BEHAVIOR OF NAILED CONNECTIONS AT ELEVATED TEMPERATURES

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ABSTRACT

The lateral resistance of plywood-to-wood nailed joints with interlayer gaps was measured at four temperatures of ambient (30°C), 120°C, 200°C, and 265°C in an exploratory test program. As temperature increased from ambient, strength decreased by 13%, 15%, and 26%, respectively, and slip modulus decreased by 47%, 61%, and 54%, respectively. The largest incremental percent decreases in strength and slip modulus occurred at the lowest temperature increment, between ambient and 120°C. Slip modulus was more negatively affected by temperature than strength. Failure mode IV (two-point nail yield) occurred on nailed joints tested at ambient, 120°C, and 200°C, but shifted to failure mode IIIs (one-point nail yield in main member) at 265°C. The shift in failure mode occurred because nonuniform temperatures throughout the joint differentially changed the embedding strength of the wood members. The yield theory predicted failure mode IV for nailed joints tested at ambient, but overestimated the strength of the joint by 40%. The results of this research support recent findings reported by Noren (1996).

Keywords: Nails, fire, high temperature, lateral resistance, strength, slip modulus, failure mode, yield theory.

INTRODUCTION

For several decades, the lateral resistances of nailed joints have been tested and theoretical models have been developed to describe the failure, strength, and slip modulus of joints. Despite the amount of research conducted on the lateral resistances of nailed joints, most studies have focussed on testing and modeling nailed joints at ambient temperature (Kuenzi 1955; Foschi 1974; Foschi and Bonac 1977; Larsen 1977; Aune and Patton-Mallory 1986a, b; Pellicane 1991, 1993; Pellicane et al. 1991; Sa Ribeiro and Pellicane 1992) and until recently, relatively few studies had been done on joints tested at elevated temperatures. The motivation for testing nailed joints at elevated temperatures has resulted from some of the drawbacks of current fire endurance testing. Fire endurance tests for nailed wood structures (ASTM 1997a) typically involve exposing a full-scale assembly to a fire and recording the time until the assembly collapses. Such tests provide qualification information on the structural integrity of these assemblies, but often the assemblies are too complex to fully understand or model their be-

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havior. To understand and predict failure of assemblies at elevated temperatures, researchers (Fuller 1990; Fuller et al. 1992; Noren 1996) have begun to focus on testing subcomponents of the assemblies, such as nailed joints. These tests are similar to those that have been conducted at ambient temperatures.

Our main objective was to demonstrate how temperatures in a controlled thermal environment affect the failure mode, strength, and slip modulus of a plywood-to-wood nailed joint subjected to lateral loading. We designed a test device as close as feasibly possible to the devices (Liu and Soltis 1984; Lau and George 1987) that have been suggested as replacements to the standard (ASTM 1997b) for testing nailed joints. We exposed nailed joints (one configuration and one nail size) to four temperatures of ambient (30°C), 120°C, 200°C, and 265°C with five load tests at each condition. These temperatures were chosen to correspond in a general way with temperatures that might occur within joints in a protected assembly, rather than a situation where combustion, charring, and temperature rise are unabated. The test program was not designed to measure or estimate the actual temperatures that occur within connections in a standardized-protected-assembly fire test. This test program was exploratory and intended to reveal general trends. We did not attempt to statistically define data distributions of load-displacement. A secondary objective was to gain an initial understanding of the mechanics of the connection where temperature and moisture contents within the connection were not uniform. For ambient temperature only, we compared the resulting failure mode, strength, and load-displacement curve (including slip modulus) to that predicted by the yield theory. Finally, we discuss some issues of applying the yield theory to nailed joints tested at elevated temperatures. Our study parallels Noren's (1996) work, and we compared and contrasted our results with his results.

