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Bending Properties of Reinforced and Unreinforced Spliced Nail-Laminated Posts

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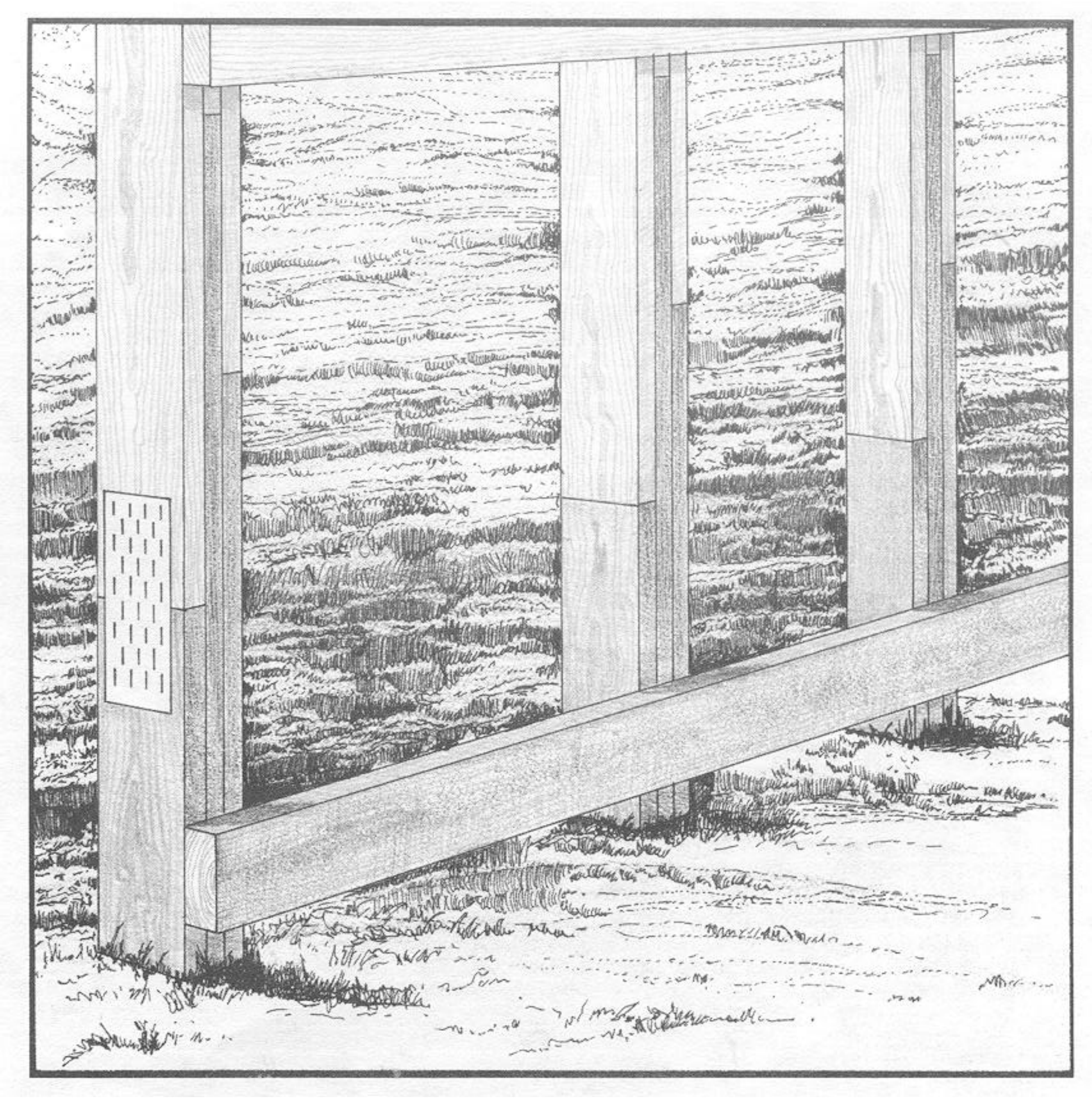

Abstract

Efficient design of post-frame wood buildings requires accurate information on the properties of the nail-laminated posts. To characterize structural post properties, 140 three-layer nail-laminated posts were tested to failure in bending. Of these assemblies, 28 contained no splices, 56 contained unreinforced splices, and the remaining 56 contained splices reinforced on the outside butt joints. Spliced posts were fabricated with gun-driven or machine-driven nails. In addition to the posts, 56 individual pieces of lumber were loaded to failure in bending. The average strength (modulus of rupture) of the single members was found to be higher than that of the unspliced posts. However, the 5th percentile of strength for the unspliced posts, which is the basis for design, was significantly higher than that for the single members. Joint reinforcement significantly increased bending strength and stiffness of spliced posts. However, even with butt joint reinforcement, spliced posts had substantially lower bending strength and stiffness than did unspliced posts.

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Bending Properties of Reinforced and Unreinforced Spliced Nail-Laminated Posts

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Introduction

The basic structural components of a post-frame wood building include wood posts, trusses, girts, and purlins (Fig. 1). An individual truss and the posts to which it is connected are referred to as a post-frame. Each post-frame receives its lateral support and loads from girts and purlins. Girts and purlins are laterally supported by the exterior sheathing (generally metal panels), and with the sheathing they form large wall and roof diaphragms. These diaphragms add considerable rigidity to the building.

Today, builders of post-frame wood structures compete with builders of “pre-engineered” low-rise, steel-frame structures. In many respects, both building systems are identical. The only essential difference is the material used for the frame, However, with respect to fire codes, this is a major difference, and it generally determines under what conditions a wood post-frame building will be economically competitive with a steel-frame structure.

The wood posts make the post-frame building unique. Although the posts may be bolted to the top of a concrete frost wall or floating slab foundation, they are generally embedded in the soil. When embedded, the posts transfer load directly to the soil and thereby function as the foundation for the building. When designing posts, engineers are most interested in their bending capacity: under the load combinations that typically control post design, usually at least 75 percent and often more than 85 percent of the maximum fiber stress in the post is due to the applied bending moment.

A recent trend has moved the post-frame building industry away from the use of solid-sawn wall posts toward the use of nail-laminated posts. This trend can be attributed to the high cost and scarcity of long, stress-rated, solid-sawn, preservative-treated posts. This trend can be expected to continue as (1) a greater number of taller structures are built, (2) long timber becomes increasingly more expensive and difficult to obtain, (3) the cost of preservative-treated lumber increases, and (4) an economic advantage exists for using laminated members when posts exceed a certain length (see Fig. 2 and App. A).

Nail-laminated posts fall into two main categories: unspliced and spliced. Unspliced posts are those assemblies in which each layer consists of only one piece of dimension lumber. Spliced posts are those assemblies in which at least one layer contains two or more pieces of dimension lumber butt-jointed together. Spliced posts can be classified further by whether or not the butt joints are reinforced.

Both spliced and unspliced nail-laminated posts are designed to resist loads applied parallel to the interlayer planes or wide faces of the layers. Posts designed to resist loads in this direction are referred to as vertically laminated. Nail-laminated posts are seldom designed to resist loads applied normal to the interlayer planes because the strength in this direction is only a fraction of that for bending about the strong axis. Thus, posts must be provided with adequate lateral support. When spliced nail-laminated posts are not laterally supported, loads applied normal to the interlayer planes tend to cause delamination of the assembly in the joint area.

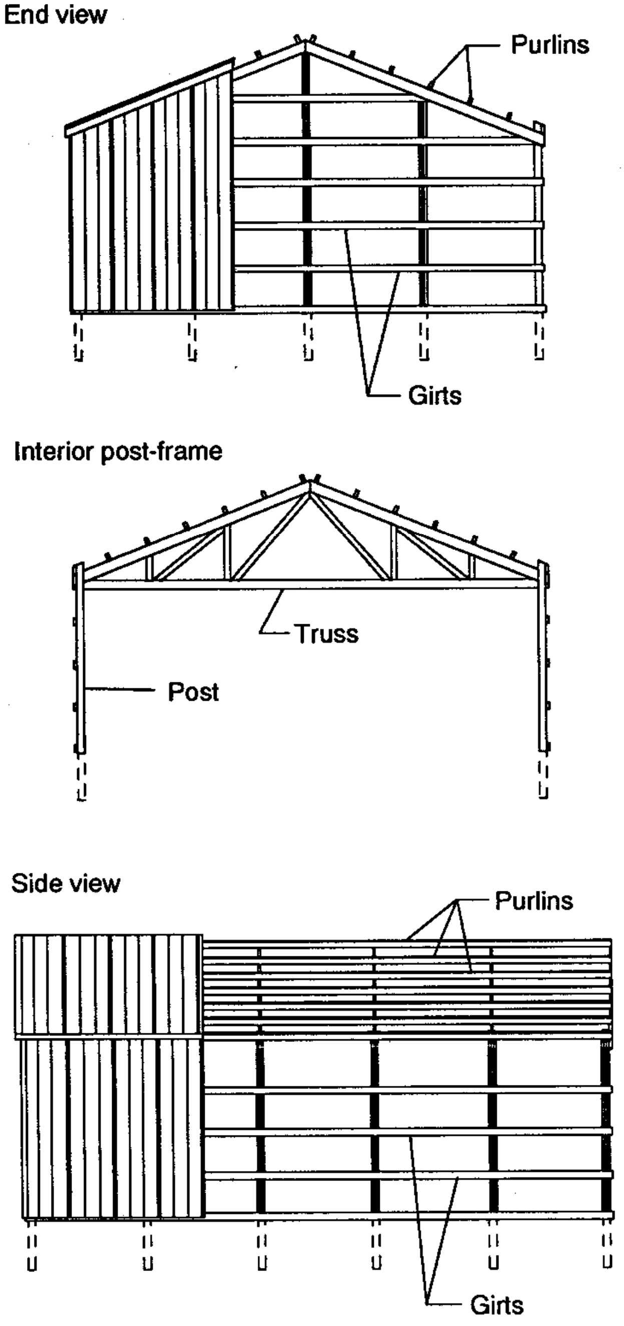

Figure 1—Framing for a post-frame building.

A commonly used spliced-post design is a three-layer (trilaminated) assembly fabricated from six pieces of nominal 2- by 6-in. (38- by 140-mm) lumber. The three butt joints are normally staggered and spaced either 18 or 24 in. (0.5 or 0.8 m) apart for an overall splice length of 3 or 4 ft (0.9 or 1.2 m), respectively (Fig. 3). The general objective of this report is to provide information that will assist in developing design bending properties for nail-laminated posts of this type.

