PARALLEL-TO-GRAIN DOWEL-BEARING STRENGTH OF TWO GUATEMALAN HARDWOODS

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ABSTRACT

Current philosophy of lateral connection design strength is based on the yield theory that relates connection performance to fastener bending strength and wood dowel-bearing strength. This study investigated the parallel-to-grain dowel-bearing strength of two nail sizes and three bolt sizes in two high-density Guatemalan hardwood species: Danto (*Brosimum alscastrum*) and Ramon (*Vatairea lundellii*). The objective was to determine the bearing strength of higher specific gravity (SG) wood to augment the database for determining bolt- and nail-bearing strength SG relationships. Results indicate that bolt-bearing stiffness is influenced by the diameter of the bolt, but bolt-bearing strength is not influenced by the diameter of the bolt. For nails, both the bearing stiffness and strength are significantly influenced by the diameter of the nail. Comparison of the dowel-bearing strength of a similar-sized nail and bolt indicate a statistically significant difference. Finally, existing U.S. and European expressions relating dowel-bearing strength to SG and dowel diameter fail to predict mean values or trends in these high-density wood species.

Lateral design capacities for both nailed and bolted connections in the United States are currently calculated by the yield theory. This methodology has replaced empirical expressions as the standard for connection design in the National Design Specifications (NDS) for Wood Construction (1) and is the basis for the connection design in the new standard for load and resistance factor design (LRFD) for engineered wood construction (2). These specifications use the yield theory to relate the 5 percent diameter offset connection load to geometry, dowel-bearing strength, and dowel-bending strength. The NDS uses and the LRFD recommends dowel-bearing expressions for connection design values developed by Wilkinson (14) for solid wood. Wilkinson's dowel-bearing expressions were determined for both nails and bolts in common wood species with a specific gravity (SG) range between 0.36 and 0.52. These expressions are sometimes unknowingly extrapolated for use in a connection made with high-density wood.

The primary objective of this research was to determine the dowel-bearing strength for nails and bolts in higher SG wood, namely Danto (*Brosimum alscastrum*) and Ramon (*Vatairea lundellii*). Danto and Ramon are high-density Guatemalan hardwood species. Secondary objectives included the following: 1) determine the probability distribution functions for the 5 percent diameter offset dowel-bearing strength; 2) evaluate the significance of dowel diameter on bearing strength and stiffness; and 3) compare current U.S. and proposed European design expressions (6) for dowel-bearing strength to data generated from high-density wood species.

BACKGROUND

Evaluation of the dowel bearing properties of wood in the United States is relatively new. Recently, a standard for evaluating dowel-bearing strength was developed and accepted by the American Society for Testing and Materials (ASTM) (5). This standard calls for the application of a uniform deformation over the entire length of the dowel and defines the dowel-bearing strength at the intersection of the initial stiffness line (defined in the linear portion of the load-deformation curve) offset by 5 percent of the dowel diameter with the load-deformation curve (Fig. 1). This standard is relatively new; therefore, only limited dowel-bearing strength data have been generated according to this new method in the United States.

Wilkinson (14) determined the dowel-bearing strength for several wood species with procedures identical to the current

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Forest Prod. J. 49(6):77-87.

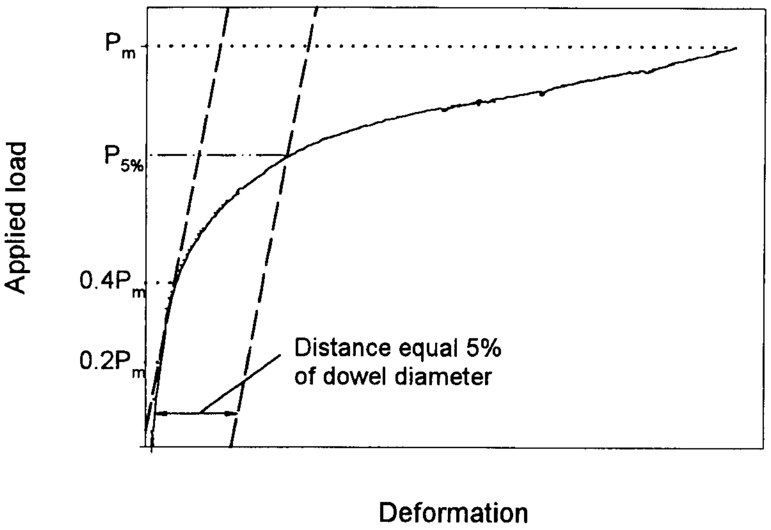

Figure 1. — Definition of 5 percent diameter offset stress.

TABLE 1.—Material used in bolt- and nail-bearing tests.

Dowel type	Species	Diameter	Sample size	Average specimen dimensions Length	Width	Thickness
		(mm)		(mm)		
Bolt	Ramon	6.4	46	114	36.9	86.6
		12.7	45	164	36.8	86.4
		19.1	48	178	36.9	86.7
	Danto	6.4	46	114	37.1	86.4
		12.7	46	164	37.1	86.4
		19.1	47	178	37.3	86.6
Nail	Ramon	3.3	47	86.6	17.5	76.0
		6.2	48	86.1	18.0	75.9
	Danto	3.3	47	86.6	17.6	75.8
		6.2	47	86.8	18.2	75.8

ASTM (5) procedure. His material ranged between 0.36 and 0.52 in SG and focused on 19.1-mm (3/4-in.) bolts and 4.11-mm (0.162-in.) nails. Expressions were developed that related the SG and dowel diameter for bolts aligned parallel and perpendicular to the grain and nails driven into the side grain. Grain orientations (14) or ring thickness (15) have little effect on the 5 percent diameter dowel-bearing strength. These expressions were later accepted into the current NDS wood construction specifications (1) and are recommended by the LRFD code (2). Design 5 percent diameter dowel-bearing strengths of nails applicable for both the main and side wood members are expressed by the following:

$$F_e = 114.45(SG)^{1.84}$$

where:

F_e = 5 percent diameter dowel-bearing strength (N/mm^2)

SG = SG using ovendry weight and ovendry volume

Design 5 percent diameter dowel-bearing strengths for bolts aligned parallel to the grain are expressed as:

$$F_e = 77.25(SG)$$

where F_e is expressed in N/mm^2 and G is defined using ovendry weight and ovendry volume.

