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INTERLAYER SHEAR CAPACITY REQUIREMENTS FOR SPLICED, NAIL-LAMINATED POSTS

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Summary:

Thirty-six spliced nail-laminated post designs were modeled to determine the sensitivity of post strength and stiffness to changes in interlayer shear stiffness. Simulation results were then used to develop equations for calculating (1) bending stiffness modification factors, (2) effective interlayer shear capacities, and (3) maximum wood shear stresses.

Keywords:

Post, Post design, Mechanical lamination, Nail-laminated posts, Bending properties, Bending strength, Post-frame buildings

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SPLICED NAIL-LAMINATED POSTS

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ABSTRACT

The product of nail density and nail-joint stiffness determines the interlayer shear stiffness and interlayer shear capacity of a spliced, nail-laminated post. Changes in these variables can significantly affect the strength and stiffness of the entire post. To determine the sensitivity of spliced posts to changes in interlayer shear stiffness, 36 different post designs were modeled. Simulation results were then used to develop equations for calculating (1) bending stiffness modification factors, (2) effective interlayer shear capacities, and (3) maximum wood shear stresses.

INTRODUCTION

A mechanically-laminated post is an assembly consisting of suitably selected wood laminations joined together with nails, bolts, and/or other mechanical fasteners. When nails are the only fastener type used to join individual layers, the assembly is generally referred to as a nail-laminated post.

Mechanically-laminated posts are classified as either spliced or unspliced. A spliced post is one that contains end-joints. These end joints may be either structural glued joints or simple butt joints. Posts with glued end joints behave and are treated like unspliced posts and can be completely designed under provisions of the National Design Specifications (NDS) for Wood Construction (AWPA, 1991). The behavior of posts with simple butt-joints is more complex than that of unspliced posts, and unlike unspliced posts, cannot be completely designed using the 1991 NDS. For this reason, ASAE committee SE 201/5 is currently developing an engineering practice (EP) for the design of mechanically-laminated posts. A major objective of this undertaking is to provide design guidelines and information for nail-laminated posts containing butt joints.

The complexity of the design of posts with butt joints is due to complex behavior resulting from the internal redistribution of load around each butt joint. This load redistribution is highly dependent on (1) the spacing and arrangement of butt joints, (2) the density and stiffness of interlayer fasteners near the butt joints, and (3) the presence of butt-joint reinforcement. Past research into the effects of joint spacing, joint arrangement, and butt joint reinforcement on post behavior by Bohnhoff (1989) and Williams (1993) has provided information critical to the development of the EP for mechanically-laminated post. Unfortunately, the effect that nail density and stiffness have on spliced post behavior has not been fully researched and consequently data needed to support the EP is lacking.

RESEARCH OBJECTIVES

The objectives of this research were to:

1. Determine how variations in nail-joint stiffness effect the overall stiffness of nail-laminated posts with butt joints.
2. Establish interlayer shear capacity requirements for the design of nail-laminated posts with butt joints.

SCOPE

The scope of this investigation was limited to finite element analysis of 3- and 4-layer posts without butt-joint reinforcement.

POST DESIGN OVERVIEW

Major variables in nail-laminated post design include (1) number of layers, (2) overall splice length, (3) joint arrangement, (4) member depth, (5) nail type, density and spacing, and when used, (6) type and location of butt-joint reinforcement.

Overall Splice Length and Member Depth

As shown in Figure 1, overall splice length is defined as the distance between the two farthest removed end joints. Overall splice lengths in 3- and 4-layer posts have been studied by Bohnhoff (1989) and Williams (1993), respectively, using a combination of computer modeling and laboratory testing. Both researchers have shown that wood stresses and nail shear forces within the splice region (also defined in Figure 1) increase at an increasing rate as the overall splice length is reduced. Based on their research, Bohnhoff and Williams (1994) recommend that where engineers are interested in maximizing the strength and stiffness of the splice region, the minimum overall splice lengths in Table 1 be used. It is important to note that the recommended minimum overall splice lengths increase as the width of the lumber (dimension "d" in Fig. 1) increases. This occurs because the bending strength of a post increases as the depth of the assembly increases. Unless the minimum overall splice length is increased along with depth, the strength gain associated with increased depth will be compromised by a lower bending strength in the splice region.

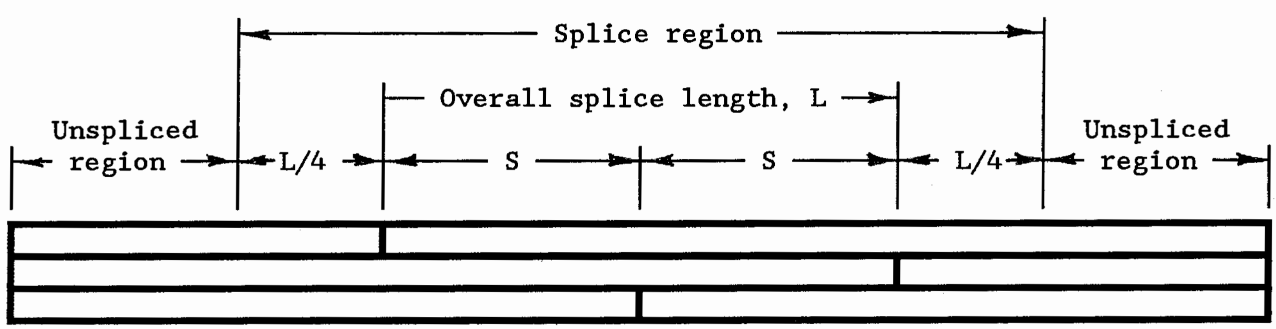

Figure 1 - Spliced post definitions.