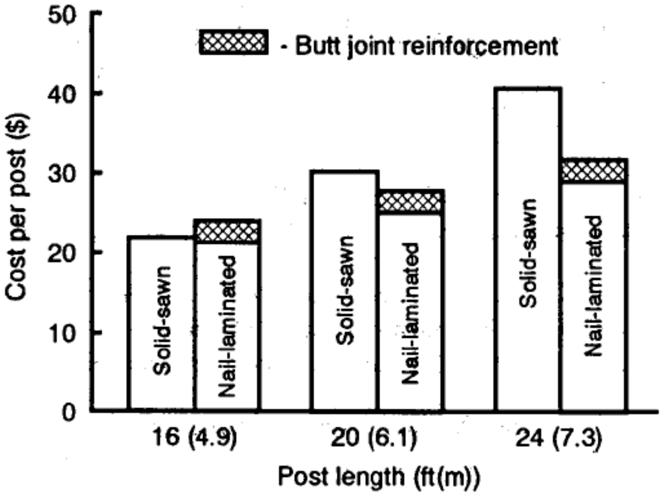

Figure 2—Relative cost of solid-sawn and nail-laminated Southern Pine posts.

Background

Unspliced Beams

Only a few studies have been conducted on the effect of number of layers on strength properties of vertically laminated beams without butt joints. Bonnickson and Suddarth (1966) showed that three-layer nail-laminated bending specimens had about the same average strength as that of single members but significantly reduced variability for a Standard and better grade of green Douglas Fir. Wolfe and Moody (1979) found similar results for glued specimens of the higher grades of lumber but also found a slight increase in strength of lower grades. Sexsmith and others (1979) studied 6-, 12-, and 18-layer specimens held together with a transverse stressing technique. They found that allowable properties for the multiple layer assemblies were significantly higher than those for single members

Overall, research on unspliced beams indicates that multiple-layer members, compared to single members, have the following properties:

1. similar mean strength for high grades and somewhat increased mean strength for lower grades of lumber;
2. similar mean stiffness regardless of grade;
3. reduced variability in both strength and stiffness, with coefficient of variation decreased inversely as square root of number of layers; and
4. significantly higher increases in lower 5th percentile values than are presently recognized by the 15-percent “load sharing” factor from the National Design Specification (NFPA 1988).

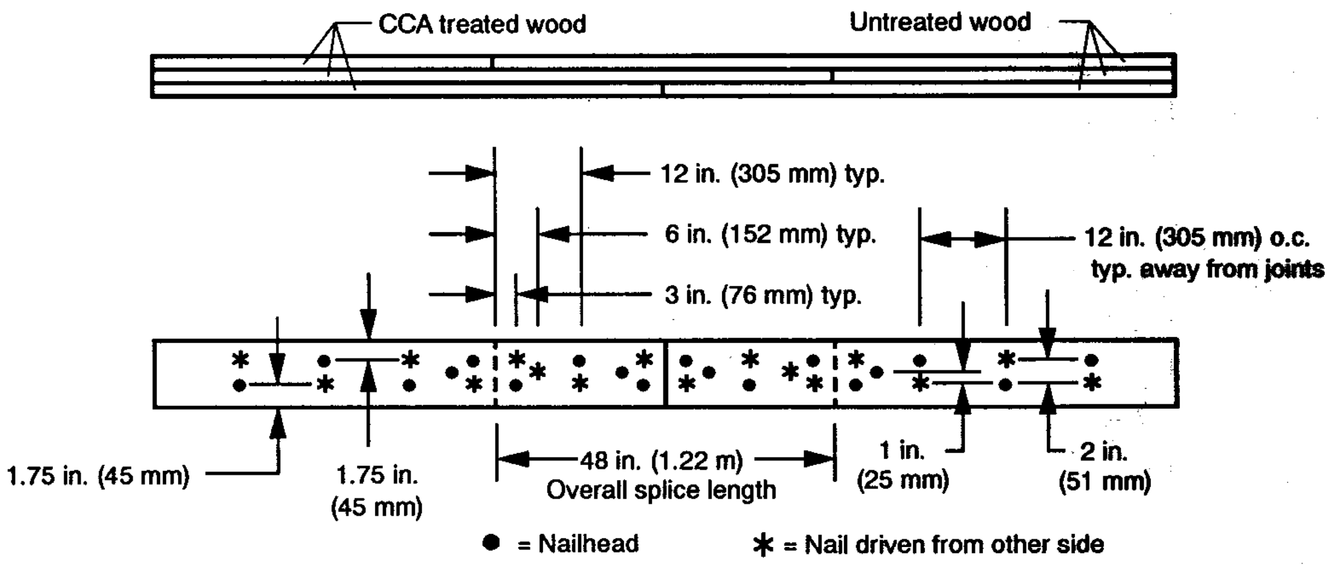

Figure 3—Spliced post design. Nailing pattern taken from Bohnhoff (1989).

Spliced Beams

Test results for three-layer, nail-laminated assembly designs with staggered butt joints that have been tested and reported to date are compiled in Table 1. Although this table includes only 10 different designs, the data gathered from these tests have been quite valuable; they have significantly increased our understanding of spliced nail-laminated assembly properties. Specifically, the tests have shown that (1) strength properties are related to lumber grade, (2) 20d (4.5- by 102-mm) ring-shank nails can be used if properly located, and (3) maintenance of an adequate overall splice length is extremely important.

The program FEAST was developed to learn more about the strengths and weaknesses of various nail-laminated assembly designs (Bohnhoff 1988, Bohnhoff and others 1989). FEAST is a finite element method of analysis program for analyzing vertically and mechanically laminated assemblies. Bohnhoff (1989) modeled three-layer, nail-laminated assemblies with staggered joints and no reinforcement using this analytical method. He concluded the following:

1. Without additional butt joint reinforcement, an overall splice length of 2 ft (0.6 m) is too short to effectively redistribute forces in the immediate vicinity of a butt joint. An overall splice length of at least 3 ft (0.9 m) appears necessary for a three-layer assembly.
2. High localized stresses in the wood layers cannot be effectively decreased by increasing nail density.
3. Regardless of splice length and individual wood member modulus of elasticity (MOE) values, the longest wood member in the center layer is almost always the most highly stressed member.
4. Regardless of splice length and individual wood member MOE values, the most highly stressed nails are always located adjacent to a butt joint in an outer layer.
5. Increasing nail density decreases maximum nail shear forces. However, it is not known to what level nail density can be increased without having an adverse effect on the ultimate strength of an assembly (that is, without increasing the number of nail-related or nail-induced assembly failures).

On the basis of conclusions 3 and 4, two rational alternatives for increasing the strength of the assemblies would be (1) to increase the grade of the longest member in the center layer because this member-is the most highly stressed and (2) to reinforce the outside butt joints. By reinforcing only the outside joints, less load is channeled into the center layer and stresses in the center layer are reduced. Reinforcing the joints also reduces the amount of interlayer slip at the joints, thus lowering nail forces in the vicinity of the joints. Assuming that reinforcing the outside butt joints increases assembly strength, it is not surprising that of the 10 designs in Table 1, design 7 was associated with the highest mean ultimate strength. Design 7 not only featured an overall splice length of 4 ft (1.2 m) but also was the only design tested that featured No. 1 or better lumber in combination with outside butt joint reinforcement.

Table 1—Bending strength of three-layer spliced posts reported in literature[a]

Source	Design	Number of tests	Lumber type[b]	Nail specifications: Size[c]	Nail specifications: Shank type	Nail specifications: Driving method	Nail specifications: No.[d]	Butt joint reinforcement	Overall splice length (ft (m))	Ultimate midspan bending moment[e]: Mean (in-lb (kN-m))	Ultimate midspan bending moment[e]: COV (%)	Allowable design bending moment[f] (in-lb (kN-m))
DeBonis and others (1984)	1	20	No. 2D SP	12d	Common	Hand	48	None	4 (1.22)	73,800 (8.34)	33.1	19,600[g] (2.21)
Winistorfer (1985)	2	5	No. 2 HF	20d	Ring	Hand	16	None	2 (0.61)	34,000 (3.84)	20.6	—[h]
	3	5	No. 2 HF	20d	Ring	Hand	16	None	4 (1.22)	67,700 (7.65)	11.5	—[h]
	4	5	No. 2 HF	20d	Ring	Hand	16	—[i]	2 (0.61)	60,500 (6.83)	10.2	—[h]
	5	5	No. 2 HF	20d	Ring	Hand	16	—[i]	4 (1.22)	79,300 (8.96)	12.5	—[h]
Woeste and others (1985)	6	25	No. 1DSP	A	Thread	Gun	48	—[j]	4 (1.22)	115,000 (12.99)	11.0	44,500[k] (5.03)
Woeste and others (1988)	7	20	No. 1D SP	B	Thread	Gun	48	—[l]	4 (1.22)	130,800 (14.78)	8.3	53,200[k] (6.01)
Bohnhoff (1988)	8	4	No. 1 SP	10d	Common	Hand	56	None	4 (1.22)	97,700 (11.04)	8.7	—[h]
	9	4	No. 1 SP	20d	Ring	Hand	12	None	4 (1.22)	95,300 (10.76)	32.8	—[h]
	10	4	No. 1 SP	20d	Ring	Hand	20	None	4 (1.22)	151,900 (12.66)	7.8	—[h]

[a] Nominal 2- by 6-in. (standard 38- by 140-mm) lumber used in all assemblies. All assemblies loaded to failure in bending under two-point loading.

[b] SP is Southern Pine, KD15. HF is Hem-Fir, surface dry.

[c] Nail dimensions: 10d common, 0.14 by 3.0 in. (3.8 by 76 mm); 12d common, 0.14 by 3.3 in. (3.8 by 83 mm); 20d ring-shank, 0.18 by 4.0 in. (4.5 by 102 mm). Other nail sizes were as follows: A, 0.1 by 3 in. (3 by 76 mm); B, 0.1 by 3 in. (3 by 76 mm).

[d] Number of nails in center 4 ft (1.2 m) of assembly.

[e] Moment between load points at maximum applied load. COV is coefficient of variation.

[f] 5-percent exclusion value for ultimate midspan bending moment divided by 2.1.

[g] Based on lognormal distribution.

[h] Sample size not large enough to obtain a good 5-percent exclusion value.

[i] One 5- by 10-in. by 19-gauge (127- by 254- by 1.2mm) nail plate per outside joint.

[j] One 5 by 24-in. by 20-gauge (127- by 610- by 0.9-mm) AISI 1010 steel sheet per joint.

[k] Based on three-parameter Weibull distribution.

[l] One 5.1- by 10.8-in. by 18-gauge (130- by 275 by 1.2-mm) metal plats connector per outside joint.