Note that both expressions are only a function of the SG of the wood material and are not a function of the dowel size. Wilkinson also noted a 20 percent difference between the 5 percent diameter bearing strengths of nails and bolts of similar size. He stated this difference is due, in part, to the bearing surface generated by fabrication.

European communities have researched the use of the yield model for connection strength since Johanson's (8) original work on bolted connections and Möller's (10) work on nailed connections. European communities focus on predicting the ultimate strength of the connection whereas U.S. research is referenced to a 5 percent offset diameter strength. This results in some slightly different design input parameters. Published dowel-bearing expressions by Smith et al. (13) and Elhbeck and Werner (7) used a testing procedure that is different than the recently adopted ASTM (5) standard. The accepted European dowel-bearing strength testing standard pushes the nails by loads applied at both ends of the nails and determines the bearing strength at ultimate load or load at 5 mm of deformation. To reduce the effects of dowel flexibility, the wood members have a thickness equal to two dowel diameters.

Smith et al. (13) found that nail- and bolt-bearing strength values are a function of both SG and nail diameter. They developed the following relationships for nail dowel-bearing strength in softwoods and tropical hardwoods:

$$S = 0.048\rho\left(\frac{d}{6}\right)^{-0.36} \quad \textit{Softwoods}$$

$$S = 0.071\rho\left(\frac{d}{6}\right)^{-0.28} \quad \textit{Tropical Hardwoods}$$

where:

S = maximum bearing strength (N/mm^2)

d = nail diameter (mm)

ρ = timber density (kg/m") with mass and volume at 13 percent moisture content (MC)

These researchers did note a nail-bearing-strength difference between the parallel and perpendicular grain orientations, but the difference was small; therefore, they combined all data for regression analysis.

For bolt dowel bearing, they noticed that perpendicular- and parallel-to-grain dowel bearing had significant orientation effects. No bearing difference was observed between hardwood and softwood species with bolts loaded parallel to the grain. They characterized bolt-bearing parallel to the grain by:

$$S = (0.082 - 0.00082d)\rho$$
Softwoods and Tropical hardwoods

and for bolt-bearing perpendicular to the grain, they derived the following:

$$S = (0.041 - 0.00088d)\rho \quad \textit{Softwoods}$$

$$S = (0.043 - 0.00081d)\rho \quad \textit{Tropical Hardwoods}$$

Finally, comparison between values generated by either compressive or tensile load showed no practical difference.

Ehlbeck and Werner (7) expanded the work by Smith et al. (13) by conducting dowel-bearing tests on several species of wood parallel to the grain, perpendicular to the grain, and at three intermediate angles. Parallel-to-grain tests were conducted both in tension and compression. They observed that compression parallel-to-grain strength was less than in tension and dowel diameter significantly influenced results. Based largely on the previous two studies, the following dowel-bearing expression was proposed for the new European wood construction design code, entitled EUROCODE 5:

$$f_{h,\alpha} = \frac{f_{h,0}}{(k_{90}\sin^2\alpha + \cos^2\alpha)}$$

where:

$f_{h,0} = 0.082(1 - 0.01d)\rho$

$k_{90} = 1.35 + 0.015d$ (*softwoods*)

$k_{90} = 0.90 + 0.015d$ (*hardwoods*)

α = the angle between the load direction and the grain of the member

For nailed joints with a diameter less than 8 mm, the following expression was developed (7):

$$f_h = 0.082d^{-0.30}\rho \quad \textit{driven nails}$$

$$f_h = 0.082(1 - 0.01d)\rho \quad \textit{predrilled}$$

These expressions are independent of the direction of load or grain angle. For typical sizes and specific gravities, the just-stated driven and predrilled nail expressions predict a 37 to 25 percent increase in dowel-bearing strength for predrilled holes, larger than the 20 percent observed by Wilkinson (14).

European research indicates that maximum dowel-bearing strength in hardwoods and softwoods has different design expressions for both nails and bolts. In addition, European dowel-bearing design expressions indicate that dowel diameter affects bearing strength. Wilkinson's research, which was limited in sample size and time, could not more conclusively evaluate the effects of dowel diameter on the 5 percent offset diameter strength. In addition, Wilkinson did not test tropical species or high SG wood in the development of bolt- and nail-dowel-bearing design expressions. This study augments Wilkinson's original research by determining the 5 percent offset diameter strength for two tropical hardwoods and uses large sample sizes for statistical comparison of dowel diameter effects on the 5 percent offset diameter strength.

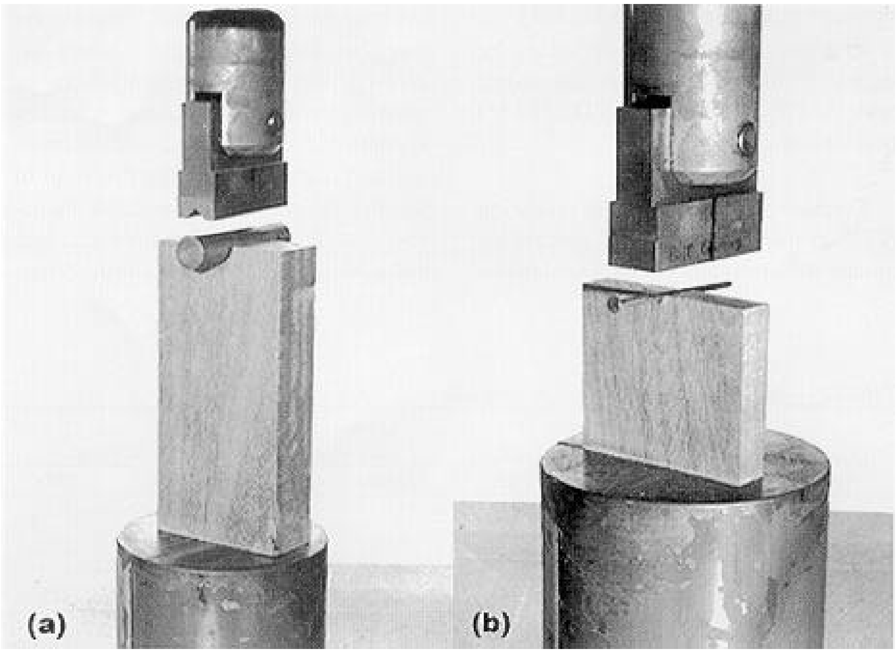

Figure 2. —Dowel-bearing test setup: a) bolt-bearing test and b) nail-bearing test.

