of test specimens (Table 11). To convert the $m_5$ (min/mm$^{1.23}$) char rate values reported in this paper to the nominal char rate $\beta_n$ (in/h) of TR 10, one needs to calculate char depth at 1 h:

$$\beta_n = \frac{(60/m_5)^{0.813}}{25.4} \qquad (10)$$

For the $m_5$ values in Table 11, the corresponding $\beta_n$ (in/h) range from 1.46 in/h (0.7073 min/mm$^{1.23}$) to 1.70 in/h (0.5831 min/mm$^{1.23}$). Except for the yellow-poplar LSL, the differences between observed and predicted failure times of the tension specimens ranged from 1% to 19% (Table 11). Difference for the yellow-poplar LSL was 27%.

Estimated degradation of load capacity of the specimen with time is illustrated for each test (Figs. 20 to 32). Estimated failure time is the time at which predicted load capacity no longer exceeds applied load (Figs. 20 to 32).

**Table 11. Observed and predicted failure times for tension tests**

| Test number | Material number[a] | Species and composite type | Allowable stress[b] (MPa) | Applied load (kN) | Char rate[c] $m_5$ (min/mm$^{1.23}$) | Observed failure time (min) | Predicted failure time[d] using $m_5$ (min) | Predicted time minus observed time (min) | Difference between observed and predicted[e] (%) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | Yellow-poplar LSL | 12.11 | 89.6 | 0.6759 | 35.3 | 44.8 | 9.6 | 27 |
| 2 | 3 | Aspen LVL | 10.21 | 66.8 | 0.6281 | 13.0 | 14.6 | 1.6 | 12 |
| 3 | 4 | Douglas-fir LVL | 13.76 | 113.8 | 0.6486 | 72.7 | 73.6 | 0.9 | 1 |
| 4 | 4 | Douglas-fir LVL | 13.76 | 176.7 | 0.6486 | 77.3 | 92.0 | 14.7 | 19 |
| 5 | 5 | Douglas-fir LVL | 11.14 | 9.0 | 0.6827 | 20.9 | 22.7 | 1.8 | 9 |
| 6 | 5 | Douglas-fir LVL | 12.45 | 88.7 | 0.6827 | 46.4 | 46.9 | 0.4 | 1 |
| 7 | 5 | Douglas-fir LVL | 12.45 | 90.3 | 0.6827 | 68.5 | 73.7 | 5.2 | 8 |
| 8 | 6 | Douglas-fir LVL | 12.65 | 176.2 | 0.6880 | 86.2 | 94.0 | 7.7 | 9 |
| 9 | 7 | Eucalyptus LVL | 16.55 | 44.5 | 0.7073 | 17.6 | 19.9 | 2.3 | 13 |
| 10 | 8 | Southern Pine LVL | 16.08 | 44.4 | 0.6039 | 18.2 | 19.2 | 1.0 | 6 |
| 11 | 9 | Southern Pine LVL | 13.75 | 179.2 | 0.6286 | 79.6 | 82.1 | 2.5 | 3 |
| 12 | 11 | Yellow-poplar LVL | 14.65 | 67.5 | 0.5831 | 14.4 | 16.0 | 1.6 | 11 |
| 13 | 12 | Douglas-fir PSL | 15.50 | 176.7 | 0.6900 | 100.5 | 102.5 | 2.0 | 2 |

[a]Material numbers are consistent with those listed in Table 1 for the materials used in the small vertical-furnace tests.
[b]Allowable load design values obtained from the manufacturer's literature or correspondence. For design values that depended on the length of the member, values were adjusted for a length of 1.8 m.
[c]Char rates obtained in the small vertical-furnace tests for both charring directions relative to the plane of the veneers (Table 5).
[d]Predicted failure times obtained using calculation procedure in Technical Report 10 (American Forest & Paper Association 2003). Assumptions were (1) Ultimate to allowable stress ratio is 2.85, (2) cross-sectional area from measured dimensions (Table 10), (3) char rate $m_5$ from small vertical-furnace tests (Table 5 and 11), and (4) allowable stresses from manufacturer or their literature (Table 11).
[e]Percentage calculated as (Predicted – Observed)/Observed × 100.

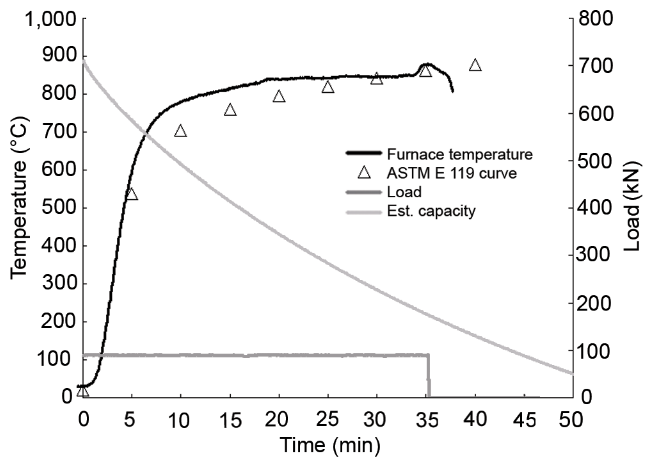



**Figure 20. Furnace temperature, applied load, and estimated residual load capacity in tension test of yellow-poplar LSL (Test Number 1).**