Although laboratory tests and modeling indicate that reinforcing outside butt joints should increase assembly strength, the magnitude of such an increase in assemblies fabricated with No. 1 lumber is not known. Woeste and others (1988) did not test unreinforced assemblies of No. 1 or better lumber. Although Bohnhoff (1988) did test unreinforced specimens (designs 8, 9, and 10), the work of Bohnhoff and that of Woeste and others cannot be compared for the following reasons: (1) different nails and nailing patterns were used, (2) lumber came from different. "batches" and there is no good way to account for differences in lumber properties, and (3) test conditions, such as loading rates, specimen conditioning, and lateral constraints, were not the same.

As Figure 2 shows, the addition of splice plates to a post increases the material cost of the assembly by about 10 percent (see App. A). Before this cost can be justified, the structural benefit of additional reinforcement must be ascertained.

There is also a need to determine the "design strength" of assemblies fabricated using the nailing pattern shown in Figure 3. This pattern was recommended by Bohnhoff (1989) for assemblies fabricated using nails equivalent in size to a 20d (4.5 by 102-mm) ring shank. The pattern is a hybrid of the nailing patterns associated with designs 9 and 10 in Table 1. The relatively high ultimate strengths associated with designs 9 and 10 demonstrated that nails equivalent in size to 20d (4.5 by 102-mm) ring shanks could be used effectively in laminated assemblies. In the majority of the tests conducted to date, nails no larger than a 12d (3.8- by 76-mm) common nail have been used. There is a major disadvantage to using the smaller nails: typically, twice as many nails are needed per assembly.

Teat specimens used to determine allowable design properties for spliced posts are generally fabricated with all untreated wood or with preservative-treated wood on one end of the post and untreated wood on the other end. Regardless of which arrangement is used to establish design properties, a designer may want to interchange treated and untreated wood for a particular field application. Such interchanging is not likely to affect post strength and stiffness if the strength and stiffness of the untreated and preservative-treated wood are not significantly different. When the design properties of the treated and untreated lumber are different, additional laboratory testing may be required to determine the strength and stiffness of the new design. In teats with No. 1 Southern Pine lumber, Winandy and Boone (1988) found relatively little difference between the strength of untreated and treated lumber when preservative retentions were limited to 0.6 lb/ft^3 (9.6 kg/m^3) and redrying temperature was limited to 190°F (88°C).

Design Properties

A major difference between spliced and unspliced nail-laminated posts lies in the procedure used to determine the allowable bending capacity of the assemblies. The bending strength of unspliced posts is almost always calculated using the "repetitive member use" bending stress values listed in the National Design Specifications (NDS) for Wood Construction (NFPA 1986). The repetitive member use values are 15 percent greater than the single member design values established according to ASTM Standard D 245. This standard permits the use of repetitive member use values any time "three or more load-carrying members such as joists, rafters, studs, or decking are contiguous or are spaced not more than 24 in. (0.6 m) in frame construction and are joined by transverse floor, roof, or other load distributing elements" (ASTM 1989a). Nail-laminated posts fall into this category if the nails connecting the layers are categorized as load-distributing elements. Because relatively little interlayer slip occurs in unspliced posts, the size, type, and location of nails have virtually no influence on the strength of the assemblies.

The strength and stiffness of spliced nail-laminated posts, unlike those of unspliced posts, are highly dependent on nail type, size, and location as well as the relative location of the butt joint or joints in each layer and the type, amount, and location of butt joint reinforcement (when such reinforcement is used). Because of the complex interaction of these variables, the strength of spliced posts is currently determined by laboratory tests of a representative sample of actual assemblies. A two-point load, applied in accordance with ASTM Standard D 198 (ASTM 1989b) is commonly used to establish the ultimate bending strength of each post To arrive at an allowable bending moment for design the 5th percentile of the distribution of the ultimate bending moment for all sample posts tested is divided by 2.1, which is a product of a load duration factor of 1.6 and a traditional safety factor of 1.3 (ASTM 1989b; Hoyle and Woeste 1989). The load duration factor is used to adjust the strength determined in a 5-min test to that expected under a load with-a duration of 10 years.

Because different procedures are used to arrive at the allowable bending moment values for spliced and unspliced posts, a design value for a spliced post with butt joint reinforcement can be found that is greater than that calculated for an unspliced post fabricated using the same size, grade, and species of lumber This leads to confusion because the designer is led to conclude that the spliced region of the post is stronger than the unspliced region. Because of the relatively light reinforcement currently used in spliced nail-laminated posts, this is seldom, if ever, true. The bottom line is that if the same procedure used to determine the allowable bending moment for spliced posts were used for unspliced posts, the allowable bending stress for unspliced posts would, in most instances, be higher than that based on published allowable stress values.

Research Needs

To date, laboratory tests comparing properties of spliced and unspliced assemblies have not been conducted. Consequently, the true reduction in strength associated with the addition of butt joints has never been accurately presented. In addition, only Winistorfer and others (1987) have conducted side-by-side tests on spliced posts with and without butt joint reinforcement, Inasmuch as these tests involved only five specimens of each design, more testing is needed on both reinforced and unreinforced joints. Such test data are needed to determine in what applications joint reinforcement would be economical.

Objectives

The specific objectives of the research were as follows:

1. to determine how bending strength and stiffness of single members of dimension lumber are related to bending strength and stiffness of three-layer, unspliced nail-laminated posts;
2. to compare bending strength and stiffness of three types of three-layer nail-laminated posts: (a) unspliced, (b) spliced without butt joint reinforcement, and (c) spliced with butt joint reinforcement; and
3. to determine the effect of nail type on bending strength and stiffness of three-layer, spliced nail-laminated posts.

Methods

Experimental Design

The experimental design for the single-member tests and three-layer nail-laminated post tests is described in Table 2. As indicated in the table, five different post designs were tested: one unspliced design and four spliced designs. In addition to the 140 posts, fifty-six 12-ft (3.76-m) nominal 2- by 6-in. (standard 38- by 140-mm) pieces of lumber were loaded to failure in bending. The single-member tests were conducted to characterize the properties (stiffness and ultimate strength) of the lumber used to fabricate the laminated posts.

Table 2—Experimental design

Board and nail type	Number tested	Butt joint reinforcement
Single member	56	NA
Unspliced posts		
Machine driven	28	NA
Spliced posts		
Gun driven	28	No
	28	Yes
Machine driven	28	No
	28	Yes

The sample size of 28 was suggested by Woeste (personal communication) and based on ASTM D 2915 requirements for estimating the 5-percent nonparametric tolerance limit (75 percent confidence level) 1989c). If the test data are normally distributed with a coefficient of variation of 20 percent and there is no interaction between nail type and butt joint reinforcement, then this sample size is large enough to permit one to detect a 10-percent difference in means at a 0.05 significance level with 0.75 probability.

Nail-Laminated Post Designs

Member designs for spliced and unspliced posts are illustrated in Figures 3 and 4, respectively. All posts were three-layer assemblies, 12 ft (3.76 m) in length, which were fabricated from nominal 2- by 6-in. (standard 38- by 140-mm) No. 1 dense (hereafter called No. 1D) KD15 Southern Pine lumber. As shown in Figure 3, the three butt joints in the spliced posts were staggered and spaced 24 in. (0.6 m) apart for an overall splice length of 4 ft (1.2 m). All spliced posts were fabricated from three pieces of treated lumber and three pieces of untreated lumber. We originally considered fabricating the assemblies entirely from untreated wood. The decision to use treated wood on one end of each spliced post was based on the premise that preservative treatment is more likely to decrease rather than increase lumber strength. Thus, using some treated wood should produce a more conservative estimate of post strength than using all untreated wood.

The nailing pattern for the spliced posts was designed by Bohnhoff (1989) to be used in conjunction with a nail similar in type and length to a 20d (4.5- by 102-mm) ring shank. As shown in Table 2, two different nails were used in the assembly of the laminated posts. The first type was a gun-driven ring-shank nail, 0.145 in. (3.68 mm) in diameter and 4 in.

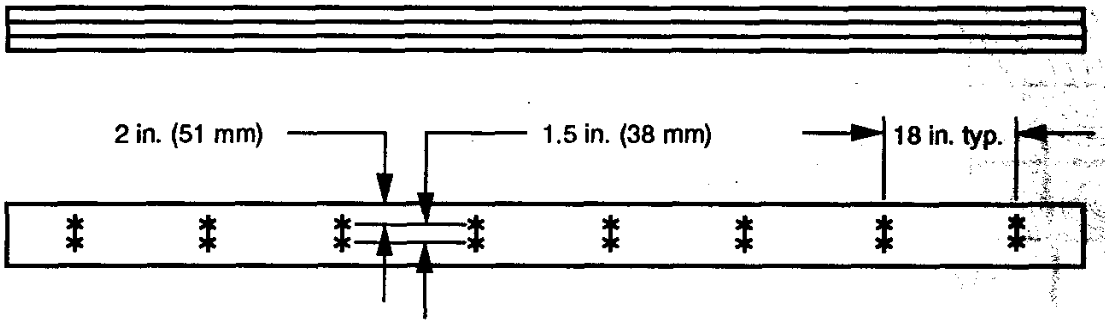

Figure 4—Unspliced post design.

(102 mm) in length. This nail was used in the fabrication of one-half the spliced posts. The other half of the spliced posts and all the unspliced posts were fabricated using a autonailing machine. This machine drove and cut a spirally threaded wire (outside diameter 0.187 in. (4.8 mm)) to a 4.5-in. (115-mm) length.

High strength, 20-gauge (0.9-mm) toothed metal plate connectors with a width of 5.25 in. (133 mm) and length of 8.75 in. (222 mm) were applied to the outside butt joints of those spliced posts designated for reinforcement. The plates had a tension yield stress rating of 60,000 lb/in^2 (417 MPa).

Lumber Allocation

A total of 440 pieces of lumber 16 ft (4.98 m) in length were obtained for the study. Of these pieces, 146 were randomly selected and treated with chromated copper arsenate (CCA) to a retention level of 0.6 lb/in^2 (9.6 kg/m^3). Both the treated and untreated pieces were conditioned to an equilibrium moisture content of 12 percent. Each piece was then numbered and weighed, and the MOE value was determined using a flatwise vibration technique. Prom the 146 treated pieces, 140 were selected for the experiment. Similarly, 280 untreated pieces were selected for the experiment.

The lumber was divided into six groups: a group for each of the five post designs (one unspliced and four spliced) and a group for the single-member tests. Lumber allocation was designed so that each group consisted of wood with a similar MOE distribution. Another goal of the allocation process was to apportion the lumber so that 28 matched sets were created for the four spliced post designs. The allocation process was as follows:

The 280 untreated boards were first ranked by MOE. An adjacent pair of boards was selected from the 10 boards with the lowest MOE values. These boards were cut in half to produce four 8-ft (2.4-m) boards. A two-step procedure was used to allocate the boards into the teat groups:

1. A set (or replicate) number between 1 and 28 was selected.
2. The boards were randomly distributed to the four spliced test groups within the selected set.

