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Bending Properties of Four-Layer Nail-Laminated Posts

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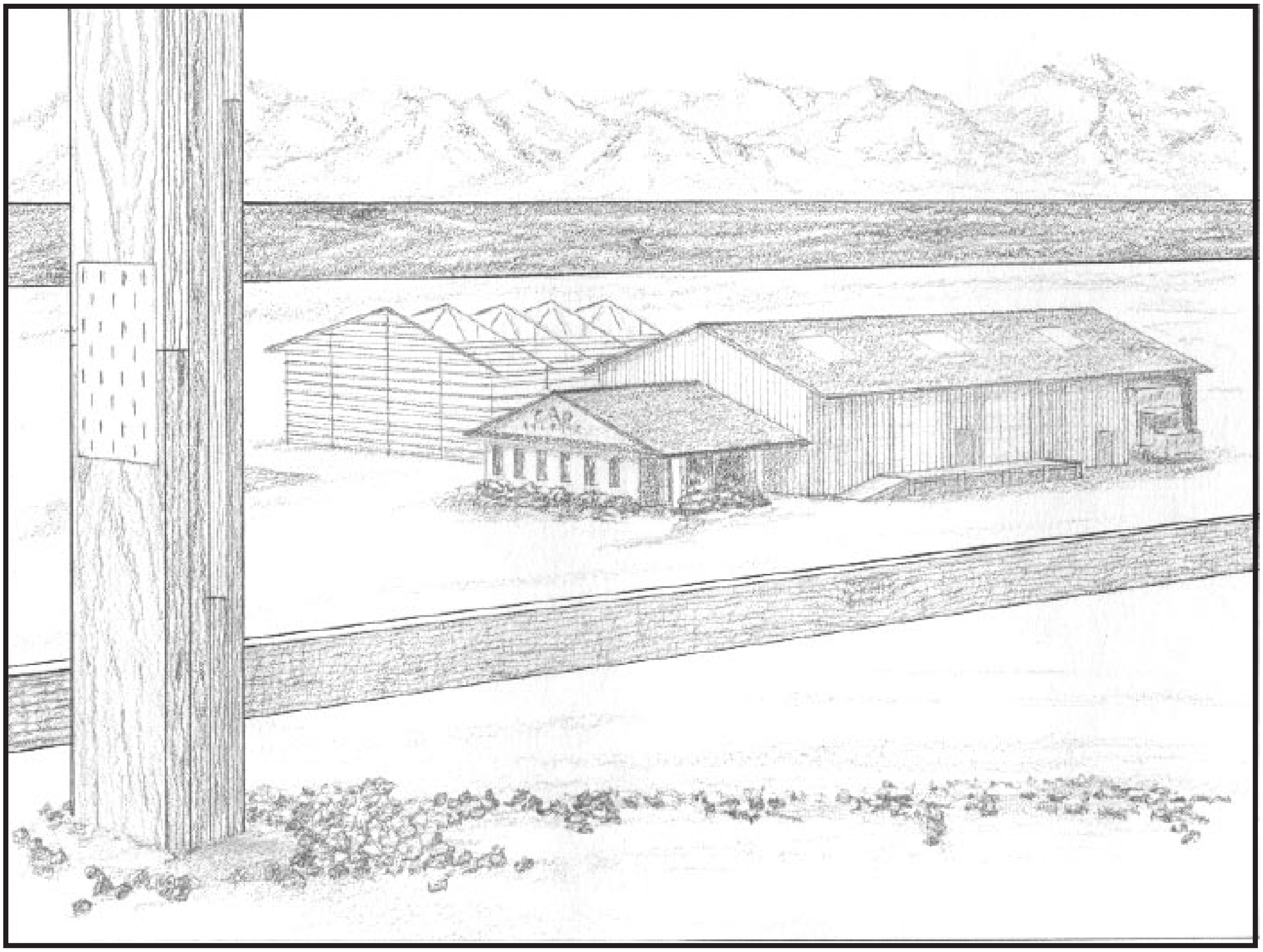

Summary

Nail-laminated posts are used in post-frame buildings as the main vertical supports. Research to date has focused on the three-layer posts that are commonly used. This report describes research on four-layer nail-laminated posts, which can withstand the greater lateral forces sustained by tall buildings.

Both unspliced and spliced posts were tested for strength and stiffness. For tests on spliced posts, variables were splice length, splice arrangement, and presence or absence of outside butt-joint reinforcement. Results of tests on unspliced posts indicated that the 15-percent increase in bending design stress currently permitted for unspliced laminated assemblies is conservative. Four-layer unspliced nail-laminated posts could be assigned an allowable bending stress 30 percent greater than current design values for single members. In tests on spliced posts, strength and stiffness were increased by longer splices and outside butt-joint reinforcement. Splice arrangement also affected strength and stiffness.

Results from this study should be helpful to builders and designers in selecting designs for four-layer nail-laminated posts.

Keywords: Nail-laminated posts, bending, strength, stiffness, post-frame structures, structural design.

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Introduction

In recent years, the percentage of post-frame structures built with nail-laminated posts has increased steadily. This trend can be attributed to the high cost and decreasing supply of long, stress-rated, solid-sawn, preservative-treated posts. This trend can be expected to continue as (1) a greater number of tall structures are built, (2) long timber becomes less available and more costly, (3) the cost of preservative treatment of lumber increases, and (4) more post-frame builders recognize the economic advantage of using laminated posts rather than long sawn timber.

When designing nail-laminated posts, engineers are most interested in bending strength because lateral loads, such as wind, can induce 75 percent or more of the maximum allowable fiber stress in a post. Nail-laminated posts are generally orientated so that the greatest bending loads are applied parallel to the interlayer planes (that is, surfaces of contact between layers). These posts are commonly referred to as vertically laminated assemblies. Conversely, nail-laminated posts are not generally oriented such that loads are applied perpendicular to the interlayer planes (horizontally laminated assemblies), since the posts are not as strong (or as stiff) in bending when loaded in this direction.

Nail-laminated posts are classified as unspliced or spliced. In unspliced posts, all layers are continuous (no butt joints). In spliced posts, one or more layers are discontinuous (one or more butt joints). Spliced posts can be further classified as reinforced or unreinforced depending on the presence or absence of butt-joint reinforcement.

The bending strength and bending stiffness (hereafter referred to as strength and stiffness) of spliced nail-laminated posts are highly dependent on several factors: interlayer shear transfer capacity, splice arrangement, splice length, and use of butt-joint reinforcement (if such reinforcement is used). Shear transfer capacity is influenced by type, size, density, and arrangement of nails. Splice length and arrangement have a significant effect on how wood stresses are transferred between individual layers. Post strength and stiffness can also be affected by the size, species, and grade of lumber.

Table 1—SI conversion factors

English unit	Conversion factor	SI unit
inch (in.)	25.4	millimeter (mm)
inch-pound (in-lb)	0.113	newton-meter (N-m)
foot (ft)	0.3048	meter
pound-force (lb)	4.448	newton (N)
pound-force per inch (lb/in)	0.1751	newton per meter
pound-force per square inch (lb/in^{2})	6.894	kilopascal (kPa)

As a result of the complex interaction of post variables, current National Design Specifications (NDS) for wood construction (AFPA 1991) cannot be used to determine the strength and stiffness of *spliced* nail-laminated posts. Consequently, full-scale testing of representative samples must be used to determine the strength and stiffness properties of the assemblies. In addition, unspliced posts must be tested in conjunction with spliced posts to determine the reduction in strength and stiffness associated with splicing.

Research has focused on three-layer assemblies made from nominal 2- by 6-in. lumber because such assemblies are most commonly used in post-frame construction. (See Table 1 for SI conversion factors.) However, four-layer posts made from nominal 2- by 10-in. lumber are often used in applications where eaves are relatively high and/or lateral forces are higher than normal. For spliced posts, an increase in the number of layers increases the number of ways for arranging the joints. Moreover, more fasteners are needed to handle the larger shear forces in the assembly. To our knowledge, there have been no studies on four-layer assemblies. Research is needed to identify which joint arrangement to use in a four-layer assembly and where to place fasteners for optimal post performance. More importantly, tests have not been conducted to determine to what degree splicing reduces strength and stiffness of four-layer posts.

The objectives of this study were to determine

- how the bending strength and stiffness of unspliced four layer nail-laminated posts are related to strength and stiffness of single members,
- how splicing affects the strength and stiffness of four-layer nail-laminated posts, and
- how splice length, splice arrangement, and outside butt-joint reinforcement affect post strength and stiffness.

Previous Work

Unspliced Posts

To date, two studies have involved unspliced nail-laminated assemblies. Bonnickson and Suddarth (1966) showed that three-layer unspliced bending specimens of standard and better grade of Douglas Fir lumber had about the same average strength as single members but significantly reduced variability. Bohnhoff and others (1991) showed that (1) the mean modulus of rupture (MOR) of three-layer unspliced assemblies was about the same as that of single members and (2) the variability of MOR of three-layer unspliced posts was considerably lower than that of single members. Results of these studies showed that the design bending stress of a three-layer assembly was 46 percent (Bonnickson and Suddarth 1966) and 28 percent (Bohnhoff and others 1991) greater than the design bending stress of a single member. Both studies indicated that the present method of using the repetitive member factor of 1.15 to assign design stresses to multiple-layer nail-laminated assemblies is very conservative.