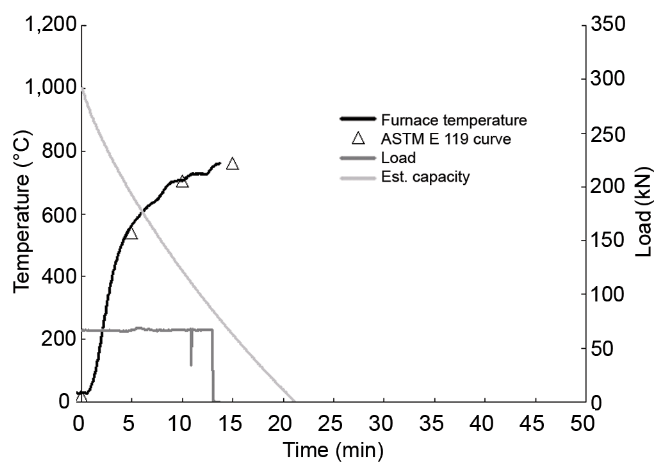



**Figure 21. Furnace temperature, applied load, and estimated residual load capacity in tension test of aspen laminated veneer lumber (Test Number 2).**

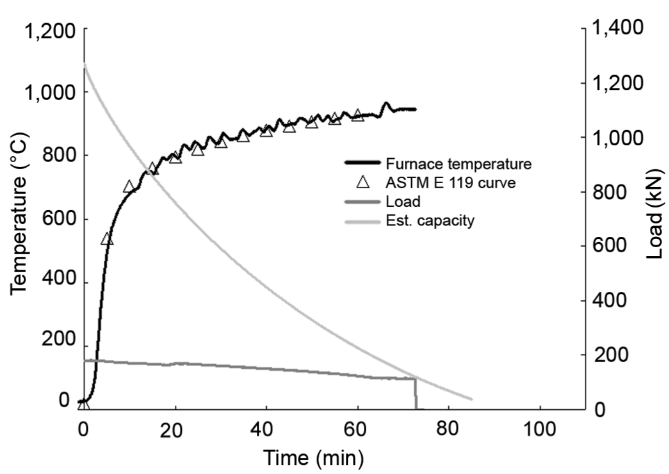



**Figure 22. Furnace temperature, applied load, and estimated residual load capacity in tension test of Douglas-fir laminated veneer lumber (Test Number 3).**

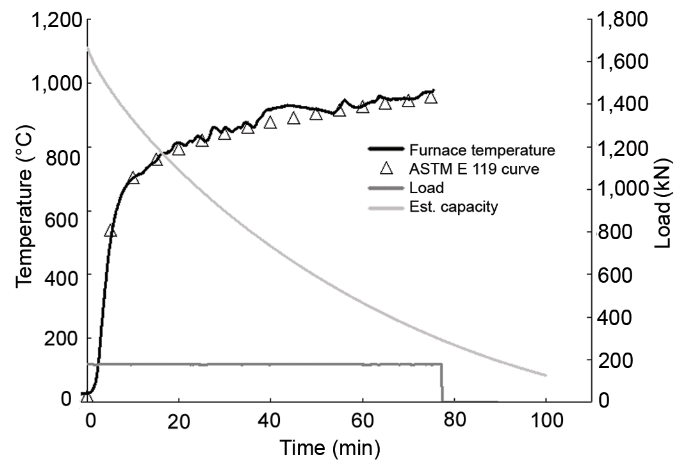



**Figure 23. Furnace temperature, applied load, and estimated residual load capacity in tension test of Douglas-fir laminated veneer lumber (Test Number 4).**

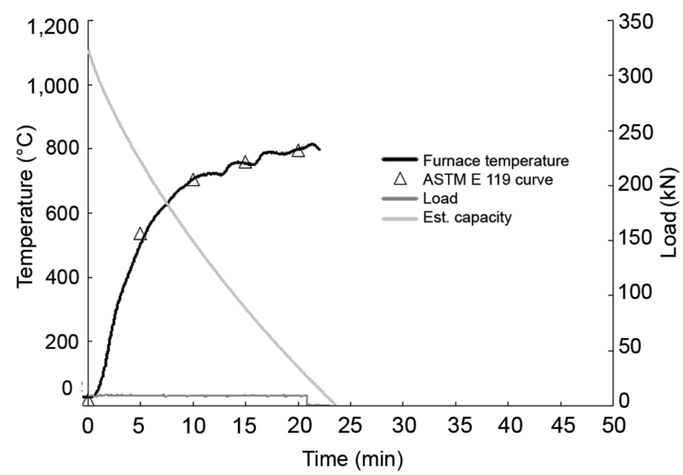



**Figure 24. Furnace temperature, applied load, and estimated residual load capacity in tension test of Douglas-fir laminated veneer lumber (Test Number 5).**

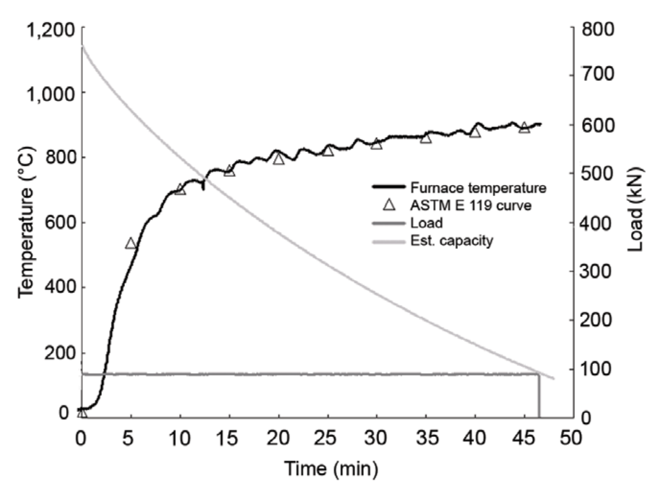



**Figure 25. Furnace temperature, applied load, and estimated residual load capacity in tension test of Douglas-fir laminated veneer lumber (Test Number 6).**

