FIRE RESISTANCE OF WOOD MEMBERS WITH DIRECTLY APPLIED PROTECTION

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ABSTRACT

Fire-resistive wood construction is achieved either by having the structural elements be part of fire-rated assemblies or by using elements of sufficient size that the elements themselves have the required fire-resistance ratings. For exposed structural wood elements, the ratings in the United States are calculated using either the T.T. Lie method or the National Design Specifications (NDS) Method. There is no widely accepted methodology in the United States to determine the fire-resistance rating of an individual structural wood element with the protective membrane directly applied to the exposed surfaces of the element. In these tests, we directly applied one or two layers of 16-mm thick fire-rated gypsum board or 13-mm thick southern pine plywood for the protective membrane to the wood element. The wood elements were Douglas-fir laminated veneer lumber (LVL) specimens and Douglas-fir glued-laminated specimens that had previously been tested without any protective membrane. The methodology for the tension testing in the horizontal furnace was the same used in the earlier tests. The fire exposure was ASTM E 119. For the seven single-layer gypsum board specimens, the improvements ranged from 25 to 40 min. with an average value of 33 min. For the three double-layer specimens, the improvement in times ranged from 64 to 79 min. with an average value of 72 min. We concluded that times of 30 min. for a single layer of 16-mm Type X gypsum board and at least 60 min. for a double layer of 16-mm Type X gypsum board can be added to the fire rating of an unprotected structural wood element to obtain the rating of the protected element.

INTRODUCTION

Fire-resistive wood construction is achieved either by including the structural elements within an assembly that is protected by a protective membrane or by using members of sufficient size that the members themselves have the required fire-resistance ratings. For wood-frame walls and floors with protective membranes, the fire-resistance rating is either obtained from (1) listings of rated assemblies, such as American Forest & Paper Association (AF&PA) DCA No. 3,[1] that are based on standard fire-resistance tests such as E 119[2] or (2) from calculations using the component additive method (CAM) described in AF&PA DCA No. 4[3]. These ratings for assemblies are only valid for the structural elements used in the fire tests. For exposed structural wood members, the fire-resistance ratings are calculated in the United States using either the T.T. Lie method[4, 5] or the NDS Method described in the National Design Specifications for Wood Construction (NDS)[6]. Technical Report No. 10[7] provides a full discussion of the NDS procedure. For larger structural members with spacing between elements that are greater than 400 or 610 mm (16 or 24 in.), there is no widely accepted methodology in the United States to determine the fire-resistance rating of the member with the protective membranes directly applied to all the exposed surfaces of the structural members.

The objective of this study was to identify and evaluate procedures to calculate a fire-resistance rating of a large structural member with the protective membrane directly applied to all the exposed surfaces of the member. Intermediate-scale tests were conducted in the FPL horizontal furnace/tension apparatus to create a database of failure times for protected structural elements loaded in tension while exposed to the ASTM E 119 fire exposure. Protective membranes tested included single and double layers of 16-mm (5/8-in.) thick fire-rated gypsum board and 13-mm (½-in.) thick plywood.

PREVIOUS FOREST PRODUCTS LABORATORY RESEARCH

Direct protection of wood with a protective membrane has been investigated previously at the U.S. Forest Service, Forest Products Laboratory (FPL). In a study by White and Cramer[8] on improving the fire endurance of wood truss systems by adding 16-mm (5/8-in.) thick fire rated gypsum board to all four sides of a "2×4" lumber specimen, the times for failure to support the load in tension increased from 13 min. to 50 min. For the specimen with a metal-plate connection, the improvement was from 5 min. to 33 min. Adding 13-mm (½-in.) thick fire-rated gypsum board to a load-bearing sandwich panel (plywood faces) increased the ASTM E 119 failure times from 3 min. to 24 min. in a study by Eickner[9]. More recently, the use of gypsum board to improve the fire resistance of engineered wood rim board products was investigated by White[10]. Adding a single layer of 16-mm (5/8-in.) thick fire-rated gypsum board increased the times for 572°F (300°C) on the back of a 28-mm (1-1/8 in.) thick OSB from 37 min. to 76 min. and 89 min. (two tests). A double layer of 16-mm (5/8-in.) thick fire-rated gypsum board increased the time to 134 min. Previous research on the fire penetration of wood-based panel products was reviewed by White[10]. The use of coatings to improve the fire resistance of wood products has also been investigated by White[11].