TABLE 1 - Minimum Overall Splice Lengths

Face width of laminations, nominal inches	Minimum Overall Splice Length, feet	
	Glued end joints	Butt joints
6	2	4
8	3	5
10	3	6
12	4	8

Joint Arrangement

The relative location of end joints in a spliced post is referred to as the "joint arrangement" and, as previously mentioned, has a significant influence on post behavior. With an equal spacing, S, between joints (Fig. 1), there are eight different splice arrangements possible in a 4-layer post and two in a 3-layer post. Table 2 lists joint arrangements recommended by Bohnhoff (1993) for both reinforced and unreinforced posts. The arrangements are illustrated in Figure 2.

TABLE 2 - Permissible Joint Arrangements (Bohnhoff, 1993)

Number of layers	Joint type	Outside butt joint reinforcement	Permissible joint arrangements[a]
3	Butt joints	no	3A
	Butt joints	yes	3A, 3B
	Glued end joints	NA	3A, 3B
4	Butt joints	no	4B, 4C
	Butt joints	yes	4A
	Glued end joints	NA	4A, 4B, 4C

[a] See Figure 2

Nail Spacing

To reduce the likelihood of wood splitting, Bohnhoff (1993) recommended that the minimum nail spacing in Table 3 be followed. The values in Table 3 were based on a study of actual post failures, and are more conservative than the nail spacings published in the 1991 NDS Commentary (AWPA, 1993). To ensure a good distribution of nails, Bohnhoff (1993) recommended that each post have a minimum of two nail rows with one row located within 20 nail diameters of one edge and another nail row located within 20 nail diameters of the other edge. Bohnhoff also recommended that the spacing (pitch) between nails in each of these two rows not exceed 12 inches. In addition, Bohnhoff recommended that at least half of the nail rows have a fastener within 20 nail diameters of each side of each butt joint and that all nail rows have a fastener within 35 nail diameters of each side of each butt joint.

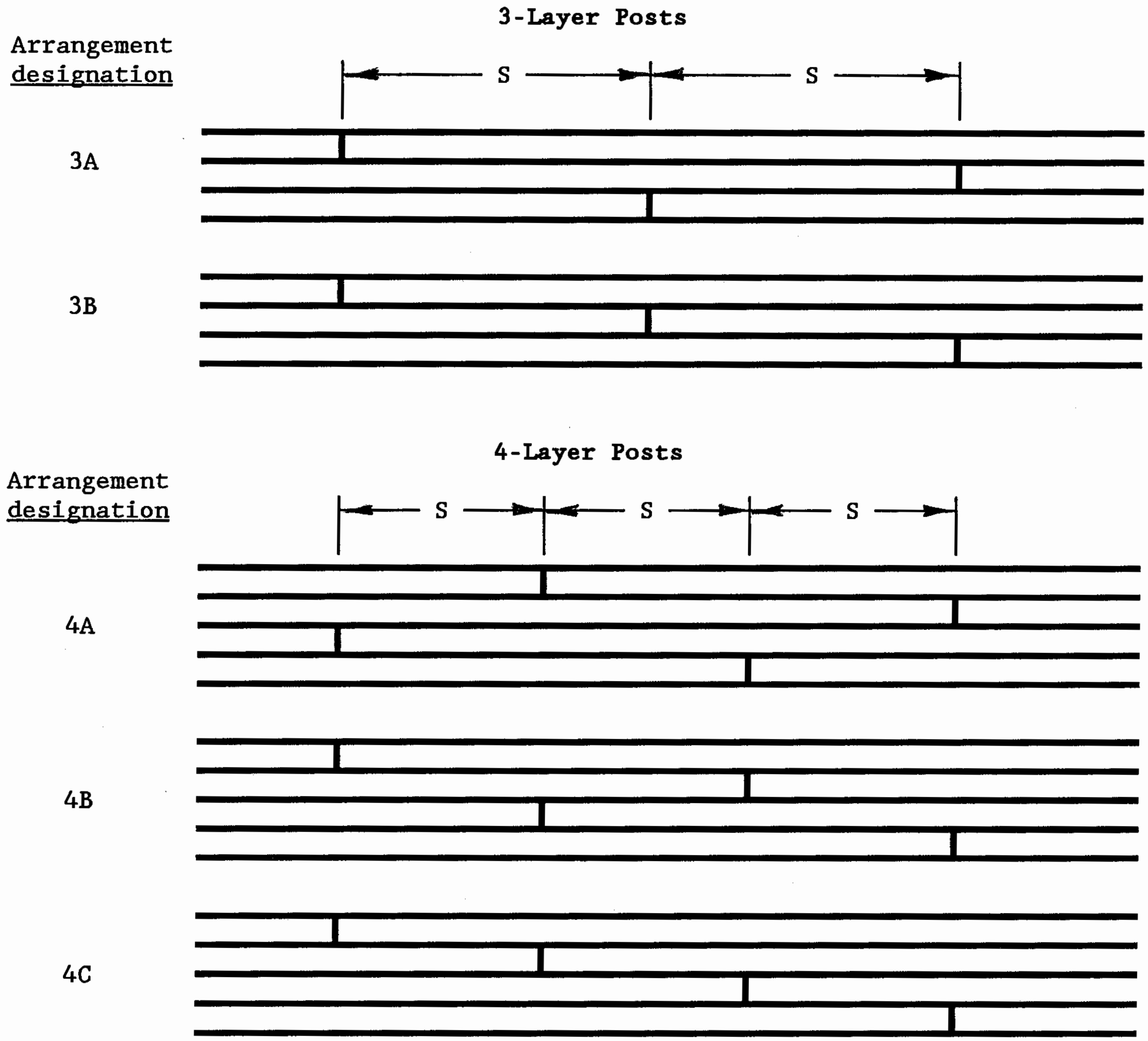

Figure 2 - Joint arrangements for 3- and 4-layer spliced posts.