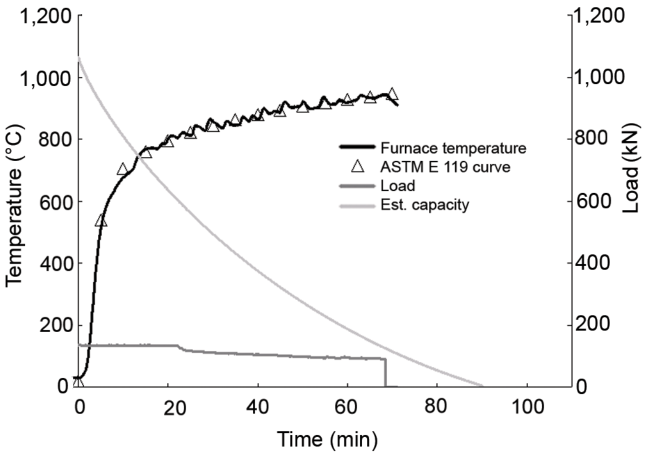



**Figure 26. Furnace temperature, applied load, and estimated residual load capacity in tension test of Douglas-fir laminated veneer lumber (Test Number 7).**

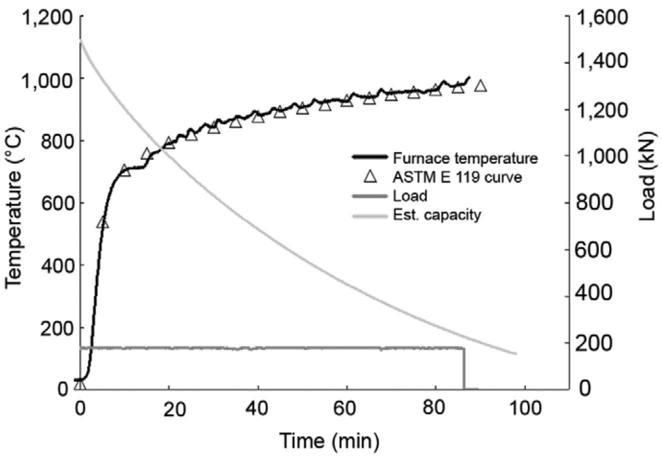



**Figure 27. Furnace temperature, applied load, and estimated residual load capacity in tension test of Douglas-fir laminated veneer lumber (Test Number 8).**

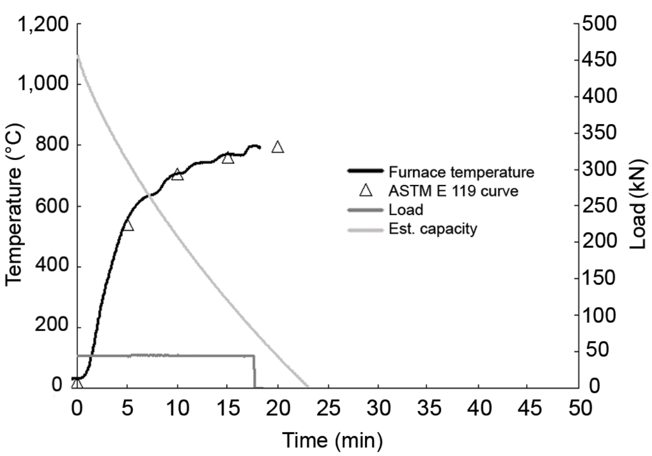



**Figure 28. Furnace temperature, applied load, and estimated residual load capacity in tension test of eucalyptus laminated veneer lumber (Test Number 9).**

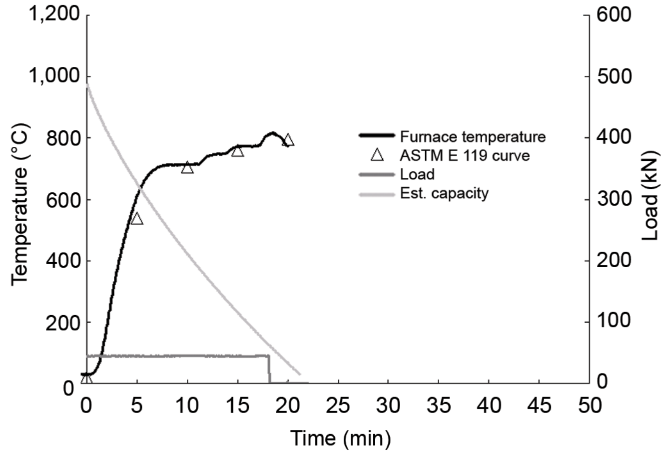



**Figure 29. Furnace temperature, applied load, and estimated residual load capacity in tension test of Southern Pine laminated veneer lumber (Test Number 10).**