CALCULATION PROCEDURES

Procedures for assigning a fire-resistance rating to a wood member with a protective membrane directly applied are of two general types. The first type of procedure is an additive method in which the time for the protective membrane is simply added to the fire-resistance rating of the structural wood membrane without any protection. At the conclusion of that duration, one is assuming the charring of protected wood member proceeds as it would for an exposed wood member. For U.S. applications, the fire-resistance time for the exposed wood member is calculated using the T.T Lie method[4] or the NDS method[6,7]. The second type of procedure uses an equation for the char rate for the wood beneath the protective membrane to obtain the reduced sectional area. Since the T.T. Lie method does not allow the adjustment of the char rate, the adjusted char rate is then used in the NDS method to obtain the time for structural failure of the protected structural wood element. The Eurocode 5[12] provides for similar such procedure. All the procedures are based on the type and thickness of the protective membrane and possibly the structural elements. The fasteners or other methodology for attaching the membrane to the structural elements are not considered in the analyses.

Additive Procedures

To estimate the fire-resistance ratings of the same element with protective membranes directly applied, data for fire-rated wall and floor assemblies provide two options for values to add to the fire rating of the unprotected structural wood element. One option is to use the finish ratings for the protective membrane obtained in the fire-resistance tests of the wall or floor assemblies. The finish rating of the protective membrane is the resistance time for thermocouples placed between the wood stud or joist and the gypsum board to record a temperature rise of 139°C or individual temperature rise of 181°C. This temperature rise of 139°C corresponds to an actual temperature of 159°C for an initial temperature of 20°C. Because this finish rating temperature is less than the 288°C (550°F) or 300°C commonly assumed for the base of the char layer, a conservative assumption is that the structural wood element will not char prior to the duration of the finish rating. Finish ratings can be found in product listings such as the Underwriters Laboratories Fire Resistance Directory (www.ul.com). For wood stud wall assemblies, such a finish rating for double layer 16-mm (5/8-in.) thick gypsum board protective membrane includes 66 min. for UL Design No. U301. Finish ratings for a single layer of 16-mm thick fire-rated gypsum wall board include 30 min. (UL Design No. L501), 20 to 26 min. (UL Design No. U305), and 27 min. (UL Design No. U309).

The second option is to use the times assigned to the protective membrane in the Component Additive Method (CAM) for fire-resistance ratings of wood wall and floor assemblies. The procedure is described in AF&PA DCA NO. 4[13]. The times for the membranes are from the membrane table of the component additive method (Table 1). In the component additive method, the membrane times are added to the times for "2×4" studs, 406 mm (16 in.) on center (20 min.) or "2-in. nominal" thick joists, 406 mm on center (10 min.). These times for the membranes are based on full-scale ASTM E 119 tests of wall and floor assemblies.

1. Times assigned to protective membrane in the Component Additive Method (CAM[13])

Protective membrane	Assigned time, min.
3/8-in. thick Douglas-fir plywood	5
½-in.-thick Douglas-fir plywood	10
5/8-in.-thick Douglas-fir plywood	15
3/8-in.-thick gypsum board	10
½-in.-thick gypsum board	15
5/8-in.-thick gypsum board	20
½-in.-thick Type X gypsum board	25
5/8-in.-thick Type X gypsum board	40
Double 3/8-in. thick gypsum boards	25
½- + 3/8-in. thick gypsum boards	35
Double ½-in. thick gypsum board	40

Reduced Section Procedures

Data for the char rates of wood protected by gypsum board provide modified char-rate equations to use in reduced section methodologies for calculating the fire-resistance rating of structural wood elements. One such equation provided by White[10] is:

$$t_{300°C} = m_1 x_c + b_1 \quad [1]$$

where x_c = char depth from original surface
$t_{300°C}$ = time for the 300°C assumed for the base of the char layer

Values given by White[10] for the parameters m_1 and b_1 are listed in Table 2. The NDS method and Equation (1) can be used to calculate the time $t_{300°C}$ for the protected element for the char depth x_c that corresponds to failure of the structural wood member to support the applied load for the unprotected element.