Spliced Posts

During the 1980s, several research studies were conducted on three-layer spliced nail-laminated posts. The results of these studies, which were summarized by Bohnhoff and others (1991), showed that the use of higher quality lumber, increases in splice length, and addition of reinforcement to outside butt joints can significantly increase post strength and stiffness. These studies also showed that nails as large as 20d ring-shanks, when properly located, could be used to laminate spliced assemblies without causing splitting, which could significantly decrease post strength.

The most extensive study on three-layer nail-laminated posts was conducted by Bohnhoff and others (1991). In addition to testing spliced posts with and without butt-joint reinforcement, the researchers tested unspliced posts fabricated from the same lumber sample used to fabricate the spliced posts. This enabled the researchers to assess the reduction in strength and stiffness associated with splicing.

Table 2—Properties of three-layer nail-laminated posts tested by Bohnhoff and others (1991)[a]

	Ultimate midspan bending moment ($\times 10^3$ in-lb)		
Post type	Mean	Fifth percentile[b]	Initial stiffness[c] (lb/in)
Unspliced post	222	173	5,200
Spliced posts			
Nail A, no reinforcement	109	75.1	3,080
Nail B, no reinforcement	105	73.6	3,140
Nail A, reinforcement	126	99.0	3,930
Nail B, reinforcement	118	91.4	3,850

[a] Twenty-eight, 12-ft-long posts of each type were tested. Spliced posts featured a staggered arrangement of joints with a 4-ft overall splice length. See Table 1 for SI conversion factors. Nail type A = gun driven; Nail type B = machine driven.
[b] Based on normal distribution.
[c] Ratio of applied load to average load point deflection.

Researchers found that posts with splices and no reinforcement had 55 percent lower design strength and 40 percent lower initial stiffness than unspliced members (Table 2). By adding reinforcement to the outside butt joints, researchers found that approximately 10 percent of the design strength and 15 percent of the initial stiffness lost by splicing could be recovered.

Information on the properties of three-layer posts can provide guidance in predicting the performance of four-layer posts. However, four-layer posts are considerably more complex, and data are needed to quantify the effects of splicing on strength properties.

Materials and Methods

To evaluate the properties of four-layer posts, we compared single members, unspliced posts, and spliced posts with various splice arrangements and with different splice lengths. We also studied the effect of outside butt-joint reinforcement on the strength and stiffness of spliced posts.

Splice Length and Arrangement

Splices between 2 and 4 ft long have been studied in research on three-layer posts. Four-layer posts require longer overall splices. Therefore, we studied 4- and 6-ft-long splices.

Previous investigations of three-layer posts considered two splice arrangements (Fig. 1). For four-layer posts, eight splice arrangements are possible (Fig. 2). Because it was not

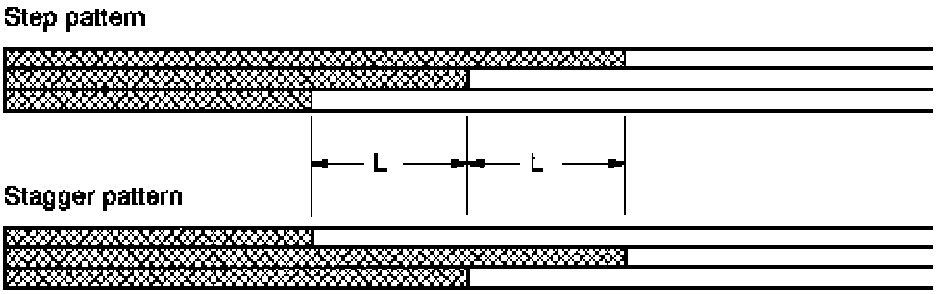
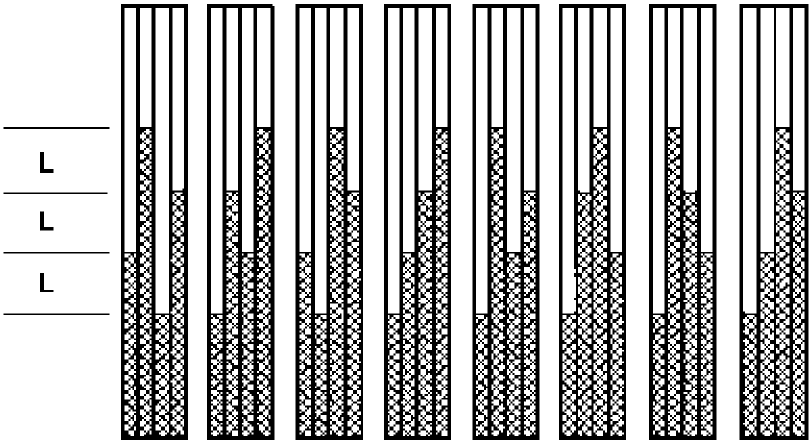


Figure 1—Possible splice arrangements for three-layer posts. L is distance between individual butt joints. In this study, L is defined as one-third of the overall splice length.



Arrangement	(A)	(B)	(C)	(D)	(E)	(F)	(G)	(H)
Symmetric design	Y	Y	Y	Y	N	N	N	N
Total length of contact between shaded and unshaded portions	7L	5L	5L	3L	6L	5L	5L	4L
Length of contact between longest members in the center layers	3L	L	3L	L	2L	L	L	2L

Figure 2—Possible splice arrangements for four-layer posts.

feasible to evaluate all these variations, we chose splice arrangements A and B on the basis of the following criteria:

- joint symmetry
- length of contact between members on opposite ends of post
- length of contact between longest members in middle layers
- length of overall splice

In a symmetric joint, both ends of the posts are identical. In Figure 2, splice arrangements A through D are symmetric whereas E through H are unsymmetric. Because the distribution of loads is less uniform and stress concentrations on average are higher in asymmetric designs, the asymmetric arrangements were eliminated from further consideration.

The total length of contact between members on opposite ends of the post controls the total amount of area available for transferring load from the members on one end of the post to members on the opposite end. Figure 2 shows the

Table 3—Experimental design for tests on four-layer posts

Post design	Number tested	Overall splice length (ft)	Splice arrange-ment[a]	Butt-joint reinforce-ment
Unspliced	15	0	None	No
Spliced				
A4	15	4	A	No
B4	15	4	B	No
A6	15	6	A	No
A6-R	15	6	A	Yes

[a]See Figure 2.

relative length of the contact area. The greater the contact area between adjacent layers, the more nails are involved in load transfer and the lower the average load on individual fasteners. Arrangement D was removed from the study because of the relatively low amount of contact.

The length of contact between the longest members in the middle layers governs the stiffness of the connection and the attraction of load to the middle members. The longer the lap length between any members, the stiffer the connection between the members and the more load they attract. In unreinforced assemblies, the two longest members in the center should not have a long lap because the center layers generally carry the highest percentage of the load (Bohnhoff 1989). Arrangements with the shortest lap in the center layers, such as arrangements B and D, should probably be used in such assemblies. However, in assemblies with reinforced outside butt joints, the outer layers attract more load. In such assemblies, a longer middle lap (like that in arrangements A and C) may improve the balance of load.

Based on these criteria, arrangements A and B were selected for fabrication and tests.

Experimental Design

Five four-layer post designs (one unspliced and four spliced post designs) were selected for evaluation (Table 3). The spliced post designs are shown in Figure 3. The first character in the designation for post design denotes splice arrangement, as shown in Figure 2. The second character denotes the overall splice length in feet; R indicates that the outside butt joints were reinforced. This experimental layout allowed us to isolate the effect of splice arrangement by comparing designs A4 and B4, the effect of splice length by comparing designs A4 and A6, and the effect of butt-joint reinforcement by comparing designs A6 and A6-R.

Fifteen replicates of each post design were tested to detect a 10 percent significant difference in strength properties at a 90 percent confidence level. Thus to test five post designs, we fabricated 75 four-layer assemblies. An additional 40 single members were tested to characterize the properties of the lumber.

Lumber Selection and Allocation

All specimens were fabricated from 20-ft-long nominal 2- by 10-in. machine-stress rated (MSR) 2250f–1.9E Southern Pine lumber. (Note: nominal 2 by 10 in. = standard 38 by 253 mm.) We selected this size of dimension lumber because it is used in the majority of four-layer post-frame building posts. We selected 20-ft-long posts to ensure bending-type failures in unspliced assemblies. A support spacing of 19 ft and a load head spacing of 8 ft provided a shear span-to-depth ratio of over 14, the appropriate ratio to ensure bending failures in unspliced assemblies under a two-point loading (ASTM 1992b). Although treated lumber is generally used for the underground portion of a post, we did not use treated wood in the assemblies; little difference has been found between the bending strength and stiffness of treated and untreated lumber (Winandy and Boone 1988).

A total of 340 pieces of lumber were conditioned to an equilibrium moisture content (EMC) of 12 percent, numbered at three locations, and weighed. Modulus of elasticity (MOE) values were then determined using a flatwise vibration technique (Ross and others 1991). (This will be referred to as the dynamic MOE.) The pieces were placed into six groups: single-member tests (one group), spliced post designs (four groups), and unspliced post design (one group); each group had a similar MOE distribution.