Another adjacent pair of untreated boards was then randomly selected from the eight remaining boards and cut into four 6-ft (1.8-m) lengths (plus two “excess” pieces 4 ft (1.2 m) in length). These boards were then assigned to a randomly selected matched set of four assemblies using the preceding two-step process. Another board from the original group of 10 boards was then randomly selected, cut into four 4-ft (1.2-m) pieces, and randomly assigned to one of the 28 matched sets.

The five remaining boards were cut to a length of 12 ft (3.7 m). Two of these boards were assigned to the single-member test group, and the remaining boards were randomly assigned to the unspliced post test group (see Table 2 for experimental design).

This procedure for allocating lumber was repeated for the remaining 27 groups of 10 boards.

The 140 treated boards were also ranked by their MOE values and then divided into 28 groups of five boards each. The five boards in each group were assigned to the spliced post test group by the same method used for assigning the untreated wood to test groups.

Specimen Fabrication

Posts manufactured with gun-driven nails were assembled in a conditioning room; those manufactured with machine-driven nails were assembled at a manufacturing facility and then returned to the conditioning room. None of the assemblies was tested until 2 weeks after fabrication.

Problems were encountered when driving both types of nails. Because of the high density of some the Southern Pine lumber, the nail gun did not completely drive all the 4-in.- (102-mm-) long nails. This problem was considerably reduced after the air pressure

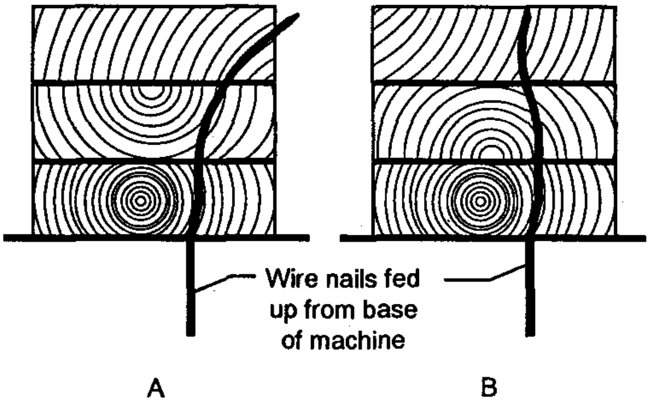

Figure 5—Problem associated with machine-driven nails. Nails deflected (A) outward and (B) inward by denser latewood.

to the gun was increased to 140 lb/in^2 (965 kPa), which is 20 lb/in^2 (138 kPa) beyond the recommended maximum safe operating pressure. Where nails were underdriven, attempts were made to finish driving the nails by hand. However, because of the ductility of the gun-driven nails, these attempts were not always successful.

The problem associated with driving the machine-driven nails is illustrated in Figure 5. The nails tended to follow the path of least resistance as they were being driven. In several cases, the nails were deflected by the dense latewood. Thus, the nails followed annual rings, staying in the earlywood until they exited from the assembly (Fig. 5A). This problem could be virtually eliminated by turning boards so that annual rings formed arches instead of troughs (Fig. 5B). With this arrangement, nail points were deflected toward the center of the assembly. Because there was no guarantee that the orientation of the lumber would be controlled during future production of nail-driven posts, no attempt was made to control lumber orientation during fabrication of the test specimens.

Although reinforcing plates can be pressed into place before individual layers are nailed together, all plates used in this study were pressed into their respective assemblies after the layers had been nailed together.

Testing Procedures

The MOR and MOE for each single member were determined according to ASTM D 198 (ASTM 1989b). The two-point load arrangement shown in Figure 6 was used in combination with a loading rate of 0.30 in/mm (7.62 mm/min). To measure midspan deflection, a spring-tensioned wire was drawn between nails driven into the centroidal axis of the member directly above the supports. The relative displacement between the wire and the member at midspan was measured by clamping a linear variable differential transformer (LVDT) to the specimen at midspan and hooking the core of the LVDT to the wire. To avoid damage to the LVDT, it was removed once the total deflection reached 2 in. (51 mm). A computer-based data acquisition system was used to record midspan deflection and load data at 2-s intervals.

Specimens from the five different nail-laminated assembly groups were randomly selected for test. Where applicable, ASTM D 198 (ASTM 1989b) was followed. The load-head rate was fixed at 0.40 in/min (10 mm/min) for all tests. The location of the load points, support reactions, and points of lateral support for all laminated assembly teats are shown in Figure 6. Four single-turn potentiometers were used to measure the deflection of the outside laminae at the load points. A computer-based data acquisition system was used to record load-point deflection and load data at 2-s intervals.

Results

Lumber Properties

Lumber properties for the CCA-treated lumber, untreated lumber, and both groups combined are compiled in Table 3. The table lists mean values and corresponding coefficients of variation for both dynamic MOE and specific gravity.

Single-Member and Post Properties

The MOR distribution characteristics for single members and unspliced posts are compared in Table 4 (see App. B for individual data); the MOR distributions are shown in Figure 7. The mean MOE values for single members and unspliced posts were 2.48 × 10^6 lb/in^2 (17.1 GPa) and 2.45 × 10^6 lb/in^2 (16.9 GPa), respectively. Corresponding coefficients of variation were 20.6 and 9.23 percent. The ratio of post to single-member values for MOE was 0.99.

Distribution characteristics for ultimate midspan bending moment and initial stiffness are shown in Table 5 for unspliced and spliced posts (see App. B for individual data). Values in Table 5 are presented in terms of ultimate moment resistance and stiffness rather than MOR or MOE. For spliced posts, MOR and MOE have no physical meaning because of the complex stress distributions in the assemblies. However, moment

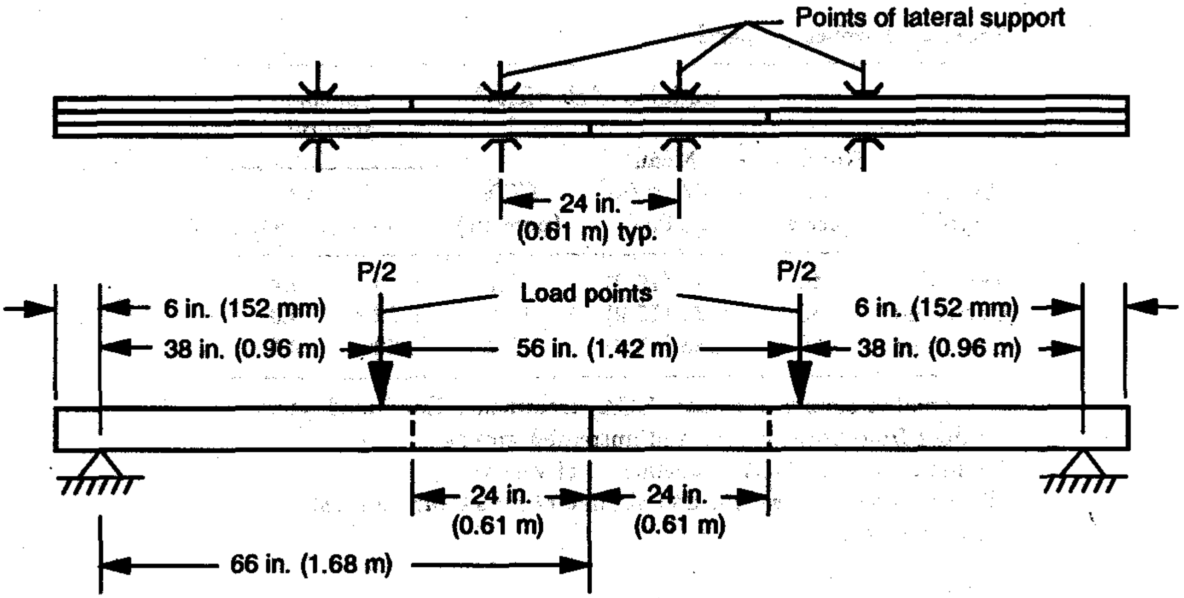

Figure 6—Location of bad points, support reactions, and points of lateral support for all laminated assembly tests.

resistance and stiffness are realistic bases for comparing post types.

Tables 4 and 5 both contain parametric and nonparametric estimates of the 5th percentiles for bending strength as well as a lower 75-percent confidence bound on the 5th percentile (referred to as the 5-percent tolerance limit). The Shapiro-Wilk test only rejected the normal distribution for the MOR of the single members. For this particular case, the lognormal distribution fit well.

Table 6 summarizes post properties that were significantly different at the 5-percent level. Levels of significance for various analyses are given in Appendix C. As Table 6 indicates, spliced posts had significantly lower strength and stiffness properties than those of unspliced posts. The magnitude of the differences is shown in Table 7, which contains ratios of spliced to unspliced post properties. Reinforced posts were also significantly stronger and stiffer than unreinforced posts (Table 6); ratios of these properties are shown in Table 7. Table 6 also indicates that posts made with gun- and machine-driven nails did not have significantly different strength and stiffness properties. Thus, results of the two nail types are combined in Table 7 (last column) and Figure 8. Figure 8 compares ultimate midspan bending moment of unspliced posts, spliced posts with reinforcement, and spliced posts without reinforcement.

Failure Types

All specimens were examined after the bending tests to characterize the probable types of failure. For the single members, failure types were as follows:

Failure type	Percentage of failure
Tension at grade-controlling knots or slope-of-grain	15
Splintering tension in clear wood or from small knots	56
Compression wrinkling at or between load points	29

Because the middle layers of the three-layer unspliced posts could not be readily examined, their failures were more difficult to characterise. However, the failures appeared to closely parallel the failure types of the single members.

For spliced posts, wood and nail joint failures were categorized into 13 types as shown in Figure 9. Although the diagrams do not provide information on the type of wood failure, they help identify regions of high force or stress. In general, wood failures that occurred at member ends were parallel-to-grain splits, and those that occurred away from member ends were parallel-to-grain tension failures or, in some instances, tension failures resulting from knots and/or slope-of-grain. In reinforced posts, the metal plate connectors failed before maximum load was reached, in almost all cases.

Table 3—Lumber properties

Lumber type[a]	Number of pieces	Modulus of elasticity[b] Mean (×10^6 lb/in^2 (GPa))	Modulus of elasticity[b] COV (percent)	Specific gravity[c] Mean	Specific gravity[c] COV (percent)
Treated	140	2.35 (16.2)	17.2	0.63	9.4
Untreated	280	2.31 (15.9)	17.9	0.62	9.0
Combined	420	2.32 (16.0)	17.7	0.62	9.2

[a] Chromated copper arsenate (CCA) treatment. Combined refers to data from both treated and untreated groups.

