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IMPROVING THE FIRE ENDURANCE OF WOOD TRUSS SYSTEMS

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SUMMARY

The objective of this research project was to investigate ways to improve the fire resistance of wood truss systems without improving the ceiling membranes. In this report, we describe tests to identify the range of current performance of metal plate connectors and to evaluate possible modification or protection of the plates to improve their fire endurance. For constant temperature and constant load (plenum) tests, the variables were number of teeth, plate length, steel thickness, and tooth length. A revised thermal degrade model was developed for the metal plate connectors. Plate modifications included the addition of nails, screws, bolts, fabric, and fire-retardant coating. The best protection was obtained with a fire-rated gypsum board envelope that covered the connection.

INTRODUCTION

The overall project was initiated to help address concerns about the fire safety of metal-plate-connected (MPC) wood trusses. To meet building code requirements, an entire assembly is tested using a standard test procedure such as ASTM E 119 (ASTM 1988) or ISO 834 (ISO 1975). The requirements for a rated assembly can generally be met by adding a ceiling of one or two layers of gypsum board to the MPC truss system (Schaffer 1988). Such rated assemblies have not alleviated the concerns of some fire fighters about their actual safety in the field (Routley 1989). Concerns include fire spread into the plenum as a result of improper penetrations of the gypsum barriers for utilities and construction practices that are inferior to that used in the construction of the test specimen.

In this project, our objectives were to identify and evaluate ways to improve the fire endurance of wood truss systems without improving the ceiling membrane. Our approach was to better understand the intrinsic fire performance of the MPC truss member by adding to the experimental data base and by computer simulations. The total project had six general phases: (1) to identify the range of current plate performance; (2) to identify the collapse mechanisms and critical elements in existing truss designs from fire endurance model simulations; (3) to evaluate the thermal performance of fire-resistive coatings; (4) using the results from these tests, to propose potential technical innovations or detailing to improve the safety of trusses in fire conditions; (5) to evaluate the technical innovations with component fire testing; and (6) to evaluate the technical innovations with fire endurance model simulations using the component testing data. In this report, we discuss the fire tests (items 1 and 5).

In a previous study, a model for evaluating the fire endurance of MPC trusses was developed (Shrestha 1992, White et al. 1993). This single truss model can be

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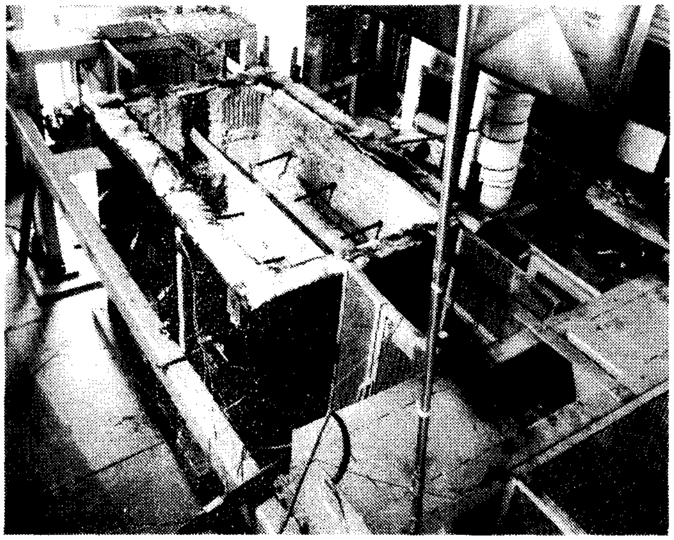

Figure l—The Forest Products Laboratory tension apparatus and furnace (cover removed for photograph).

used to calculate the stresses and deflections of the truss components and to identify those that are critical as the temperatures of the various components are increased to reflect continued fire exposure. As part of the initial study of the research described here, we conducted extensive component fire testing to develop the necessary input and submodels for thermal degradation of the wood members and connections. Because the standard test is conducted on multiple-truss assemblies, a current project is to expand the single-truss model to a system model.