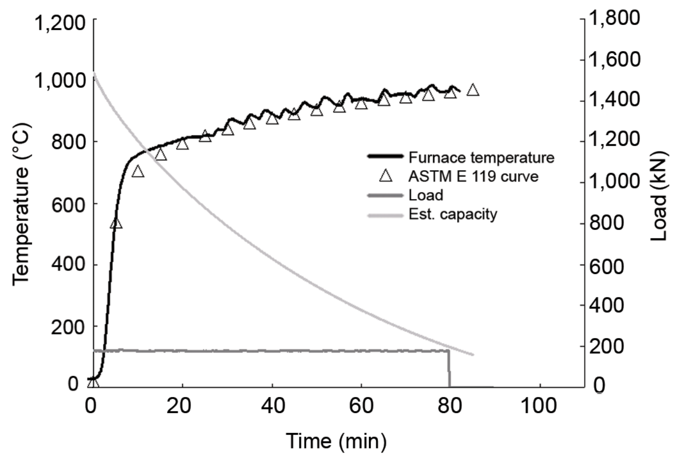



**Figure 30. Furnace temperature, applied load, and estimated residual load capacity in tension test of Southern Pine laminated veneer lumber (Test Number 11).**

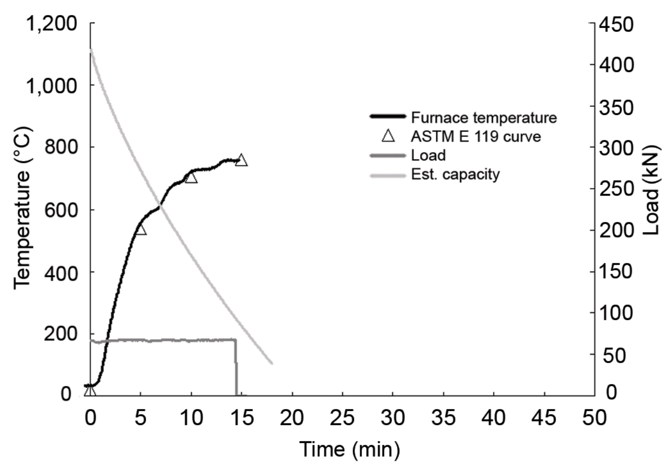



**Figure 31. Furnace temperature, applied load, and estimated residual load capacity in tension test of yellow-poplar laminated veneer lumber (Test Number 12).**

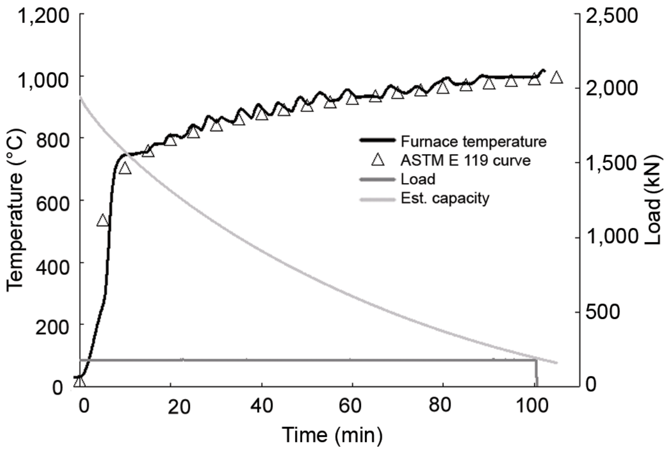



**Figure 32. Furnace temperature, applied load, and estimated residual load capacity in tension test of Douglas-fir PSL (Test Number 13).**

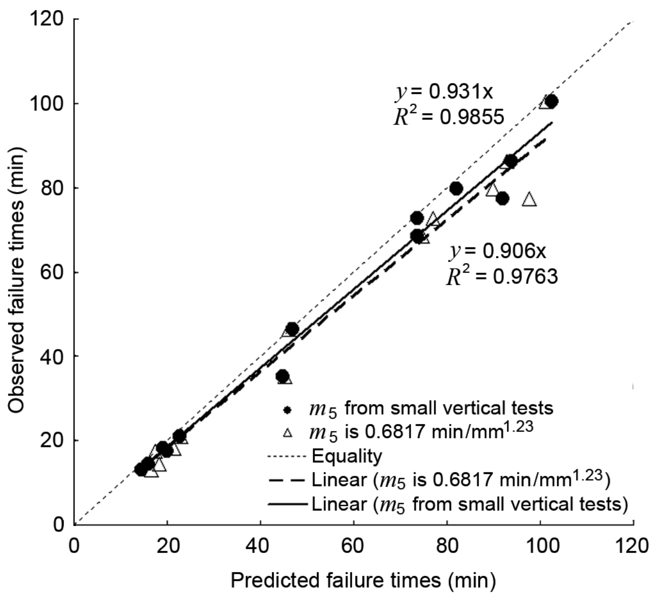



**Figure 33. Comparison of the experimental observed failure times for the tension specimens with the predicted failure times from the TR 10 methodology.**

Overall, predicted failures times were slightly greater than observed failure times. Linear regression with zero-intercept indicated that predicted failure times were 7% greater than observed failure times when $m_5$ data from the small vertical-furnace tests are used in calculations (Fig. 33). For four tests (Numbers 3, 6, 11, and 13), differences between observed and predicted failure times were 3% or less. These included tests for Materials Number 4 (Douglas-fir LVL), 5 (Douglas-fir LVL), 9 (Southern Pine LVL), and 13 (Douglas-fir PSL). The test of the wider specimen of Material 4 (Douglas-fir LVL) resulted in a 19% difference between observed and predicted failure times. If 0.6817 min/mm$^{1.23}$ ($\beta_n$ of 1.5 in/h) is used for $m_5$ in calculation of predicted failure times, the result of the linear regression with zero-intercept indicated that predicted failure times were 10% greater than observed failure times (Fig. 33).