[b] Dynamic values. COV is coefficient of variation.

[c] Based on ovendry weight and volume at a moisture content of 12 percent.

Table 4—Distribution characteristics for modulus of rupture of single members and three-layer unspliced posts [a]

Distribution characteristic	Modulus of rupture[b] (lb/ins (MPa)) Single members	Modulus of rupture[b] (lb/ins (MPa)) Unspliced posts	Ratio of post to single-member values
Mean	11,040 (76.1) [33.9%]	9,800 (67.6) [13.6%]	0.89
5-percent exclusion value			
Normal	4,940 (34.1)[c]	7,640 (52.7)	—[c]
Lognormal	6,060 (41.8)	7,760 (53.5)	1.28[d]
Weibull[e]	5,580 (38.5)	7,630 (52.6)	1.37[f]
Nonparametric	6,130 (42.3)	7,790 (53.7)	1.27
5-percent tolerance limit[g]			
Normal	4,370 (30.1)[c]	7,340 (50.6)	—[c]
Lognormal	5,760 (39.7)	7,510 (51.8)	1.30
Weibull[e]	5,320 (36.7)	7,380 (50.9)	1.39
Nonparametric	4,800 (33.1)	6,730 (46.4)	1.40

[a] Modulus of rupture values for posts are average (“effective”) values calculated using post width of 4.5 in. (114.3 mm) and height of 5.5 in. (139.7 mm). Posts were made with machine-driven nails.

[b] Values in brackets are coefficient of variation.

[c] Normal fit of single members rejected by Shapiro–Wilk test

[d] 95-percent confidence bound = 1.10–1.49.

[e] Three-parameter Weibull distribution.

[f] 95-percent confidence bound = 1.14–1.59.

[g] One-sided lower 75-percent confidence bound on 5-percent exclusion value.

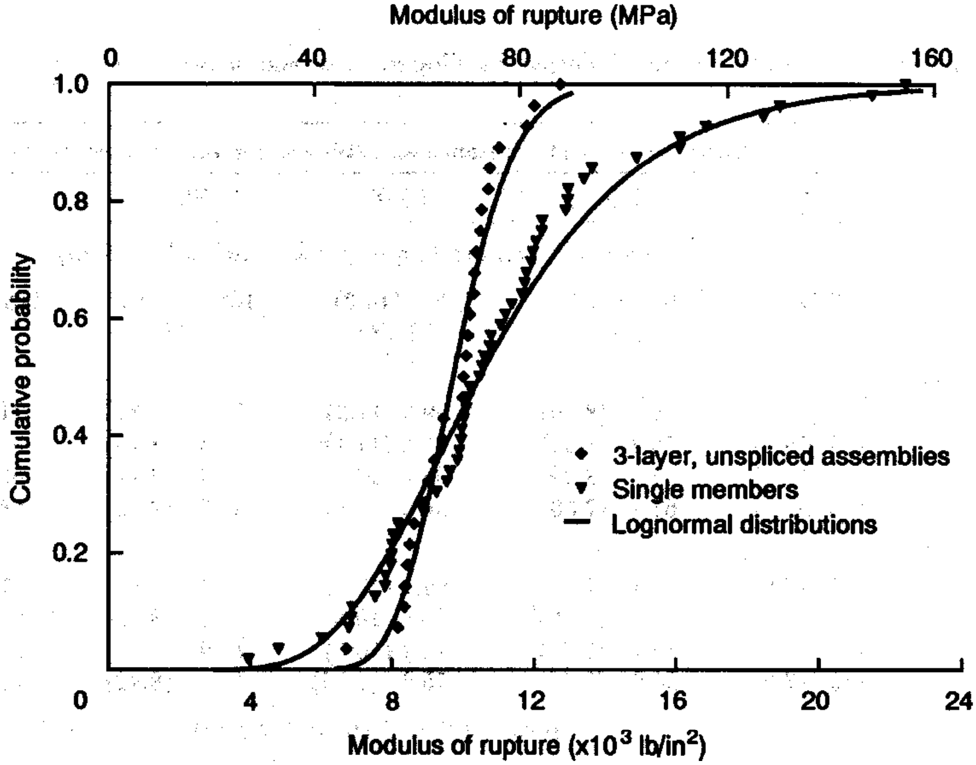

Figure 7—Cumulative distributions for modulus of rupture for single members and three-layer, unspliced assemblies.

More than half the plates were completely torn in half by high bending forces. The only plates that did not fail were those connecting members 1 and 2 in posts exhibiting failure types 1, 2, and 3. The failure types and number of failures associated with the four spliced post designs are described in Tables 8 and 9. The failure types identified with individual tests of the spliced posts are given in Table B3, Appendix B.

Discussion

Single Members

The strength and stiffness of the 56 single members exceeded expected values based on published design properties (NDS). The design stress in bending is 1,850 lb/in^2 (12.65 MPa) and the design MOE is 1.9 × 10^6 lb/in^2 (13.1 GPa) for No. 1D Southern Pine lumber used in dry conditions.

Using a lognormal distribution for bending strength (a normal distribution was rejected) and the reduction factors in ASTM D 2915 for the 5th percentile from Table 4, a design stress of 2,740 lb/in^2 (18.9 MPa) -would be applicable to the sample. This is 48 percent higher than the published value. The mean MOE of 2.48 × 10^6 lb/in^2 (17.1 GPa) would be applicable for the designs using the sample material. This is 31 percent higher than the published value.

Single Members and Unspliced Posts

As shown in Table 4 and Figure 7, the mean MOR of the unspliced posts was found to be only 89 percent that of the single members. This is not surprising. In a similar study involving Douglas Fir lumber, Bonnickson and Suddarth (1966) found that the mean MOR of three-layer assemblies was only 94 percent that of single members. The lower mean MOR for three layer unspliced posts can be attributed to the fact that one layer in an assembly must fail before the remaining layers are stressed to their maximum capacity. Unfortunately, most three-layer assemblies cannot take additional load after the first failure occurs. Consequently, the resulting MOR is the average of the extreme fiber stresses in one layer that is loaded to its maximum capacity and two layers that are not loaded to their maximum capacity. Thus, it is not surprising that the mean MOR of three-layer assemblies is slightly lower than the mean MOR of single members. On the other hand, as long as defects are spread out, a weak area in one layer is supported by strong areas in adjacent layers. In our study, this resulted in a lowering of the MOR

Table 5—Distribution characteristics for ultimate midspan bending moment and initial stiffness of unspliced and spliced posts

Distribution characteristic	Ultimate moment resistance and stiffness for various post types [a]				
	UM	SG	SG–R	SM	SM–R
	Ultimate midspan bending moment (× 10^3 in-lb (kN-m))				
Mean	222 (25.1) [13.4%]	109 (12.3) [18.8%]	126 (14.2) [12.9%]	105 (11.9) [18.1%]	118 (13.3) [13.7%]
5-percent exclusion value					
Normal	173 (19.6)	75.1 (8.49)	99.0 (11.2)	73.6 (8.32)	91.4 (10.3)
Lognormal	176 (19.9)	76.2 (8.61)[b]	98.6 (11.1)[b]	77.5 (8.76)	92.0 (10.4)[b]
Weibull[c]	173 (19.6)	73.4 (8.29)	96.5 (10.9)	79.4 (8.97)	88.6 (10.0)
Nonparametric	176 (20.0)	67.8 (7.66)	95.6 (10.8)	81.3 (9.19)	88.5 (10.0)
5-percent tolerance limit[d]					
Normal	167 (18.8)	70.4 (7.96)	95.1 (10.8)	69.1 (7.81)	87.6 (9.90)
Lognormal	170 (19.3)	72.6 (8.20)[b]	95.4 (10.8)[b]	74.5 (8.42)	88.9 (10.0)[b]
Weibull[c]	168 (18.9)	69.1 (7.80)	91.7 (10.3)	77.9 (8.79)	84.2 (9.51)
Nonparametric	153 (17.2)	56.6 (6.40)	75.6 (8.54)	74.5 (8.42)	77.4 (8.74)
	Initial stiffness[e] (lb/in (kN/m))				
Mean	5,200 (910) [9.2%]	3,080 (540) [10.7%]	3,930 (688) [10.3%]	3,140 (550) [10.8%]	3,850 (674) [12.2%]

[a] Values in brackets are coefficients of variation. Abbreviations for post types: U is unspliced, M machine-driven nails, S spliced, G gun-driven nails, and R reinforced.

[b] Lognormal fit rejected by Shapiro–Wilk test.

[c] Three-parameter Weibull.

[d] One-sided lower 75-percent confidence bound on 5-percent exclusion value.

[e] Total load as opposed to average load point deflection.

Table 6—Significant differences in post properties

Comparison of post types [a]	Significant difference [b]		
	Mean ultimate midspan bending moment	Ultimate strength (5-percent exclusion value)	Mean bending stiffness
Unspliced and spliced			
UM and SG	Yes	Yes	Yes
UM and SG–R	Yes	Yes	Yes
UM and SM	Yes	Yes	Yes
UM and SM–R	Yes	Yes	Yes
Unreinforced and reinforced			
SG and SG–R	Yes	Yes	Yes
SM and SM–R	Yes	Yes	Yes
SG + SM and SG–R + SM–R	Yes	—	Yes
Gun- and machine-driven nails			
SG and SM	No	No	No
SG–R and SM–R	No[c]	No	No
SG + SG–R and SM + SM–R	No	—	No

[a] See Table 5 (footnote a) for definitions of post types.

[b] 5-percent confidence level.

[c] Significant at a 5- to 10-percent level of confidence.

Table 7—Property ratios for spliced to unspliced and reinforced to unreinforced posts[a]

Property and distribution characteristic	Ratio for spliced to unspliced posts				Ratio for reinforced to unreinforced posts		
	SG	SG–R	SM	SM–R	SG–R to SG	SM–R to SM	SG–R + SM–R to SG + SM
Ultimate midspan bending moment							
Mean	0.49	0.56	0.47	0.53	1.16	1.12	1.14
5th percentile[b]	0.43	0.57	0.42	0.53	1.32	1.24	1.28
95-percent CI on 5th percentile[c]	0.35–9.51	0.49–0.65	0.35–0.50	0.45–0.60	1.08–1.55	1.02–1.46	1.11-1.43
5-percent tolerance limit[b]	0.42	0.57	0.42	0.53	1.35	1.27	1.31
Initial stiffness							
Mean	0.59	0.76	0.60	0.74	1.27	1.23	1.25

[a] See Table 5 (footnote *a*) for definitions of post types.
[b] Normal distribution.
[c] CI is confidence interval.

coefficient of variation for the three-layer unspliced posts compared to that for the single members. Consequently, the estimated 5th percentile of strength for the unspliced posts was approximately 28 percent higher than that for the single members. When design values are based on the 5th percentile, the ratio of the 5th percentiles is equal to the ratio of the design bending stresses. On the basis of our results, three-layer unspliced posts should be assigned an allowable bending stress about 30 percent greater than that assigned to single members. Unfortunately, the repetitive use criteria of the NDS allow a designer to use a design bending stress for a three-layer assembly that is only 15 percent greater than the single member value.

