ANGLE TO GRAIN STRENGTH OF DOWEL-TYPE FASTENERS

Lawrence A. Soltis

Supervisory Research Engineer
Forest Products Laboratory,[1] Forest Service
U.S. Department of Agriculture, Madison, WI 53705

Suparman Karnasudirdja

Visiting Scientist
Forest Products Research Institute
Bogor, Indonesia

and

James K. Little

Mathematical Statistician
Forest Products Laboratory,[1] Forest Service
U.S. Department of Agriculture, Madison, WI 53705

(Received October 1985)

ABSTRACT

Timber structures require adequate connections between components. Connection design is based on the performance criterion of a single fastener. This study is part of a research effort by the Forest Products Laboratory to establish a common basis design criteria for lateral strength of dowel-type fasteners that includes nails, screws, lag screws, and bolts. A general dowel lateral strength model is determined. It depends on specific gravity, dowel diameter, minimum penetration, and load direction to the angle of grain. The model is then used to determine the diameter at which parallel- and perpendicular-to-grain strength becomes unequal. A nail model is also determined and compared to existing models.

Keywords: Nails, fasteners, timber, connections, strength, density, grain angle.

INTRODUCTION

The safety and economy of a timber structure depend on adequate connections between its components. Connection design criteria are based on the strength value for a single fastener, which is then modified for joint geometry and condition of use. Single-fastener lateral strength values have different bases depending on type of fastener. This study is part of a research effort at Forest Products Laboratory to establish design criteria for dowel-type fasteners in which nail, screw, lag screw, and bolt lateral strength is determined on a common basis.

Nail lateral design criteria are based on strength at a deformation of 0.015 inch, and a minimum penetration into the main structural member. Lateral strengths for parallel- and perpendicular-to-grain loads are equal. Screw and lag screw design criteria are based on strength at proportional limit and a minimum penetration;

---

[1] Maintained in cooperation with the University of Wisconsin. This article was written and prepared by U.S. Government employees on official time, and it is therefore in the public domain (i.e., it cannot be copyrighted).

Wood and Fiber Science, 19(1), 1987, pp. 68-80

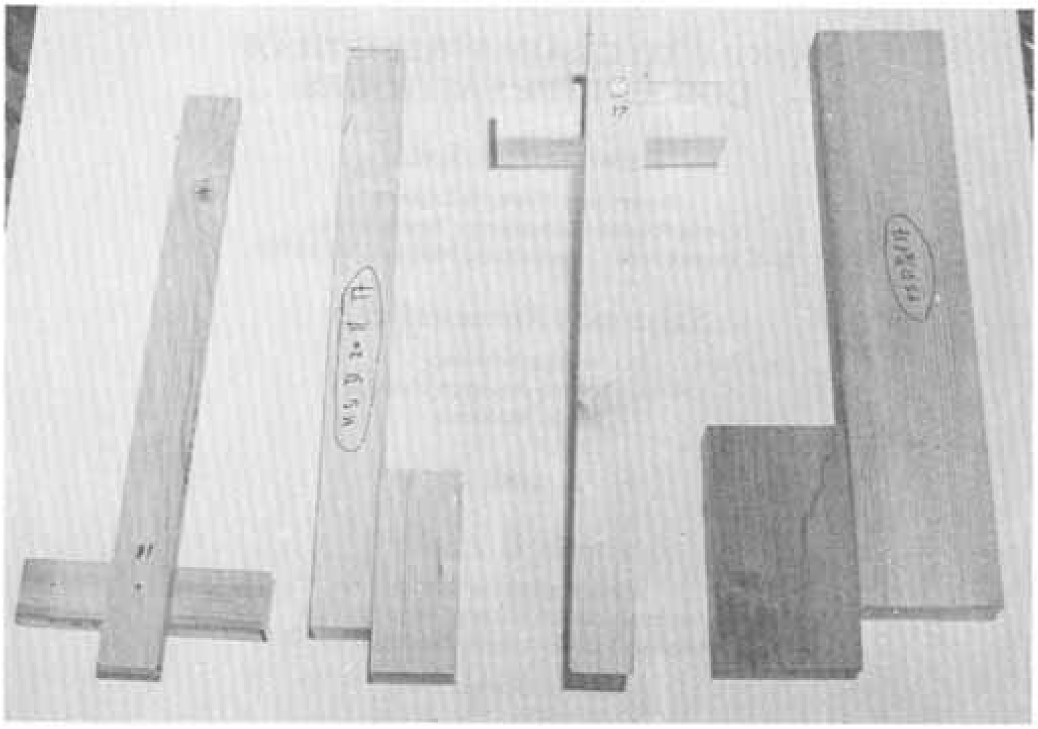

FIG. 1. **Joint configurations for parallel- and perpendicular-to-grain tests.**

lateral strengths for parallel- and perpendicular-to-grain loads are equal for screws but unequal for lag screws. Bolt design criteria are based on strength at proportional limit and the ratio of length of bolt in the main member to the diameter of bolt; lateral strength is unequal for parallel- and perpendicular-to-grain loads.