Predicted failure times for the 44-mm-wide specimens were also a linear function of percentage of design load ($R^2$ = 0.975). Using the NDS predicted failure times for linear regression, estimated failure times from the regression for these LVL products of five different species were 23.6 min for an unloaded member to 8.5 min for a member loaded to full design load (compared with 21.8 and 7.1 min for observed failure times). Predicted times for two 89-mm-wide specimens were nearly identical (45 and 47 min) and consistent with observed failure time of the Douglas-fir LVL (46 min). Yellow-poplar LSL failed in less time (35 min). Predicted failure times for the two 127-mm-wide Douglas-fir LVL specimens were both 73 min and consistent with observed 73-min failure time for the one specimen. The other specimen failed at a slightly shorter time of 68 min.

As with observed failure times, Douglas-fir PSL had the longest predicted failure times among the four 178-mm-wide specimens. Its predicted failure time also agreed with the observed failure time (102 and 100 min, respectively).

The NDS model predicts loss in ultimate load capacity of the element over duration of fire exposure. Predicted failure time is the time at which applied load exceeds estimated ultimate load capacity. Ultimate load capacity used in the calculations is an estimate of the average value for the population. Comparison of this predicted time is with observed performance of an individual member of the population. The 2.85 value for $K$, the nominal design capacity to average ultimate capacity adjustment factor, assumes the coefficient of variation in tensile strength of individual pieces is 16% (American Forest & Paper Association 2003). Char rates used in calculations are also average results for test data. As noted earlier, coefficients of variation of the char rate data ($m_1$ and $m_5$) for the LVL tests were 8%. Coefficients of variation of the predicted times in the small vertical-furnace tests ranged from 5.2 to 10.8 (Table 5). As discussed previously, the ASTM E 119 standard allows some deviation from the standard time–temperature curve. Besides fire exposure, factors that can affect char rate include density, moisture content, chemical composition, and permeability (White 1988, White and Nordheim 1992). All of these properties vary somewhat within the population of a particular material. Given this expected variability in materials and fire exposure, reported differences between "average" predicted failure times and actual observed failure times for individual test specimens (Table 11 and Fig. 33) were within expectation.

Data reported in Table 11 are times for failure. Using observed failure times, decreases in estimated ultimate load capacity were calculated for the last minute of the tests. This provides some insight as to what the corresponding changes

**Table 12. Results for three tests of the yellow-poplar LSL (Material Number 2) and effect of input values on the predictions of the failure times**

| Test number | Model letter[a] | Initial width[b] (mm) | Char rate $m_5$ (min/mm$^{1.23}$) | Initial ultimate load capacity[b] (kN) | Observed failure time (min) | Predicted failure time[c] (min) | Difference between observed and predicted[d] (%) |
|---|---|---|---|---|---|---|---|
| 7 | A | 128 | 0.6827 | 1067 | 68.5 | 73.7 | 8 |
| 7 | B | 126 | 0.6827 | 1051 | 68.5 | 72.2 | 6 |
| 7 | C | 128 | 0.6144 | 1067 | 68.5 | 66.3 | –3 |
| 7 | D | 128 | 0.6827 | 961 | 68.5 | 72.1 | 5 |
| 12 | A | 44 | 0.5831 | 422 | 14.4 | 16.0 | 11 |
| 12 | B | 42 | 0.5831 | 403 | 14.4 | 15.0 | 4 |
| 12 | C | 44 | 0.5248 | 422 | 14.4 | 14.4 | 0 |
| 12 | D | 44 | 0.5831 | 380 | 14.4 | 15.6 | 8 |

[a] Model A: Best estimates used for the required input to the model (same as Table 11).
Model B: The input for the initial width of the specimen was decreased by 2 mm.
Model C: The input for the char rate parameter $m_5$ was reduced by 10%.
Model D: The input for the initial load capacity was decreased by 10%.
[b] Initial width and ultimate load capacity refer to values for the uncharred cross section prior to any fire exposure.
[c] Predicted failure times were calculated at 0.05-min intervals. Reported time is the last calculated residual load capacity of the specimen that exceeded the applied load.
[d] Percentage calculated as (Predicted – Observed)/Observed × 100.

in ultimate load capacity were in the tests. For the five specimens with widths of 41 to 45 mm, average decrease in estimated load capacity at the end of the test was 14 kN per min (standard deviation of 3 kN/min). Applied loads for these tests were 9 to 68 kN. For the eight specimens with widths of 89 to 178 mm, average decrease in estimated load capacity at the end of the test was 8 kN per min (standard deviation of 1 kN/min). Applied loads for these tests ranged from 89 to 179 kN.