METHODS

The connection configuration consisted of two pieces of aspen plywood nailed to a southern pine 2-by-4 (38-mm by 89-mm) (Fig. 1). The 2-by-4 members were cut from four clear boards, 1.2 m. (4 ft) in length. The plywood members were cut from one 16-mm (⅝-in.)-thick sheet (5 ply, type CD) such that the orientation of the face grain was perpendicular to the direction of loading. All wood members were conditioned at 23°C and 50% relative humidity for a least five days before the specimens were assembled. When we assembled and tested the specimens, the moisture content of the 2-by-4 members ranged from 11% to 15%. One 6d common nail connected each plywood member to the 2-by-4. For each specimen, the two nails were vertically offset by 6 mm (¼ in.). We used a hand press to drive the nails into the wood such that the nailheads were flush with the plywood. To prevent interlayer friction (Liu and Soltis 1984; Lau and George 1987) from developing between the plywood and 2-by-4, we situated two 1.6-mm shims adjacent to each nail while pressing the nails into the wood. Before testing the specimens, we removed the shims. This interlayer gap was used to produce test results independent of interlayer friction that may or may not develop in connections in service.

We modified the test device from the standard (ASTM 1977b) for testing two member nailed joints, and the devices that Liu and Soltis (1984) and Lau and George (1987) recommended replace the standard. The test device that we designed for a three-member specimen allowed a concentric load to be applied, which was more suitable for testing a nailed joint within a small oven with vertically aligned holes to the outside. We also eliminated the rollers that had been used (Liu and Soltis 1984; Lau and George 1987) to support the main member, because the rollers would expand and potentially bind at elevated temperatures. Our test device (Fig. 2) had lateral brackets that fully supported the plywood and adjustable angles that clamped down on top of the plywood. A stirrup surrounded the 2-by-4 and was bolted to a cylinder that was attached to a 22.2-kN (5,000-lb) load cell outside of the oven (Fig. 3). A tensile load applied to the

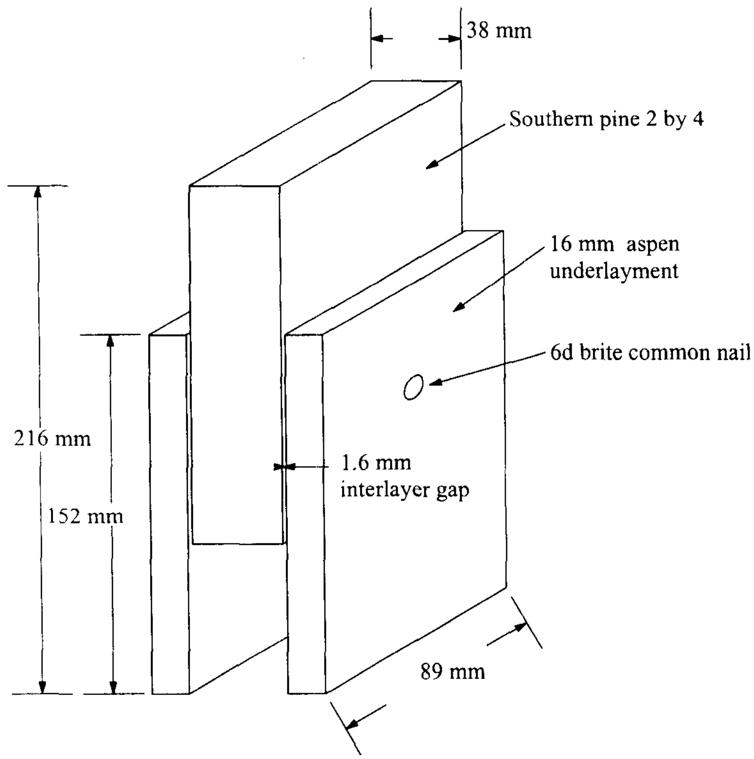

FIG. 1. Test specimen.

stirrup lifted the 2-by-4 at a displacement rate of 2.5 mm/min while the adjustable angles held the plywood stationary. As load was applied, a rod resting on a bracket attached to the 2-by-4 extended up out of the oven and attached to the core of an LVDT that was mounted to the top exterior of the oven (Fig. 3). After each test, we disassembled each specimen and determined the moisture content (ASTM 1997c) of the 2-by-4. Five joints were tested at each temperature of ambient (30°C), 120°C, 200°C, and 265°C. All temperatures were below the level that would char the wood or cause combustion. For the tests conducted at elevated temperatures, we preheated the oven to the designated testing temperature, secured the specimen in the test device, and inserted thermocouples (Type T) into 1.6-mm holes drilled in the plywood and 2-by-4 (Fig. 4). We sealed the thermocouple holes with tape, heated the specimen for an additional 60 to 80 min, and then tested the joint. The total joint displacement was 25 mm and the duration of each load-displacement test was 10 min.