RESEARCH METHODS

The dowel-bearing strength of two high SG Guatemalan hardwood species, Danto and Ramon, was investigated. Specimens were cut from the undamaged remnants of 38- by 89-mm (2- by 4-in.) bending test specimens. Discussion of the characteristics and origin of these hardwood species was presented by Rosales and Green (11).

Dowel-bearing strength was determined for three bolt diameters: 6.4 mm (1/4 in.), 12.7 mm (1/2 in.), and 19.1 mm (3/4 in.), and for two nail diameters: 3.3 mm (0.131 in.) and 6.2 mm (0.244 in.). To generate the specimens, the entire bending source material for each species was sorted by SG and divided into two groups with approximately the same SG distribution. From one source group, the 6.4-mm (1/4-in.) bolts and the 3.3-mm (0.13 1-in.) and 6.2-mm (0.244-in.) nail-bearing specimens were fabricated. From the other source group, the 12.7-mm (1/2-in.) and 19.1-mm (3/4-in.) bolt-bearing specimens were fabricated. For bolt-bearing tests, half holes were oversized 1.6 mm (1/16 in.) to be consistent for all dowel tests. In practice, 6.4-mm bolts have only a 0.8-mm (1/32-in.) oversized hole. The specimens and average sizes for the bolt-bearing tests are listed in **Table 1.** For the nail-bearing specimens, a pilot hole approximately 90 percent the diameter of the shank was drilled prior to nailing. Smaller-diameter pilot holes were tried, but these sizes caused splitting of the member. The specimens and average sizes for the nail-bearing tests are listed in **Table 1. Figure 2** shows typical bolt- and nail-bearing test configurations.

Deflection of the testing machine load head was measured with a linear variable differential transducer. Load and deformation readings were used to calculate the stiffness between 20 and 40 percent of the maximum load for determination of the 5 percent diameter offset yield load, shown in **Figure 1.** Research methods conformed to ASTM D 5764 (5).

After testing, MC and SG values for each specimen were found in accordance with ASTM D 4442 (4) and D 2395 (3) procedures.

RESULTS

Average and coefficient of variation (COV) values for stiffness, 5 percent diameter offset strength, and ratio of maximum load to 5 percent diameter offset load for each species and bolt size are given in **Table 2.** Stiffness values increased with increasing bolt diameter, whereas the 5 percent diameter bearing strength values decreased with increasing bolt diameter. Note that the ratio of the maximum load and 5 percent diameter offset load decreased for increasing bolt size. The COV values for the 5 percent diameter offset strengths for these bolts were within the range of Wilkinson's findings, 5 to 20 percent. The ratio of maximum load to 5 percent diameter load averaged 1.04 for the 12.7-mm and 19.1-mm bolts in both species. For the 6.4-mm bolts, average ratio was 1.19. This higher ratio is attributed to the effect of 1.6-mm oversizing of the 6.4-mm bolt. Also, the 6.4- and 12.7-mm bolts had

TABLE 2. —Results from bolt- and nail-bearing tests.

Dowel type	Species	Dowel diameter	MC	Specific gravity		Stiffness		5% diameter yield strength		Maximum load ÷ 5% diameter load	
				Mean	COV	Mean	COV	Mean	COV	Mean	COV
		(mm)	(%)			---- (kPa/mm) ----		---- (MPa) ----			
Bolt	Ramon	6.4	11.0	0.76	6.8	118.2	24.3	71.6	13.2	1.20	5.6
		12.7	11.5	0.76	6.6	102.2	14.1	70.2	9.8	1.06	2.5
		19.1	11.7	0.75	7.1	72.0	17.4	67.2	10.8	1.05	3.1
	Danto	6.4	9.8	0.70	5.9	130.2	22.3	61.8	11.2	1.18	4.6
		12.7	10.4	0.70	7.0	93.0	16.8	60.1	11.3	1.04	2.5
		19.1	10.2	0.70	5.7	82.4	15.9	59.4	11.41	1.02	1.9
Nail	Ramon	3.3	11.7	0.75	7.5	175.8	29.4	66.9	15.0	1.05	3.8
		6.2	11.8	0.75	7.6	135.8	26.2	60.2	13.1	1.04	2.9
	Danto	3.3	10.3	0.70	5.6	173.7	23.6	58.2	10.0	1.08	3.4
		6.2	10.2	0.69	6.4	119.6	28.3	50.6	10.7	1.07	3.7

TABLE 3.—Five percent-diameter offset strength probability distributions for bolts.

Species	Bolt diameter	Distribution”	Scale parameter (α)	Shape parameter (β)	x^2	K-S[2]	A-D[c]
	(mm)						
Ramon	19.1	Normal	48.9	79.4	9.872	0.116	0.746
		Lognormal	4.20	0.123	12.946	0.121	1.131
		Weibull[d,e]	70.6	11.9	4.510	0.090	0.274
	12.7	Normal	70.2	45.9	7.636	0.116	0.515
		Lognormal[e]	4.25	0.010	8.000	0.129	0.687
		Weibull[e]	73.2	11.9	5.818	0.073	0.419
	6.4	Normal[e]	71.6	87.6	4.478	0.182	0.486
		Lognormal[d]	4.26	0.016	7.609	0.083	0.321
		Weibull	75.9	6.8	15.043	0.128	1.623
Danto	19.1	Normal[d]	59.4	44.7	4.511	0.077	0.355
		Lognormal	4.08	0.014	8.723	0.096	0.598
		Weibull[e]	62.3	10.5	6.809	0.080	0.190
	12.7	Normal	60.1	44.9	7.600	0.141	0.689
		Lognormal[d,e]	4.09	0.012	12.400	0.119	0.466
		Weibull	63.2	8.8	9.200	0.163	1.410
	6.4	Normal	61.8	46.9	4.478	0.081	0.661
		Lognormal[d,e]	4.12	0.012	5.261	0.080	0.477
		Weibull	64.9	9.3	14.652	0.123	1.149