To justly reward those designers who currently use unspliced nail-laminated posts, design criteria could be established for the posts that would allow the engineer to take advantage of higher design values than the values currently allowed, These design criteria should address the number of laminations; spacing between laminations; type, number, and location of fasteners; and method of loading. More specifically, the design criteria should include provisions that limit the gap between two adjacent layers and do not allow nail fasteners to be located too close to member edges. In all cases, specifications should be written to ensure that the applied loads will either be distributed uniformly to all layers or applied through a load-distributing element that forces all layers to have similar displaced geometries. Once a design methodology using higher design values is implemented, manufacturers of unspliced posts will need to establish a system to assure these design values are maintained.

In an unspliced post, the effective MOE should equal the average MOE of the individual layers when all three layers in the assembly are the same size and are forced to have the same displaced geometry. Thus, as was expected, the mean MOE values of the three-layer unspliced posts and the single members were essentially equal.

Unspliced and Spliced Posts

The ratios in Table 7 demonstrate the significant reduction in strength associated with splicing. The estimated 5th percentiles of strength for the spliced posts without butt joint reinforcement (which are used to calculate design values for the posts) were found to be less than 45 percent of the 5th percentile values for the unspliced post design. This is much lower than some engineers would predict. A common belief is that a three-layer post should have a design bending strength that is approximately two-thirds that for an unspliced post because two of the layers are continuous at each joint. The problem with this assumption is that it fails to consider' the following three factors: (1) bending moments in the two continuous layers adjacent to a joint can be quite different because of the redistribution of forces in the vicinity of the joint, (2) nail forces are much higher in spliced posts and precipitate failures in the posts that are not common to unspliced posts, and (3) design strengths are highly dependent on the

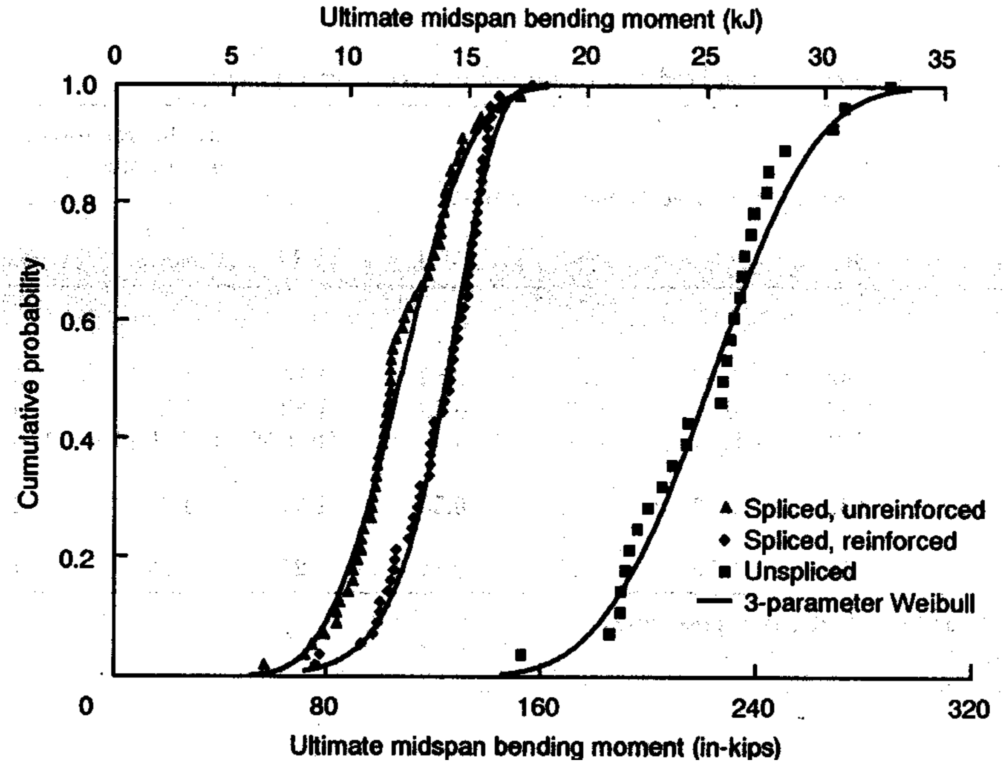

Figure 8—Cumulative distribution of ultimate midspan bending moment for three-layer assemblies.

variability in strength of individual specimens, and such. variability is generally higher for spliced posts than it in for unspliced posts.

Another reason that the ratios in Table 7 are lower than typically perceived is that design values based on test results for spliced posts are often incorrectly compared to NDS allowable design values for unspliced poets. Because these NDS values are applicable to all lumber from a broad range of sources, they are often conservative for specific groups of lumber. Engineers who compare the design values for spliced posts to NDS values for unspliced posts are mistakenly led to conclude that splicing is not nearly as critical as is actually the case. For this reason, evaluation of spliced posts must include unspliced posts built using lumber randomly selected from the same lot as that used to fabricate the spliced posts. The actual strength reduction associated with splicing can be ascertained only when lumber from the same lot is used.

The ratios in Table 7 also demonstrate the significant reduction in stiffness associated with splicing. Spliced posts with and without butt joint reinforcement were respectively about 75 and 60 percent as stiff as unspliced posts. It is important to realize that these percentages are based on average load point deflections and are unique to the test setup shown in Figure 4–the actual bending stiffness of a spliced post is not constant but varies along the length of the assembly. For this reason spliced posts should be sectioned into elements for modeling purposes. Those elements that do not contain joints can be treated like unspliced posts. Those elements that contain one or more joints should be assigned a different bending stiffness, the actual value of which is dependent on the length of the elements as well as several other design variables (Bohnhoff and Moody 1991).

When evaluating spliced posts by tests, the stiffness of the individual pieces that make up a spliced post should be measured before the post is fabricated. Averaging the MOE values of the pieces allows one to estimate the stiffness of an unspliced post fabricated from the same lumber. This information along with the displacements measured during spliced post tests can be used to calculate the reduction in stiffness resulting from splicing. For this type of comparison, MOE values from the NDS should not be used to estimate the stiffness of an unspliced post because lumber is quite variable, even within the same grade and species. When individual lumber strength and stiffness are not measured, it is impossible to determine where the batch or lot of lumber ranks with respect to other batches or lots of the same grade.

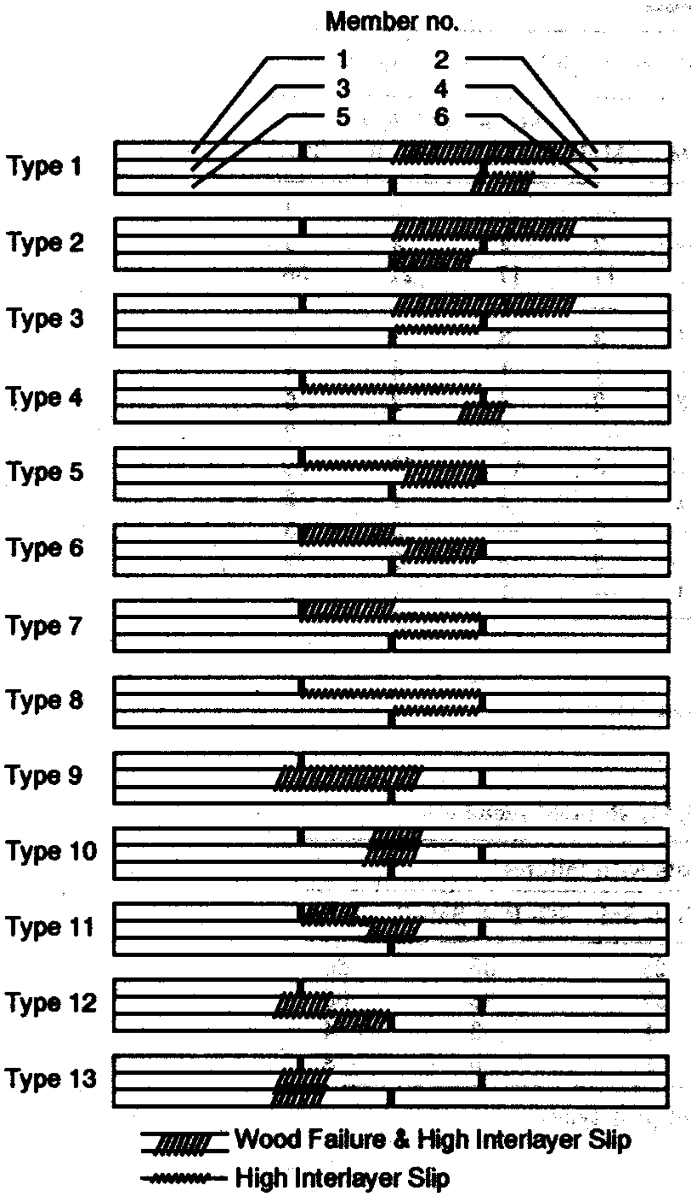

Figure 9—Failure types and locations in spliced posts. Members 1, 3, and 5 treated with CCA. Members 2, 4, and 6 untreated.

Reinforced and Unreinforced Posts

The addition of reinforcement to the spliced posts was found to significantly increase the mean strength, 5th percentile value, and initial stiffness of the assemblies (Table 7 and Fig. 8). Specifically, the mean ultimate bending moment increased approximately 14 percent, the 5th percentile about 28 percent, and the initial stiffness approximately 25 percent.

The location of the reinforcement was based on earlier computer modeling (Bohnhoff and others 1989), which, as previously mentioned, showed that spliced posts with unreinforced staggered joints have an inherent weakness–the longest member in the center layer (member 3 in Fig. 9) is almost always the most highly stressed member. This can be attributed to two factors. First, member 3 is the major load-distributing element in the assembly, and it therefore experiences high loads regardless of its individual stiffness. If joints are not reinforced, all forces in members 1 and 5 must be transferred through member 3 to reach members 2, 4, and 6. Second, the lap between member 3 and member 2 is twice as long as any other lap in the assembly. Consequently, these two members make up 8 very stiff component in the assembly and attract much of the load. For this reason, member 2 in Figure 9 is usually the second most highly stressed member in the assembly (Bohnhoff 1969). By reinforcing only the outside joints, we hoped that less load would be channeled into the center layer, resulting in a more uniform distribution of the forces in the assembly.