METHODS

The experimental work consisted of three parts: (1) initial evaluation of fire-resistive coatings, (2) evaluation of plate parameters, and (3) component testing of modified or protected metal plate connectors. In part 1, we evaluated the thermal performance of metal connecting plates treated with various coatings. In part 2, we evaluated a broader range of plate types for thermal degradation and fire endurance. In part 3, single components with a modified metal plate joint were evaluated under both thermal and structural loads. The coating that performed the best in part 1 was used in the component testing in part 3. The tests conducted in part 1 were similar to those done previously on coated plywood (White 1986). Results for parts 2 and 3 are discussed in this paper.

Evaluation of Plate Parameters

A variety of light-gauge metal connecting plates *were* tested in tension while subjected to either high temperatures or fire exposures. Specimens were nominal 2- by 4-in. lumber (actual 38- by 89-mm) (hereafter called 2 by 4) with a single tension splice of the metal connecting plates.

The tension apparatus and furnace (Fig. 1) allow a tension load of up to 445 kN to be applied to a 4.9-m-long specimen as 1.8 m of the specimen is subjected to high temperatures or fire exposure. The tension machine is a modified tension proof tester consisting of a clamp assembly and a support frame. Tensile force is applied by two hydraulic cylinders with oil supplied by a hydraulic power unit. An extensometer system, consisting of a reference arm that goes around the furnace, a linear variable differential transducer (LVDT) at one end, and clamps with magnetic attachment plates, provides the elongation measurements. Orientation of the specimen is such that the wider sides are vertical. The extensometer gauge length is 3.3 m. The specimen is 4.9 m long with 0.6 m in each of the two grips.

Thirteen plates were tested in the plate parameter tests. Six different types of plates *were* tested: from three companies, half 16-gauge (1.6-mm-thick) and half 20-gauge (l-mm-thick) steel. The tooth densities were 6.1-6.4 and 10.5-12.1 $\times 10^3$ teeth per square meter for the 16- and 20-gauge plates, respectively. We tested two plate lengths: 76-153 mm, with 72-144 teeth, and 153-253 mm, with 108-240 teeth; one type of 20-gauge plate was tested at three lengths: 78, 127, and 253 mm; 72, 144, and 240 teeth, respectively. The tooth lengths were 8.2, 8.2, and 8.6 mm for the 20-gauge plates and 9.3, 9.6, and 10.0 mm for the 16-gauge plates. The lumber was No. 1 Dense Southern Pine, kiln dried. The lumber and plated specimens were conditioned at 23°C, 50 percent relative humidity (9 percent moisture content) before testing.

Two types of tests were conducted: constant temperature tests and constant load tests. For the constant temperature tests, the specimens were heated in the furnace for 30 min and then ramp loaded to failure. For all plates, we conducted tests at constant temperatures of 200°C and 300°C, and at room temperatures. Some plates were also tested at constant temperatures of 250°C and 275°C. Some 300°C specimens ignited before the load could be applied. A thermocouple attached to the wide side of the 2 by 4 lumber was used to control the furnace temperature. We inserted a second thermocouple in a hole in the 2 by 4 lumber so the bead was at the center of the cross section of the specimen. However, the lead to the recording devices was exposed to the elevated temperatures of the furnace interior.

For the constant load or plenum tests, the specimen was first loaded to a specified load. The applied load for the different plates ranged from 7.4 to 25.9 kN. The specimen was then subjected to an exposure that represents the temperatures in the plenum of a protected truss assembly in an ASTM E 119 test. We derived the plenum time-temperature curve from various ASTM E 119 test results for protected truss assemblies. Some temperatures on the curve were 65, 93, 188, 260, and 327°C at 10, 20, 30, 45, and 60 min, respectively. The temperature rise after 45 min was 22.2°C/5 min. As in the constant temperature tests, a thermocouple attached to the side of the 2 by 4 lumber was used to control the furnace temperature. The results from such plenum tests were time-elongation curves and times of failure.

Evaluation of Modifications

We evaluated various modifications or protections to the metal plate connections (Tables 1 and 2) using the plenum test procedure. Similar tests were also run with the standard ASTM E 119 fire exposure. Some temperatures on the standard ASTM E 119 time-temperature curve are 704, 795, 843, 892, and 927°C at 10, 20, 30, 45, and 60 min. The control thermocouples were in capped pipes located vertically even with the specimen, but 150 mm horizontally away from the surface of the specimen. Plates were 253 mm, 20-gauge steel, with 144 8-mm-long teeth. The tooth density was 6.4 x10^3 teeth per square meter. The applied load was 19.5 kN. When ramp loaded to failure at room temperature, the plates failed as a result of steel failure at 32.2 kN.