In a study of using coatings to improve the fire resistance of wood[11], the equation developed for the total times (t_2) to 288°C (550°F) (char depth) was

$$t_2 = 123 + 1.717\,(g_{16}\, x_w) + 1171\, x_w \quad [2]$$

where g_{16} = gain in time (s) obtained in a tests of coated 16-mm (5/8-in) thick plywood,
x_w = plywood, wood or char thickness, in.

2. Char-rate parameters for Equation (1) from White[10]

Protective membrane	m_1	b_1
	min./mm	min.
Single layer of ½ in.-thick Type X gypsum board	1.515	19.3
Single layer of 5/8 in.-thick Type X gypsum board	1.833	23.8
Double layers of ½ in.-thick Type X gypsum board	2.267	56.4
Double layers of 5/8 in.-thick Type X gypsum board	2.043	71.7

Section 3.4.3 of the Eurocode 5 (prEN 1995-1-2:2003 (E))[12] provides procedures for calculating the fire resistance of beams and columns with surfaces initially protected from fire exposure. The Eurocode 5 procedure divides the rated time period into four intervals with different charring rates depending on the effect of the membrane on the charring rate. With the protection, the start of charring is delayed. For wood-based protective membranes, the initial delay in charring is calculated from charring rate data. The delayed time in minutes for one layer of gypsum board types A, F or H is [$2.8 \times h_p - 14$], or [$2.8\ h_p - 23$] for locations near joints with unfilled gaps of width greater than 2 mm. The variable h_p is the thickness of the panel in mm. For two layers of gypsum board F, the thickness of the inner layer is reduced by 20 percent and the same equation is used. During the subsequent stage, the charring occurs at lower rate than that for exposed wood member if fire protection has not failed. The charring rate is k_2 times the charring rate for initially unprotected wood member. For gypsum plasterboard type F, k_2 is [$1-0.018\ h_p$], where h_p is the thickness, in mm, of a single layer or the inner layer for multiple layers. The nominal char rate for both glued laminated timber and laminated veneer lumber (LVL) is 0.65 mm/min. The next stage begins with the failure of fire protection membrane. The charring rate is increased above that assumed for an initially unprotected wood member. Failure of the fire protection may be due to failure or collapse of the protecting member or excessive deformation of the protecting member. During this stage, the charring rate is the charring rate for initially unprotected wood member multiplied by a factor of 2. The next stage begins when the charring depth equals either the charring depth of the same member without fire protection or 25 mm, whichever is less. During this final stage, the charring rate reverts to the value for the initially unprotected wood member.

The procedure is illustrated in various figures in the Eurocode 5 document. The method is applicable to fire protection claddings, other protection materials (includes intumescent coatings and impregnation), or other structural members. The test methods are given in ENV 13381-7 Test methods for determining the contribution to the fire resistance of structural members – Part 7: Applied protection to timber members[13]. The ENV 13381-7 test method states that the effects of unfilled gaps greater than 2 mm at joints in the cladding on the start of charring and, where relevant, on the charring rate before failure of the protection should be taken into account. An equation for the required length of the fasteners is also provided.

METHODS

Materials

Twelve specimens each with a protective membrane were tested as part of this study (Table 3). For the protective membrane, we used 16-mm (5/8-in.) thick fire-rated Type X gypsum board and 13-mm

(½-in.) thick southern pine plywood. One or two layers of the protective membrane were attached using screws. We used Douglas-fir LVL and Douglas-fir glu-lam specimens remaining from previous studies in which specimens without protection were tested. The LVL-4 was made by using hot setting phenol-resorcinol-formaldehyde (PRF) adhesive to glue 2.5 mm (1/10 in.)-thick veneers into 22.2-mm (7/8-in.) thick panels in a plywood press. These panels are finger-jointed with a cold setting PRF adhesive and pressed into final product using a cold setting isocyanurate adhesive. The LVL-5 was made with a phenol-formaldehyde adhesive. Prior to testing, the wood products were dried in a room with an ambient atmosphere of 50% relative humidity and temperature of 23°C.