The 27% difference for the yellow-poplar LSL test (Number 1) was the highest for the 13 tests. As a result, two additional tests of the yellow-poplar LSL were conducted. In the first additional test, applied load was slightly greater (106 kN or 42% of design load). Observed failure time was 33 min or a 29% difference between the observed time and predicted time of 43 min. A second additional test of yellow-poplar LSL was conducted to obtain char rate data. Thermocouples were inserted from the top of the specimen at a distance of 25 mm from the fire-exposed surfaces of the test specimen, and the top of the specimen was protected with ceramic fiber. In the three tests of yellow-poplar LSL, recorded furnace temperatures were initially below the curve and then exceeded the standard time–temperature curve specified in ASTM E 119. While within tolerances of ASTM E 119 for area under the standard curve, deviations from the standard time–temperature curve were greater in yellow-poplar tests compared with the rest of the tests. Compared with the small vertical-furnace charring rates, char rate obtained in yellow-poplar LSL tension test by using the average time for eight thermocouples inserted at 25 mm from the exposed surface to reach 300°C was considerably faster (0.475 min/mm$^{1.23}$ vs. 0.676 min/mm$^{1.23}$). If this 0.475 min/mm$^{1.23}$ char rate is used to predict failure times, predicted failure times for the two yellow-poplar LSL tension tests are 11% and 9% greater than observed failure times in the two tests. Density gradient of yellow-poplar LSL was also examined. Density affects both char rate and ultimate load capacity of the element. These are the two main inputs to the NDS model. Densities of samples cut from the center of the 89-mm-wide yellow-poplar LSL specimens were 2% to 7% less than densities of samples from the outer third of the cross section. With an applied load representing a relatively low percentage of full allowable load (36% to 42%), the remaining section at the time of structural failure primarily would be the center third of the original cross section. At predicted time of failure for Test 1 (45 min), the corresponding predicted “effective” char depth (from $\beta_{\text{eff}}$ of Equation (7)) was 40 mm, and effective residual cross section was 9 mm wide. Without the 1.2 factor of Equation (7), corresponding predicted char depth was 33 mm, and residual cross-section width was 23 mm. With only the lower density core remaining, actual ultimate load capacity of the remaining section was likely lower than that calculated from allowable stress values for an intact product. It appears likely that differences between observed failure times for yellow-poplar LSL and predicted times were largely due to faster charring of specimens compared with results of the small vertical-furnace tests.

Data for two tests were used to examine the effect of variations in input data on predictions from the NDS model (Table 12). Tests were of a 128-mm-wide Douglas-fir LVL (Test Number 7) and of a 44-mm-wide yellow-poplar LVL (Test Number 12). Variations in dimensions along the length of the specimen or measurement errors can affect the appropriate value for dimensions. A 2-mm reduction in the width of the specimen used as input to the model caused a 1.5-min reduction and a 1-min reduction in predicted failure times of the 128-mm- and 44-mm-wide specimens, respectively (Table 12). With the experimental nature of fire exposure and material variability, there is a degree of uncertainty in char rate. A 10% reduction in the char rate parameter (min/mm$^{1.23}$, i.e., faster charring) reduced predicted failure times by 7.4 and 1.6 min for the 128-mm- and 44-mm-wide specimens, respectively (Table 12). Besides char rate, the other important parameter of the NDS model is reduced area for failure of the specimen $A_f$, which depends on calculation of the ultimate load capacity. No tension testing of specimens at room temperature was done as part of this study. Values for allowable design stress were either published values or obtained from the manufacturer. To evaluate impact of variations in ultimate load capacity, initial ultimate load capacity prior to any fire exposure was reduced by 10%. Resulting change in predicted times for the 128-mm- and 44-mm-wide specimens (Test Numbers 7 and 12) were 1.6 and 0.4 min, respectively (Table 12). These results are consistent with a conclusion that deviations in char rate had a greater influence on failure times than deviations in the ultimate load capacity of the specimen in tests conducted for this study.

Relative impact of any deviations in char rate and ultimate load capacity would be different if applied loads are at or near full allowable design load. Using input values of Table 11, predicted failure times for a member loaded to 100% of the allowable design load were 40.0 and 11.1 for the specimens of Tests 7 and 12, respectively. With these shorter failure times compared with that for the 24/46% loaded test specimens, there is less charring of the element before failure. In the case of these two test specimens, impacts of the 10% reductions in the inputs for char rate and initial ultimate load capacity on predicted failure times of a fully loaded member were very similar for the fully loaded scenario. For Test 7, reductions in predicted times were 3.6 min for the 10% reduction in load capacity and 4.0 min for the 10% reduction in char rate ($m_5$). For Test Number 12, reductions in predicted times were 0.9 min for the 10% reduction in load capacity and 1.1 min for the 10% reduction in char rate ($m_5$). Conversely, charring rate will likely increase as the remaining cross section becomes very small for elements with little or no applied load as evidenced in the horizontal-furnace charring experiments.

Results of this study support the application of the TR 10 method to structural composite lumber. In terms of potential structural composite lumber products that may be different than those tested in the study, the TR 10 method assumes a cross section with fairly uniform properties. In Section 16.2.4 of the NDS, additional tension lamination(s) are required for fire-rated structural glued-laminated timbers that have an outer tension lamination. The assumption is that existing outer high-strength tension lamination for room temperature structural design will be charred away in the 1- or 2-h fire test. Similar provisions or adjustments to calculations should be provided for any structural composite products that are designed with higher load capacity within the outer exposed portions of the cross section and lower load capacity within the inner core of the element.

## Conclusions

In this study, we tested 14 structural composite lumber products to determine the char rate when exposed to the fire exposure of the standard fire resistance test. Products tested included LSL, LVL, and PSL. Products of five different species were tested. Based on the small vertical-furnace tests, we concluded that the char rates for composite lumber products were comparable to those of solid-sawn lumber and within the range previously found for different species of solid-sawn lumber. Additional char rate tests on 10 of the composite lumber products were conducted in an intermediate-scale horizontal furnace. There was greater variability in the data for the horizontal-furnace tests compared with the results obtained in the small vertical-furnace. Despite the differences in the construction and operation of the two furnaces, the data did not suggest any bias between the char rate results for the two furnaces. Thus, it is reasonable to expect the char rate data from the small vertical-furnace to be applicable to the large furnaces specified in ASTM E 119. Initially, 13 tests were conducted in which the composite lumber products were loaded in tension as they were subjected to the standard fire exposure of ASTM E 119. These tension tests included 10 different materials. For most of the tests, the applied load was about 30% of the full allowable design load. The TR 10 design procedure for calculating the fire resistance ratings of exposed wood members was used to predict the failure times in the tension tests. The char rate data of the small vertical-furnace were used in the calculations. The differences between the “average” predicted failure times and the actual observed failure times for individual test specimens of structural composite lumber were within expectations for sawn lumber or structural glued-laminated timbers. In 11 of the 13 tests, the predicted failure times exceeded the observed times by less than 14%. In four tests, the differences were 3% or less. In the tests of this study, variability in the char rates was likely the primary factor responsible for differences between the predicted and observed failure times. If the specimens had been loaded to full design load, the potential impact of variability in the actual room temperature ultimate load capacity of the individual test specimens would have been greater than was the case in these tests.