The data in Table 9 support the theoretical prediction that members 2 and 3 are usually the most highly stressed members in an unreinforced spliced post. Of the 56 unreinforced spliced posts (SM+SG posts) tested, 32 were associated with a wood failure in member 3 and 28 with a wood failure in member 2 (several posts had failures in both of these members). When the outside butt joints were reinforced, the number of wood failures in member 3 decreased slightly, and, as one would expect, the number of failures in member 2 increased slightly. Overall, the distributions of failures in the reinforced and unreinforced posts were not very different. This can be attributed to the fact that above a certain load level, plates in reinforced posts were not very effective, and consequently the reinforced posts behaved like unreinforced posts. The major advantage of butt joint reinforcement was that it prevented more failures from occurring at lower loads. Because of this, the coefficient of variation associated with the ultimate bending moment of reinforced posts was somewhat lower than that of the unreinforced posts. The difference in coefficient of variation explains why the difference between the mean ultimate bending moment values of the reinforced and unreinforced posts was smaller than the difference between the 5th percentile values for the two post types.

Nail Type

Bending strength and stiffness values of spliced posts fabricated with gun-driven nails were on the average slightly higher than those of spliced posts fabricated with machine-driven nails. However, the differences were not significant.

Table 8—Distribution of failures in spliced posts

Failure type[a]	Location of failure (post members)[b] 1	2	3	4	5	6	Number of failures in various post types[c] SG	SG–R	SM	SM–R	SG + SM	SG–R + SM–R	Total
1		*				*	—	2	—	—	—	2	2
2		*				*	2	1	—	2	2	3	5
3		*					10	10	7	11	17	21	38
4						*	1	—	—	—	1	—	1
5			*				2	—	1	3	3	3	6
6		*	*				1	2	—	1	1	3	4
7		*					1	—	3	2	4	2	6
8							2	—	—	—	2	—	2
9			*				9	10	15	5	24	15	39
10		*	*				—	1	1	—	1	1	2
11		*	*				—	1	—	2	—	3	3
12			*		*		—	—	—	2	—	2	2
13			*		*		—	1	1	—	1	1	2

[a] See Figure 9 for definitions of-failure types.
[b] See Figure 9 for post member location.
[c] See Table 5 (footnote *a*) for definitions of post types.

Table 9—Frequency of post failures in highly stressed members

Post member[b]	Number of posts with failures[a] SG	SG–R	SM	SM–R	SG + SM	SG–R + SM–R	Total
2	14	17	11	18	25	35	60
3	12	15	20	13	32	28	60
5	0	1	1	2	1	3	4
6	3	3	0	2	3	5	8

[a] See Table 5 (footnote *a*) for definitions of post types.
[b] See Figure 9 for post member location.

Conclusions

Bending strength and stiffness of three-layer, unspliced nail-laminated posts were compared to that of single members of dimension lumber. The unspliced posts were also compared to spliced posts with and without butt joint reinforcement, The effect of nail type on strength and stiffness was evaluated by comparing spliced posts fabricated with gun-driven or machine-driven nails. Our results led to the following conclusions:

1. The three-layer unspliced assemblies evaluated could be assigned an allowable bending stress about 30 percent greater than that assigned to the single members. The mean MOR of unspliced posts was slightly lower than that of single members, but the variation in MOR of the posts was considerably lower than that of the single members. Based on a lognormal distribution, the 5th percentile of MOR for the posts was 28 percent higher than that for the single members. This value is considerably higher than the 15 percent presently allowed.

2. If the individual layers in an unspliced post are forced to have the same displaced geometry, the effective MOE can be obtained by averaging the MOE values of the individual layers.

3. Splicing, even with reinforcement, substantially reduces the bending strength of a post. The estimated 5th percentile values (which are used to calculate allowable design values) for the spliced posts without butt joint reinforcement were found to be <45 percent of the 5th percentile value for the unspliced post design. The 5th percentile values of strength for the reinforced spliced posts were found to be <58 percent of the 5th percentile for the unspliced post design.

4. Splicing can significantly reduce the stiffness of nail-laminated posts. Spliced posts with and without butt joint reinforcement averaged only 75 and 60 percent, respectively, of the mean stiffness of the unspliced posts.

5. Reinforcing outside butt joints can significantly increase mean strength, 5th percentile of strength, and initial stiffness of posts. The mean ultimate bending moment increased approximately 14 percent, the 5th percentile about 28 percent, and initial stiffness approximately 25 percent when metal splice plates were added to outside joints of spliced posts.

6. The two nail types used in this study performed similarly in the spliced posts. There was no significant difference between the bending strength and stiffness of spliced posts fabricated with gun-driven nails and those fabricated with machine-driven nails.

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Appendix A
Cost Comparison of Sawn and Laminated Posts

Table A1 provides information on wholesale prices of various sizes and types of Southern Pine lumber. Table A2 shows costs of typical laminated members and solid-sawn treated posts.

Table A1—Wholesale Southern Pine lumber prices[a]

Type	Grade	Size[b]	Length (m(ft))	($/ board ft)
Untreated	No. 1 KD	2 by 6	≤4.3 (≤14)	0.280
CCA-treated[d]	No. 1	2 by 6	≤4.3 (≤14)	0.375
	No. 2[e]	6 by 6	≤4.8 (≤16)	0.455
			6.1 (20)	0.505
			7.3 (24)	0.565

[a] Approximate wholesale price during March 1989. Price includes cost of shipping to southern Wisconsin
[b] Nominal dimensions: 2 by 6 in. = standard 38 by 140 mm, 6 by 6 in. = standard 140 by 140 mm.
[c] 1 board ft = 0.0024 m^3.
[d] CCA is chromated copper arsenate. For lumber kiln dried after treatment, AWPA Standard C16 (1985) requires a minimum retention level of 0.60 lb/ft^3 (9.6 kg/m^3) for any CCA-treated structural post.
[e] Not stress-rated.

Table A2—Cost of typical laminated members and solid-sawn treated posts[a]

16-ft (4.8-m) nail-laminated member[b]	
24 BF untreated dimension lumber @ 0.280/BF[c]	$6.72
24 BP treated dimension lumber @ 0.375/BF	9.00
42 20d pneumatically driven nails @ 0.028/nail	1.18
Labor & equipment for fabrication–handling @ 20/h	4.30
Total	$21.20
20-ft (6.1-m) nail-laminated member[b]	
36 BF untreated dimension lumber @ 0.280/BF	$10.08
24 BF treated dimension lumber @ 0.375/BF	9.00
50 20d pneumatically driven nails @ 0.028/nail	1.40
Labor & equipment for fabrication–handling @ 20/h	4.65
Total	$25.13
24-ft (7.3-m) nail-laminated member[b]	
48 BF untreated dimension lumber @ 0.280/BF	$13.44
24 BF treated dimension lumber @ 0.375/BF	9.00
58 20d pneumatically driven nails @ 0.028/nail	1.62
Labor & equipment for fabrication–handling @ 20/h	5.00
Total	$29.06
Addition of splice plates to outside butt joints of assembly	
2 Splice plates (18 gauge) @ 0.75/plate	$1.50
Labor & equipment for fabrication–handling @ 20/h	1.20
Total	$2.70
Solid-sawn treated 6 by 6 lumber (actual size = 5.5 by 5.5 in.)	
16-ft post - 48 BF @ 0.455/BF	$21.84
20-ft post - 60 BF @ 0.505/BF	$30.30
24-ft post - 72 BF @ 0.565/BF	$40.68

[a] Based on prices in Table A1.
[b] Actual member size is 114 by 140 mm (4.5 by 5.5 in.).
[c] BF is board foot (1 board ft = 0.0024 m^3).

Appendix B
Results of Bending Tests

Tables B1 through B3 present data from bending tests on single members, unspliced posts, and spliced posts. The tables provide data on specific gravity, modulus of elasticity (MOE), initial-stiffness, MOE based on initial stiffness, modulus of rupture, and ultimate midspan bending moment. (1 lb/in = 175 N/m; 1 lb/in^2 = 6.89 kPa; 10^6 lb/in^2 = 6.89 GPa; 1,000 in-lb = 112.9 J.)

Table B1—Test data for single members

Replicate number	Specific gravity	Dynamic MOE ($\times 10^6$ lb/in^2)	Initial stiffness[a] (lb/in)	MOE based on initial stiffness[b] ($\times 10^6$ lb+in^2)	Modulus of rupture (lb/in^2)
1	0.633	2.643	1,546	2.736	10,750
2	0.593	2.083	1,324	2.344	10,086
3	0.728	3.617	2,306	4.081	13,406
4	0.618	1.534	919	1.626	7,822
5	0.722	3.696	2,089	3.698	12,939
6	0.571	1.840	1,098	1.943	7,527
7	0.654	2.361	1,315	2.328	7,798
8	0.659	2.645	1,558	2.758	12,890
9	0.661	2.183	1,386	2.453	11,906
10	0.687	2.961	1,774	3.141	11,733
11	0.632	1.867	1,071	1.896	22,409
12	0.704	2.472	1,510	2.672	11,955
13	0.583	2.116	1,210	2.141	12,201
14	0.557	2.438	1,447	2.561	7,970
15	0.586	1.982	1,112	1.969	11,783
16	0.602	1.789	1,099	1.946	9,544
17	0.761	2.680	1,556	2.754	16,087
18	0.610	2.009	1,106	1.958	16,087
19	0.585	2.207	1,330	2.354	14,881
20	0.598	2.190	1,257	2.226	11,192
21	0.622	2.424	1,380	2.442	11,045
22	0.679	2.526	1,381	2.444	9,249
23	0.637	2.276	1,231	2.178	9,962
24	0.460	1.656	1,069	1.892	4,797
25	0.655	1.949	1,153	2.041	10,184
26	0.531	1.862	1,117	1.977	8,905
27	0.581	2.583	1,604	2.839	12,226
28	0.537	1.551	952	1.685	6,887
29	0.621	2.800	1,600	2.832	10,528
30	0.703	2.530	1,578	2.794	16,826
31	0.550	2.282	1,463	2.589	10,012
32	0.539	1.746	1,073	1.899	8,167
33	0.523	1.856	1,003	1.775	6,027
34	0.657	1.956	1,278	2.262	8,929
35	0.648	2.141	1,314	2.326	12,963
36	0.630	2.634	1,725	3.054	13,625
37	0.703	2.967	1,980	3.504	10,774
38	0.556	2.193	1,393	2.466	9,938

Table B1—Test data for single members—concluded

Replicate number	Specific gravity	Dynamic MOE ($\times 10^6$ lb/in^2)	Initial stiffness[a] (lb/in)	MOE based on initial stiffness[b] ($\times 10^6$ lb/in^2)	Modulus of rupture (lb/in^2)
39	0.625	2.234	1,484	2.627	11.365
40	0.501	2.021	1,274	2.255	6,850
41	0.706	2.607	1,397	2.473	8,029
42	0.725	2.808	1,577	2.791	10,577
43	0.650	2.807	1,936.	3.426	18,428
44	0.693	2.325	1,422	2.516	11,658
45	0.654	2.733	1,544	2.733	18,896
46	0.735	2.412	1,327	2.349	9,625
47	0.593	2.285	1,394	2.467	8,004
48	0.684	2.635	1,505	2.664	6,776
49	0.597	2.313	1,391	2.462	7,982
50	0.654	2.447	1,525	2.700	10,460
51	0.632	2.470	1,551	2.746	9,839
52	0.541	1.653	964	1.706	9,889
53	0.623	2.020	1,195	2.115	3,953
54	0.681	2.813	1,824	3.229	12,047
55	0.573	2.078	1,197	2.119	21,484
56	0.629	2.380	1,520	2.691	10,150
(Mean)	0.626	2.327	1,399	2.476	11,036
(Standard deviation)	0.064	0.449	288.6	0.511	3,740
(Coefficient of variation)	10.18	19.30	20.63	20.63	33.89

[a] Ratio of total load to average midspan deflection.