To allocate the lumber to each group, all the lumber was first ranked by MOE. Then, 40 pieces for the single-member tests were selected from across the MOE distribution. The remaining 300 pieces were divided into 60 lots of five pieces each by MOE value, in order of highest to lowest value; that is, pieces in the first lot had the highest MOE values, in the second lot the next highest MOE values, and so on. The five pieces in each lot were randomly assigned to the post groups. Each piece was then randomly assigned a replicate number (1 to 15) and a layer number (1 to 4). For the spliced assemblies, each replicate was randomly assigned a mated short piece of lumber from another assembly in a location where it would be matched lengthwise.

Specimen Fabrication

After allocation to the test groups, the lumber was removed from the conditioning room, cut, stacked, and sorted into groups. Posts were then assembled with an air-powered nail gun using a jig, clamps, and nailing pattern templates. Posts were stored for at least 2 weeks before testing.

The nailing pattern (Fig. 4) was designed by Williams (1993) using maximum nail spacings based on recommendations by Bohnhoff (1990). Gun-driven nails with a diameter of 0.130 in., a length of 3.75 in., and an electroplated finish coat with a chromate seal and organic overcoat barrier were used to fabricate all posts.

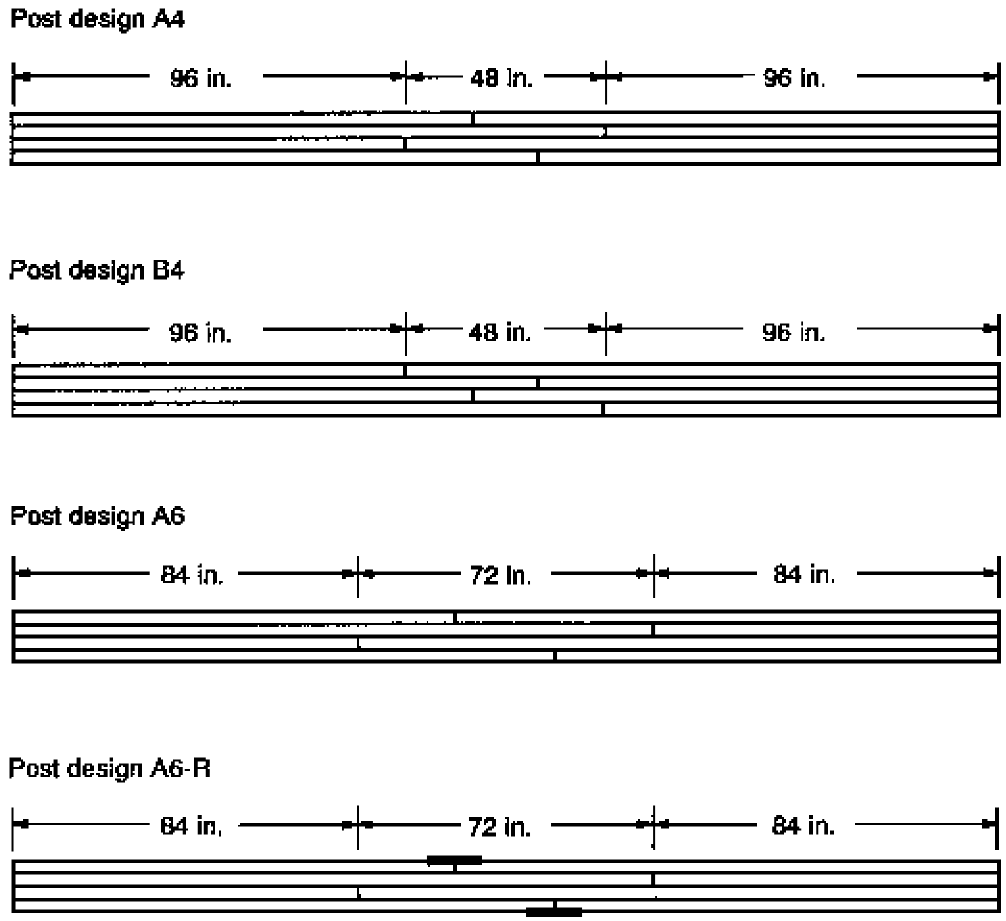


Figure 3—Spliced post designs.

High-strength 16-gauge metal truss-plate connectors with a width of 9 in. and a length of 13.25 in. were used to reinforce the outside butt joints on design A6-R. These plates have an average tension yield stress of 41,500 lb/in^2, three teeth per square inch, and tooth length of 0.62 in.

The high density of the lumber caused problems in driving the nails. Because the nail gun did not completely drive all nails at an air pressure of 120 lb/in^2, the air pressure was increased to 140 lb/in^2, which is 20 lb/in^2 above the rated operating pressure for the gun.

During driving, some nails were deflected outward and actually protruded from the edges of the assembly. This problem was previously noted by Bohnhoff and others (1991). Although the problem can be corrected by orienting the growth rings such that nails are deflected inward along the less dense earlywood, the assembly procedure was not modified because it is unlikely that such special orientation would be used during production.

The reinforcing plates were pressed into place after the specimens were fabricated. A force of 110,000 lb acting over the entire plate surface was required to completely seat each plate.

Testing Procedures

The MOR and MOE for each single member were determined according to ASTM D198 (ASTM 1992b). The two-point load arrangement (Fig. 5) was used in combination with a loading rate of 0.5 in/min. To measure midspan deflection, spring-tensioned wires were drawn between nails driven into the centroidal axis of the member directly above the supports. The relative displacement between each wire and the member at midspan was measured by attaching a linear variable differential transformer (LVDT) to the specimen at midspan and hooking the LVDT core to the wire. A computer-based data acquisition system was used to record midspan deflection and load data at 1-s intervals.

For the nail-laminated posts, ASTM D198 (ASTM 1992b) was followed where applicable. The load-head feed rate was fixed at 0.4 in/min for all tests to achieve failure between 5 and 10 min. The location of the load points, support reactions, and points of lateral support for all laminated assembly tests are shown in Figure 5. The 96-in. spacing of the load points assured that all joints and highly stressed fasteners near the joints were located within the maximum moment region. The same method of measuring and recording

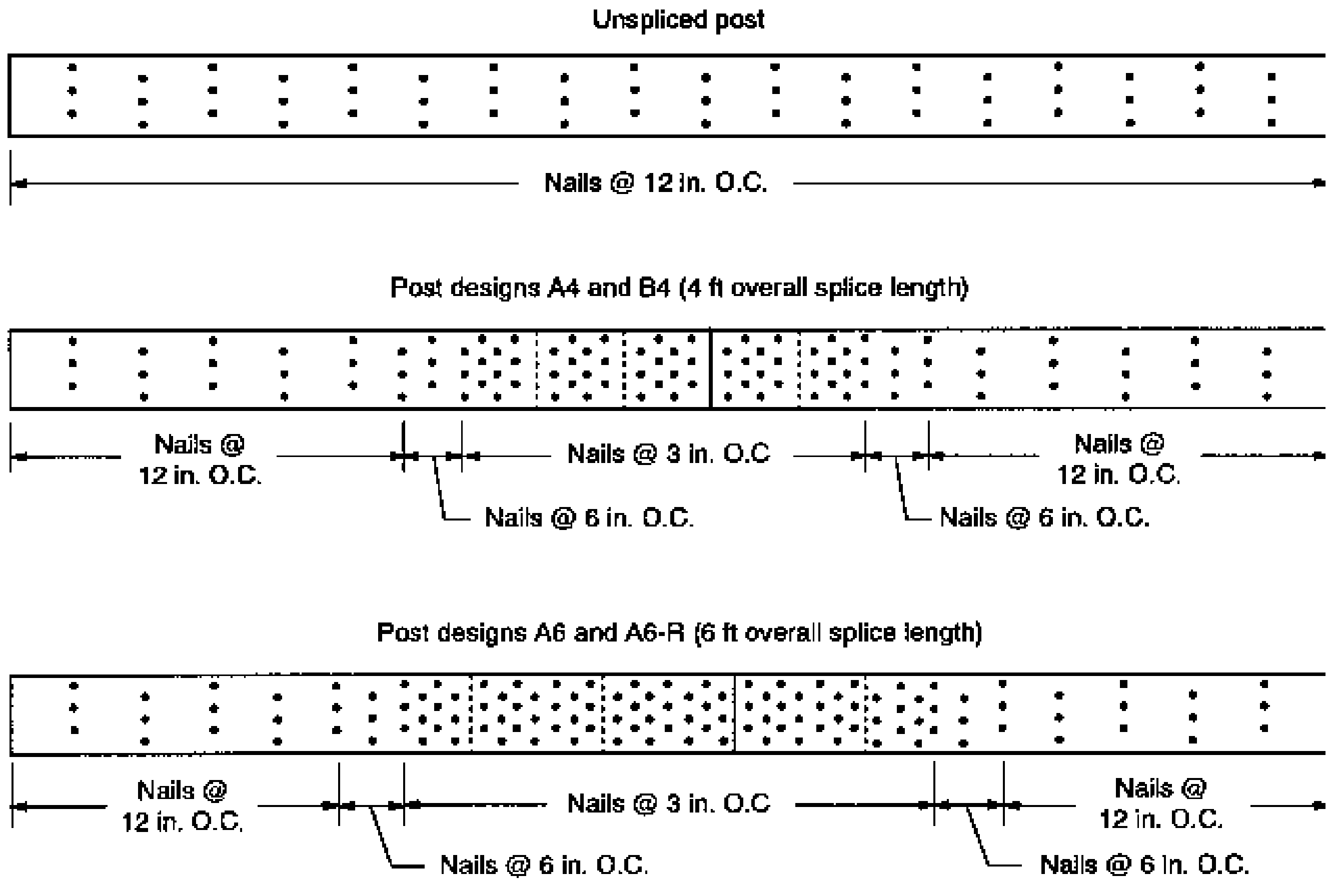


Figure 4—Nailing pattern for four-layer posts. The same pattern was used on both sides; spacing between nail rows was fixed at 1-1/4 in. Outside rows were 1-1/2 in. from the edges. O.C. is on center.

deflections of the single members was used for the laminated assemblies.