TABLE 3 - Minimum Nail Spacings

	Nail diameters
Edge distance	10
End distance	15
Spacing (pitch) between fasteners in a row	20
Spacing (gage) between rows of fasteners	
- in-line	10
- staggered	5

Nail Density and Stiffness

Nail density and stiffness dictate interlayer shear capacity and interlayer shear stiffness. Interlayer shear capacity is the amount of load that is transferred by nails per unit area of wood contact. For example, if 5 nails are located in a contact area of 25 square inches, and each nail is transferring a shear load of 150 lbs, the interlayer shear capacity would be equal to 5*150/25 or 30 psi. Interlayer shear stiffness is the shear stiffness of the nail connections per unit of contact area. If 5 nails are located in a contact area of 25 square inches, and each nail connection has a shear stiffness of 4000 lbs per inch, the interlayer shear stiffness would be equal to 5*4000/25 or 800 lbs per cubic inch. Both interlayer shear capacity and interlayer shear stiffness increase with increases in (1) nail bending yield strength, (2) nail diameter, (3) nail density, and (4) wood specific gravity.

Nail type and density must be selected to provide a sufficient amount of interlayer shear capacity. If the interlayer shear capacity is too low, individual connections will be overloaded and fail before design bending and shear stresses are reached in the wood. The oozing apart of an assembly under load signifies that the interlayer shear capacity is too low. While increasing nail density will increase interlayer shear capacity, nail density cannot be increased without bound, since at some point, nailing induced stresses will result in wood splitting and premature post failure. Note that nail density is effectively limited by the minimum nail spacings in Table 3.

During a computer analysis, the quickest way to determine that nail joints aren't overloaded (i.e., that interlayer shear capacity is sufficient) is to check nail-joints slips and make sure that they are not much greater than 0.015 inches. To understand why this is true, one must first understand individual nail-joint load-slip behavior.

NAIL-JOINT LOAD-SLIP BEHAVIOR

Figure 3 contains relationships between shear load and interlayer slip for four different nail type connections as determined by Sun (1991). Nail type I was used by Williams et al. (1994) to fabricate 4-layer posts and nail types II and III by Bohnhoff et. al. (1991) to fabricate 3-layer posts. Properties for these nail joints are given in Table 4.

The relationships in figure 3 illustrate the following characteristics which are common to all nail joints (not just the 4 included in the plot). First, nail-joint stiffness continually varies, however, there tends to be a pronounced change in stiffness at a interlayer slip of 0.015 inches. This pronounced change in stiffness is typically referred to as the proportional limit for the connection (FPL, 1987). Second, in softwood connections, the maximum load resisted by the joint generally approaches 3.5 times the proportional limit load (FPL, 1987). Third, the slip at maximum load will generally be more than 20 times the 0.015 inch slip used to define the proportional limit.

Up until the 1991 NDS, design loads for nail joints were based on the shear load in nails at an interlayer slip of 0.015 inches. This shear force was related to nail diameter by the following equation (USDA, 1935).

$$P_{0.015} = K*D^{1.5} \qquad [1]$$

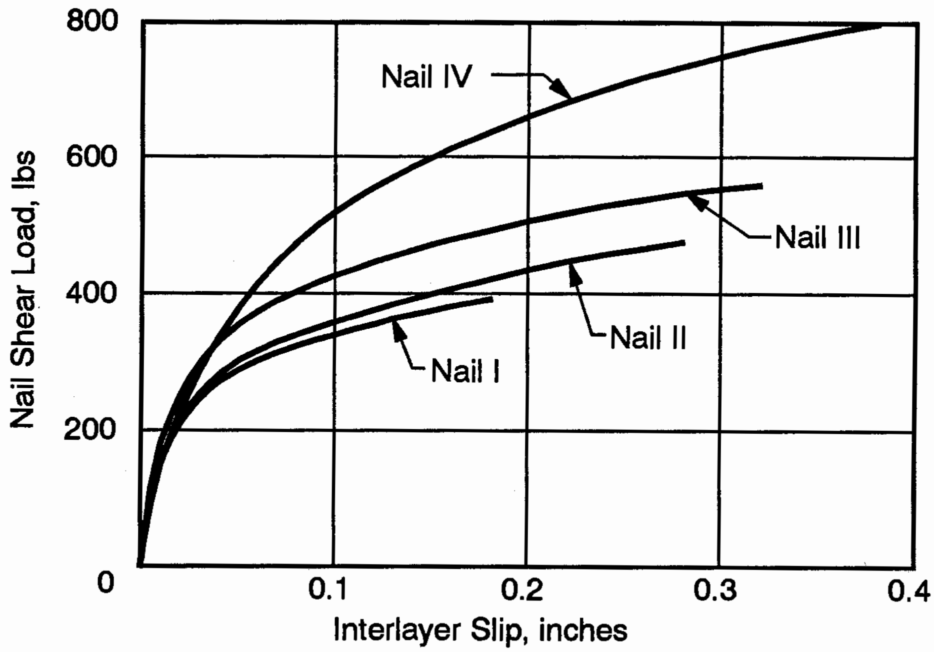

Figure 3 - Relationship between shear load and interlayer slip for four nail connection types (Sun, 1991). Curves represent average slips for perpendicular- and parallel-to-grain loadings. See Table 4 for nail-joint properties.