For ambient temperature only, we used the yield theory to predict the ultimate strength and failure mode (NDS 1997) of the joint. Technically, the yield theory is used to predict the yield strength of a nailed joint. Here we assumed the yield strength to be equivalent to the ultimate strength, as Aune and Patton-Mallory (1986a) suggested was appropriate. We derived all yield theory equations, because they were not provided for a joint with both an interlayer gap and wood members with unequal embedding strengths (Peyer 1995). The resulting equations included expressions for the ultimate strength and required thickness of the plywood and 2-by-4 that produce a given failure mode.

For exposure temperatures of ambient,

120°C, and 200°C, we observed failure mode IV, and at 265°C we observed failure mode IIIs. Failure mode IV (two-point nail yield) (Fig. 5) occurs when Eqs. 1 and 2 are satisfied.

$$t_1 \geq 2\sqrt{\frac{M_y}{\beta f_e}} + \frac{\sqrt{\Delta^2 + \frac{4M_y}{f_e} + \frac{4M_y}{\beta f_e}} - \Delta}{\beta + 1} \qquad (1)$$

$$t_2 \geq 2\sqrt{\frac{M_y}{f_e}} + \frac{\beta\sqrt{\Delta^2 + \frac{4M_y}{f_e} + \frac{4M_y}{\beta f_e}} - \beta\Delta}{\beta + 1} \qquad (2)$$

The ultimate strength (F_u) for two-point nail yield can then be computed using Eq. (3).

$$F_u = \frac{2\sqrt{\beta f_e(\beta f_e \Delta^2 + 4M_y)} - 2\beta f_e \Delta}{\beta + 1} \qquad (3)$$

The parameters in Eqs. (1), (2), and (3) are as follows:

- t_1 = plywood (side member) thickness,
- t_2 = 2-by-4 (main member) thickness,
- M_y = yield moment of nail,
- f_e = effective embedding strength of the 2-by-4,
- β = plywood embedding strength divided by 2-by-4 embedding strength, and
- Δ = dimension of the interlayer gap.

Failure mode IIIs (one-point nail yield in main member) (Fig. 5) occurs when Eqs. (4) and (5) are satisfied, and the ultimate strength can then be computed using Eq. (6).

$$2\sqrt{\frac{M_y}{\beta f_e}} - \frac{\sqrt{\Delta^2 + \frac{4M_y}{f_e} + \frac{4M_y}{\beta f_e}} + \Delta}{\beta + 1} < t_1 < 2\sqrt{\frac{M_y}{\beta f_e}} + \frac{\sqrt{\Delta^2 + \frac{4M_y}{f_e} + \frac{4M_y}{\beta f_e}} - \Delta}{\beta + 1} \qquad (4)$$

$$t_1 > \frac{\sqrt{\Delta^2 + \frac{4M_y}{f_e} + \frac{4M_y}{\beta f_e}} - \Delta}{\beta + 1} \qquad (5)$$

$$F_u = \left[2f_e\left(\frac{4\beta M_y(2\beta + 1)}{f_e} + 2\beta^2(\beta t_1^2 + 2\Delta^2 + t_1^2 + 2t_1\Delta)\right)^{1/2} - 2\beta\Delta - \beta t_1\right] \Big/ (2\beta + 1) \qquad (6)$$

Parameters used in Eqs. (4), (5), and (6) are the same as those defined for Eqs. (1), (2), and (3). Refer to Peyer (1995) for derivations.