3. List of test specimens and amount of applied load

Test No.	Membrane		Wood Specimen			Load (kN)	Percent allowable load
	Type[1]	No.	Type[2]	Width (mm)	Height (mm)		
1	Gypsum board	1	LVL-5	44	241	8.7	7.4
2	Gypsum board	1	LVL-5	44	241	8.8	7.5
3	Gypsum board	1	LVL-5	90	241	88.5	32.9
4	Gypsum board	1	Glu-lam	128	224	152	48.2
5	Gypsum board	1	LVL-4	133	241	115	25.4
6	Gypsum board	1	LVL-4	180	241	174	28.8
7	Gypsum board	1	LVL-4	180	241	176	29.3
8	Gypsum board	2	LVL-5	90	241	88	32.4
9	Gypsum board	2	Glu-lam	128	224	151	49.1
10	Gypsum board	2	LVL-4	133	241	115	25.9
11	Plywood	2	LVL-5	133	241	89.3	23.6
12	Plywood	1	LVL-5	133	241	90.5	24.0

[1] Plywood was 13-mm (1/2-in.) thick, southern pine C-D plywood. Gypsum board was 15.9-mm (5/8-in.) thick USG Sheetrock brand Firecode core Type X, (Type SCX).

[2] The laminated veneer lumber (LVL) and glued laminated lumber (glu-lam) specimens were Douglas-fir. Number refers to material number cited in White[14] and reflects two different manufacturers.

Test Methodology

The tension testing in the intermediate-scale horizontal furnace (Figure 1) was done using the methodology of the earlier tests of the wood elements without any protection. The results for the unprotected Douglas-fir LVL tests were reported by White[14] and results for the unprotected glulam specimen was reported White[15] (Table 4). In the fire tests, the specimens were exposed to a natural gas fire that was controlled so the temperatures determined by thermocouples in six capped pipes followed the standard ASTM E119 time-temperature curve while the specimen was also subjected to a constant tensile load. Due to the limitations of the bolted connections (Figure 2) outside the furnace, the load levels were restrictive to values less than the full allowable load determined in accordance with the NDS (Table 3). The low load for tests one and two reflected the load used in the original test of a specimen without protection. Its load was low because initial application of a higher load resulted in failure of the bolted connection.

Single layer of the Type X gypsum board was installed on the wide 241-mm (9.5-in.) surfaces so it overlaps the gypsum board on the narrow edges. We installed 2.1 m (7 ft) of a single 2.4 m (8 ft) length (no joints) of gypsum board lengthwise on specimen, centered at mid-length. There was no taping of gypsum board. The screws were Type S wall board screws, 57-mm (2-1/4 in.) Type S, No. 7 except for the 44-mm (1.75-in.) wide specimens. We used screw length of 41 mm (1-5/8 in.) for the 1.75-in. thick specimen. Spacing along the length of the specimen was 305 mm (12 in.) on center. One at mid-length, then 305 mm (12 in.) from mid-length, 610 mm (24 in.) from mid-length, and 914 mm (36 in.) from mid-length. No screw at the ends of gypsum, i.e., 1.1 m (3.5 ft.) from mid-length. The two screws on top and bottom of the wide surfaces 241 mm (9.5 in. surface) were 22 mm (7/8 in.) from wood edge (or 38 mm (1-1/2 in.) from the edge of the 16-mm (5/8-in.) thick gypsum board edge.) Screws on narrow edge pieces were one row of screws down the middle for the 44-mm (1.75-in.) specimens. For the 89, 133, 178 mm (3-1/2, 5-1/4, and 7 in.) wide specimens, two rows of screws, 22 mm (7/8 in.) from each of the two wood edges down the length. We off-set the two rows of the screws down the length of the member (i.e. one-half of 305 mm (12 in.) spacing between screws of two rows). For both rows, one was at 914 mm (36 in.) from mid-length.

4. Test results for unprotected specimens previously tested

Test no.[1]	Wood specimen[2]	Width (mm)	Height (mm)	Applied load (kN)	Percent allowable	Failure times (min.)	Estimated char depth at failure[3] (mm)
7	LVL-5	128	235	90.3	24	68	44.2
5	LVL-5	43	240	9	8	21	16.8
6	LVL-5	90	240	88.7	33	46	30.8
5	Glu-lam	128	224	153	48	58	37.0
3	LVL-4	135	241	113.8	25	73	46.4
4	LVL-4	178	239	176.7	30	77	48.8

[1] From White[14] for the laminated veneer lumber (LVL) specimens and White[15] for the glu-lam specimen.
[2] See Table 1 for additional information.
[3] Calculated from the observed failure times and the char rates reported in White[14] for the LVL specimens and White[15] for the glu-lam specimen.