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# Appendix—Individual Test Results for Each Small Vertical-Furnace Test

These estimates of parameters for two time–location models (Eqs. (1) and (5)) are for three individual layers of test specimens with inserted thermocouples and for the combined data set.

| Material number | Species composite type | Direction | FPL test number | $m_1$ of Equation (1) | | | | $m_5$ of Equation (5) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Layer 1 | Layer 2 | Layer 3 | All | Layer 1 | Layer 2 | Layer 3 | All |
| 1 | Aspen LSL | Parallel | 1673 | 1.620 | 1.650 | 1.575 | 1.615 | 0.6879 | 0.7004 | 0.6686 | 0.6856 |
| | | | 1676 | 1.638 | 1.570 | 1.552 | 1.586 | 0.6956 | 0.6662 | 0.6590 | 0.6736 |
| | | Perpendicular | 1663 | 1.548 | 1.535 | 1.595 | 1.560 | 0.6564 | 0.6470 | 0.6755 | 0.6598 |
| | | | 1668 | 1.580 | 1.575 | 1.508 | 1.554 | 0.6707 | 0.6688 | 0.6404 | 0.6600 |
| 2 | Yellow-poplar LSL | Parallel | 1662 | 1.649 | 1.602 | 1.550 | 1.600 | 0.7004 | 0.6794 | 0.6592 | 0.6797 |
| | | | 1674 | 1.603 | 1.578 | 1.516 | 1.571 | 0.6810 | 0.6700 | 0.6562 | 0.6704 |
| | | Perpendicular | 1665 | 1.578 | 1.573 | 1.491 | 1.548 | 0.6705 | 0.6680 | 0.6347 | 0.6578 |
| | | | 1670 | 1.649 | 1.649 | 1.615 | 1.638 | 0.7004 | 0.6995 | 0.6857 | 0.6952 |
| 3 | Aspen LVL | Parallel | 1741 | 1.693 | 1.552 | 1.603 | 1.616 | 0.7181 | 0.6579 | 0.6798 | 0.6853 |
| | | | 1739 | 1.460 | 1.423 | 1.334 | 1.406 | 0.6200 | 0.6050 | 0.5658 | 0.5969 |
| | | Perpendicular | 1742 | 1.419 | 1.447 | 1.485 | 1.450 | 0.6039 | 0.6147 | 0.6318 | 0.6168 |
| | | | 1744 | 1.458 | 1.433 | 1.446 | 1.445 | 0.6170 | 0.6079 | 0.6135 | 0.6126 |
| 4 | Douglas-fir LVL | Parallel | 1669 | 1.496 | 1.570 | 1.502 | 1.523 | 0.6349 | 0.6666 | 0.6362 | 0.6459 |
| | | | 1672 | 1.561 | 1.533 | 1.526 | 1.540 | 0.6634 | 0.6508 | 0.6472 | 0.6538 |
| | | Perpendicular | 1664 | 1.515 | 1.562 | 1.490 | 1.523 | 0.6437 | 0.6626 | 0.6318 | 0.6461 |
| | | | 1667 | 1.529 | 1.534 | 1.527 | 1.530 | 0.6476 | 0.6499 | 0.6481 | 0.6485 |
| 5 | Douglas-fir LVL | Parallel | 1652 | 1.704 | 1.764 | 1.708 | 1.725 | 0.7225 | 0.7490 | 0.7249 | 0.7321 |
| | | | 1659 | 1.584 | 1.633 | 1.571 | 1.596 | 0.6727 | 0.6920 | 0.6666 | 0.6771 |
| | | Perpendicular | 1646 | 1.529 | 1.536 | 1.458 | 1.508 | 0.6488 | 0.6502 | 0.6185 | 0.6392 |
| | | | 1655 | 1.672 | 1.621 | 1.539 | 1.611 | 0.7077 | 0.6872 | 0.6519 | 0.6823 |
| 6 | Douglas-fir LVL | Parallel | 1647 | 1.608 | 1.567 | 1.553 | 1.576 | 0.6823 | 0.6653 | 0.6588 | 0.6688 |
| | | | 1656 | 1.776 | 1.606 | 1.645 | 1.676 | 0.7525 | 0.6809 | 0.6765 | 0.7100 |
| | | Perpendicular | 1651 | 1.694 | 1.702 | 1.635 | 1.677 | 0.7196 | 0.7208 | 0.6938 | 0.7114 |
| | | | 1660 | 1.576 | 1.575 | 1.536 | 1.562 | 0.6659 | 0.6676 | 0.6520 | 0.6618 |
| 7 | Eucalyptus LVL | Parallel | 1743 | 1.930 | 1.782 | 1.551 | 1.780 | 0.8170 | 0.7537 | 0.6624 | 0.7551 |
| | | | 1740 | 1.648 | 1.473 | 1.587 | 1.567 | 0.6985 | 0.6243 | 0.6803 | 0.6661 |