This study determines the diameter at which parallel- and perpendicular-to-grain lateral strengths become unequal. This is accomplished by developing a general dowel lateral strength model that depends on specific gravity, dowel diameter, minimum penetration, and load direction to the angle of grain. A nail model is then determined based on the same parameters. Future efforts will develop common basis models for screws and lag screws.

BACKGROUND

Criteria for the lateral strength for a single fastener for nails, screws, lag screws, and bolts are summarized in the Wood Handbook (USDA 1974). The lateral strength, p, for a single nail, screw, or lag screw is:

$$p = KD^n \tag{1}$$

where

p = lateral strength at proportional limit deformation, pounds
K = constant dependent on species density
D = fastener diameter, inches
n = 1.5 for nails, 2.0 for screws and lag screws.

The average proportional limit deformation assumed is 0.015 inch for nails, 0.007 to 0.01 inch (dependent on species density) for screws, and 0.014 to 0.055

TABLE 1. *Fastener and joint properties.*

Size	Fastener properties			Member thickness	
	Length	Diameter	Yield stress	Main	Side
	In.	*In.*	*× 10^3 psi*	*In.*	*In.*
Dowel					
6d	1.5	0.113	108	1.0	0.5
20d	3.5	0.192	78	2.0	1.5
60d	5.5	0.242	57	3.0	2.5
$^3/_8$	7.0	0.375	81	3.5	3.5
$^1/_2$	9.0	0.500	62	4.5	4.5
Nail					
6d	2	0.113	108	1.5	0.5
20d	4	0.192	78	2.5	1.5
60d	6	0.242	57	3.5	2.5

inch (dependent on diameter) for lag screws (Newlin and Gahagan 1938). The K values applying to nails, screws, and lag screws are given in the Wood Handbook (1974).

Equation (1) defines lateral strength parallel to grain. Perpendicular-to-grain values are equal to parallel-to-grain values for nails and screws, and vary inversely from 0.5 to 1.0 times parallel-to-grain strength for lag screw diameters of $^3/_{16}$ to 1 inch. This criterion for lag screws was based on bolt research (Trayer 1932).

Lateral strength for nails, screws, and lag screws is based on two-member (main and side) tests where the fastener has some minimum penetration into the main member. Bolt bearing strength is based on proportional limit deformation of three-member tests (Trayer 1932) and depends on the ratio of main member length to bolt diameter. Average proportional limit deformation is 0.025 inch. The perpendicular-to-grain strength varies from the parallel-to-grain strength dependent on bolt diameter.

The effect of grain direction on the lateral strength of a nailed joint is controversial. The Wood Handbook and National Design Specification (NFPA 1982) equate parallel- and perpendicular-to-grain lateral strength. Several researchers (Chu 1978; Foschi 1974; Mack 1960) have found perpendicular-to-grain lateral nail strengths 15–20% lower than parallel to grain. McLain (1976) found different lateral strengths at large deformations but that perpendicular and parallel strengths coincide at small deformations (about 0.01 in.). The Canadian Forest Service (Leach 1964) surveyed 28 references and concluded only that there is disagreement among research results. Virtually no data exist to compare perpendicular- and parallel-to-grain strengths for screws and lag screws. Trayer (1932) found a difference for bolts.

The test method, ASTM D 1761, for lateral strength is also controversial (Pellicane and Bodig 1984). They found lateral strength at small deformations (i.e., proportional limit) to be sensitive to test method, whereas above 0.1-inch deformation results were insensitive to test method. Similar results were found by Liu and Soltis (1984), who suggested using the 0.1-inch criterion as opposed to the proportional limit criterion.

In summary, a model exists for lateral strength at proportional limit deformation