Figure 1
Specimen in intermediate-scale horizontal furnace

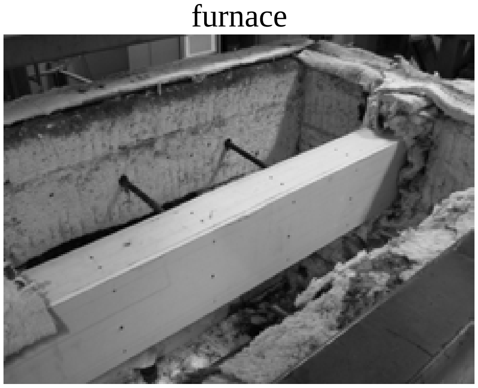
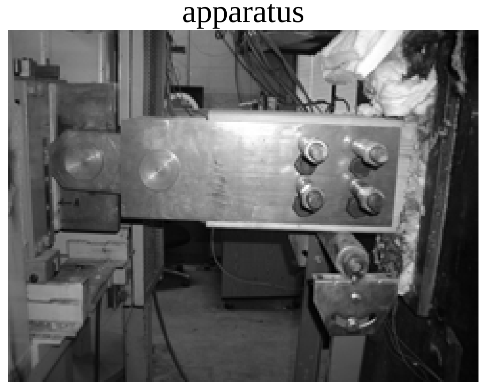


Figure 2
Bolted connection of specimen to tension apparatus



For the double layer of 16-mm (5/8-in.) Type X gypsum board, we installed the first layer as with single layer, the screws 305 mm (12 in.) on center, except the screws started at 152 mm (6 in.) from mid-length. The spacing of screws for the second layer alternated at the 305-mm (12-in.) on-center placement of screws with that of the first layer; i.e., the second layer of the double layer was like the single-layer placement of screws. The second layer was placed with screws at 914 mm (36 in.) from mid-length. We overlapped the wider sides gypsum of the first layer with the second layer on narrow edges. Screws were

19 mm (3/4 in.) from wood edge (or 51 mm (2 in.) from the edge of the outer 16-mm (5/8-in.) thick gypsum board edge. For the double layer gypsum board specimens, an additional row of screws was added at mid-height. The 13-mm (½-in.) thick plywood was attached in a manner similar to gypsum board. The plywood was southern pine C-D plywood. There were no joints within any of the protective membranes installed on a given face of a test specimen.

Additional thermocouples were inserted on a specimen between wood and the gypsum board (or plywood). Eight thermocouples were attached to the wood member. Two thermocouples were placed on each of the four surfaces: one coming out the north end and one coming out the south end of the test specimen. Each thermocouple located one foot from mid-length, and at mid-width of each surface. We attached the thermocouple with tape.

RESULTS AND DISCUSSION

For the seven single-layer gypsum board specimens, the improvements ranged from 25 to 40 min. with an average value of 33 min. (Table 5). The results for the finish ratings ranged from 21 to 23 min. with an average of 22 min. The 16-mm (5/8-in.) thick USG Sheetrock brand Firecode core Type X, (Type SCX) has a listed finish rating of 24 min. in UL Design U305. The times for a temperature of 300°C at the interface ranged from 28 to 30 min. with an average of 29 min. For the three double-layer gypsum board specimens, the improvement in times ranged from 64 to 79 min. with an average value of 72 min. Two of the results for the finish ratings were 52 and 56 min. with an average of 54 min. These results are less than the 66 min. finish rating listed for UL Design U301. There was some discrepancy in the finish rating data for test no. 9. The times for a temperature of 300°C at the interface ranged from 63 to 66 min. with an average of 64 min.