[a] Normal distribution:

$$f_x(x) = \frac{1}{\beta\sqrt{2\pi}} e^{[-(\frac{x-\alpha}{\sqrt{2}\beta})^2]}$$

Lognormal distribution:

$$f_x(x) = \frac{1}{x\beta\sqrt{2\pi}} e^{[-(\frac{\ln x-\alpha}{\sqrt{2}\beta})^2]}$$

Weibull distribution:

$$f_x(x) = \frac{\alpha}{\beta^\alpha} x^{\alpha-1} e^{-(x/\beta)^\alpha}$$

[b] Kolmogorov - Smirnov test.
[c] Anderson - Darling test.
[d] Best-fit distribution for 5 percent diameter bearing strength
[e] Best-fit distribution for specific gravity.

similar 5 percent diameter strength values; therefore, it was hypothesized that oversizing only affects the maximum dowel-bearing strength.

Average and COV values for stiffness, 5 percent diameter offset strength, and ratio of maximum load to 5 percent diameter offset load for each species and nail size are listed in **Table 2.** Stiffness values increased with increasing nail diameter, whereas the 5 percent diameter bearing strength values decreased with increasing nail diameter. The COV values for the 5 percent diameter offset strengths for these nails were within the range of Wilkinson's findings, 5 to 20 percent. The ratio of maximum load to 5 percent diameter load was fairly consistent, an average of 1.06, for both nail diameters and wood species.

SG (dry weight/volume at 12% MC) and average MC are listed in **Table 2.** SG values for these species were within values published by Rosales and Green (11).

DISCUSSION

STRENGTH DISTRIBUTION

As the wood building design community moves toward a load and resistance design philosophy, there is a need to quantify the underlying strength distributions. Each test grouping had a minimum of 45 replications; therefore, an analysis of the 5 percent diameter offset strength distribution was warranted. Three types of distributions were examined by maximum likelihood estimators: normal, lognormal, and two-parameter Weibull. These distributions were chosen because they are typically used to classify mechanical response in wood and wood-based materials. Chi-squared, Anderson-Darling, and Kolmogorov-Smirnov tests were performed to evaluate the goodness-of-fit of these distributions to data. **Figures 3** through **6** show 5 percent diameter bearing strength histograms for bolts and nails with the normal, lognormal, and Weibull distributions superimposed on the figures. All distribution parameters found by the likelihood estimators along with the goodness-of-fit estimates are listed in **Table 3** for bolts and in **Table 4** for nails. Based on goodness-of-fit comparisons, the best-fit distribution for each dowel size is highlighted in **Tables 3** and **4.** Also identified in these tables is the best-fit distribution of the specimen SG results. No single probability distribution seemed to successfully model the 5 per-

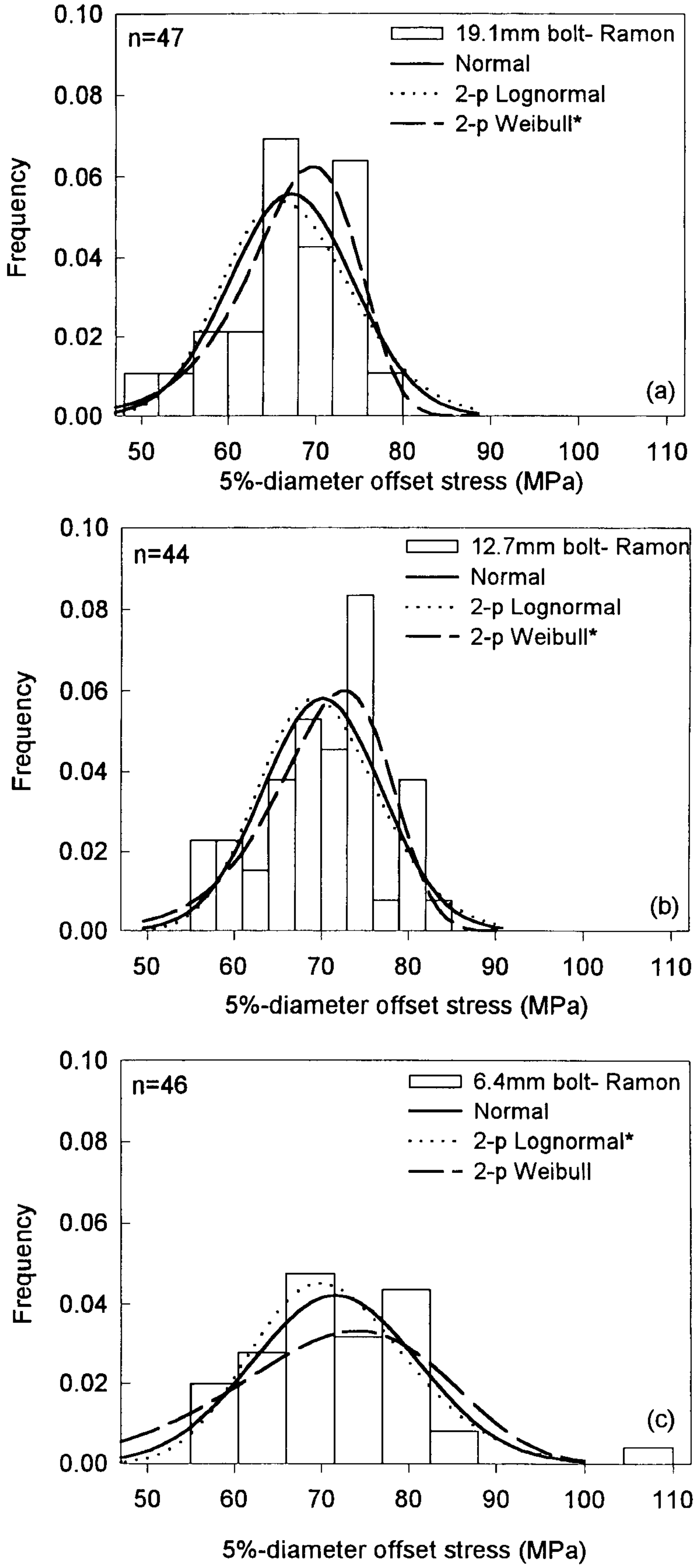

Figure 3. — Histogram of 5 percent offset diameter strength for bolts tested in Ramon: a) 19.1-mm-diameter bolt; (b) 12.7-mm-diameter bolt; and c) 6.4-mm-diameter bolt; the asterisks identify the best-fit distributions.