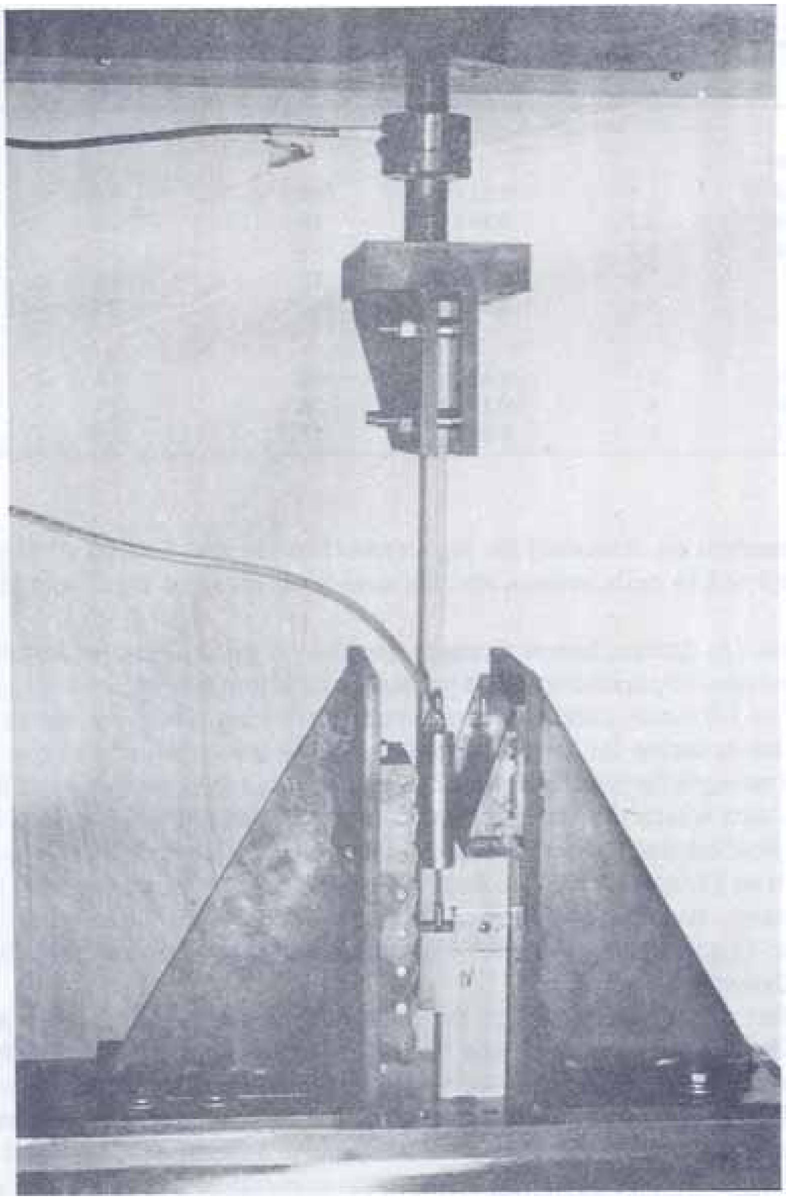

FIG. 2. Laterally loaded specimen in test apparatus.

for parallel-to-grain load. There are questions on the grain angle effect and on the sensitivity of test method at small deformations. Information is needed on angle-to-grain strength and models at larger deformation.

METHOD

Lateral strength values were experimentally determined for five dowel sizes, three nail sizes, two wood species (low and high density), and parallel- and perpendicular-to-grain loads.

Eight series of tests determined dowel and nail lateral strength. Five series were

TABLE 2. *Average[1] lateral strength parallel and perpendicular to rain at 0.015- and 0.10-inch deformation and at ultimate load.*

	Parallel to grain					Perpendicular to grain				
			lateral strength					lateral strength		
Type fastener	Moisture content	Specific gravity	0.015	0.10	Ultimate	Moisture content	Specific gravity	0.015	0.10	Ultimate
	%		Lb			%		Lb		
					HEM-FIR					
Dowell										
6d	12.2	0.345	61	113	120	11.9	0.342	57	116	138
20d	11.2	0.344	172	364	421	11.3	0.345	171	331	425
60d	11.7	0.336	129	400	519	11.6	0.333	179	366	495
$^{3}/_{8}$	12.0	0.341	479	1,170	1,420	11.9	0.337	553	1,010	1,235
$^{1}/_{2}$	12.6	0.343	1,160	2,170	2,420	12.3	0.355	980	1,705	1,990
Nail										
6d	11.4	0.355	75	135	149	11.5	0.344	74	152	182
20d	11.7	0.331	190	382	455	11.3	0.348	226	395	477
60d	11.5	0.336	150	449	586	10.7	0.345	157	413	589
					DOUGLAS-FIR					
Dowell										
6d	12.6	0.443	97	166	178	12.3	0.438	88	157	184
20d	10.9	0.448	184	429	488	12.1	0.402	276	469	549
60d	12.0	0.427	189	566	717	11.7	0.444	471	748	960
$^{3}/_{8}$	11.2	0.450	789	1,555	1,800	11.9	0.451	709	1,330	1,590
$^{1}/_{2}$	12.6	0.436	1,450	2,660	2,950	12.7	0.441	1,330	2,250	2,560
Nail										
6d	11.8	0.453	124	205	230	11.6	0.447	119	216	247
20d	11.8	0.400	217	455	536	12.1	0.403	304	496	587
60d	11.5	0.442	285	703	885	11.5	0.449	287	607	811

[1] Average of 17 replications.

dowel tests; three series were nail tests. Each series consisted of 68 tests; seventeen replications of two wood species tested with load parallel and perpendicular to grain. Regression models were developed for each series.

Each series of tests consisted of a two-member joint configuration with a single fastener in single shear (Fig. 1). Five sizes of dowel fasteners were tested: dowels cut from 6d, 20d, and 60d common wire nails and $^{3}/_{8}$- and $^{1}/_{2}$-inch-diameter steel rods. Three nail sizes were tested: 6d, 20d, and 60d common wire nails. Fastener properties are given in Table 1. Nail yield strength was determined by three replications of a bending test with the load applied at the center of span. Note that the 60d diameter is less than the 0.263 inch listed in the NDS. Holes were predrilled to ensure that the fastener was driven perpendicular to the main and side members. The predrilled holes were 75% of the fastener diameter for the 6d, 20d, and 60d nails and 96% for the $^{3}/_{8}$–and $^{1}/_{2}$-inch diameter dowels.