5. Test results for protected specimens

Test no.	Membrane		Wood specimen[1]	Failure time (min.)	Unprotected failure times (min.)	Increase (min.)	Finish rating (min.)	Average time for 300°C (min.)
	Type[1]	No.						
1	Gypsum board	1	LVL-5	54	21	33	21	29
2	Gypsum board	1	LVL-5	54	21	33	23	29
3	Gypsum board	1	LVL-5	87	46	40	23	30
4	Gypsum board	1	Glu-lam	89	58	31	23	29
5	Gypsum board	1	LVL-4	98	73	25	21	28
6	Gypsum board	1	LVL-4	108	77	30	23	30
7	Gypsum board	1	LVL-4	114	77	36	23	30
8	Gypsum board	2	LVL-5	125	46	79	52	63
9	Gypsum board	2	Glu-lam	131	58	73	-	64
10	Gypsum board	2	LVL-4	136	73	64	56	66
11	Plywood	2	LVL-5	84	68	15	15	20
12	Plywood	1	LVL-5	77	68	8	9	12

[1] See Table 1 for additional information.

The improvements with the 13-mm thick plywood as the protective membrane were 8 min. for a single layer and 15 min. for a double layer. The finish ratings from the thermocouples between the wood and the membrane were 9 for the single layer and 15 min. for the double layer. The corresponding times for a temperature of 300°C at the interface were 12 and 20 min. In tests of 13-mm thick southern pine plywood conditioned with 30 percent relative humidity and placed over foam plastics, the times for the 139/181°C finish rating criteria were average of 7 min.[16] In previous tests of two layers of 24-mm thick plywood, the time recorded for the 139/181°C finish rating criteria on the non-fire surface of first layer of 24-mm thick southern pine plywood specimens was 24 min.[10] Additional tests of wood elements protected with wood panel products are planned.

Additive Models

A simple model for estimating the fire-resistance ratings of wood elements with protective membranes is to assign values to the different types of membranes and add those assigned values to the fire-resistance ratings of the structural wood member without any protective membrane. As just discussed, the average improvements were 33 min. for the single layer of 16-mm thick Type X gypsum board and 72 min. for two layers of 16-mm thick Type X gypsum board.

Various regression models were investigated. One such model is one in which there are separate lines for the zero, one, and two layers of gypsum board, but the slope of the failure times with the width of the structural wood element is the same for all three lines (Figure 3). The 10 tests with gypsum board (Table 5) and the six tests with no protection (Table 4) were included in the data set for the regression analysis. The slope of the three lines is 0.408 min./mm. The y-intercept of the line for the unprotected elements was 8.2 min. The y-intercept for the wood elements with one layer of gypsum board was 39.5 min. or 31.3 min. greater than the y-intercept for the specimens tested with no protective membranes. The y-intercept for the wood elements with two layers of gypsum board was 83.1 min. or 74.9 min. greater than the y-intercept for the specimens tested with no protective membranes. The R^2 for this model was 0.978 and the coefficient of variation for the predicted failure times was 6.8 percent. Using only the data for elements without protection (Table 4), the regression of failure times with the width of the element had a R^2 of 0.94 and predictive coefficient of variation of 11.8 percent. Adding the percentage allowable load to the model did not improve the results. Using only the 10 tests with gypsum board (Table 5), regression analysis was done on the failure times with two variables including a variable with value of 0 for two layers and 1 for one layer and the failure times for the corresponding element without protection. The R^2 was 0.97 and the predictive coefficient of variation was 5.6 percent. The model assigned a value of 38.0 min. for one layer gypsum board and 77.7 min. for two layers gypsum board and a slope of +0.90 min./min. for the unprotected wood element failure time variable.

Besides the number of layers of gypsum board, other factors did not provide meaningful improvements to regression models for the increases in failure times because of the protection. Analysis of the data indicated that improvements provided by two layers of gypsum board decreased with the increase in failure times for the unprotected element (Figure 4) and similar variables such as failure times for the protected elements. This likely is due to physical loss of the outer layer of the gypsum board during the test. The improvements provided by one layer were not similarly affected by the failure times of the unprotected element (Figure 4).

Physical Failure of Membrane

The screws used for most of the tests were 57 mm long. With the single layer of gypsum board, this resulted in a wood penetration depth of 40 mm. For the double layer of gypsum board, the wood penetration was approximately 25 mm. For the 44-mm wide specimens, the screws were 41 mm long, which resulted in a wood penetration depth of 25 mm. Visual observation of the specimens during the tests was very limited. During the tests of the single-layer gypsum board specimens of wood element thickness greater than 44 mm, observations of gypsum board on the floor of the furnace were made between 49 and 60 min. and an average of 55 min. In the case of two of the double layer tests, such observations were made at 60 min. in one test and 111 min. in another test.