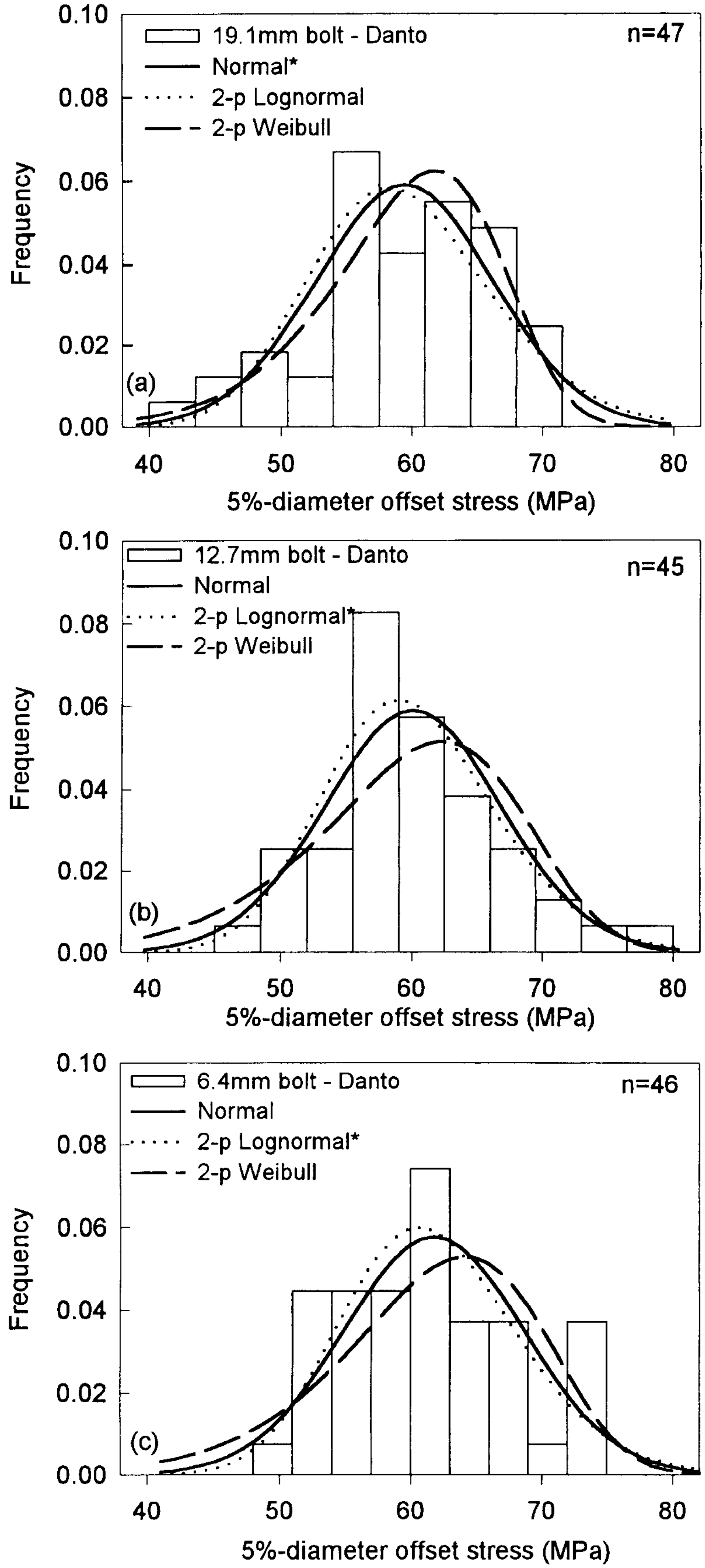

Figure 4. —Histogram of 5 percent offset diameter strength for bolts tested in Danto: a) 19.1-mm-diameter bolt; b) 12.7-mm-diameter bolt; and c) 6.4-mm-diameter bolt; the asterisks identify the best-fit distributions.

cent diameter bearing strength for either bolts or nails.

Dowel-bearing Performance

An analysis of variance (ANOVA) was performed to determine if dowel diameter significantly influenced stiffness and 5 percent diameter dowel-bearing strength values. ANOVA calculations were performed using a general linear model and Tukey's studentized range test for multiple comparison hypotheses at a 0.05 level of confidence (12).

Stiffness performance. — An ANOVA was conducted to determine if the diameter of the bolt or nail significantly affects the 20 to 40 percent stiffness responses. **Table 5** summarizes the ANOVA results for bolts and nails. Average values in **Table 5** that have a common double underline are not significantly different at a 0.05 level of confidence. Stiffness results for bolts tested in Ramon are significantly different for each bolt diameter. For bolts tested in Danto wood species, stiffness values for the 19.1- and 12.7-mm sizes were not significantly different, but these two diameter sizes had stiffness values that were significantly different from the smallest bolt size tested. For all nail results, stiffness values were significantly different for each nail diameter. A comparison of all ANOVA information indicates that dowel diameter significantly affects the bearing stiffness in high-density woods and bearing stiffness increases with dowel diameter.

Strength performance. — Because of the limited number of test replications in Wilkinson's (14) study, an ANOVA was conducted to determine if the size of the dowel significantly affects the dowel-bearing strength. Average values in **Table 5** that have a common double underline are not significantly different at a 0.05 level of confidence. Bolt-bearing results in Ramon showed no significant difference between the 19.1- and 12.7-mm sizes, and in Danto there was no significant difference among all bolt sizes. Therefore, this analysis indicates that the bolt diameter has no effect on 5 percent diameter bearing strength in high-density wood, which is in line with Wilkinson's findings. For nail-bearing results, the ANOVA indicated that the size of the nail has a significant effect on 5 percent diameter nail-bearing strength, which contradicts Wilkinson's work.