The main and side members were cut from 2- × 8-inch hem-fir and Douglas-fir boards. Two side members were cut from the same location as two main members to have paired main and side members for matched parallel- and perpendicular-to-grain tests. Each of the eight test series had one matched main and side member for parallel- and perpendicular-to-grain tests cut from the same

TABLE 3. ***Model parameters for nail and dowell fasteners parallel and perpendicular to grain at 0.10-inch and ultimate deformation.***

Deformation	Parallel to grain			Perpendicular to grain		
	α	ß	γ	α	ß	γ
Dowels						
0.10 inch	21,800	0.99	1.92	21,400	1.25	1.76
Ultimate	24,300	0.92	1.96	22,000	1.13	1.74
Nails						
0.10 inch	24,300	1.29	1.73	14,200	1.29	1.43
Ultimate	36,300	1.27	1.90	22,000	1.18	1.62

board. Thus the seventeen replications in each test series were randomly selected from seventeen boards with the different series containing wood from the same board.

The side member thickness (Table 1) was constant for both dowel and nail tests. The main member thickness was varied so that it ensured adequate penetration (minimum 12 × diameter) for the nail tests, whereas the thickness was governed for the dowel tests by the length of dowel which was cut from standard length nails. The sum of the thicknesses of the main and side members for both dowel and nail tests equaled the fastener length.

All materials were conditioned at constant 65 F temperature and 74% humidity; their average moisture content at time of testing was approximately 12%. The specific gravity was determined for main and side members.

The tests were performed in an apparatus (Fig. 2) that minimizes the eccentricity (Liu and Soltis 1984) that made the standard ASTM D 1761 test controversial. Pellicane and Bodig (1984) found that test method is important at small deformation with decreasing sensitivity further along the load-slip curve. The load was applied at a rate of 0.1 inch per minute until failure. Load-slip curves were recorded.

RESULTS

Results were compared at three levels, 0.015- and 0.10-inch deformation and at ultimate load. The average lateral strength, specific gravity, and moisture content of seventeen replications for each test series are given in Table 2.

Equation (2) was fitted to the data for dowel- and nail-type fasteners for both parallel- and perpendicular-to-grain loading at the two deformation levels and ultimate load.

$$p = \alpha s^{\beta} D^{\gamma} \tag{2}$$

where

p = lateral strength, pounds
s = specific gravity
D = diameter, inches
α, β, γ = regression parameters.

The parameters α, β, γ were determined by a linear regression based on the logarithm transform of Eq. (2). Results are given (Table 3) for 0.10-inch defor-

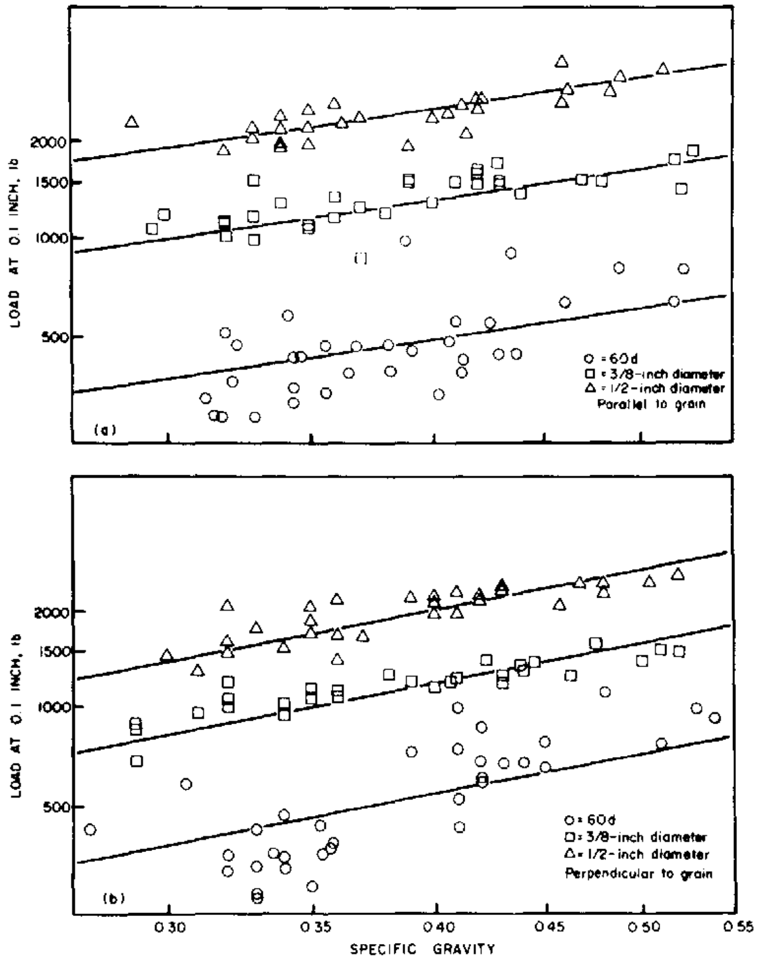

FIG. 3. Example of data scatter for 60d, 3/8-, and 1/2-inch dowels loaded (a) parallel to grain and (b) perpendicular to grain plotted on log scales.

mation and ultimate for each fastener type and direction of load. No results are given at the 0.015-inch deformation because of some of the unusual data for the 60d fasteners.