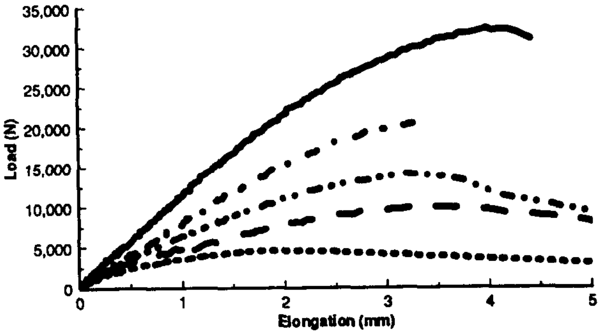

Figure 2—Examples of load-displacement curves obtained from constant temperature tests. From top to bottom, the curves are for room temperature (24°C), 200°C, 250°C, 275°C, and 300°C.

RESULTS AND DISCUSSION

Evaluation of Plate Parameters

The additional data on the different plates were used to develop a revised thermal degrade model for the maximum load at different temperatures. Load-displacement curves after constant temperature exposure were obtained. Figure 2 shows some curves for one plate type and length. The room temperature failure was caused by tooth withdrawal. The 200°C curves for some plate types and lengths were similar to their room temperature curves. The room temperature performance was limited by steel plate failure in a manner similar to the reduction in tooth withdrawal strength caused by elevated temperature. The failure at 200°C was caused by tooth withdrawal or steel failure.

Maximum load at room temperature for all the plates ranged from 12.8 to 66.8 kN (Fig. 3). In the analysis, the different types of plates and lengths were separated based on the failure mode at room temperature-either tooth withdrawal or metal failure. Tooth withdrawal can also involve wood failure beneath the plate. The 78-mm-long plate was the only 20-gauge plate to fail by tooth withdrawal. The maximum load ranged from 2.7 to 16.9 kN for the 300°C exposure. With few exceptions, failure at 275°C and 300°C was caused by tooth withdrawal. For surface

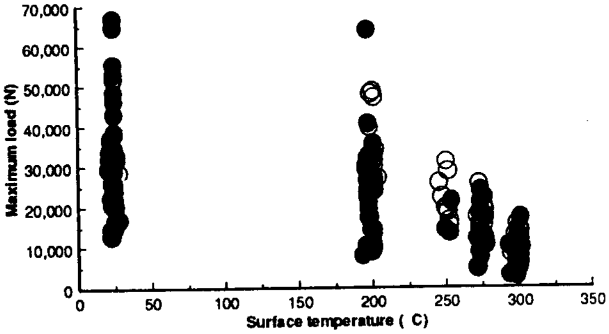

Figure 3-Maximum load obtained in constant temperature tests. Each data point is for a separate test. Solid circles indicate plate types and lengths that failed by teeth withdrawal at room temperature. Open circles indicate plate types and lengths that failed by steel failure at room temperature.

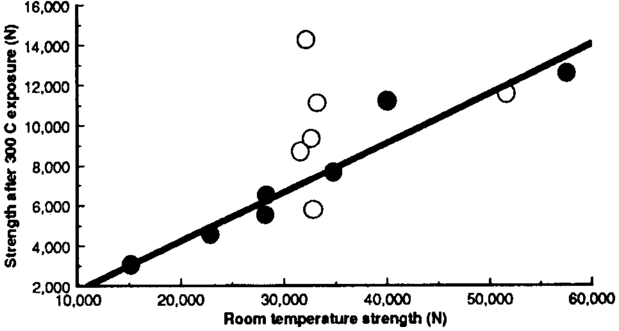

Figure 4-Comparison of average strength for different plate types and lengths after 300°C exposure with average strength at room temperature in constant temperature tests. The line is regression line for the data indicated by solid circles. (See Fig. 3 caption for definition of solid and open circles.) Data indicated by open circles would likely be in better agreement with the line if steel failure had not occurred at lower loads than the load necessary for tooth withdrawal at room temperature.

temperatures of 24, 200, 250, 275 and 300°C, the center temperature on average was 24, 114, 129, 137, and 162°C respectively, when the load was increased to failure.