Dowel type. — A comparison was made to determine the effect of testing procedure, or in practice the method of fabrication, on dowel-bearing results. Typically for bolted connections, oversized holes are used, whereas for nailed connections with SG values greater than 0.60, a pilot hole is drilled at 90 percent of the nail diameter. Therefore, driving a nail will damage the fibers around the dowel and can result in a different 5 percent diameter offset strength. An approximate comparison of these effects in high-SG woods was examined by comparing the 6.4-mm (1/4-in.) bolt and the 6.2-mm (0.244-in.) nail results. Assuming that moisture effects for nail- and bolt-bearing were equivalent, all data were adjusted to an MC of 12 percent using relationships developed by Winistorfer (16) for bolts. All data were adjusted to a common SG, assuming that the nail-bearing strength varied by SG to the 1.84 power and bolt-bearing strength was linearly related to SG (1). For the Ramon species, data were adjusted to an SG of 0.75; for the Danto species, data were adjusted to an SG of 0.70.

An ANOVA on the adjusted 5 percent diameter offset values for both Ramon and Danto indicated that the nail values were significantly less than a similar-sized bolt with a 0.05 level of confidence. For Danto, average nail-bearing strength was 17 percent less than similar-sized bolts, and for Ramon, average nail-bearing strength was 12 percent less than similar-sized bolts. Wilkinson (14) also noted a similar trend when comparing nail- and bolt-bearing results in southern pine, but he observed a 20 percent decrease. It is speculated that this difference is related to the damaging of fibers when driving a nail into wood.

COMPARISON WITH CURRENT DESIGN EXPRESSIONS

Dowel-bearing results were compared with the current NDS/LRFD and proposed EUROCODE design expressions for parallel-to-grain dowel bearing. NDS/LRFD expressions were first adjusted to SG values based on ovendry weight and volume at an MC of 12 percent.

The 5 percent diameter bolt-bearing results are shown in **Figure 7** along with the modified parallel-to-grain NDS/LRFD bolt-bearing design expression. This design expression tends to underpredict the dowel-bearing strength for the higher SG material. Comparisons were made using the EUROCODE expressions for parallel-to-grain dowel-bearing strength where these expressions consider the SG and the diameter of the nail. **Figure 7b** shows the bolt results calculated with the maximum load along with the EUROCODE parallel-to-grain expression for the 6.4- and 19.1-mm dowel diameters. Based on visual inspection of **Figures 7a** and **7b,** the modified NDS expression generally predicts the Danto species but underpredicts the response in the higher-SG Ramon species. The EUROCODE expression underpredicted dowel-bearing strength in both species and the deviation increased with increasing SG.

The 5 percent diameter nail-bearing results are shown in **Figure 8a** along with the modified NDS nail-bearing design expression. This design expression tends to overpredict the nail-bearing strength for the high-SG material. The modified NDS/LRFD expressions for nails overpredicts data, and the error increases as the SG increases. A further comparison is made to the EUROCODE expressions for nail-bearing strength where these expressions consider the type of wood (tropical hardwood or softwood), SG, and the diameter of the nail. **Figure 8b** shows the nail-bearing results

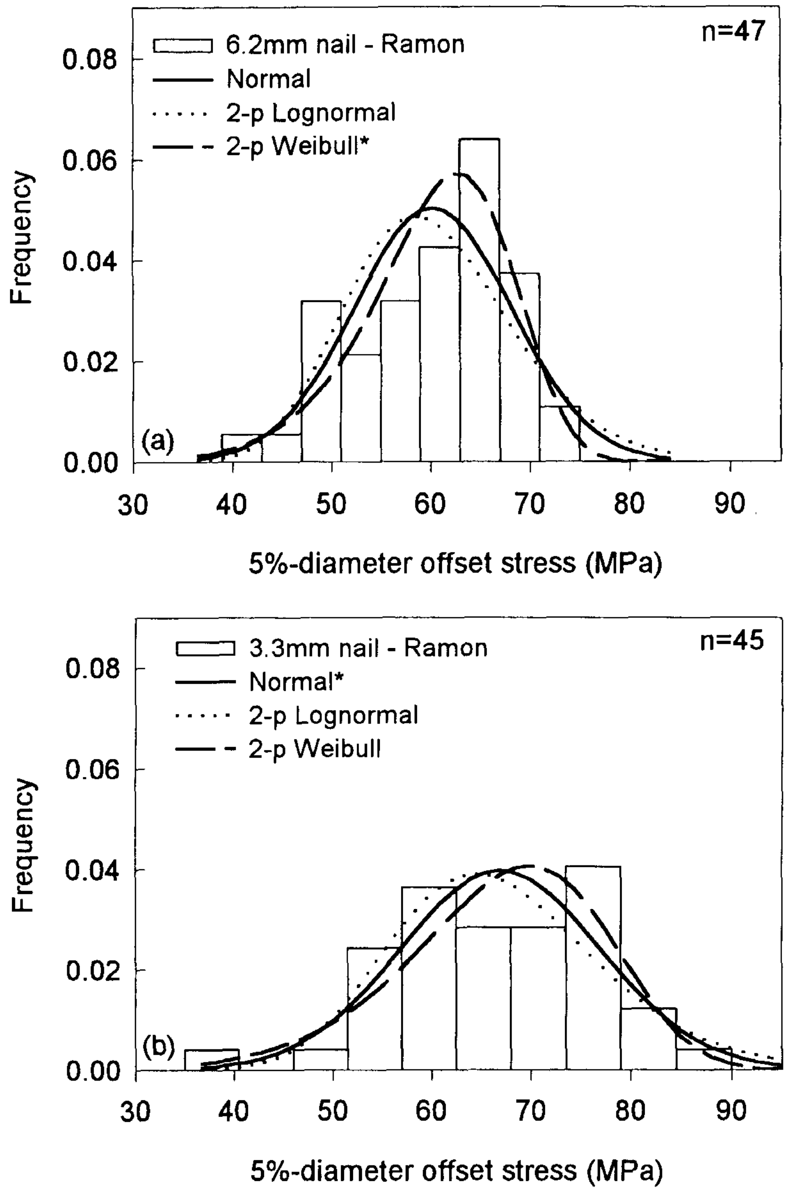

Figure 5. — Histogram of 5 percent offset diameter strength for nails tested in Ramon: a) 6.2-mm-diameter nail; and b) 3.3-mm-diameter nail; the asterisks identify the best-fit distributions.

calculated with the maximum-recorded load along with the EUROCODE expression for driven nails at each diameter. The EUROCODE expression seems to capture both the changing relationship of SG and the dowel-bearing effect and some of the effect of diameter, but generally underpredicts the mean values of data.