The parameters in Table 3 are based on fitting the data of all five dowel diameters. The statistical analysis and theory of failure modes (discussed later) indicated that some change occurred between the two smaller diameters and the three larger diameters. Models were then fitted to only the largest diameters. A plot of the three larger diameters is given (Fig. 3) to indicate the data scatter. The parameters of Eq. (2), determined by fitting each group of diameters separately, did not differ markedly from the parameters determined from all five diameter data.

The statistical analysis indicated that we cannot combine parallel- and perpendicular-to-grain strength for the larger diameter dowels. The paired t-tests, using an overall significance level of 0.05, found statistical difference for the 3/8- and 1/2-inch hem-fir, and the 60d, 3/8-, and 1/2-inch Douglas-fir dowels. The model (Eq.

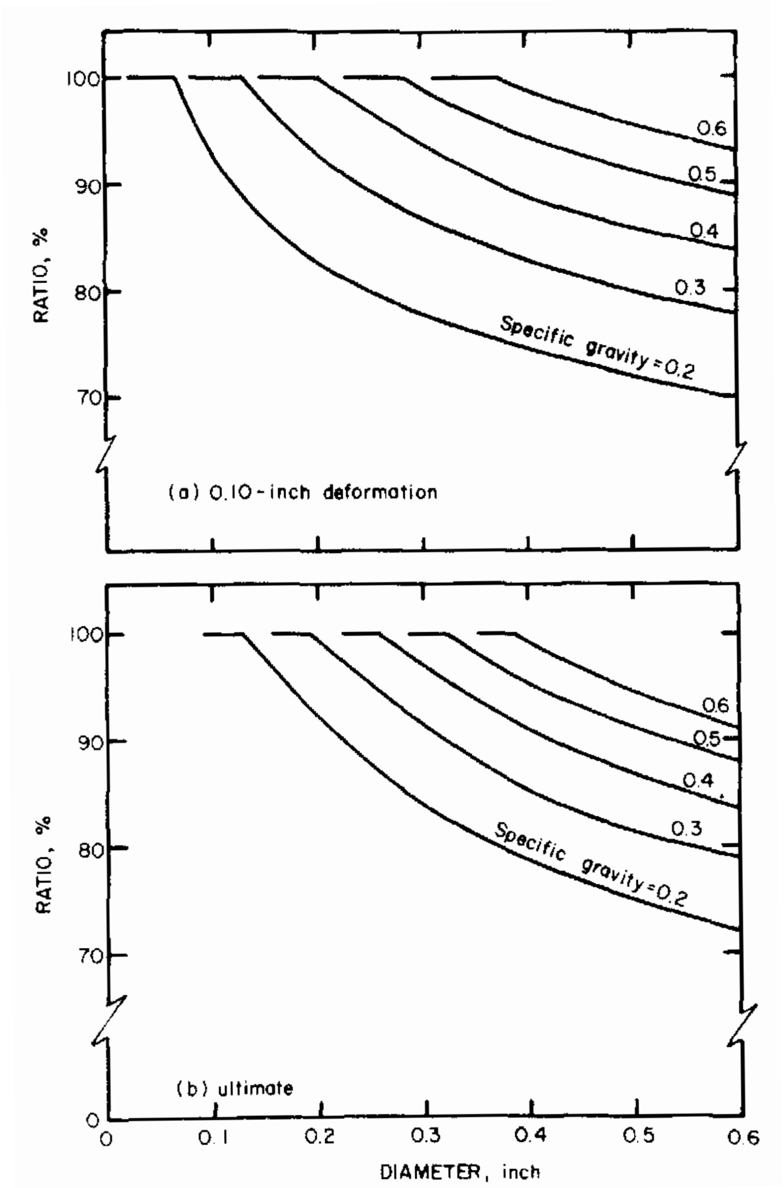

FIG. 4. **The ratio of perpendicular- to parallel-to-grain lateral strength for dowel fasteners at (a) 0.10-inch deformation and (b) ultimate.**

(2), Table 3) determined when parallel- and perpendicular-to-grain strengths differed. Results from equating the strength models for the two directions of grain for various specific gravities and diameters are given for 0.10-inch deformation (Fig. 4a) and ultimate load (Fig. 4b).