Following failure, moisture content of the lumber was determined near the load points using a resistance-type meter.

Analysis

The specific gravity of each piece of lumber was calculated using the weight obtained during the measurement of dynamic MOE, volume at time of test, and moisture content.

The actual dimensions of the lumber (depth of 9.25 in. and width per layer of 1.5 in.) were used to calculate strength properties. Strength properties for the spliced posts were calculated in terms of ultimate bending moment and stiffness instead of MOR and MOE; MOR and MOE have no significant physical meaning because of the complex stress distributions that occur in spliced assemblies.

Post stiffness was defined as the ratio of applied load to average load-point deflection. Because the ratio of load to average deflection at point of load was nonlinear, two stiffness values were calculated for each post. One stiffness value was computed from the ratio of the load and deflection values at 40 percent of maximum individual post load. The other stiffness value was computed from the ratio of the load and deflection at a load equal to the product of the National Design Specification (NDS) allowable 10-min design strength of the unspliced posts (308,000 in–lb) multiplied by the ratio of the mean ultimate midspan bending moment of the respective spliced post to that of unspliced posts. These ratios are discussed in the Results.

Statistical analyses were conducted on the ultimate bending moment of the four-layer posts and on the MOR of the unspliced and single members to determine the mean, fifth percentile point estimate, and 5-percent tolerance limit for each test group. Ratios of the spliced to unspliced post ultimate bending moment and their respective 95 percent confidence intervals were computed. The mean stiffness values and associated ratios for spliced to unspliced stiffness were computed for each post design. Additionally, an analysis of variance was conducted to determine if there were significant differences between post designs.

After testing, all specimens were examined to determine the type and location of failures.

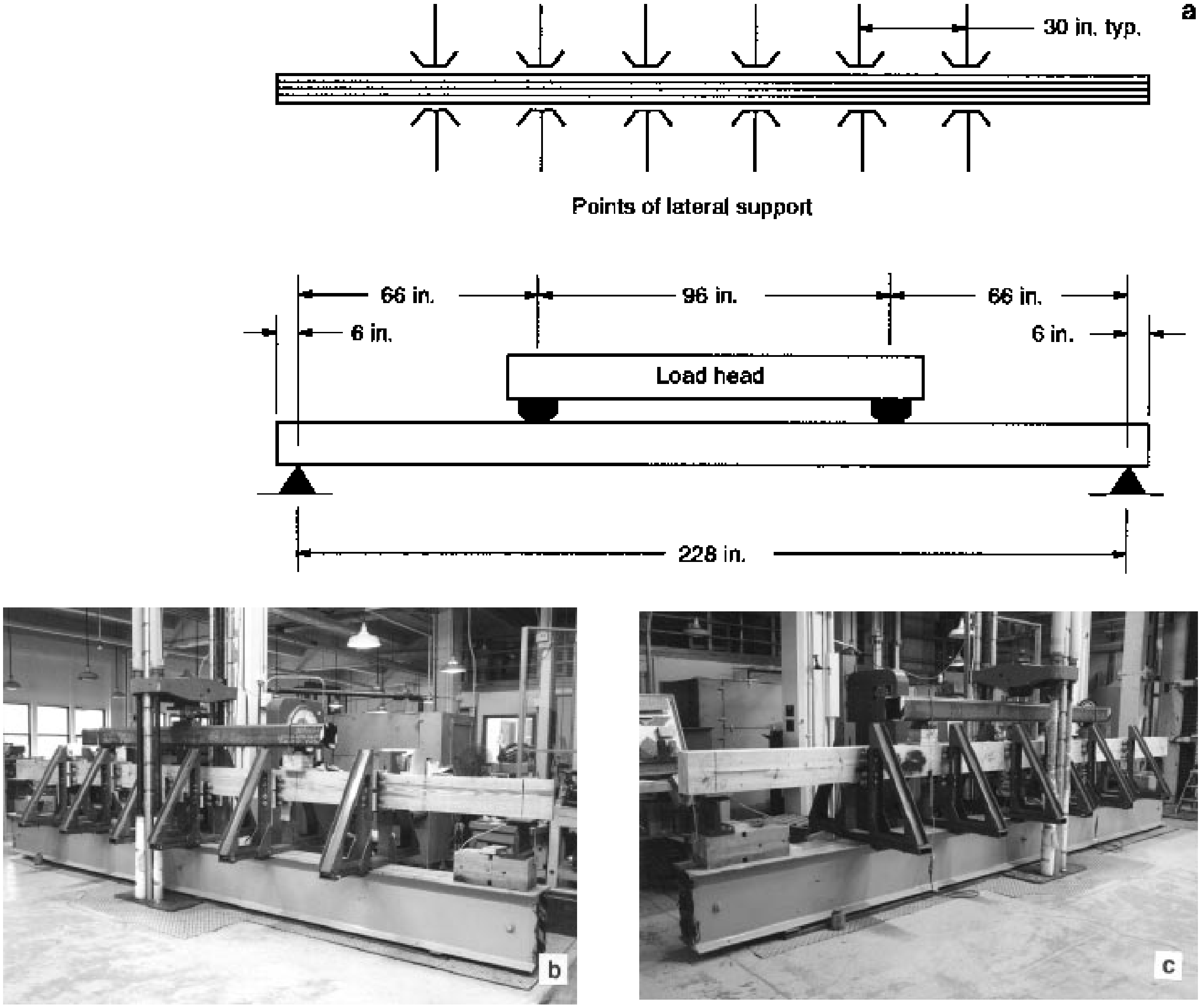


Figure 5—Configuration of test equipment showing (a) location and load points, support reactions, and lateral supports. Actual single-ply (b) and four-layer (c) specimens are shown prior to tests. (M92 0030–12, 0016–4)

Results and Discussion

The properties of the lumber used for single-member specimens and four-layer posts are given in Table 4.

Failures were classified into two general categories: failures caused by high wood bending stress and failures caused by high nail shear force and high wood shear stress. Specific types and locations of failures for each post are summarized in Table 5. Most posts failed at two or more locations; thus, the total number of failures exceeded the number of specimens. Failure locations given in the first column of Table 5 and the procedure for coding the failure type have been previously described and are depicted in Figure 6. Examples of failures are shown in Figure 7.

As expected, nearly all of the single members and unspliced posts failed as a result of high bending stresses. In general, the stronger post designs (A6, A6-R, and the unspliced posts) were more likely to fail because of high bending stress. Almost all of these failures were tension failures in the lumber. These failures typically occurred in a layer adjacent to a butt joint in the two middle layers. Inspection of the failed specimens revealed that the longest members in the center layers were the most highly stressed members in the assembly.

The lower strength post designs (A4 and B4) developed high nail shear forces, and the assembly layers rigidly rotated about these highly stressed fasteners after developing splits at the butt joints. Splitting apparently occurred at the butt joints because of a combination of high nail shear forces (which caused high perpendicular-to-grain tensile stresses) and high shear stresses in the lumber. Splitting typically occurred near the centroidal axes of the members.

Table 4—Lumber properties

Lumber use	No. of pieces	Moisture content	Specific gravity	Modulus of elasticity[a]	
				Mean ($\times 10^6$ lb/in^2)	COV[b] (%)
Single members	40	9.8	0.55	2.35	14.5
Four-layer posts	300	9.4	0.56	2.31	13.1
Combined	340	9.4	0.56	2.32	13.3

[a] Dynamic MOE.

[b] COV is coefficient of variation.

Table 5—Types and locations of post failures

Failure location[a]	Number of posts with failure					
	Unspliced	A4	B4	A6	A6-R	Total
	Wood bending failure					
1-2, 4-3	—	—	—	2	3	5
2-3, 3-2	—	7	—	14	15	36
2-4, 3-1	—	—	—	1	—	1
1-3, 4-2	—	—	—	—	1	1
1-L, 4-R	—	—	—	—	1	1
1-x	11	—	—	—	—	11
2-x	7	—	—	—	—	7
3-x	9	—	—	—	—	9
4-x	12	—	—	—	—	12
Total	39	7	0	17	20	83
	Nail and/or shear failure					
1-L, 4-R	—	13	4	13	12	42
1-R, 4-L	—	8	15	5	4	32
2-L, 3-R	—	6	12	3	7	28
2-R, 3-L	—	18	7	19	20	64
3-2, 2-3	—	—	—	—	2	2
2-x	2	—	—	—	—	2
3-x	2	—	—	—	—	2
Total	4	45	38	40	45	172

[a] See Figure 6 for schematic of failure locations. Failure locations were paired because of symmetry; that is, location 4-3 is the mirror of location 1-2.