Complete statistical analysis to isolate the effect of each plate parameter was difficult as a result of significant correlations between some parameters. These parameters included number of teeth, plate length, steel thickness (gauge), and tooth length. The plates of

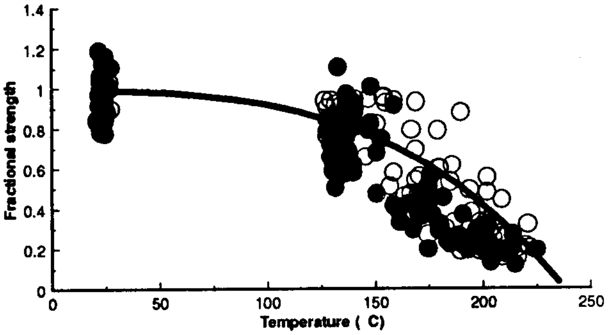

Figure 5-Fractional strength of metal plate connectors as a function of temperature (constant temperature tests). Fractional strength is the maximum load for the plate tested divided by the average maximum load obtained in room temperature tests of that plate type and length. The temperature is that estimated from Equation (1) with a = 0.7. See Figure 3 caption for definition of circle types.

thicker steel (16-gauge) had the longer teeth. The longer plates had more teeth. Failure loads appeared to increase with increasing steel thickness, tooth length, and plate length. For plate types and lengths that failed at room temperature as a result of tooth withdrawal, the relative performance of the different plate types and length at the elevated temperatures (such as 300°C in Fig. 4) was similar to their relative performance at room temperature.

In the analysis, the data were normalized by dividing the maximum load values by the average room temperature value for the particular type of plate (Figure 5). The strength of the plate types that failed at room temperature as a result of tooth withdrawal (solid circles in Fig. 5) apparently decreased more than the strength of the plates that failed as a result of steel failure. This was because the average room temperature maximum loads (used to nornalized the data) were underestimates of room temperature performance resulting from tooth withdrawal when plate failure was due to steel failure. Tooth withdrawal was the mode of failure at the higher temperatures. Additional tests are needed to obtain estimates of the room temperature-tooth withdrawal failure loads for these plates. Using only the data for the seven plates with room temperature tooth withdrawal failure, we correlated the fractional strength with temperature. To obtain a simple thermal degrade model, we also wanted the degradation to be a function of a single temperature. Previously, we used the surface temperature (Shrestha 1992, White et al. 1993). Since plate failure appeared to be a function of wood degradation away from the surface, we considered temperatures that correspond to different fractional depth of the total tooth penetration. Assuming a parabolic temperature profile, the temperature is

$$T = (T_s - T_c)(1 - ah/19)^2 + T_c \qquad (1)$$

where

T_S is temperature at surface of wood member,

T_C temperature at center of wood member,

a fraction of total tooth penetration from surface, and

h tooth penetration or length (mm).

The number 19 is the half-width of the 38-mm--thick lumber specimen.

The regression of ln(1 - f) with $1/T$ of the average data for each of the seven plates resulted in

$$f = 1 - \exp\{6.851 - [3,500/(T + 273.15)]\} \qquad (2)$$

where

f is failure load expressed as fraction of load necessary to cause tooth withdrawal at room temperature, and

T temperature (°C) given by Equation (1) with a = 0.7. The number 273.15 is the conversion to absolute temperature, in Kelvin.

This equation is the curve given in Figure 5. The temperature in Figure 5 is Equation (1) with a = 0.7. Similar equations and agreement with the data can be obtained for other values of a.