The lateral strength parallel and perpendicular to grain is statistically equal for nails. Thus an additional model is determined for the nail data based on regression analysis of the combined parallel- and perpendicular-to-grain data.

$$P_{0.015} = 5{,}500s^{1.49}D^{1.20} \tag{3a}$$

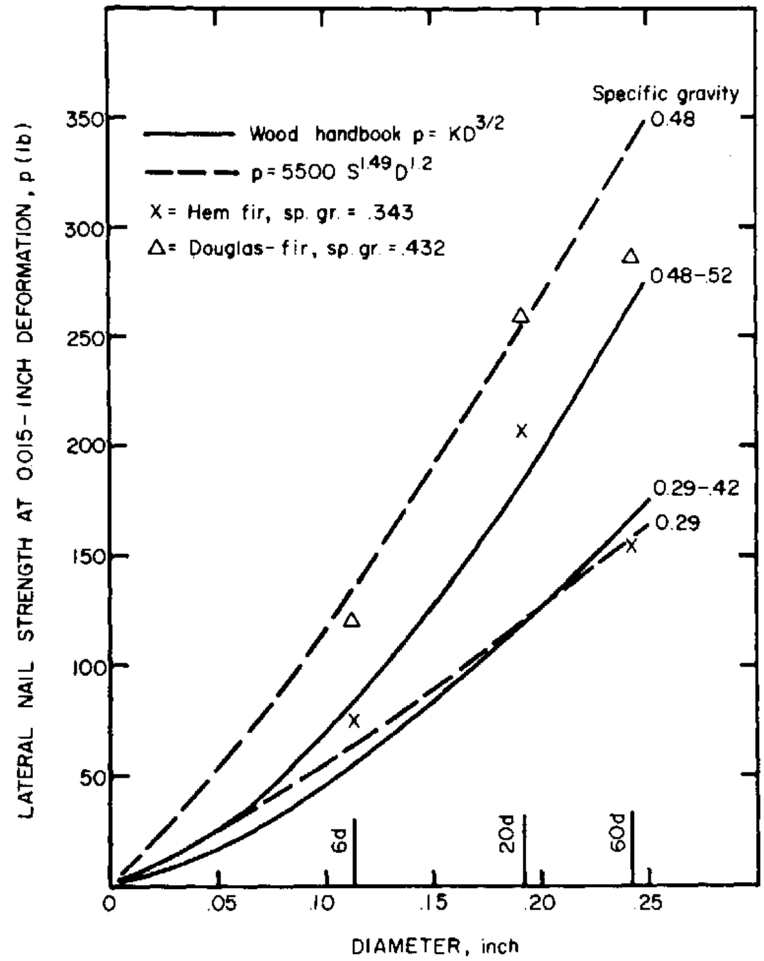

FIG. 5. Comparison of nail models and experimental data at 0.015-inch deformation.

$$P_{0.10} = 18{,}200s^{1.27}D^{1.58} \tag{3b}$$

$$P_{ult} = 28{,}600s^{1.21}D^{1.76} \tag{3c}$$

where the subscripts refer to deformation level. The other parameters are defined in Eq. (2). The lateral strength at 0.015-inch deformation is included for comparison to the existing model (Fig. 5) for two specific gravities. The experimental data are also compared to the existing Wood Handbook model. Each experimental point (Fig. 5) is the average of thirty-four tests, half parallel and half perpendicular to grain.

Dowel and nail strength cannot be compared by Eq. (2). The parameters for the dowel strength are based on results from the five different diameters, whereas the nail parameters are based on three diameters. The 6d, 20d, and 60d nail and dowel results were, however, compared directly by an analysis of variance. For the most part, nails are 10 to 20% stronger than dowels. This result was not substantiated by the results of the 20d and 60d fasteners in hem-fir, thus no conclusions are made.

DISCUSSION

Previous researchers (Liu and Soltis 1984; Pellicane and Bodig 1984) noted that results are dependent on test method at low deformation levels. Some of the unusual strength values for the 60d fasteners at 0.015 inch (Table 2) confirm this. Thus the dowel strength models are given only at 0.10-inch and ultimate deformation.

An example plot (at 0.1-in. deformation) of the residuals (Fig. 6) derived from the regression analysis fitting the model to the data shows a curved pattern and nonconstant spread at each diameter, indicating that Eq. (2) does not follow the data over the range of diameters in this study. The curved pattern persisted even when we omitted the 60d data in fitting the equation. Also, the residuals from joints fastened by both 20d and 60d fasteners showed consistently more spread (for both grain angles) than the residuals from the other diameters.

We tried to characterize this lack of fit by analysis of covariance for the dowel data; treating $\log_e$ (specific gravity (SG)) as the covariate, we fitted this "parallel lines" model

$$\log P_{ij} = a_i + \omega(x_{ij} - \bar{x}) \tag{4}$$

where

P_{ij} = the load observed for the j-th joint of fastener type i
a_i = an intercept that depends on the fastener
x_{ij} = the $\log_e$ (SG) of the j-th joint of fastener type i
ω = the slope
$\bar{x}$ = the mean value of $\log_e$ (SG) over all joints.

We used orthogonal polynomials (appropriate for the actual values of the $\log_e$ (diameters)) to see if the lack of fit arose because of a quadratic trend. We found, however, that cubic and even quartic polynomials were statistically significant. This "high order" lack of fit means that we could not fix up the fit merely by adding second order terms to the regression.

We believe the explanation for the 20d fastener lack of fit results is the deformed shape of the fastener related to the failure mode. The European-based yield theory (Aune and Patton-Mallory 1986) predicts ultimate lateral strength by comparing all possible failure modes (Fig. 7). A yield theory analysis was made to determine failure mode. The 6d fasteners always failed by a mode 3 (Fig. 7) failure. The 60d, $^3/_8$-, and $^1/_2$-inch fasteners always failed by a mode 4 failure. The 20d sometimes failed by mode 3 and sometimes by mode 4 depending on specific gravity. Thus more variation would be expected for the 20d results.