Outside butt-joint reinforcement typically buckled on the compression side of the plates at a load around 8,000 lb, which was about 60 percent of the average ultimate load. This apparently did not have a great effect on post properties because the load–displacement curves did not significantly change with plate buckling. However, at ultimate load, the plates either tore or withdrew on the tension side of the plate.

Single Members

Based on a normal distribution, a factor of safety of 1.3, a load duration factor of 1.6 (ASTM D245 1992a), and use of the fifth percentile point estimate from Table 6, a design bending stress of 2,500 lb/in^2 would be applicable to the sample of single members (ASTM 1992c). This is 11 percent greater than the published value of 2,250 lb/in^2. The mean static MOE was 2.27×10^6 lb/in^2, which is 19.5 percent greater than the published value of 1.9×10^6 lb/in^2. Thus, the strength and stiffness of the single member exceeded expected levels based on NDS values.

The MOE values for each single member (Table 4), which were measured using a dynamic flatwise vibration technique and calculated from the edgewise static bending test (Table 6), are related by the following equation:

$$\text{Static MOE} = 0.965(\text{Dynamic MOE}) \qquad r^2 = 0.794$$

Single Members and Unspliced Posts

Results of the bending tests on single members and unspliced posts are given in Table 6. Cumulative distribution functions (CDFs) for MOR and MOE are compared in Figures 8 and 9, respectively. Data for individual members and posts are shown in Appendix A.

The mean MOR of the four-layer unspliced posts was 97 percent of the value for single members (Table 6). For three-layer assemblies, Bohnhoff and others (1991) found an 89 percent ratio and Bonnickson and Suddarth (1966) found a 94 percent ratio. This slight reduction in mean MOR happens when one layer in an unspliced post reaches maximum stress and fails, causing a redistribution of stress to the other members in the assembly. This load redistribution will typically cause the structure to fail.

Although the mean MOR of the unspliced four-layer posts was about the same as that of the single members, the variability in MOR of the posts was considerably less than that for the single members. This reduced variability was due to load-sharing. Consequently, the estimated fifth percentile values for the unspliced posts were about 30 to 50 percent greater than that for the single members (Table 6); the value depended on the type of distribution assumed. As a result of reduced variability, these four-layer posts could be assigned an allowable stress at least 30 percent greater than that for single members. The NDS currently allows for an increase in bending stress of 15 percent when single members are vertically laminated into assemblies with three or more layers.

When all layers in an unspliced post are the same size and are forced to have the same displaced geometry, (1) the effective MOE of the unspliced post should equal the average MOE of the individual layers and (2) the coefficient of variation (COV) of the effective MOE should equal the COV of the individual layers divided by the square root of the number of layers (Wolfe and Moody 1979). Consequently, the lack of a significant difference between the mean effective static MOE of the four-layer assemblies (2.25×10^6) and the MOE of the single members (2.27×10^6) is not surprising. Based on a COV of mean MOE of

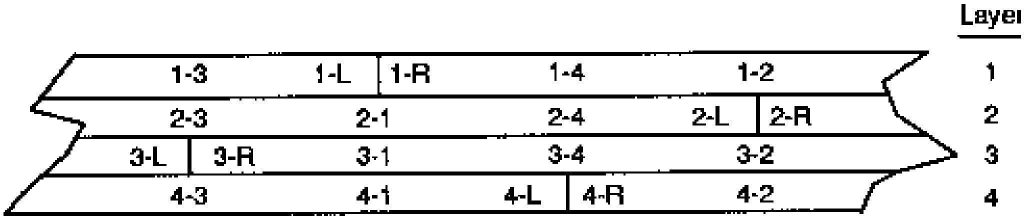


Figure 6—Location of failures from top view of post. The first number designates the layer in which the failure actually occurred and the second number the relative location of the failure with respect to a butt joint in an adjacent layer. For example, 2-3 indicates that the failure occurred in layer 2 at a location adjacent to the butt joint in layer 3. The letters L and R indicate that the failure was located to the left and right of the joint.

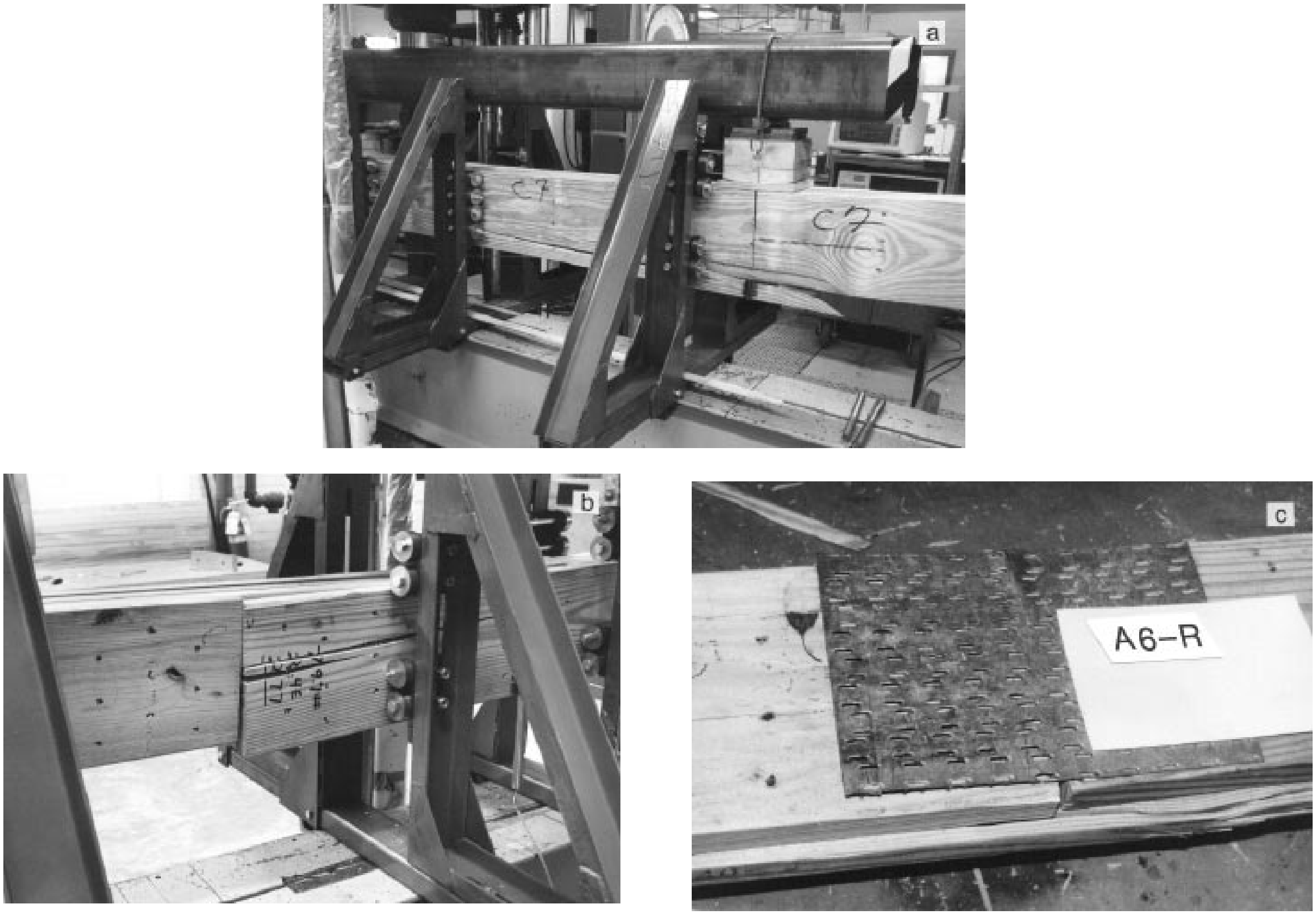


Figure 7—Failure of test specimens: (a) wood failure of unspliced member, (b) splitting from butt joint in spliced post caused by high tension perpendicular-to-grain stresses, and (c) buckling on compression side of metal plate connectors of reinforced post (A6-R). (M92–0041–6, M92–0016–17, M93–0069–3)

13.6 percent for the single members, the predicted COV of the mean effective MOE of the four-layer posts would be 6.8 percent. This is close to the COV of 5.5 percent calculated from the test results.

The relationship between the static MOE of the four-layer posts and the average dynamic MOE of the lumber used in the fabrication was determined to be as follows:

$$\text{Static MOE} = 0.972(\text{Dynamic MOE}) \qquad r^2 = 0.507$$

Results of the statistical analyses showed no significant difference between the mean properties of the single members and unspliced posts (Table 7).

Unspliced and Spliced Posts

Ultimate midspan bending moment and stiffness values for spliced and unspliced posts are given in Table 8, and ratios of post strength and stiffness are given in Table 9.