[b] Calculated by multiplying initial stiffness by 1,769.9/in.

Table B2—Test data for machine-driven unspliced posts[a]

Replicate number	Average MOE of members $(\times 10^6\ \mathrm{lb/in^2})$	Initial stiffness[b] (lb/in)	MOE based on initial stiffness[c] $(\times 10^6\ \mathrm{lb/in^2})$	Ultimate midspan bending moment $(\times 10^3\ \mathrm{in\text{-}lb})$[d]
1	2.429	5,219	2.456	189.4
2	2.035	4,873	2.293	189.9
3	2.550	6,006	2.826	235.1
4	2.252	4,976	2.342	214.4
5	2.361	5,509	2.593	199.6
6	2.247	4,778	2.249	212.8
7	1.999	4,482	2.109	227.1
8	2.198	5,084	2.393	192.8
9	1.984	4,615	2.172	185.5
10	2.636	5,726	2.695	289.1
11	2.345	5,007	2.356	195.7
12	2.319	4,961	2.335	231.1
13	2.246	5,018	2.361	249.8
14	2.363	5,484	2.581	237.5
15	2.445	5,636	2.652	234.1
16	2.588	6,264	2.948	272.2
17	2.387	5,102	2.401	243.9
18	2.329	4,806[e]	2.262	204.7
19	2.040	5,213	2.453	238.5
20	2.356	5,619	2.644	213.8
21	2.347	5,142	2.420	187.1
22	2.150	5,473[e]	2.576	229.9
23	2.177	5,226	2.459	228.6
24	2.206	5,213	2.453	267.7
25	2.380	5,321	2.504	233.4
26	2.339	5,193	2.444	243.0
27	2.694	5,615	2.642	226.5
28	1.905	3,922	1.846	152.6
(Mean)	2.297	5,196	2.445	222.3
(Coefficient of variation)	8.67	9.23	9.23	13.6

[a] Wood properties (MOE, specific gravity) for individual posts can be found in Bohnhoff and others (1091).

[b] Ratio of total load to average load point deflection.

[c] Calculated by multiplying initial stiffness by 470.6/in.

[d] To convert to modulus of rupture, divide by section modulus of 22.69 in^3.

[e] Based on three rather than four measurements.

Table B3—Test data for spliced posts[a]

Replicate number	SG posts			SG-R posts			SM posts			SM-R posts		
	Initial stiffness[b] (lb/in)	Ultimate midspan bending moment ($\times 10^3$ in-lb)	Failure type[c]	Initial stiffness[b] (lb/in)	Ultimate midspan bending moment ($\times 10^3$ in-lb)	Failure type[c]	Initial stiffness[b] (lb/in)	Ultimate midspan bending moment ($\times 10^3$ in-lb)	Failure type[c]	Initial stiffness[b] (lb/in)	Ultimate midspan bending moment ($\times 10^3$ in-lb)	Failare type[c]
1	3,427	123.0	8	4,616	143.4	9	3,717	91.3	9	4,773	118.4	9
2	3,563	107.4	6	4,510	135.7	3	3,599	129.4	3	3,982	133.2	9
3	2,323	56.7	9	3,670	114.6	3	2,793	86.1	9	3,433	99.8	3
4	3,002	100.2	9	3,370	111.6	9	2,984	134.4	9	3,419	135.3	9
5	3,033	105.3	2	3,581	75.7	1	2,932	103.5	3	2,880	97.2	2
6	3,093	123.5	9	4,133	137.0	9	2,788	101.0	9	3,429	77.3	12
7	3,404	104.0	5	3,921	128.1	3	3,230	129.7	3	3,919	103.6	5
8	3,166	143.8	3	4,077	139.1	13	3,078	125.1	9	3,775	118.4	11
9	2,824	119.2	2	4,332	139.0	3	3,260	93.4	9	4,105	125.6	9
10	3,611	123.0	9	4,662	140.3	9	3,519	103.1	9	4,838	137.0	3
11	3,283	128.1	3	3,924	133.5	3	3,038	151.4	3	3,519	112.0	3
12	3,007	99.0	9	4,021	117.9	9	3,174	92.6	7	3,626	98.9	12
13	2,541	121.4	9	3,336	104.8	9	2,463	101.5	3	3,298	130.6	3
14	2,876	117.1	3	3,429	105.6	10	3,089	97.7	9	3,404	118.3	3
15	2,562	156.0	8	3,908	126.8	11	2,695	83.7	9	3,524	126.4	3
16	3,541	71.8	5	4,444	125.1	6	3,562	136.5	9	4,221	125.5	2
17	3,306	79.1	3	3,458,	137.4	3	3,469	125.6	9	4,154	114.5	3
18	2,621	89.6	3	3,630	102.7	3	2,356	87.9	9	3,491	92.6	9
19	3,103	103.2	9	3,956	131.9	9	2,946	96.8	13	3,851	105.2	7
20	2,835	96.3	3	4,145	155.3	3	2,990	96.4	10	4,490	134.8	7
21	3,062	121.7	3	3,967	133.1	3	3,346	98.1	7	4,158	119.7	3
22	2,861	103.1	7	3,294	119.6	2	3,238	98.5	3	3,726	128.0	3
23	3,389	108.2	3	3,426	136.5	9	2,920	89.6	5	3,365	99.7	11
24	—	121.7	9	3,604	110.3	9	3,393	83.7	3	4,207	140.3	3
25	3,321	102.7	3	4,449	122.6	6	3,332	101.9	9	4,565	129.3	6
26	3,043	92.5	3	4,183	123.5	3	3,053	109.9	9	3,852	113.7	3
27	3,175	114.5	4	4,027	131.9	1	3,530	74.4	7	3,913	131.9	5
28	3,329	112.4	9	3,921	134.9	9	3,489	117.6	9	3,922	139.1	5
(Mean)	3,085	108.7		3,928	125.7		3,142	105.0		3,851	118.1	
(Coefficient of variation)	10.7	18.8		10.3	12.91		10.8	18.14		12.2	13.7	

[a] Wood properties (MOE, specific gravity) for individual posts can be found in Bohnhoff and others (1991). Post types: SG, gun-driven nails, unreinforced joints; SG-R, gun-driven nails, reinforced joints; SM, machine-driven nails, unreinforced joints; SM-R, machine-driven nails, reinforced joints.

[b] Ratio of total load to average load point deflection.

[c] See Figure 9 for description of failure apes.

Appendix C
Significance Levels for Analyses of Post Properties

Tables C1 through C3 provide significance levels for statistical analyses of mean ultimate bending moment, mean initial bending stiffness, and ultimate midspan bending moment of spliced and unspliced posts. The following abbreviations are used for post types:

Abbreviation	Post description
SG	Spliced posts, gun-driven nails
SG-R	Spliced posts, gun-driven nails, reinforced butt joints
SM	Spliced posts, machine-driven nails
SM-R	Spliced posts, machine-driven nails, reinforced butt joints
UM	Unspliced posts, machine-driven nails

Table C1—Significance levels for comparison of mean ultimate bending moment of various post types

Comparison of post types	Student's *t*-test	ANOVA	Paired *t*-test	Wilcoxon test	Signed rank test
		Unspliced and spliced posts			
UM and SG	0.0001	—	—	0.0001	—
UM and SG-R	0.0001	—	—	0.0001	—
UM and SM	0.0001	—	—	0.0001	—
UM and SM-R	0.0001	—	—	0.0001	—
		Unreinforced and reinforced butt joints			
SG and SG-R	0.0011	—	0.0007	0.0005	0.0008
SM and SM-R	0.0076	—	0.0072	0.0046	0.0088
SG + SM and SG-R + SM-R	—	0.0001	0.0001	—	—
		Gun-and machine-driven nails			
SG and SM	0.4799	—	0.5015	0.2446	0.3842
SG-R and SM-R	0.0858	—	0.0586	0.0629	0.0712
SG + SG-R and SM + SM-R	—	0.0986	0.0950	—	—

Table C2—Significance levels for comparison of mean initial bending stiffness of various post types

Comparison of post types	Student's *t*-test	ANOVA	Paired *t*-test	Wilcoxon test	Signed rank test
Unspliced and spliced posts					
UM and SG	0.0001	—	—	0.0001	—
UM and SG-R	0.0000	—	—	0.0001	—
UM and SM	0.0001	—	—	0.0001	—
UM and SM-R	0.0000	—	—	0.0001	—
Unreinforced and reinforced butt joints					
SG and SG-R	0.0000	—	0.0001	0.0001	0.0001
SM and SM-R	0.0000	—	0.0001	0.0001	0.0001
SG + SM and SG-R + SM-R	—	0.0001	0.0001	—	—
Gun- and machine-driven nails					
SG and SM	0.5316	—	0.3076	0.6194	0.3162
SG-R and SM-R	0.5340	—	0.2505	0.4759	0.1838
SG + SG-R and SM + SM-R	—	0.8877	0.7026	—	—

Table C3—Significance levels for comparison of 5-percent exclusion values of ultimate midspan bending moment of various post types

Comparison of post types	Parametric test
Unspliced and spliced posts	
UM and SG	0.000
UM and SG-R	0.000
UM and SM	0.000
UM and SM-R	0.000
Unreinforced and reinforced butt joints	
SG and SG-R	0.002
SM and SM-R	0.014
Gun- and machine-driven nails	
SG and SM	0.849
SG-R and SM-R	0.256

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