We believe that the explanation for the 60d fastener lack of fit results is the quality of the nails used. We previously noted that the diameter was less than listed in the NDS. The yield strength (Table 1) of 57 ksi is quite low for nails. It is possible that there was large variation in the yield strength for this quality material.

We do recommend Eq. (2), however, since it is the simplest model that considers the effect of diameter and density simultaneously, and so serves as a useful benchmark for engineering applications. It has the further advantage in that direct comparisons can be made with the Wood Handbook.

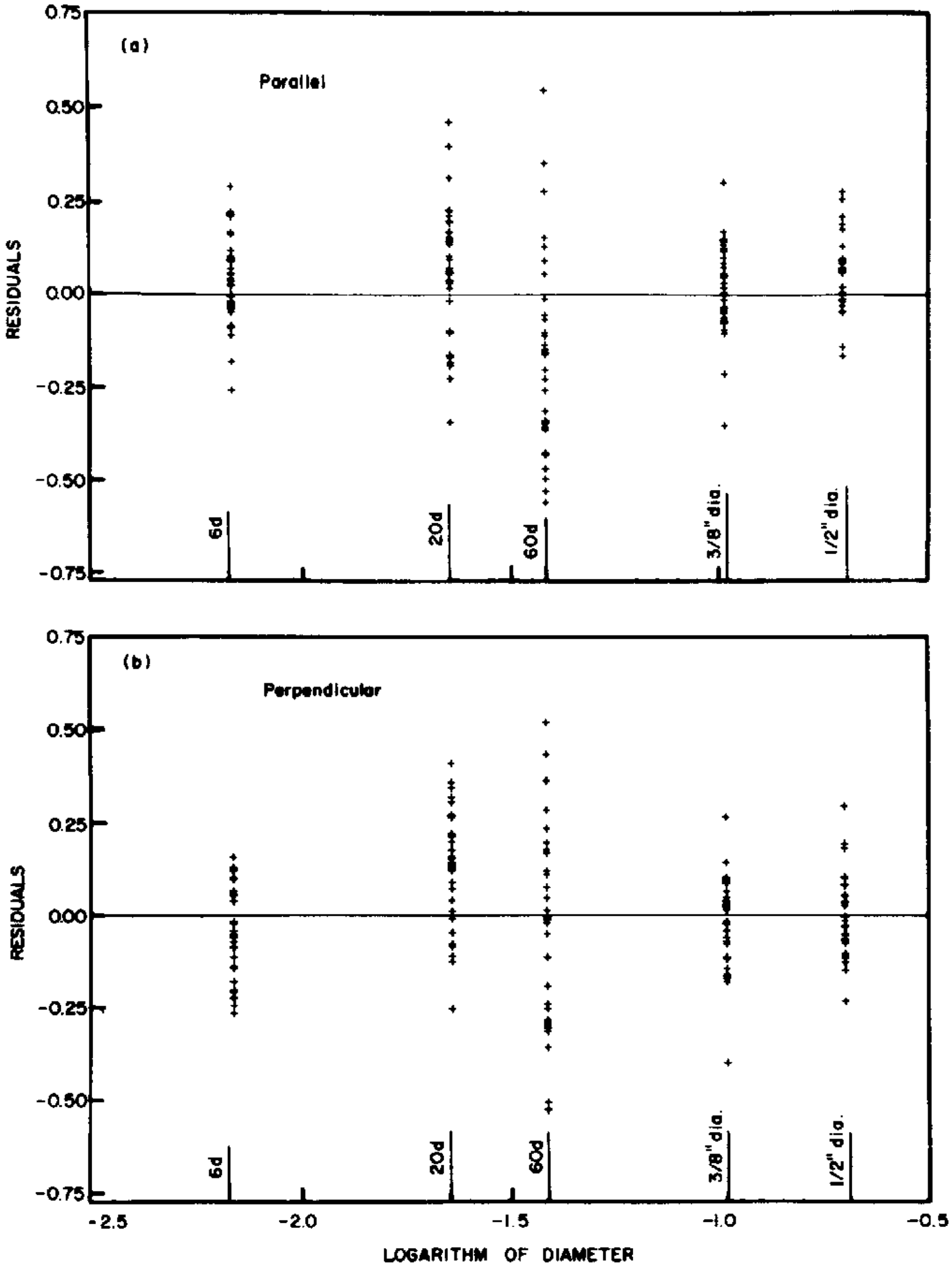

FIG. 6. Example of residuals from regression analysis vs log (diameter) indicating data spread.