Table 6—Distribution characteristics for modulus of rupture and modulus of elasticity of single members and four-layer unspliced posts[a]

Distribution characteristic	Single members	Unspliced posts	Ratio of post to single member values
Modulus of rupture (lb/in^2)			
Mean	8,670	8,420	0.97
	[24.0%]	[13.9%]	0.58
Fifth percentile (point estimate)			
Normal	5,250	7,560	1.44
Lognormal	5,500	7,770	1.41
Weibull[b]	5,290	6,900	1.30
Nonparametric	5,270	8,190	1.55
5-percent tolerance limit[c]			
Normal	4,920	7,260	1.48
Lognormal	5,240	7,440	1.42
Weibull[b]	4,970	6,790	1.37
Nonparametric	4,010	5,270	1.31
Modulus of elasticity (x10^6 lb/in^2)[d]			
Mean	2.27	2.25	0.99
	[13.6%]	[5.5%]	0.41

[a] Values in brackets are coefficients of variation (COVs).
[b] Three-parameter Weibull distribution.
[c] One-sided lower 75-percent confidence bound on fifth percentile.
[d] Determined from static edgewise bending tests using the slope of the load–deflection relationship between 20 and 40 percent of maximum load.

The CDFs for the strength of the five post designs are compared in Figure 10; stiffness values are compared in Figures 11 and 12. Individual results for all posts are included in Appendix A.

Both methods for calculating stiffness for the four-layer posts yielded essentially the same results (Table 8). Thus, we will discuss only the stiffness calculated up to 40 percent of maximum load. For the spliced posts, the mean stiffness values ranged from 63 to 77 percent of the mean stiffness of unspliced posts. These values are similar to those obtained for three-layer posts (Bohnhoff 1991).

Splicing reduced post strength significantly (Tables 7 and 9). Details of the level of significance of the differences are given in Appendix B. The mean strength of spliced posts ranged from 29 to 61 percent of the strength of unspliced posts (Table 9). The estimated fifth percentile (point estimate) of the strength (based on the normal distribution) for spliced posts ranged from 29 to 63 percent of that for unspliced posts.

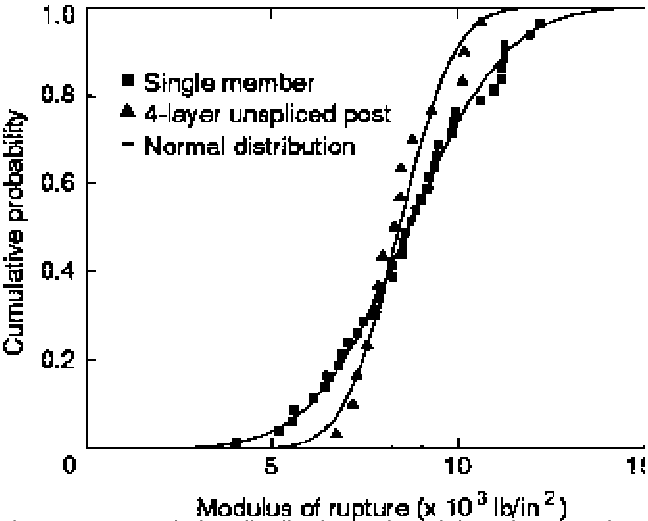


Figure 8—Cumulative distributions of modulus of rupture for single members and four-layer posts.

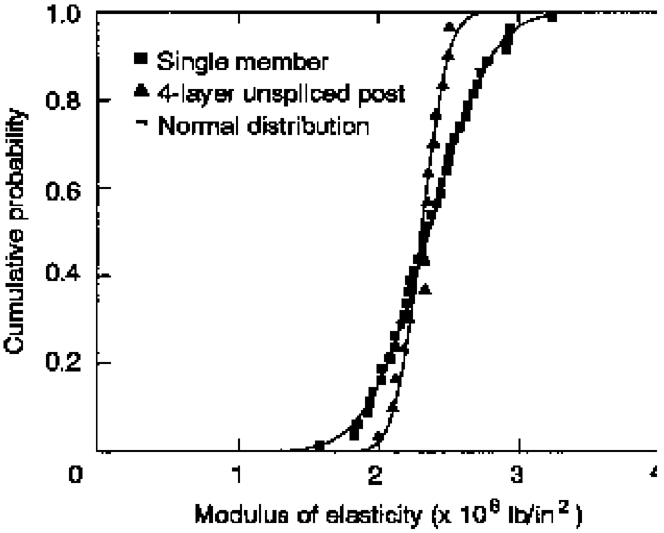


Figure 9—Cumulative distributions of modulus of elasticity for single members and four-layer posts.

The reductions in strength and stiffness found in our study are much greater than some engineers would predict. It would be a mistake to believe that four-layer spliced post strength is 75 percent of that for an unspliced post because three layers are continuous at each butt joint. This assumption fails to consider three factors: (1) bending stress in the three continuous layers adjacent to a joint is not equal because of the redistribution of forces, (2) nail forces are much higher in spliced posts and precipitate failures in posts that are not common to unspliced posts, and (3) design strengths are highly dependent on the COV of mean strength, which is higher for spliced posts than for unspliced assemblies.

Table 7—Significant differences in post properties[a]

Comparison of post designs	Ultimate midspan bending moment	Stiffness at 40% of maximum post load
Unspliced post and single member		
MOR	No	
Static MOE		No
Dynamic MOE		No
Unspliced post and A6-R	Yes	Yes
Unspliced post and A6	Yes	Yes
Unspliced post and A4	Yes	Yes
Unspliced post and B4	Yes	Yes
A4 and B4	Yes	Yes
A4 and A6	Yes	Yes
A4 and A6-R	Yes[b]	Yes
B4 and A6	Yes	Yes
B4 and A6-R	Yes[b]	Yes
A6 and A6-R	Yes	Yes

[a] Differences significant at the 0.05 level.
[b] Normal fit rejected by the Shapiro–Wilk test; used the signed rank test.

Table 8—Distribution characteristics for ultimate midspan bending moment and mean stiffness of unspliced and spliced four-layer posts[a]

Distribution characteristic	Unspliced posts	Spliced post design			
		A4	B4	A6	A6-R
Ultimate midspan bending moment (x10^3 in-lb)					
Mean	721	270	207	345	440
	[13.9%]	[15.7%]	[13.6%]	[16.4%]	[12.0%]
Fifth percentile (point estimate)					
Normal	556	200	161	252	353
Lognormal	571	203	165	258	359
Weibull[b]	591	198	164	257	365
Nonpara-metric	578	190	157	243	354
5-percent tolerance limit[c]					
Normal	532	190	154	239	341
Lognormal	545	191	157	243	345
Weibull[b]	581	184	159	242	357
Nonpara-metric	574	190	155	240	351
Stiffness at 40% of maximum post load (lb/in)					
Mean	6,230	3,890	3,540	4,120	4,820
	[5.2%]	[7.8%]	[5.3%]	[6.6%]	[6.3%]
Stiffness at percentage of post design load (lb/in)					
Mean	6,220[d]	3,880[e]	3,490[e]	4,090[e]	4,790[e]
	[5.0%]	[7.8%]	[6.4%]	[6.1%]	[6.6%]

[a] Values in brackets are coefficients of variation. Stiffness values are expressed at the ratio of load to average load–point deflection.
[b] Three-parameter Weibull.
[c] One-sided lower 75% confidence bound on fifth percentile.
[d] Stiffness at 308 x 10^3 in-lb, the NDS allowable design load for four-layer unspliced posts.
[e] Stiffness at product of ratio (Table 9, line 1) and 308 x 10^3 in-lb.

Table 9—Ratio of properties for spliced to unspliced posts

Distribution characteristic	Ratio for spliced to unspliced posts for various post designs			
	A4	B4	A6	A6-R
Ultimate midspan bending moment				
Mean	0.37	0.29	0.48	0.61
Fifth percentile (point estimate)				
Normal	0.36	0.29	0.45	0.64
Lognormal	0.36	0.29	0.45	0.63
Weibull[a]	0.34	0.28	0.43	0.62
95 percent CI on fifth percentile[b]				
Normal	0.24–0.48	0.18–0.40	0.33–0.58	0.50–0.77
Lognormal	0.30–0.42	0.25–0.34	0.38–0.54	0.54–0.73
Weibull	0.26–0.41	0.25–0.30	0.36–0.51	0.57–0.67
Stiffness at 40 percent of maximum post load				
Mean	0.62	0.57	0.66	0.77
Stiffness at percentage of design load				
Mean	0.62	0.56	0.66	0.77

[a] Three-parameter Weibull.
[b] CI is confidence interval.

Another reason that the ratios in Table 9 are lower than typically perceived values is that design values based on test results for spliced posts are often incorrectly compared to NDS allowable design values for unspliced posts. Because these NDS values are applicable to all lumber from a broad range of sources, the values are often conservative for specific groups of lumber. For example, in the study reported here, the fifth percentile of the single-member strength exceeded that predicted from the NDS design stress by 11 percent. Engineers who compare the design values for spliced posts to the NDS values for unspliced posts are mistakenly led to conclude that splicing is not nearly as critical as it is. For this reason, evaluation of spliced posts must include unspliced posts built using the same lumber sample used to fabricate the spliced posts. The actual strength reduction associated with splicing should be ascertained only in this manner.