Predicting strength and failure mode of the joint using the yield theory requires inputting the embedding strength of the wood and the yield moment of the nail. To estimate the embedding strength of the 2-by-4 and plywood at ambient temperature, we conducted non-standard embedding strength tests. We cut five 25-mm-high specimens from each of two clear 1.2-m 2-by-4s and ten 25-mm-high by 89-mm-wide specimens from the 16-mm sheet of aspen plywood. We placed a 6d common nail parallel to the 38-mm dimension of the 2-by-4 and 16-mm dimension of the plywood such that the orientation corresponded with the specimens used for the lateral resistance tests. With an 89-kN testing machine, a load was applied to the nail at a displacement rate of 2.5 mm/min. The test was stopped when the nail was embedded in the wood up to the nail diameter of 2.9 mm. The maximum load was recorded and later used as the embedment strength. For each specimen, we conducted one test in the center of the specimen for a total of ten tests each for the 2-by-4 and plywood. To estimate the yield moment of the 6d nails used in the above tests, we conducted bending tests on 10 nails. The nails were supported at both ends, allowing a span of 32 mm, and a concentrated load was applied to the nails midway between the supports. The load was applied at a displacement rate of 0.51

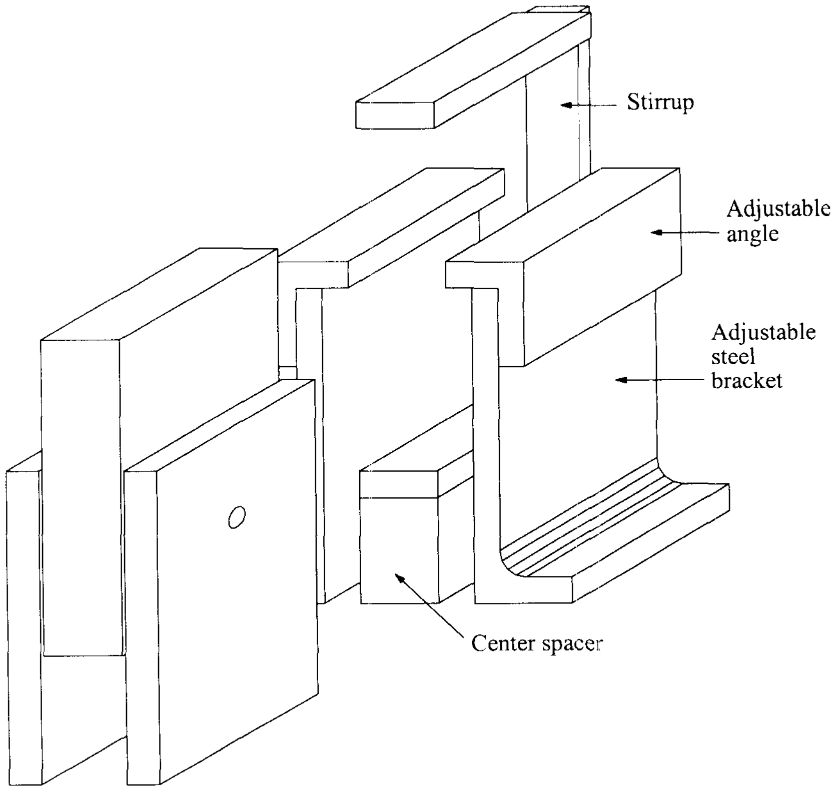

FIG. 2. Test device.

mm/min using a 534-kN testing machine until yielding occurred.

Embedding strength and nail bending tests were conducted at ambient temperature only. The scope of this research did not allow measurement of these parameters at elevated temperatures. These measurements would be needed to evaluate the yield theory at elevated temperatures as in Eqs. (3) and (6).