For a quantitative comparison of the different current dowel-bearing expressions, the mean percentage deviation (MPD) value and percentage standard error of estimate (PSEE) values were compared for each expression using the combined nail species and size results and the combined bolt species and size results (9). For the EUROCODE expression, which is a function of dowel size and SG, average dowel size and actual SG were used. The MPD and PSEE were calculated using the following expressions:

$$MPD = \frac{\sum_{i=1}^{n} \left(\frac{y_i - \hat{y}(g_i, d_i^{avg})}{\hat{y}(g_i, d_i^{avg})} \right) \times 100}{n}$$

$$PSEE = \sqrt{\frac{\sum_{i=1}^{n} \left(\frac{y_i - \hat{y}(g_i, d_i^{avg})}{\hat{y}(g_i, d_i^{avg})} \times 100 \right)^2}{n-1}}$$

where:

y_i = ith observed dowel-bearing strength

$\hat{y}(g_i, d_{iavg})$ = predicted dowel-bearing strength using the SG (g_i) at test and average dowel diameter (d_i) for the ith specimens in either of the equations

n = total number of specimens

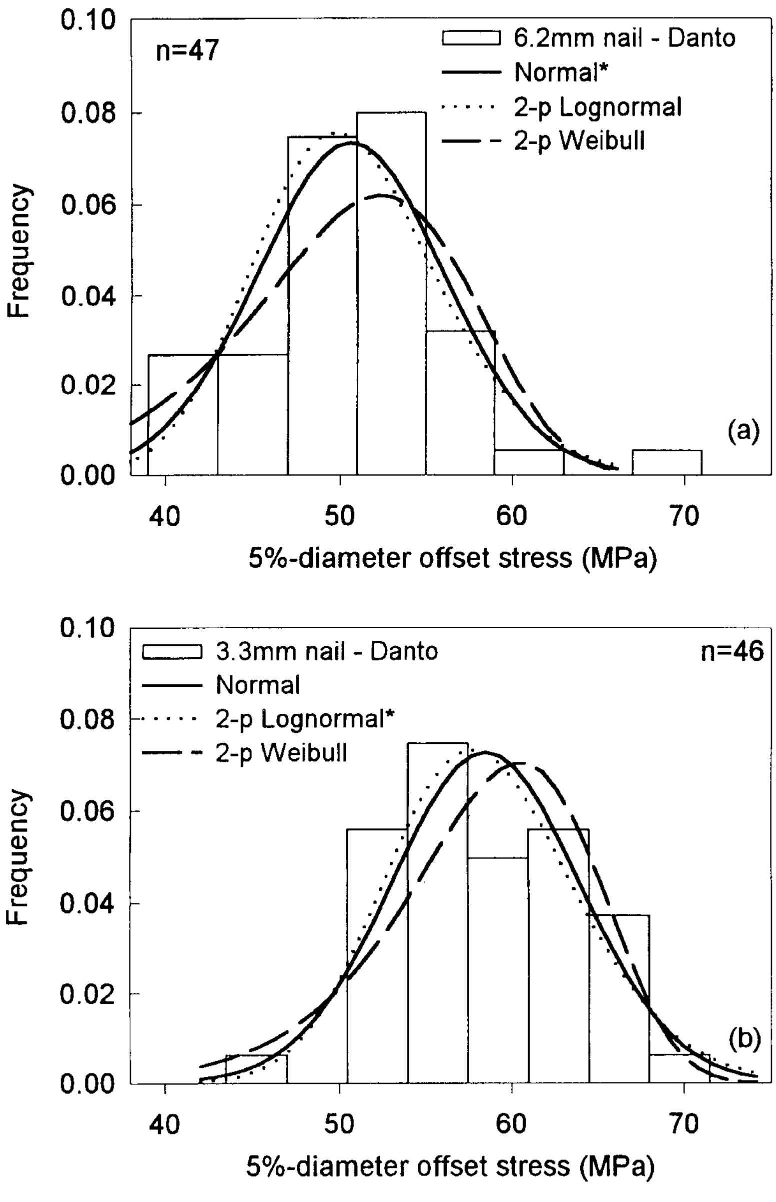

Figure 6.—Histogram of 5 percent offset diameter strength for nails tested in Danto: a) 6.2-mm-diameter nail; and b) 3.3-mm-diameter nail; the asterisks identify the best-fit distributions.

Table 6 shows the MPD and PSEE results for the NDS and proposed EUROCODE nail expressions along with the NDS and the proposed EUROCODE hardwood bolt expressions. Table 6 also lists the range of the individual mean deviations and the mean absolute deviation between the measured and predicted expressed as a percentage of the predicted value.

Comparing MPD and PSEE results, NDS/LRFD nail and bolt expressions fit the high-SG species better than do the proposed EUROCODE expressions. However, in both cases, the EUROCODE expressions were more conservative. Also note that both NDS/LRFD and EUROCODE nail expressions were better predictors for high-SG material compared with the bolt expressions. Overall, both NDS/LRFD and proposed EUROCODE expressions could be modified to better predict the trends of the high-density material tested herein.

Conclusions

Two species of Guatemalan hardwoods, Danto and Ramon, were tested to determine their parallel-to-grain dowel-bearing properties. Based on a minimum of 40 specimens for each size nail or bolt tested, parallel-to-grain dowel-bearing strength values for high SG wood were determined. An attempt to determine the best type of probability distribution for the 5 percent diameter offset strength was unsuccessful. Three bolt and two nail sizes were investigated to determine the effects of dowel size on the strength and stiffness on bearing results. Based on an ANOVA at a 0.05 level of confidence, dowel-bearing stiffness is strongly related to the diameter of the dowel for

TABLE 4. —Five percent diameter offset strength probability distributions for nails.