Splice Length

The only difference between post designs A4 and A6 was overall splice length: 4 ft for design A4 and 6 ft for design A6. The mean strength of design A6 was 28 percent greater than that of design A4, and the fifth percentile (point estimate) of design A6 was 26 percent greater than that of design A4.

Designs A4 and A6 had mean strength values equal to 37 and 48 percent, respectively, of that of the unspliced post design. Bohnhoff and others (1991) found that three-layer posts fabricated from 2- by 6-in. lumber with 4-ft overall

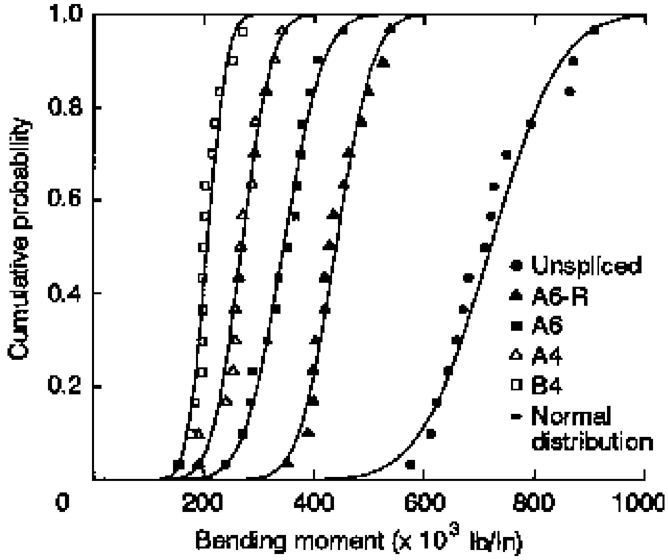


Figure 10—Cumulative distributions of maximum midspan bending moment for four-layer posts.

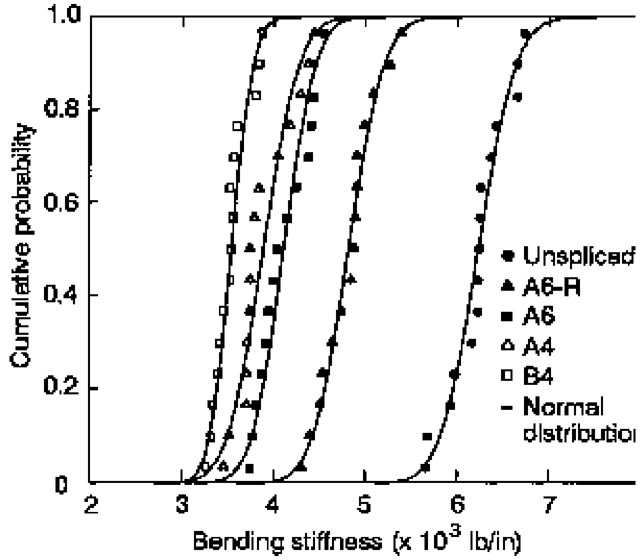


Figure 11—Cumulative distributions of stiffness at 40 percent of maximum load for four-layer posts.

splice lengths had mean strength values about 48 percent of those for unspliced posts. Based on these percentages, the overall splice length of four-layer, 10-in.-deep posts should be at least 6 ft for the posts to be as efficient as three-layer, 6-in.-deep posts with 4-ft overall splice lengths.

A change in overall splice length can also affect the overall stiffness of the assembly, although the effects are small: the mean stiffness for designs A4 and A6 differed by only 6 percent. In this study, the designs with 4-ft-long splices (designs A4 and B4) had mean stiffness values equal to 63 and 57 percent of the unspliced posts. For three-layer posts with a 4-ft overall splice length, stiffness values were

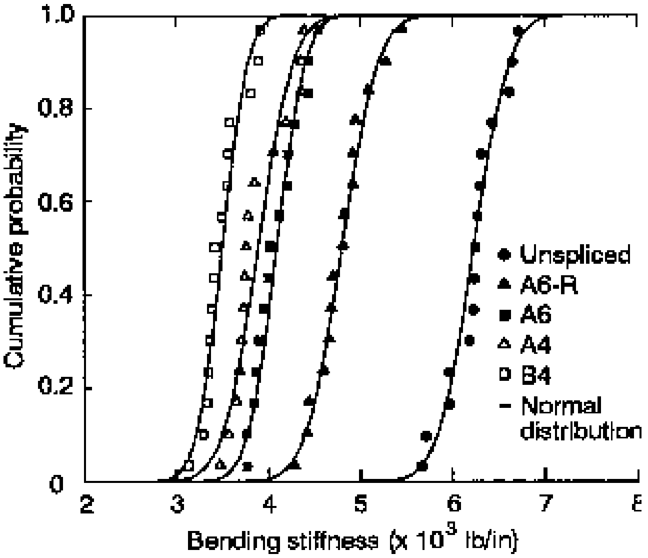


Figure 12—Cumulative distributions of post stiffness at a percentage of design load.

59 and 60 perccent of that of the unspliced posts (Bohnhoff and others 1991). The small difference between these ratios suggests that the stiffness of three- and four-layer posts is independent of the number of layers in the assembly and is probably more a function of the nails that connect the post halves.

The increase in post strength and stiffness associated with an increase in splice length can be attributed to the load transfer mechanism. Assemblies with shorter splice lengths must transfer load over a shorter distance (that is, with fewer nails), and consequently nail forces will be higher. The data in Table 5 confirm this conclusion: design A4 had only 40 percent as many wood bending failures as design A6, indicating that maximum nail shear forces were reached before maximum wood fiber stresses were attained.

Splice Arrangement

Splice arrangement can be examined by comparing designs A4 and B4. Design A4 had 30 percent greater mean strength and 24 percent greater fifth percentile (point estimate) strength than that of design B4. Design A4 also had 10 percent greater stiffness than design B4.

All failures of design B4 posts were the result of high shear forces (Table 5). Obviously, maximum nail shear forces were reached in the B4 test specimens before ultimate wood bending stresses were reached. Consequently, if the overall splice length of B4 posts were increased to at least 6 ft, the overall performance of the post would increase significantly because the average nail shear forces in the splice region would decrease.

Six of the 15 A4 posts had failures related to wood bending. Examination of the A4 failures clearly showed that maximum wood stresses developed in the long center layers of the posts. This type of post is ideal for outside butt-joint reinforcement, since such reinforcement would help to more evenly distribute load throughout the post.

Butt-Joint Reinforcement

Comparison of designs A6 and A6-R shows that the addition of outside butt-joint reinforcement increased mean post strength by 26 percent and fifth percentile (point estimate) by 40 percent. The difference between these two percentages indicates that adding reinforcement decreases variability.

The 26-percent increase in mean strength associated with the reinforcing of four-layer posts is almost twice the 14-percent increase reported by Bohnhoff and others (1991) for three-layer posts, which suggests that outside butt-joint reinforcement is more beneficial for four-layer posts. The increase in strength is likely due to a more efficient distribution of wood stress in four-layer assemblies.

Outside butt-joint reinforcement increased mean stiffness 17 percent. When compared to other variables (that is, splice length and joint arrangement), reinforcement had the greatest effect on post stiffness. The 17-percent increase in stiffness associated with reinforcement of four-layer posts was less than the increase associated with reinforcement of three-layer posts (25 percent increase in stiffness).

The major advantage of reinforcing only outside butt joints is that such reinforcement helps channel stresses away from highly stressed members in the center layers. The greater the proportion of load carried by the center layers in an unreinforced assembly, the more the assembly benefits from outside butt-joint reinforcement. Because the percentage of load carried in the center layers is dependent on joint arrangement, assemblies with different joint arrangements will respond differently to the addition of outside butt-joint reinforcement. Only one post design was reinforced in this study; thus we could not ascertain the extent to which joint arrangement and reinforcement interact to control post strength.

Conclusions

The results of our tests on unspliced and spliced four-layer nail-laminated posts led to the following conclusions:

1. The current NDS 1.15 repetitive member factor is very conservative. Four-layer unspliced nail-laminated posts could be assigned an allowable bending stress 30 percent greater than design values currently published for single members.
2. Increasing the splice length from 4 to 6 ft can have a substantial effect on the bending strength and stiffness of four-layer nail-laminated posts. Mean and fifth percentile strength values increased 28 percent and 26 percent, respectively, when the overall splice length was increased by 2 ft; mean stiffness increased 5 percent.
3. To be as efficient as three-layer, 6-in.-deep posts with 4-ft overall splice lengths, four-layer, 10-in.-deep posts should have an overall splice length of at least 6 ft. The mean strength of unreinforced four-layer posts with a 6-ft overall splice length was 48 percent of that of unspliced posts. This relative strength level is equal to that previously found for unreinforced three-layer, nominal 6-in.-deep posts with 4-ft overall splice lengths.
4. Splice arrangement can have a substantial effect on the bending strength and stiffness of four-layer nail-laminated posts. When two splice arrangements were used in posts with 4-ft overall splice lengths, the mean and fifth percentile strength values differed by 30 and 24 percent, respectively, and the mean stiffness differed by 10 percent.
5. Outside butt-joint reinforcement can significantly help recover the strength and stiffness lost by splicing. Mean and fifth percentile strength increased by 26 and 40 percent, respectively, and mean stiffness increased by 17 percent when reinforcement was added to the outside joints of posts with an overall splice length of 6 ft.