There has been controversy (previously discussed in Background section) on the effect of grain direction on lateral nail strength. Our results (Fig. 4) indicate that the specific gravity also affects the grain direction-lateral strength relationship. For example, the model predicts that a 0.25-inch-diameter fastener in a 0.3 specific gravity wood member would have perpendicular-to-grain strength about 90% of

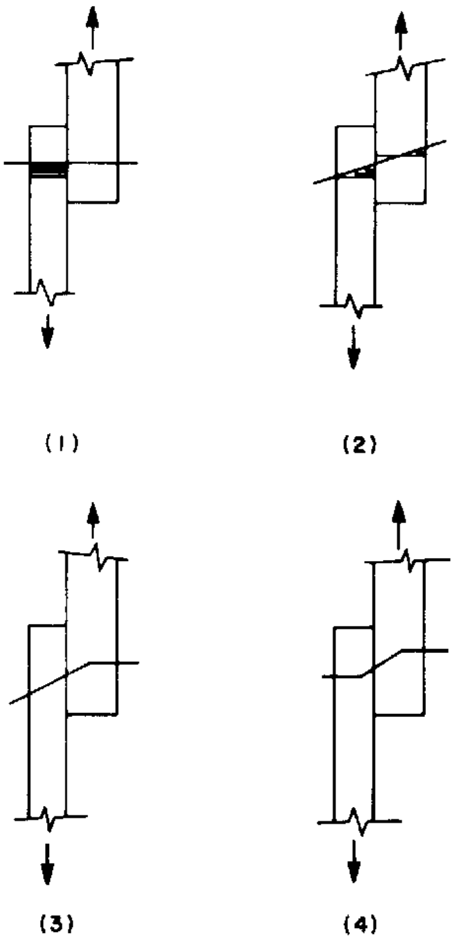

FIG. 7. Four failure modes at ultimate lateral strength from Aune and Patton-Mallory (1986).

parallel-to-grain strength at 0.10 inch deformation (Fig. 4a), and about 95% of parallel-to-grain strength at ultimate (Fig. 4b). However, the model predicts that the same 0.25-inch-diameter fastener in a 0.5 specific gravity member would have equal parallel- and perpendicular-to-grain strength.

The nail lateral strength model (Eq. (3a)) is compared to the Wood Handbook model (Fig. 5) at 0.015-inch deformation. The agreement is good at low specific gravity; at high specific gravity the Wood Handbook model appears conservative. However, the variability at low deformations observed by past researchers and this study suggest that the models at larger deformations will yield more consistent results. Experimental comparisons are also made to the Wood Handbook model (Fig. 5). Again the model is conservative except for the 60d hem-fir test series. This may be due to the failure mode (Fig. 7) which is different for large diameter than for small diameter fasteners.

CONCLUSIONS

A model for dowel lateral strength is presented (Eq. (2)) at 0.10-inch and ultimate deformation. This is part of a research effort at Forest Products Laboratory to establish common basis design criteria for dowel-type fasteners such as nails, screws, lag screws, and bolts. This study then used the lateral strength model to determine the diameter at which parallel- and perpendicular-to-grain loads become unequal (Fig. 4). This result is dependent on both nail diameter and the specific gravity of the attached members.

The model relates lateral strength to specific gravity, dowel diameter, and direction ofload. A nail model was then determined based on these same parameters. A comparison of the nail data to existing models suggests that current design criteria are more conservative for small diameter nails than large diameter nails due to a difference in failure modes.

REFERENCES

AUNE, P., AND M. PATTON-MALLORY. 1986. Theoretical development: lateral load-bearing capacity of nailed joints based on the yield theory. USDA For. Serv. Res. Pap. FPL 469. For. Prod. Lab., Madison, WI.

CHU, Y. P. 1978. Strength of nailed joints. Malaysian Forester 41(1):53–73.

FOSCHI, R. O. 1974. Load-slip characteristics of a nail. Wood Sci. 7(1):69–76.

LEACH, K. E. 1964. A survey of literature on the lateral resistance of nails. Dept. For. Publ. No. 1085. Canadian For. Serv., Ottawa, Canada.

LIU, T. J., AND L. A. SOLTIS. 1984. Lateral resistance of nailed joints. For. Prod. J. 34(1):55–60.

MACK, J. J. 1960. The strength of nailed joint. Tech. Pap. No. 9. CSIRO, Melbourne, Australia.

MCLAIN, T. E. 1976. Curvilinear load-slip relations in laterally loaded nailed joints. Proc., For. Prod. Res. Soc. 30th Annu. Meet., pp. 33–51, Toronto, Canada.

NATIONAL FOREST PRODUCTS ASSOCIATION. 1982. National design specification for wood construction. Washington, D.C.

NEWLIN, J. A., AND GAHAGAN, J. M. 1938. Lag screw joints: Their behavior and design. USDA Tech. Bull. 597. For. Prod. Lab., Madison, WI.

PELLICANE, P. J., AND J. BODIG. 1984. Comparison of nailed joint test methods. J. Testing Eval. 12(5):261–267, Sept.

TRAYER, G. W. 1932. The bearing strength of wood under bolts. USDA Tech. Bull. 332, For. Prod. Lab., Madison, WI.

U.S. DEPARTMENT OF AGRICULTURE, FOREST SERVICE. Wood Handbook. 1974. Agric. Handb. 72 (rev.). Washington, DC.