TABLE 4 - Nail-Joint Properties from Sun (1991)[a]

Nail Joint Designation[b]	I	II	III	IV
Nail diameter, inches	0.131	0.146	0.165	0.185
Nail length, inches	3.75	4.0	4.5	4.0
Shank type	Plain	Annular threads	Helical flutes	Annular threads
Driving method	Gun	Gun	Machine	Hand
Nail bending yield stress, psi	95200	107600	108600	176200
Specific gravity[c]	0.623	0.565	0.523	0.524
Shear load, lbs				
@ 0.015 inch slip	185	187	219	187
@ 0.020 inch slip	210	214	251	223
@ 0.030 inch slip	246	254	298	284
Secant stiffness, lbs/in				
@ 0.015 inch slip	12330	12470	14600	12460
@ 0.020 inch slip	10500	10710	12570	11160
@ 0.030 inch slip	8200	8460	9940	9475
Average maximum load, lbs				
parallel-to-grain	362	420	523	728
Perpendicular-to-grain	431	530	598	870

a Wood members were 1.5 inches wide and at a 12% moisture content. Shear load and stiffness values correspond to a load duration of 10 minutes.

b Designations correspond to designations in Figure 3.

c Average wood specific gravity based on ovendry weight and volume at 12% moisture content.

where:

$P_{0.015}$ = Nail shear load at an interlayer slip of 0.015 inches, lbs
K = Value dependent on wood specific gravity
D = Nail diameter, inches

From published reports it would appear that K values were largely based on tests conducted on oak, southern yellow pine, and northern white pine (Markwardt and Gahagan, 1935; Scholten, 1963). Values of K assigned to these three species were 2720, 2200, and 1440, respectively. These values only apply to bright, common wire nails, driven into the side grain of seasoned wood. In addition, the wood members being connected must be of approximately the same density, and the thickness of the side member should be about one-half the depth of penetration of the nail in the member holding the point. For actual design, the proceeding K-values are reduced 25% for safety and to adjust to a normal load duration (AWPA, 1993).

Scholten (1963) noted that in general, lateral nail loads vary about as the 1-1/4 power of specific gravity. Based on this fact, K in equation [1] was equated to $C*G^{1.25}$, where C is a constant and G the wood specific gravity. To determine C, the previously listed K values for oak, southern yellow pine, and northern white pine were regressed on specific gravities of 0.68, 0.55, and 0.37, respectively. This regression yielded a value for C of 4554, which when properly substituted into equation 1 yields:

$$P_{0.015} = 4554*G^{1.25}*D^{1.5} \qquad [2]$$

When divided by the slip of 0.015 inches, equation 2 becomes an expression for $K_{0.015}$ -- the secant stiffness of the load-slip curve at the 0.015 inch slip:

$$K_{0.015} = 303600*G^{1.25}*D^{1.5} \qquad [3]$$

It is important to note that the specific gravities in equations 2 and 3 must be based on ovendry weight and volume, and that the restrictions placed on use of the previously listed K values apply. Given that the nail joints described in Table 4 do not meet these restrictions, the data in the Table cannot be used to test the accuracy of equations 2 and 3.

COMPUTER ANALYSES

Overall Experimental Design

Thirty-six, 16-foot long, nail-laminated post designs were analyzed using a modified version of FEAST - a finite element analysis program originally developed for the analysis of mechanically laminated assemblies (Bohnhoff et. al., 1989). The overall splice length, depth, and joint arrangement for each of the 36 designs are given in Table 5. Note that each design is identified by a 4 or 5 character ID with the first character identifying the number of layers in the assembly, the second character the splice arrangement (as defined in Figure 2), the third character the overall splice length in feet, and the last character(s) the nominal depth of the member in inches.

TABLE 5 - Experimental Design

Overall Splice Length, feet	Nominal Depth, inches	Actual Depth, inches	Design ID			
			Joint Arrangement[a]			
			3A	3B	4B	4C
4	6	5.5	3A4-6	3B4-6	4B4-6	4C4-6
5	6	5.5	3A5-6	3B5-6	4B5-6	4C5-6
5	8	7.25	3A5-8	3B5-8	4B5-8	4C5-8
6	6	5.5	3A6-6	3B6-6	4B6-6	4C6-6
6	8	7.25	3A6-8	3B6-8	4B6-8	4C6-8
6	10	9.25	3A6-10	3B6-10	4B6-10	4C6-10
8	8	7.25	3A8-8	3B8-8	4B8-8	4C8-8
8	10	9.25	3A8-10	3B8-10	4B8-10	4C8-10
8	12	11.25	3A8-12	3B8-12	4B8-12	4C8-12

[a] See Figure 2.

Wood Properties

Each wood layer was assumed to have an actual width of 1.50 inches, a true modulus of elasticity of 2.0 million psi, and a shear modulus of 140,000 psi.

Nail Location

Nails in each model were concentrated into three equally spaced rows. The distance between the rows was dependent on post depth; specifically, rows were spaced 1.25, 1.75, 2.25, and 2.75 inches apart in nominally 6, 8, 10, and 12 inch deep members, respectively. Nails within each row were spaced 3 inches apart in the splice region (Fig. 1) and 12 inches apart in the unspliced regions of the post.

Nail-Joint Stiffness

The lateral or shear stiffness (i.e. load-slip behavior) of the nail-joints was assumed to be linear. The ramifications of this assumption are discussed later.

To assess the impact of interlayer shear stiffness on post behavior, each post design was analyzed 10 times, each time with a different level of nail-joint stiffness. Specifically, simulations were conducted with nail-joint stiffness values of 250, 500, 1000, 2000, 4000, 8000, 12000, 24000, 48000, and 96000 lbs per inch.

Boundary Conditions

Each model was subjected to a constant bending moment along its entire length by applying equal but oppositely acting bending moments to each post end. All end nodes were fixed against displacement normal to the length of the post, and the end of one layer was fixed against displacement parallel to the length of the post to prevent rigid body translation of the assembly in that direction. A schematic representation of the boundary conditions for a 3-layer post is shown in Figure 4.