In the constant load (plenum) tests, the fire exposure represented the tempera-

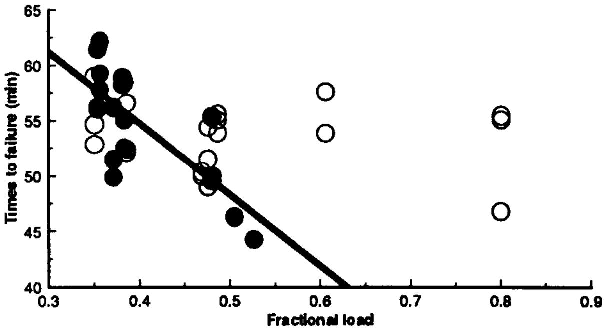

Figure 6—Times to failure of various plates in the plenum tests in which the load was kept constant. The applied load is expressed as fraction of average maximum load obtained in room temperature tests of that plate type and length. The fractional loads calculated for the open circles are overestimates since average maximum load failure at room temperature resulting from steel failure was lower than that for tooth withdrawal.

tures expected in a protected truss assembly. The failure times ranged from 44 to 62 min (Fig.6). Statistical analysis suggested that the times to failure increased with decreasing fractional load, increasing tooth length, and thinner steel plate when tooth withdrawal controlled failure. The indication of increased times with the thinner plates is based solely on three tests of the short 20-gauge plate tested with a 0.48 fractional load (Fig. 6).

Equations (1) and (2) were used to predict the times to failure in the plenum tests of the seven plates that failed as a result of tooth withdrawal in room temperature tests. Using the applied load as the fractional load, Equation (2) was used to obtain the failure temperature. Using average curves for surface temperature and center temperature as a function of time, we used Equation (1) to estimate time to reach the failure temperature obtained from Equation (2) (Fig. 7). Since we used average temperature and structural data, there were no variations in the predicted times for the same plate type, length, and fractional load. The variations in the experimental data for the same plate type, length, and fractional load were likely due to variations in the actual wood properties (thermal and structural). The different symbols in Figure 7 indicate different plate types

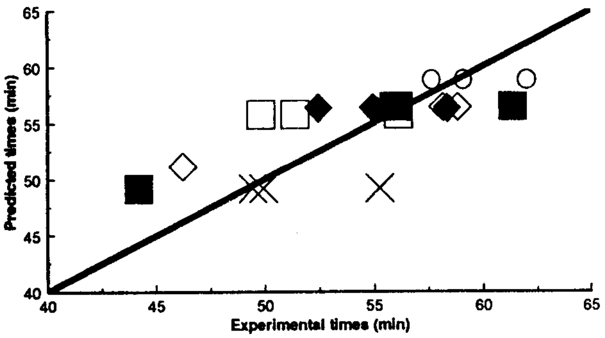

Figure 7-Predictions of failure times in plenum tests using Equations (1) and (2) and average equations for surface and center temperatures. Different symbols indicate different plate types and lengths.

and lengths. In the two cases where different loads were used for the same plate type/length, the predicted times reflected the experimental data (Fig. 7).

We selected the value of ***a*** = 0.7 to obtain best agreement with the plenum tests. Smaller ***a*** values (closer to surface) will result in a more conservative prediction of failure times. Limited data suggest that the higher ***a*** value also improves agreement with the constant load ASTM E 119 tests. Additional analysis using previously obtained data will be done to validate or select the appropriate ***a*** value to use. It may also be necessary to use a range of time-temperature curves to provide better verification of the equations.

The initial stiffness of the 3.3-m (extensometer gauge length) specimen was also determined from the load-displacement curves. The relative decrease in stiffness caused by temperature was not as great as that observed for maximum load. Statistical analysis suggested that the measured stiffness was a function of the exposure temperature, number of teeth in plate, and room temperature tensile stiffness of the lumber. The measured displacement included the displacement resulting from the 3.3-m length of the wood specimen as well as the displacement of the joint. To date, we have been unable to separate out the wood displacement because of its variability and the relatively small displacement of the plate joint. Analysis of the stiffness data is continuing.

Evaluation of Modifications

Modifications to the specimens were evaluated using both the standard ASTM E 119 time-temperature curve and the idealized plenum time-temperature curve. The addition of small nails, screws or bolts, fabric, and fire-retardant coatings generally provided only small improvements (Table 1). Larger nails, screws, or bolts may provide improvement. The fire-retardant coating did not enhance performance as well in the component tests as it had done in the preliminary small-scale tests in a small vertical furnace. Lumber nailed over the plates did provide a significant degree of protection (Table 1). Fabric placed beneath the plates, however, shortened the failure times. We believe that the fabric likely reduced the depth of wood penetration by the teeth.