Figure 3
Regression of failure times with the width of the unprotected wood element

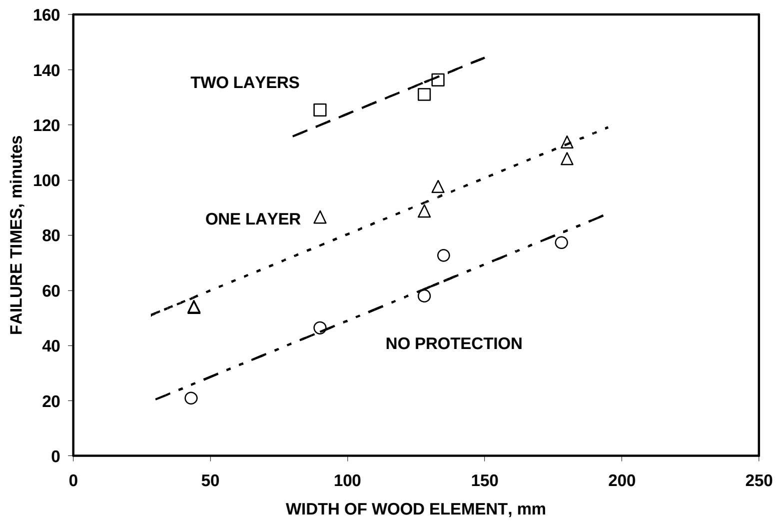
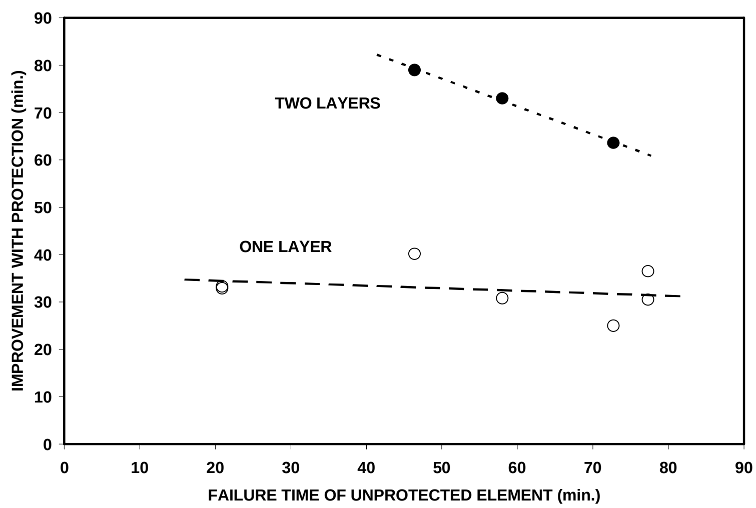


Figure 4
Effect of test duration on improvement

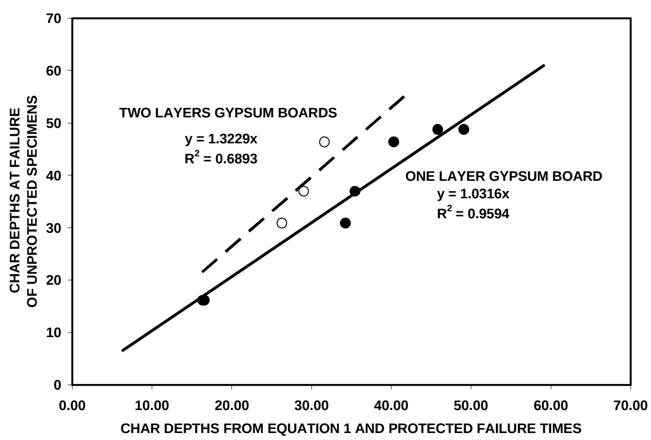


The char depths were calculated from the observed failure times and the char rates reported in White[14] for the LVL specimens and White[15] for the glu-lam specimen (Table 4). The estimated char depth at failure for the 43-mm wide specimens was 17 mm, and no observation of physical failure of the gypsum board was observed in these tests. The estimated char depths at failure of the other widths ranged from 31 to 49 mm. Using the char-rate parameters of Table 2 for a single layer of gypsum board, the observation of physical failure of the gypsum board at 55 min. would correspond to a char depth of 17 mm.