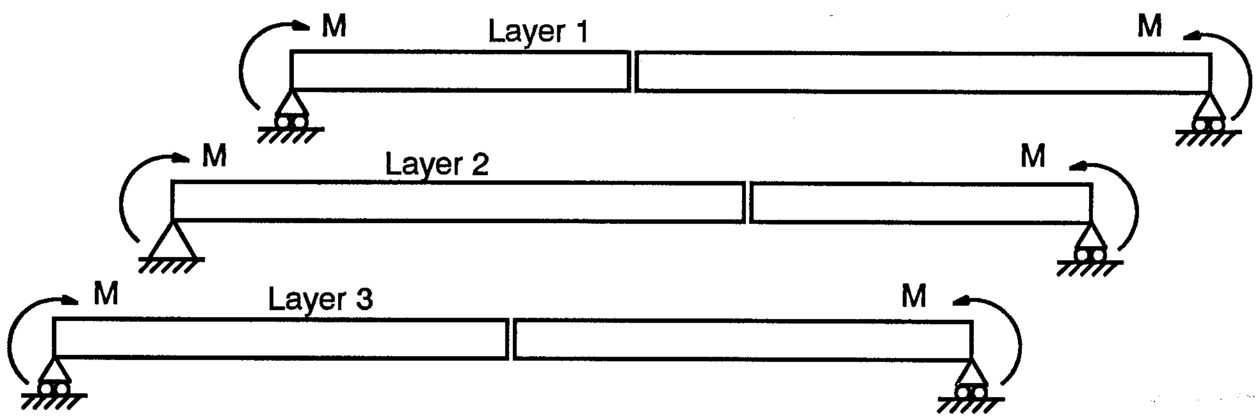

Figure 4 - Loading and displacement boundary conditions used in all simulations involving 3-layer posts.

Table 6 lists the bending moments that were applied to the end of each layer. These moments induce an extreme fiber in bending stress, f_b, that averages 1333 psi over the 3 layers of each 3-layer post, and averages 1500 psi over the 4 layers of each 4-layer post. Although the average effective f_b in 3- and 4-layer posts differ, the average effective f_b at butt-joint locations (where one layer is excluded from the average) is the same (i.e., equal to 2000 psi) in both 3- and 4-layer posts. In other words, bending moments were selected so that each post would be loaded to approximately the same maximum bending stress.

TABLE 6 - Applied Bending Moments

Nominal Depth, inches	Bending Moment Applied to End of Each Layer, inch-lbs	
	3-Layer Posts	4-Layer Posts
6	10083	11344
8	17521	19711
10	28521	32086
12	42187	47461

Post-Processing

After each simulation, the following data was recorded:

1. Location and magnitude of the maximum combined (i.e., bending plus axial) wood stress,
2. Location and magnitude of the maximum wood shear stress,

3. End node rotations for each layer,
4. Maximum nail shear force,
5. Average shear force of all nails located between the butt-joints (dimension L in Figure 1), and
6. Average shear force in the "T25" nails. T25 stands for "top 25%" and refers to the 25% most highly loaded nails located between the butt-joints.

In addition to the preceding data, a post-processing program was used to calculate (1) the maximum wood stress concentration factor, (2) the bending stiffness modification factor, (3) the interlayer shear stiffness, (4) the effective nail-joint slip, and (5) the effective interlayer shear capacity for each simulation.

The maximum wood stress concentration factor (MWSCF) is defined as the maximum combined bending and axial stress in the assembly divided by the maximum combined stress in an equivalent unspliced assembly. For the applied bending moments used in this study, the maximum combined stress in an equivalent unspliced 3-layer post is 1333 psi, and the maximum combined stress in an equivalent unspliced 4-layer posts is 1500 psi.

The bending stiffness modification factor, α, is defined as the ratio of the flexural rigidity of the spliced region of the post to the flexural rigidity of the unspliced regions (Fig. 1). When the spliced region is located in the center of the post and the post is subjected to constant bending moment along its entire length, α is given as:

$$\alpha = L_s/[L_s - L_t + 2nEI\theta/M_t] \qquad [4]$$

where:

E = Modulus of elasticity of lumber
I = Moment of inertia of a single layer
n = Number of layers
θ = Average end rotation
M_t = Total applied bending moment
L_t = Total post length
L_s = Length of the splice region
= 1.5*L where L = overall splice length

As previously noted, the interlayer shear stiffness is the shear stiffness of the nail connections per unit of contact area. In this study, interlayer shear stiffness values were calculated by first multiplying nail-joint stiffness by the number of nail shear planes located between the butt-joints (dimension L in Figure 1). This product was then divided by the total wood contact area between the butt-joints. Note that this wood contact area is equal to the product of the overall splice length, the actual depth, and the number of interlayers (i.e., the number of layers minus one).

The effective nail-joint slip was defined as the average joint-slip of the T25 nails, and was obtained by dividing the average shear force in the T25 nails by the nail-joint stiffness. The effective interlayer shear capacity was calculated by multiplying the effective nail-joint slip by the interlayer shear stiffness.

RESULTS AND DISCUSSION

Bending Stiffness Modification Factor

When modeling a spliced post during post-frame building analysis, it is good practice to section the post into spliced and unspliced regions (Fig. 1). Unspliced regions are assigned a flexural rigidity (MOE*I) by treating the region as an equivalently-sized solid-sawn member. To determine the flexural rigidity of the splice region, the flexural rigidity of the unspliced region is multiplied by an appropriate bending stiffness modification factor, α. The bending stiffness modification factor is highly dependent on the stiffness and density of nail joints, the overall splice length, and the depth of the assembly.

Because of the importance of α in post-frame building design, relationships between α and interlayer shear capacity, overall splice length, and post depth were investigated. This led to development of the following empirical relationship:

$$\alpha = 0.807 - 906*d/(L^2*K_{is}{}^{1/3}) \qquad [5]$$

where:

- α = Bending stiffness modification factor
- d = Actual post depth, inches
- L = Overall splice length, inches
- K_{is} = Interlayer shear stiffness, lbs/in^3

Figure 5 contains plots of equation 5 for all applicable combinations of post depth and overall splice length (Table 5). In addition to these combinations of depth and splice length, equation 5 is also limited to (1) interlayer shear stiffness values between 50 and 5000 lbs/in^3, and (2) applications where fasteners have not been loaded beyond their proportional limit. It is important to note that equation 5 is applicable to all 4 joint arrangements (i.e., 3A, 3B, 4B and 4C). Although individual regression analyses were performed for each of the 4 joint arrangements, the resulting standard error of estimates for α (i.e., 0.018, 0.011, 0.017, 0.015) from these regressions were not much lower than the value of 0.019 associated with equation 5.