With its control thermocouples in capped pipes, the ASTM E 119 test is not particularly suitable for testing for such short time periods. In the first 10 min, the temperature recorded by bare thermocouples varies widely from the capped pipe thermocouples as the furnace is rapidly heated up.

The addition of gypsum board to the specimen provided varying degrees of protection (Table 2). The best protection was obtained when the fire-rated gypsum board (13-m- or 16-mm-thick) was added on all four sides of the lumber and the edges were taped. Fire-rated gypsum is believed to be better than regular gypsum board since integral glass fibers help maintain integrity as the gypsum is heated.

Wood specimens without the metal plate connections were also tested (Tables 1 and 2). The applied load was 76 percent of the design load for the solid wood member. Without any protection, the solid wood member failed at 12.8 min in E 119 fire exposure. Protection of all four sides with taped 19-mm-thick fire-rated gypsum board increased the failure time for the solid wood member to 50.6 min.

Table l-Performance of specimens with plates modified or protected with coatings or fabric

Modification or protection	Failure time with E 119 fire exposure (min)	Failure time with idealized plenum exposure (min)
None	3.4, 5.6	53.8, 57.5
Small nails (35 mm long, 2 mm diameter) added at each corner of plates (eight nails)	5.4, 6.0	59.7, 59.5
Small screws (25 mm long, 2.5 mm diameter) added at each corner of plates (eight nails)	5.1, 5.7	55.8, 57.4
Bolts (3 mm diameter) added at each corner of plates (four bolts)	4.6	61.4[a]
Bolts at each corner plus four bolts added near butt joint of lumber	5.2, 4.5	–
Specimen coated with fire-retardant varnish[b]	7.0, 6.6	64.0[c], 65.2
Coated impregnated fabric placed over plates	8.7	64.5[a]
Coated impregnated fabric placed beneath plates	3.2	49.0
Specimen covered with glass fabric	9.3	65.6
Glass fabric placed beneath plates	2.2, 5.3	49.2, 55.3
2 by 4 lumber (0.6 m long) nailed to wide sides of specimen over plates	15.2[d]	67.9[a]
Solid lumber without connection	12.8	70.2

[a] Flames affected control thermocouple. Wood failure occurred away from plates.

[b] Specimen refers to entire 1.8 m of lumber specimen exposed during test.

[c] Failure occurred away from plate area.

[d] Failure occurred away from protected area.

Table 2-Performance of specimens with plates protected with gypsum board

Gypsum board protection	Location of gypsum board	Failure time with E 119 fire exposure (min)	Failure time with idealized plenum exposure (min)
None		3.4, 5.6, 4.8[a]	53.8, 57.5
Regular gypsum board, 9.5 mm thick	Central 0.6 m of wide sides of specimen	13.0[b], 14.4	
	Wide sides of specimen	14.2	74.7
	All four sides, no overlap at edges	15.8	92.8
	All four sides, edges taped	13.3	81.7
Fire-rated Type-X gypsum board, 13 mm thick	Wide sides of specimen	17.0	86.8
	All four sides, no overlap at edges	21.9[a]	97.2
	All four sides, edges taped	37.8[a], 34.7	97.9
Fire-rated Type-X gypsum board, 16 mm thick	Wide sides of specimen	17.6	80.7
	All four sides, no overlap of edges	25.8[a]	107.2
	All four sides, edges taped	31.8[a], 33.4	114.7
Fire-rated Type-X gypsum board, 16 mm thick; solid lumber	All four sides, edges taped	50.6	

[a] Temperature in enclosed pipe in initial 10 min was lower than standard exposure.

[b] Failure occurred in wood away from gypsum protection.

CONCLUSIONS

Factors that affect the relative maximum load resulting from tooth failure at room temperature will likely affect performance when the metal plate connector is heated to tempertures that thermally degrade the wood beneath the plate. Based on extensive testing, a revised thermal degrade model for metal plate connectors was developed. The model can be used to predict the effect of the applied load and increasing temperatures on the times to failure under constant load-rising temperature conditions. Data are now available to show the effects of some modifications or protections to the plates on failure times. Adding fabric beneath the plates reduced the failure times. As expected, the best protection was obtained by protecting the member with fire-rated gypsum board.

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