For structural analysis of assemblies at elevated temperature, predicting the displacement behavior of the joint is needed rather than simply the strength of the joint. We explored the derivation of a yield theory equation that would describe the entire load-displacement curve of the joint and an initial, low-load slip modulus. To derive this equation, we used the fourth-root embedding stress-deformation relationship described by Aune and Patton-Mallory (1986a, b) for a nailed joint with an interlayer gap. For simplicity we assumed that the embedding strengths of the 2-by-4 and plywood were equal, and we considered only the failure mode that occurred at ambient. While we successfully derived the load-displacement equation, including the interlayer gap in the derivation, we could not resolve the equation to a usable form (Peyer 1995). The main problem was the complexity introduced by the fourth-root embedding stress-deformation equation combined with the interlayer gap. If a more simple equation could be established to describe the shank embedding behavior, replacing the fourth-root equation, then the solution of a practical yield theory load-displacement equation would be more likely.

Although we were unable to characterize the joint load-displacement measurements with the yield theory, we did analyze the data with an empirical model. The load-displacement curves were characterized by Eq. (7)

where parameters, k, M_0, and M_1 were evaluated to provide a visual best-fit to the data (see Fig. 6).

$$F = \frac{M_0}{1.5}\arctan\left(\frac{1.5d}{M_0}(k - M_1)\right) + M_1 d \quad (7)$$

In Eq. (7),

F = force,

k = initial slope of the load-displacement curve,

M_1 = slope of the load-displacement curve representing the plastic-action plateau,

M_0 = load axis intercept of a tangent to the load-displacement curve with slope M_1, and

D = displacement.

This three-parameter equation (Eq. 7) from Shrestha et al. (1995) is modified from an equation first proposed by Foschi (1977) to characterize nailed joint load-displacement response. The Foschi equation uses the same three parameters. The modification by Shrestha et al. yields an equation that can be more readily differentiated and integrated in structural calculations.

RESULTS

As joint displacement increased, the load increased to the ultimate strength (Fig. 6) and then tapered off as the maximum displacement of 25 mm was approached. Some friction developed between the plywood and 2-by-4, but only during the end of the test at large displacements. The LVDT operated smoothly for the ambient tests, but at elevated temperatures the core of the LVDT expanded and did not glide within the LVDT casing. We compared the ambient load-displacement curves generated by the LVDT with an internal LVDT in the load actuator. Both curves were the same; therefore we assumed that the load-displacement curves at elevated temperatures were adequately described by using the displacement of the cross-head from the testing machine.

The average maximum strength of the joints decreased as the temperature increased (Fig. 7). Figure 7 is a box plot of the data showing the median surrounded by a box sized to include the quartile of data above and below the median. The lines extending above and below the box indicate the range of the extreme data values. The average slip modulus of the joints, as characterized by "k" in Eq. (7), generally decreased as temperature increased, but increased slightly between exposures of 200°C and 265°C (Fig. 8). The box plot in Fig. 8 displays the observed data in a format similar to Fig. 7. The average measured parameters corresponding to Eq. (7) are shown in Table 1. From ambient (30°C) to 120°C, 200°C, and 265°C exposures, the percent decreases were 13%, 15%, and 26%, respectively, for strength, and 47%, 61%, and 54%, respectively, for slip modulus. The strength and slip modulus decreased by the largest percent between ambient and 120°C exposure and corresponded with the largest incremental increase in the temperatures near the nail in both the 2-by-4 and plywood (Table 1). At each temperature, the percent decrease in slip modulus was greater than the percent decrease in strength.

At 120°C, 200°C, and 265°C exposures, the wood did not char, but at 265°C, the specimens were slightly discolored. Temperatures were not uniform throughout the joint for any elevated temperature exposure nor were moisture contents of the wood materials. Any attempt to achieve uniform conditions would have resulted in very long and unrealistic exposure durations. Temperatures near the nail in the plywood were always higher than the temperatures near the nail in the 2-by-4 (Fig. 9, 10; Table 1). As the exposure temperature increased, the temperatures in the plywood increased by more than the temperatures in the 2-by-4.

At ambient (30°C), 120°C, and 200°C exposures, the nails yielded in both the plywood and the 2-by-4 and corresponded with failure mode IV (Fig. 5) in the NDS (1997). Nail yield, particularly in the plywood, was less