Where applicable, equation 2 can be used to predict the interlayer shear stiffness for input into equation 5. To convert from nail-joint stiffness, K, to interlayer shear stiffness, K_{is}, simply multiply by nail density.

Effective Nail-Joint Slip

A nail-laminated post has adequate interlayer shear capacity if the forces in it's most highly loaded fasteners do not exceed allowable design values. As previously stated, the easiest and quickest way to determine if a fastener is overloaded is to look at its slip. When a nail-joint slip substantially exceeds the 0.015 inch slip generally associated with the proportional limit, then the force in the fastener has, in all likelihood, exceeded its allowable design value.

In this study, the slip of the T25 nails -- the effective nail-joint slip -- provides a good measure of maximum nail-joint slip. For this reason,

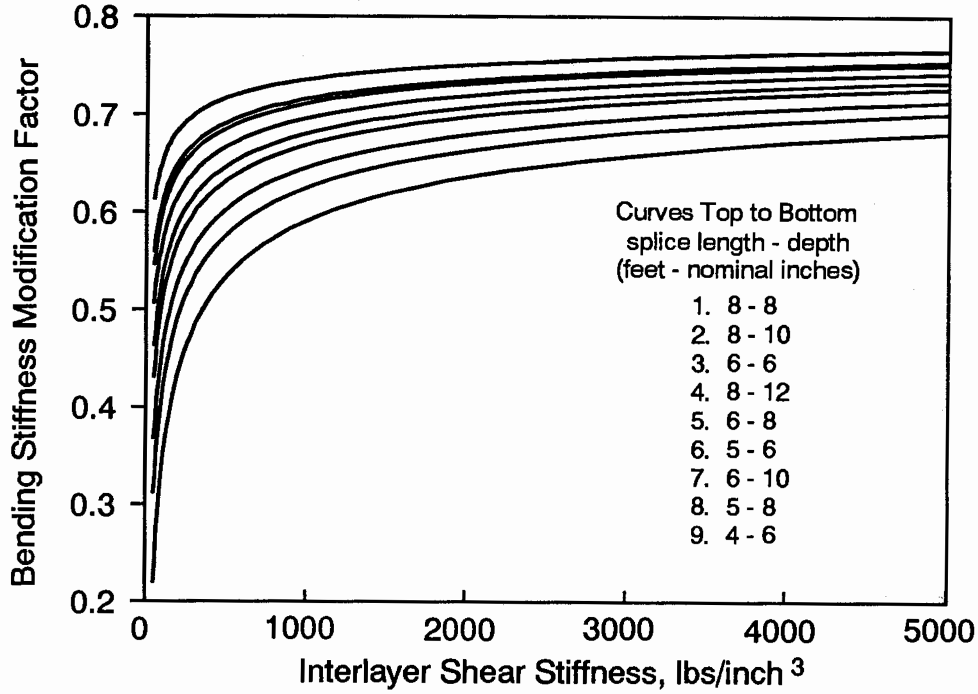

Figure 5 - Relationship between the bending stiffness modification factor and interlayer shear stiffness for different combinations of post depth and overall splice length.

simulation results were interpolated for different effective nail-joint slip values. The results of this interpolation for effective slips of 0.015, 0.020, and 0.030 inches, are given in Table 7. The results at an effective slip of 0.015 inches were included because this is the value generally associated with the proportional limit. Data at slips of 0.020 and 0.030 inches were included to help illustrate the sensitivity of post properties to changes in effective slip.

As previously noted, a linear load-slip relationship was assumed for all nail joints in this study. This is a reasonable assumption only as long as maximum nail-joint slips are limited to a value close to the proportional limit value of 0.015 inches. For this reason, the results in Table 7 for the effective nail-joint slip of 0.030 inches should be used with caution.

The effective interlayer shear capacity (EISC) and maximum wood shear stress (MWSS) values in Table 7 correspond to the bending moments in Table 6. However, because a linear analysis was used in this study, the EISC and MWSS values in Table 7 will change linearly with a change in applied load. To determine a EISC or MWSS value for a different bending moment, M_{new}, simply divide the EISC or MWSS value by the appropriate bending moment from Table 6 and multiply by M_{new}.

The effective interlayer shear capacity, when divided by the corresponding effective nail-joint slip in Table 7, yields the interlayer shear stiffness. For example, the interlayer shear stiffness for design 3A4-6 at an effective slip of 0.020 inches is equal to 19.7 psi divided by 0.020 inches or 985 lbs/in^3.

TABLE 7 - Modeling Results for Effective Nail-Joint Slips of 0.015, 0.020, and 0.030 Inches[a]