| | | Perpendicular | 1745 | 1.708 | 1.566 | 1.597 | 1.622 | 0.7206 | 0.6648 | 0.6775 | 0.6870 |
| | | | 1738 | 1.643 | 1.667 | 1.784 | 1.701 | 0.6960 | 0.7075 | 0.7590 | 0.7221 |
| 8 | Southern Pine LVL | Parallel | 1677 | 1.505 | 1.404 | 1.536 | 1.482 | 0.6386 | 0.5952 | 0.6521 | 0.6286 |
| | | | 1680 | 1.460 | 1.410 | 1.418 | 1.430 | 0.6203 | 0.5989 | 0.6013 | 0.6068 |
| | | | 1683 | 1.484 | 1.369 | 1.406 | 1.420 | 0.6289 | 0.5806 | 0.5972 | 0.6022 |
| | | Perpendicular | 1678 | 1.368 | 1.326 | 1.394 | 1.364 | 0.5812 | 0.5606 | 0.5922 | 0.5789 |
| | | | 1681 | 1.542 | 1.405 | 1.418 | 1.455 | 0.6559 | 0.5983 | 0.6026 | 0.6189 |
| | | | 1682 | 1.420 | 1.384 | 1.340 | 1.382 | 0.6042 | 0.5876 | 0.5684 | 0.5867 |
| 9 | Southern Pine LVL | Parallel | 1645 | 1.498 | 1.559 | 1.508 | 1.521 | 0.6364 | 0.6629 | 0.6396 | 0.6463 |
| | | | 1654 | 1.578 | 1.573 | 1.595 | 1.582 | 0.6699 | 0.6667 | 0.6774 | 0.6713 |
| | | Perpendicular | 1650 | 1.424 | 1.427 | 1.404 | 1.418 | 0.6052 | 0.6083 | 0.5954 | 0.6030 |
| | | | 1658 | 1.443 | 1.376 | 1.380 | 1.400 | 0.6118 | 0.5841 | 0.5861 | 0.5940 |
| 10 | Yellow-poplar LVL | Parallel | 1644 | 1.472 | 1.435 | 1.482 | 1.463 | 0.6254 | 0.6091 | 0.6292 | 0.6212 |
| | | | 1653 | 1.436 | 1.502 | 1.382 | 1.440 | 0.6090 | 0.6373 | 0.5858 | 0.6107 |
| | | Perpendicular | 1649 | 1.405 | 1.267 | 1.346 | 1.346 | 0.5978 | 0.5468 | 0.5723 | 0.5723 |
| | | | 1657 | 1.308 | 1.255 | 1.336 | 1.300 | 0.5562 | 0.5330 | 0.5683 | 0.5525 |
| 11 | Yellow-poplar LVL | Parallel | 1671 | 1.428 | 1.363 | 1.416 | 1.402 | 0.6065 | 0.5780 | 0.6007 | 0.5951 |
| | | | 1675 | 1.429 | 1.418 | 1.472 | 1.440 | 0.6068 | 0.6016 | 0.6257 | 0.6113 |
| | | Perpendicular | 1661 | 1.439 | 1.386 | 1.270 | 1.365 | 0.6138 | 0.5891 | 0.5406 | 0.5812 |
| | | | 1666 | 1.391 | 1.246 | 1.215 | 1.278 | 0.5910 | 0.5295 | 0.5154 | 0.5430 |
| 12 | Douglas-fir PSL | Parallel | 1634 | 1.639 | 1.576 | 1.693 | 1.636 | 0.6956 | 0.6698 | 0.7201 | 0.6951 |
| | | | 1640 | 1.649 | 1.626 | 1.574 | 1.613 | 0.7142 | 0.6904 | 0.6685 | 0.6885 |
| | | Perpendicular | 1637 | 1.582 | 1.678 | 1.590 | 1.617 | 0.6708 | 0.7119 | 0.6731 | 0.6853 |
| | | | 1643 | 1.635 | 1.588 | 1.662 | 1.628 | 0.6946 | 0.6734 | 0.7048 | 0.6910 |
| 13 | Southern Pine PSL | Parallel | 1633 | 1.569 | 1.614 | 1.690 | 1.624 | 0.6679 | 0.6865 | 0.7177 | 0.6907 |
| | | | 1639 | 1.565 | 1.641 | 1.662 | 1.623 | 0.6654 | 0.6970 | 0.7070 | 0.6898 |
| | | Perpendicular | 1636 | 1.664 | 1.687 | 1.639 | 1.664 | 0.7060 | 0.7152 | 0.6946 | 0.7053 |
| | | | 1642 | 1.574 | 1.606 | 1.610 | 1.596 | 0.6690 | 0.6824 | 0.6844 | 0.6786 |
| 14 | Yellow-poplar PSL | Parallel | 1631 | 1.541 | 1.482 | 1.587 | 1.536 | 0.7560 | 0.6829 | 0.7312 | 0.7162 |
| | | | 1638 | 1.548 | 1.576 | 1.559 | 1.561 | 0.6577 | 0.6691 | 0.6629 | 0.6632 |
| | | Perpendicular | 1635 | 1.595 | 1.543 | 1.561 | 1.566 | 0.6765 | 0.6547 | 0.6628 | 0.6647 |
| | | | 1641 | 1.577 | 1.585 | 1.611 | 1.591 | 0.6707 | 0.6730 | 0.6843 | 0.6760 |