Reduced Section Models

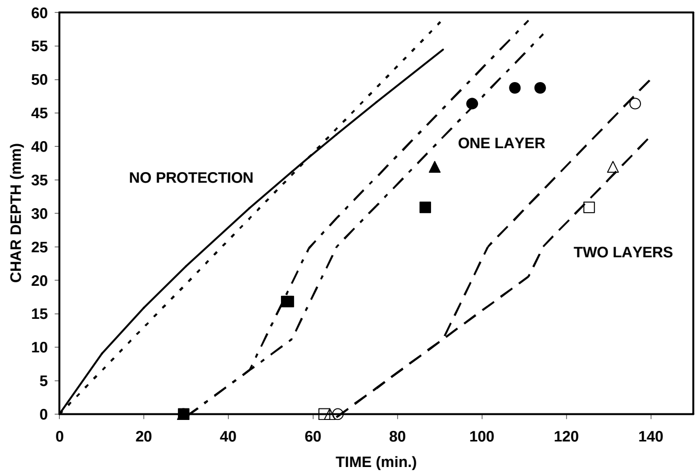
An alternative approach is to use char-rate equations to calculate the reduced cross-sectional area and directly incorporate the char depth results into reduced section fire-resistance models such as the NDS method.[6] Compared with char-rate data for wood without protection, there is very limited data for the char rate beneath layers of gypsum board. One such set of data is that obtained in tests of structural rim boards[10] (Equation (1) and Table 2). These equations for char rates beneath layers of gypsum board were used to calculate the expected char depths at the times of failure of the protected elements listed in Table 5. Using char rates and failure times of the unprotected specimens from White[14, 15] (Table 4), the estimated char depths at their times of failure were also calculated. The corresponding char depths are compared (Figure 5). Whereas there was good agreement for the one layer gypsum board data, the equation for the two layers of 16-mm thick Type X gypsum board (Table 2) overestimated the protection provided by the gypsum board. This might reflect physical failure of the outer layer of gypsum board during the tensile tests, which would reduce the thermal protection and increase the char rate.

Figure 5
Comparison of char depths calculated for the
protected wood elements with data for unprotected wood elements



As discussed earlier, Eurocode 5 has a reduced section procedure for calculating the fire-resistance rating of protected wood elements. The predictive char depths were calculated using the values for European type F gypsum board (Figure 6). For the calculations, the char rate for the wood without protection was 0.65 mm/min. (short dashed line in Figure 6). The solid line in Figure 6 is the average observed charring in the tests of samples without any protection.[14,15] The calculated delayed times for charring were 30.8 min. for the single layer of gypsum board and 66.6 min. for the double layer of gypsum board. The initial charring was calculated as 0.463 mm/min. The separate pairs of lines (dashed lines) for the predicted char depths reflect different assumptions with regard to physical failure of the gypsum board (Figure 6). For one layer of gypsum board, times were the observed 55 min. and 45 min. estimate for 44-mm wide specimens that reflected shorter screw penetration depth. For the two-layer membrane, assumed membrane failure times were 67 and 111 min. The former was based on the estimated char depth (11.2 mm) that corresponded to the 55 min. observed failure in the single-layer tests and the later value on the longer of the two observed times. The char rate after the assumed membrane failure is 1.3 mm/min. In each case, the char rate was the 0.65 mm/min. for the unprotected wood when the char depth exceeded 25 mm.

Figure 6
Comparison of char depths calculated with Eurocode 5 models (lines) with the data from experiments (markers) for one and two layers of gypsum board



CONCLUSIONS

We concluded that the fire-resistance rating of a structural wood element with a protective membrane directly applied to all the fire exposed surfaces can be obtained using a simple additive method of adding a fixed time for the protective membrane to the fire-resistance rating of the unprotected element. The tests indicated that times of 30 min. for a single layer of 16-mm Type X gypsum board and at least 60 min. for a double layer of 16-mm Type X gypsum board will result in estimates for the fire-resistance rating of the protected structural wood element consistent with the failure times observed in the tensile fire-resistance tests of protected structural wood elements. The failure times ranged from 54 to 136 min. The fasteners used to attach the gypsum board were Type S, No. 7 wallboard screws with a length of 57 mm and the spacing of the fasteners was 305 mm (12 in.) on center.

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