Post Design	Effective Interlayer Shear Capacity, psi			Maximum Wood Shear Stress, psi			Maximum Wood Stress Concentration Factor		
	Effective Nail-Joint Slip, inches								
	0.015	0.020	0.030	0.015	0.020	0.030	0.015	0.020	0.030
3A4-6	21.5	19.7	17.4	171	174	180	1.781	1.841	1.941
3A5-6	15.7	14.5	12.9	136	137	140	1.663	1.707	1.785
3A5-8	19.2	17.6	15.6	167	173	180	1.708	1.759	1.852
3A6-6	12.0	11.1	9.8	116	115	115	1.616	1.644	1.696
3A6-8	14.6	13.4	11.9	141	143	148	1.646	1.684	1.752
3A6-10	17.5	16.0	14.2	168	174	183	1.686	1.738	1.809
3A8-8	9.6	8.8	7.8	115	112	111	1.595	1.611	1.641
3A8-10	11.4	10.5	9.3	134	135	137	1.609	1.631	1.676
3A8-12	13.1	12.0	10.7	158	159	164	1.635	1.663	1.715
3B4-6	19.6	18.4	17.0	169	169	168	1.632	1.666	1.717
3B5-6	14.0	12.9	11.8	137	138	138	1.575	1.586	1.629
3B5-8	17.2	16.0	14.6	167	169	172	1.584	1.612	1.658
3B6-6	10.6	9.7	8.7	116	116	116	1.583	1.580	1.585
3B6-8	13.0	12.0	10.8	142	144	146	1.565	1.575	1.607
3B6-10	15.8	14.5	13.1	168	172	176	1.562	1.586	1.631
3B8-8	8.7	7.9	7.0	115	113	112	1.577	1.576	1.574
3B8-10	10.4	9.4	8.4	135	135	137	1.560	1.556	1.571
3B8-12	11.9	10.8	9.7	157	159	162	1.539	1.550	1.581
4B4-6	24.2	21.9	19.4	205	207	208	1.784	1.821	1.867
4B5-6	17.9	15.8	13.5	164	162	163	1.706	1.749	1.799
4B5-6	21.4	19.0	16.4	193	200	207	1.746	1.784	1.831
4B6-6	14.5	12.5	10.2	152	140	135	1.642	1.691	1.752
4B6-8	17.0	14.7	12.2	173	170	172	1.689	1.732	1.785
4B6-10	19.8	17.1	14.6	194	199	211	1.723	1.765	1.81
4B8-8	11.9	10.4	8.7	152	144	136	1.574	1.623	1.694
4B8-10	13.8	12.1	10.1	173	168	164	1.618	1.667	1.733
4B8-12	15.9	13.8	11.6	189	186	192	1.651	1.699	1.761
4C4-6	27.3	25.9	24.4	213	215	215	1.518	1.547	1.591
4C5-6	19.2	18.2	16.9	185	182	177	1.458	1.482	1.516
4C5-8	23.7	22.3	20.8	216	214	215	1.500	1.524	1.561
4C6-6	14.6	13.6	12.6	166	164	156	1.477	1.503	1.542
4C6-8	18.0	16.9	15.6	197	194	185	1.478	1.507	1.547
4C6-10	22.3	20.4	18.9	220	221	218	1.496	1.523	1.558
4C8-8	11.2	10.4	9.4	153	155	153	1.409	1.417	1.443
4C8-10	13.5	12.5	11.3	181	182	181	1.408	1.431	1.464
4C8-12	16.1	14.6	13.3	196	204	205	1.436	1.462	1.498

[a] Three-layer posts subjected to average extreme fiber in bending stress of 1333 psi. Four-layer posts subjected to average extreme fiber in bending stress of 1500 psi.

Interlayer Shear Capacity

To relate interlayer shear capacity to the loads applied to a 2-layer spliced post, Bohnhoff (1993) developed the following equation.

$$F_{max} = f_m*b*d^2/L_f^2 \quad [6]$$

where:

F_{max} = maximum nail shear force per unit length of member
L_f = length of fastener region between butt-joints
d = assembly depth
b = thickness of each layer
f_m = maximum wood bending stress

In developing equation 6, Bohnhoff (1993) assumed rigid wood members, linear load-slip behavior, and uniform distribution of fasteners over the length L_f.

Equation 6 was modified in an attempt to develop a relationship between effective interlayer shear capacity, EISC, and the average extreme fiber in bending stress, f_b, for 3- and 4-layer posts. Specifically, equation x was modified by (1) dividing through by depth, d, and replacing F_{max}/d with EISC, (2) substituting the overall splice length, L, for L_f, (3) substituting f_b for f_m, (4) replacing variable b with parameter B, and (5) adding parameter A to the right side of the equation.

$$EISC = f_b*(A + B*d/L^2) \quad [7]$$

Linear least squares regression was used to fit equation 7 to the EISC data in Table 7. Individual regressions were performed for each joint arrangement. Resulting parameter estimates and R-squared values are given in Table 8. Figure 6 contains a plot of the equations associated with an effective interlayer slip of 0.015 inches.

TABLE 8 - Parameter Estimates for Effective Interlayer Shear Capacity Equation[a]

Joint Arrangement	Effective Interlayer Slip (inches)	Parameter Estimates		R-Squared
		A	B (inches)	
3A	0.015	0.0030	5.619	0.997
3B	0.015	0.0026	5.110	0.999
4B	0.015	0.0042	5.011	0.997
4C	0.015	0.0025	6.698	0.995
3A	0.020	0.0028	5.125	0.996
3B	0.020	0.0021	4.920	0.999
4B	0.020	0.0034	4.653	0.997
4C	0.020	0.0021	6.425	0.997

[a] Effective Interlayer Shear Capacity = $f_b*(A + B*d/L^2)$, where f_b is the average extreme fiber in bending stress in psi, d is the actual depth of the assembly in inches, and L is the overall splice length in inches.