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Appendix A—Bending Properties of Individual Specimens

Tables A–1 and A–2 show bending property data for single members and four-layer posts, respectively.

Table A–1—Properties of specimens in single-member tests[a]

			Modulus of elasticity ($\times 10^6$ lb/in^2)	
Specimen number	Modulus of rupture (lb/in^2)	Specific gravity	Dynamic	Static
108	8,880	0.49	2.03	1.79
110	9,220	0.58	2.48	2.47
137	7,860	0.59	2.51	2.35
141	10,970	0.54	2.28	2.48
157	9,870	0.51	2.20	1.97
169	8,500	0.54	1.85	1.93
177	7,940	0.64	2.71	2.76
183	7,310	0.58	2.42	2.25
204	11,190	0.53	2.16	2.35
207	6,420	0.57	2.45	2.41
213	7,790	0.52	2.18	2.12
271	9,370	0.55	2.37	2.31
285	8,240	0.54	2.44	2.27
291	11,940	0.58	2.34	2.34
293	5,600	0.44	1.94	1.90
327	6,790	0.56	2.21	2.17
333	9,180	0.58	2.78	2.79
342	12,240	0.57	2.40	2.11
349	9,920	0.67	3.24	2.92
371	8,470	0.49	2.08	1.97
401	6,860	0.58	2.26	2.33
452	4,020	0.40	1.58	1.61
476	9,400	0.63	2.94	2.59
487	6,500	0.51	1.83	1.66
490	11,260	0.59	2.73	2.58
496	11,190	0.70	2.62	2.50
498	7,030	0.48	1.92	2.02
504	7,460	0.55	2.32	2.37
511	9,030	0.55	2.23	1.97
512	8,240	0.54	2.11	2.12
520	8,580	0.46	1.96	1.96
533	6,120	0.49	2.12	2.37
539	11,260	0.67	2.54	2.41
596	9,850	0.53	2.31	2.12
602	5,150	0.56	2.50	2.58
610	9,470	0.49	2.02	1.92
627	13,000	0.64	2.92	2.74
657	5,520	0.54	2.68	2.61
724	10,590	0.57	2.58	2.38
738	8,730	0.60	2.64	2.37

[a] See Table 1 in text for SI conversion factors.

Table A–2—Properties of individual posts and failure locations

		Stiffness (lb/in)		Failure location[a]				Stiffness (lb/in)		Failure location[a]	
Repli-cate	Ultimate midspan bending moment (x10^3 in-lb)	40% of maximum load	% of design load	Wood bending failure	Nail and/or wood shear failure	Repli-cate	Ultimate midspan bending moment (x10^3 in-lb)	40% of maximum load	% of design load	Wood bending failure	Nail and/or wood shear failure
		Unspliced posts						Design A6			
1	681	6,250	6,250	4-x	—	1	334	3,960	3,950	3-2	1-R,2-R
2	659	6,240	6,240	1-,2-,3-,4-x	—	2	240	4.440	4,270	—	1-L,2-R,3-L
3	672	6,650	6,600	1-,2-,3-,4-x	—	3	452	4,420	4,420	3-2	1-L,2-R
4	793	5,680	5,700	1-,2-,3-,4-x	2-x	4	271	3,940	3,890	2-3	2-R,3-L,4-R
5	870	6,230	6,220	1-,3-,4-x	—	5	393	3,810	3,840	3-2	1-L,2-R,4-L&R
6	722	6,730	6,700	1-,3-,4-x	—	6	286	4,250	4,210	3-2	2-R,4-L
7	865	5,930	5,970	2-,4-x	3-x	7	354	3,780	3,770	1-2,2-3	2-R,3-L
8	908	6,650	6,630	4-x	—	8	377	4,010	4,010	3-2	2-R,3-L
9	574	5,660	5,650	1-,2-,3-,4-x	—	9	337	4,040	4,020	2-3	1-L,2-R,3-L,4-R
10	750	6,430	6,420	4-x	—	10	316	4,150	4,110	2-3	—
11	622	6,370	6,310	1-,2-x	—	11	410	3,750	3,760	2-3,3-2	1-L,2-L&R,4-R
12	710	6,230	6,220	1-,3-,4-x	—	12	292	4,390	4,190	3-2	2-L&R,3-L
13	646	6,250	6,290	1-,4-x	2-,3-x	13	367	4,550	4,550	3-1,3-2	1-L,2-R,4-R
14	724	6,170	6,160	1-,2-,3-x	—	14	370	4,420	4,420	3-2	4-L&R
15	611	5,990	5,960	1-,3-x	—	15	377	3,880	3,890	1-2	1-L,2-L&R,4-L
		Design A4						Design A6-R			
1	327	4,300	4,370	—	1-R,2-R,3-L&R,4-R	1	522	5,400	5,450	3-2	1-L,2-R,4-L
2	263	4,450	4,360	—	1-L,2-R,3-L,4-L	2	419	4,650	4,660	3-2	2-L&R,2-3[b]
3	267	3,760	3,730	3-2	2-R,3-R	3	388	4,850	4,680	2-3	1-L,3-L
4	313	3,720	3,750	2-3,3-2	1-L	4	418	4,300	4,270	1-2,3-2	1-L,2-L
5	191	3,530	3,560	—	2-R,4-L	5	486	4,400	4,410	3-2	1-L,2-R,4-L
6	259	4,060	4,050	—	3-L,4-L&R	6	436	4,740	4,710	1-2,3-2	1-R,2-R,3-L&R,4-L&R
7	241	3,750	3,690	—	1-R,2-R,3-L,4-L	7	402	5,100	5,070	4-R	2-R,3-L,4-R
8	257	3,550	3,660	—	1-L,2-L,3-L,4-L	8	351	5,000	4,920	2-3	3-L,2-3[b]
9	254	3,470	3,480	—	1-L,3-L&R,4-R	9	538	4,550	4,590	2-3,3-2	1-L,2-R,3-L,4-R
10	338	3,720	3,770	2-3	4-R	10	428	4,510	4,450	1-2,3-2	2-L&R
11	287	3,710	3,710	—	2-R,3-L,4-R	11	455	4,920	4,900	2-3	4-R
12	190	3,800	2,900	3-2	1-R,2-R,3-L	12	498	4,880	4,930	2-3	2-R3-L,4-R
13	294	4,190	4,180	2-3	1-L,2-L	13	463	5,260	5,260	2-3,4-2	2-L,2-R,3-L&R,4-R
14	292	3,840	3,840	2-3	1-L,2-L,3-L	14	399	4,890	4,810	3-2	1-L,2-L,2-R,3-L
15	271	3,760	3,760	—	1-L,2-R,3-L,4-R	15	397	4,910	4,820	2-3	2-R,3-L
		Design B4									
1	252	3,840	3,890	—	1-L,2-L,3-R,4-L						
2	196	3,410	3,340	—	1-R,3-R						
3	196	3,820	3,790	—`	1-R,2-L,3-L&R,4-L						
4	204	3,420	3,410	—	1-L,2-R,3-R						
5	198	3,470	3,420	—	1-R						
6	198	3,540	3,500	—	1-R						
7	201	3,610	3,550	—	1-R,2-L						
8	268	3,330	3,360	—	1-L,2-R,3-L						
9	204	3,350	3,290	—	1-L,2-L,3-L,4-L						
10	155	3,580	3,380	—	1-R,2-R,4-L						
11	177	3,260	3,130	—	2-L,3-R,4-L						
12	187	3,540	3,350	—	2-L,3-R,4-L						
13	220	3,570	3,570	—	1-R, 4-L						
14	230	3,880	3,910	—	1-R						
15	215	3,570	3,550	—	3-L						

[a] First number designates layer in which failure occurred; second number, relative location of failure with respect to butt joint in adjacent layer; L, failure located left of joint; R, failure located right of joint; and x, failure not associated with butt joint.

[b] Location of horizontal splitting of wood.

Appendix B—Analysis of Variance

Table B–1—Significance levels for comparison of unspliced post and single-member properties

Unspliced post compared to single member	Student's *t*-test
MOR	0.661
Static MOE	0.762
Dynamic MOE	0.573

Table B–2—Significance levels for comparison of strength and stiffness of various post types

	Ultimate bending moment		Stiffness at 40% of maximum load	
Post design	Paired *t*-test	Signed rank test	Paired *t*-test	Signed rank test
Unspliced and A4	0.0001	0.0001	0.0001	0.0001
Unspliced and B4	0.0001	0.0001	0.0001	0.0001
Unspliced and A6	0.0001	0.0001	0.0001	0.0001
Unspliced and A6-R	0.0001	0.0001	0.0001	0.0001
A4 and B4	0.0006	0.0002	0.0016	0.0004
A4 and A6	0.0026	0.0014	0.0182	0.0181
A4 and A6-R	0.0001	0.0001	0.0001	0.0001
B4 and A6	0.0001	0.0001	0.0001	0.0001
B4 and A6-R	0.0001	0.0001	0.0001	0.0001
A6 and A6-R	0.0015	0.0007	0.0001	0.0001