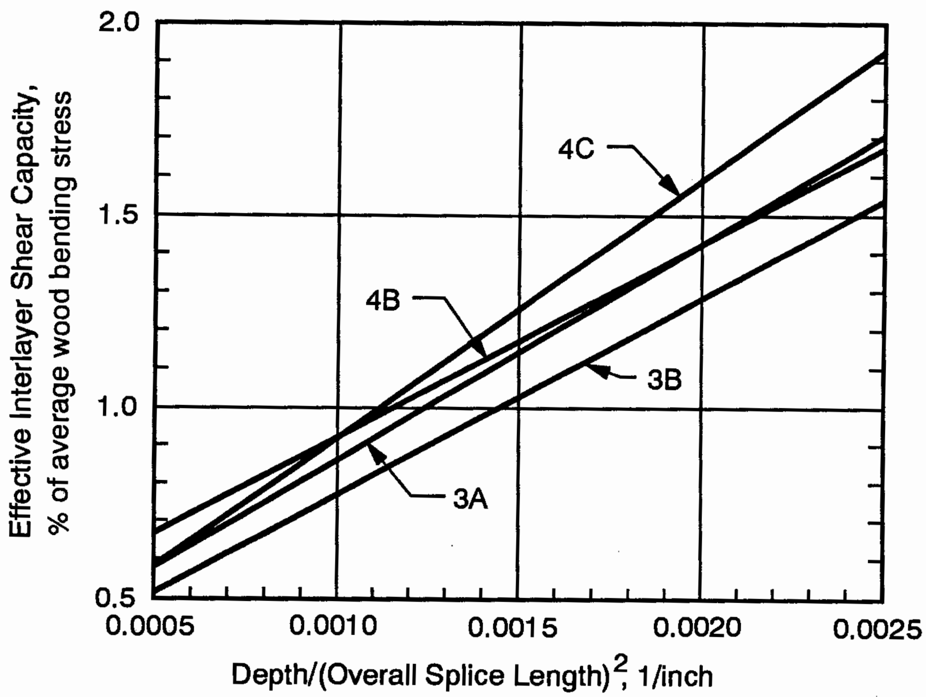

Figure 6 - Relationship between effective interlayer shear capacity (expressed as a percent of average fiber bending stress) and d/L^2 for an effective interlayer slip of 0.015 inches. L is overall splice length and d is post depth.

Based on the R-squared values in Table 8, it can be stated with confidence that equation 7 correctly defines the relative relationship between the effective interlayer shear capacity, average wood bending stress, post depth, and overall splice length. From the plots in Figure 6 it is also evident that joint arrangement has a significant effect on the effective interlayer shear capacity.

The effective interlayer shear capacities calculated using the parameters in Table 8 would appear to exceed those typically used in practice. Table 9 contains material properties and test results for the posts tested by Bohnhoff et. al. (1991) and Williams et. al. (1994). Post designs identified as 1 and 3 in Table 9 are unreinforced 3-layer posts with a 6-inch nominal depth and 4-foot overall splice length. The "design" interlayer shear capacities calculated for these two designs were 9.8 and 12.5 psi.

When using equation 7, it is important to realize that f_b is the average extreme fiber in bending stress <u>in the splice region</u>. Because the bending strength of the splice region of an unreinforced post is less than half that of the unspliced regions, the f_b used in equation 7 will be equal to approximately half the design value assigned to the unspliced regions.

TABLE 9 - Properties of Laboratory Tested Nail-Laminated Posts

Design number	1	2	3	4	5	6	7	8
Reference[a]	B	B	B	B	W	W	W	W
Number tested	28	28	28	28	15	15	15	15
Joint arrangement[b]	3A	3A	3A	3A	4A	4B	4A	4A
Overall splice length, ft	4	4	4	4	4	4	6	6
Nominal depth, inches	6	6	6	6	10	10	10	10
Butt-joint reinforcement?	N	Y	N	Y	N	N	N	Y
Nail type[c]	II	II	III	III	I	I	I	I
Wood specific gravity[d]	0.65	0.65	0.65	0.65	0.59	0.59	0.59	0.59
Allowable nail load[e], lbs	160	160	205	205	110	110	110	110
Nail density[f], nails per square inch	0.061	0.061	0.061	0.061	0.081	0.081	0.095	0.095
Design interlayer shear capacity[g], psi	9.8	9.8	12.5	12.5	8.9	8.9	10.5	10.5
Bending stiffness modification factor	0.554	0.724	0.564	0.708	0.461	0.400	0.599	0.723
Bending strength modification factor	0.43	0.57	0.42	0.53	0.35	0.28	0.44	0.63

a B = Bohnhoff et. al., 1991; W = Williams et. al., 1994.
b See Figure 2.
c See Table 3.
d Based on ovendry weight and volume.
e Based on 1991 NDS (AWPA, 1991) with load duration and penetration factors equal to 1.0.
f Nail density between butt-joints
g Equal to the product of the NDS allowable nail load and the nail density.

Wood Shear Stress

When an unspliced post is subjected to a uniform bending moment along its entire length, there is no shear force in the member. Conversely, when a spliced nail-laminated post is subjected to a uniform bending moment along its entire length, shear forces develop in the splice region that can induce some very high wood shear stresses. Quite often these stresses are ignored, despite the fact that they can surpass 200 psi under typical design bending loads.

An analysis of maximum wood shear stresses (MWSS) indicated that the magnitude of the stresses increased with an increase in member depth and a decrease in overall splice length. The magnitude of the shear stresses was not significantly effected by interlayer shear stiffness although the location of maximum stress tended to shift with changes in interlayer shear stiffness. The MWSS values for joint arrangements 3A and 3B were not significantly different. The following equations were found to best describe maximum wood shear stress

For joint arrangements 3A and 3B:

$$MWSS = f_b*(0.0213 + 0.859*d/L) \qquad [8]$$

For joint arrangement 4B:

$$MWSS = f_b*(0.0440 + 0.717*d/L) \quad [9]$$

For joint arrangement 4C:

$$MWSS = f_b*(0.0485 + 0.777*d/L) \quad [10]$$

where:

f_b = Average extreme fiber in bending stress, psi
d = Actual member depth, inches
L = Overall splice length, inches

Standard errors of estimate for MWSS were 5.1, 7.6, and 6.0 psi for equations 8, 9, and 10, respectively.

SUMMARY

Several 3- and 4-layer spliced nail-laminated post designs were analyzed using finite element analysis methods to determine the sensitivity of the designs to changes in interlayer shear stiffness. Using simulation results, equations were developed for calculating (1) bending stiffness modification factors, (2) effective interlayer shear capacity, and (3) maximum wood shear stresses. All three variables were found to increase linearly with post depth. The bending stiffness modification factor and effective interlayer shear capacity were found to be proportional to the inverse square of the overall splice length. Maximum wood stress was found to be proportional to the inverse of the overall splice length. Effective interlayer shear capacity and maximum wood stresses were dependent on joint arrangement, however, the bending stiffness modification factor was not significantly affected by joint arrangement.

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