Species	Nail diameter	Distribution[a]	Scale parameter (α)	Shape parameter (β)	x^2	K-S[a]	A-D"
	(mm)						
Ramon	6.2	Normal[b]	60.2	61.0	12.936	0.136	0.997
		Lognormal	4.08	0.019	16.766	0.161	1.392
		Weibull[c]	63.5	9.8	10.638	0.086	.535
	3.3	Normal[c]	66.9	10.0	3.600	0.079	0.245
		Lognormal	4.19	0.024	4.000	0.089	0.406
		Weibull[a]	71.1	7.8	8.400	0.083	0.259
Danto	6.2	Normal[c]	50.6	5.4	2.213	0.083	0.378
		Lognormal[b]	3.92	0.011	6.043	0.097	0.448
		Weibull	53.1	8.9	7.574	0.128	1.143
	3.3	Normal	58.5	29.5	2.913	0.094	0.336
		Lognormal[b,c]	4.06	0.089	2.522	0.076	0.278
		Weibull	61.0	11.6	8.000	0.118	0.705

[a] Refer to Table 3 footnotes for descriptions,
[b] Best-tit distribution for specific gravity.
[c] Best-fit distribution for 5 percent diameter bearing strength.

TABLE 5. — ANOVA multiple comparisons for bolt and nail 5 percent offset dowel-bearing strength with different dowel diameters. [a]

Characteristic	Species	Average values[a] for each bolt diameter (mm)			Average values for each nail diameter (mm)	
		19.1	12.7	6.4	6.2	3.3
Stiffness (kPa/mm)	Ramon	82.4	93.0	130.2	119.6	173.7
	Danto	72.0	102.2	118.2	135.8	175.8
Strength (MPa)	Ramon	67.23	70.17	71.63	60.2	66.9
	Danto	59.42	60.10	61.79	50.6	58.52

[a] Values that have a common double underline are not significantly different at the 0.05 level.

both nails and bolts. ANOVA results for 5 percent diameter bearing strength indicated that nail-bearing strength is significantly affected by nail size but bolt results indicate no effect of dowel size on bearing strength. By comparing a similar-sized nail and bolt, it was observed that nail-bearing strength is about 15 percent less than bolt-bearing strength in high-density wood.

Finally, comparisons of the proposed EUROCODE and U.S. dowel-bearing expressions to experimental bearing results question the validity of these expressions to predict the median values for higher-SG material. Proposed EUROCODE expressions give predictions that are conservative, whereas NDS/LRFD expressions are conservative for bolts but unconservative for nails or driven dowels.

TABLE 6.—Comparison of dowel-bearing strength expressions.

Dowel type	Design expression	MPD[a]	PSEE[b]	Range of MPD	Mean absolute deviation
Bolt	NDS-97	15.20	18.41	-21.6 to 49.5	16.12
	EUROCODE	35.76	38.22	-4.4 to 73.5	35.81
Nail	NDS-97	-6.18	13.87	-41.8 to 26.9	11.35
	EUROCODE	11.94	17.16	-23.5 to 40.4	14.00

[a] MPD = mean percentage deviation.
[b] PSEE = percentage standard error of estimate.

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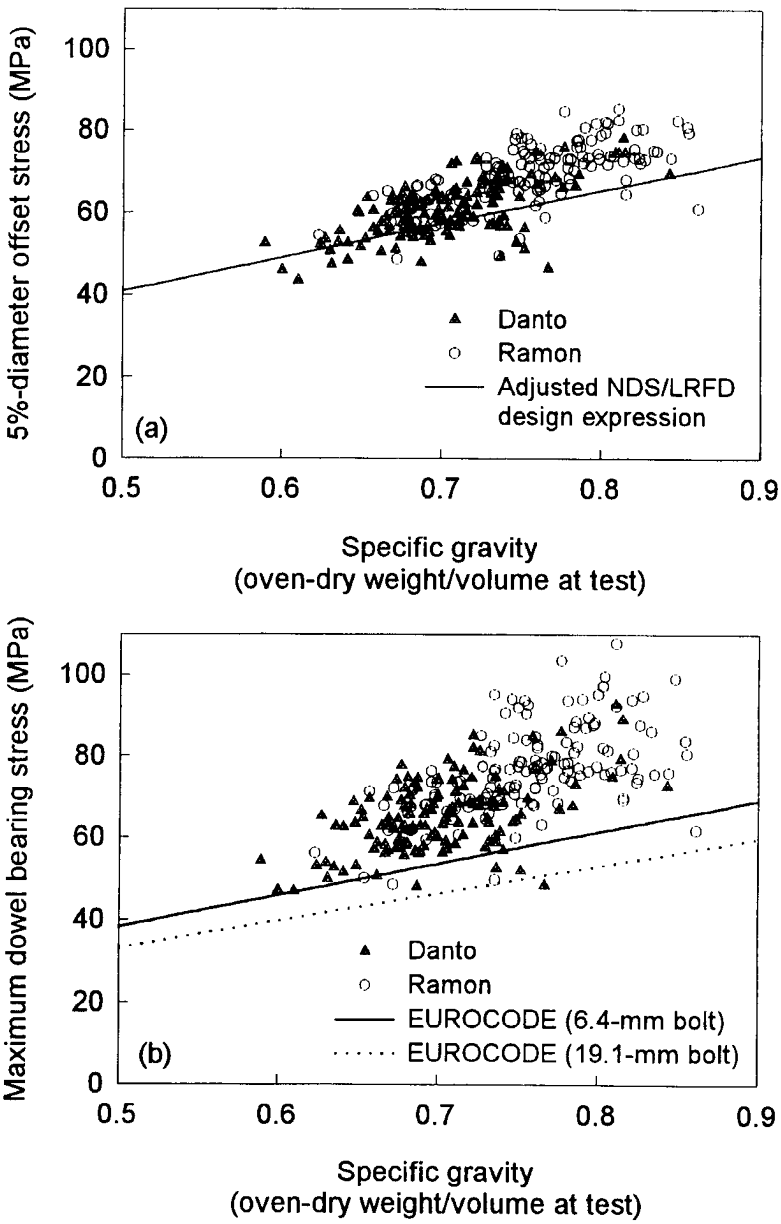

Figure 7. — Comparison of Danto and Ramon results with current bolt-bearing design expressions adjusted to represent average experimental values: a) NDS/LRFD expression adjusted at 12 percent SG; and b) proposed EUROCODE expression.

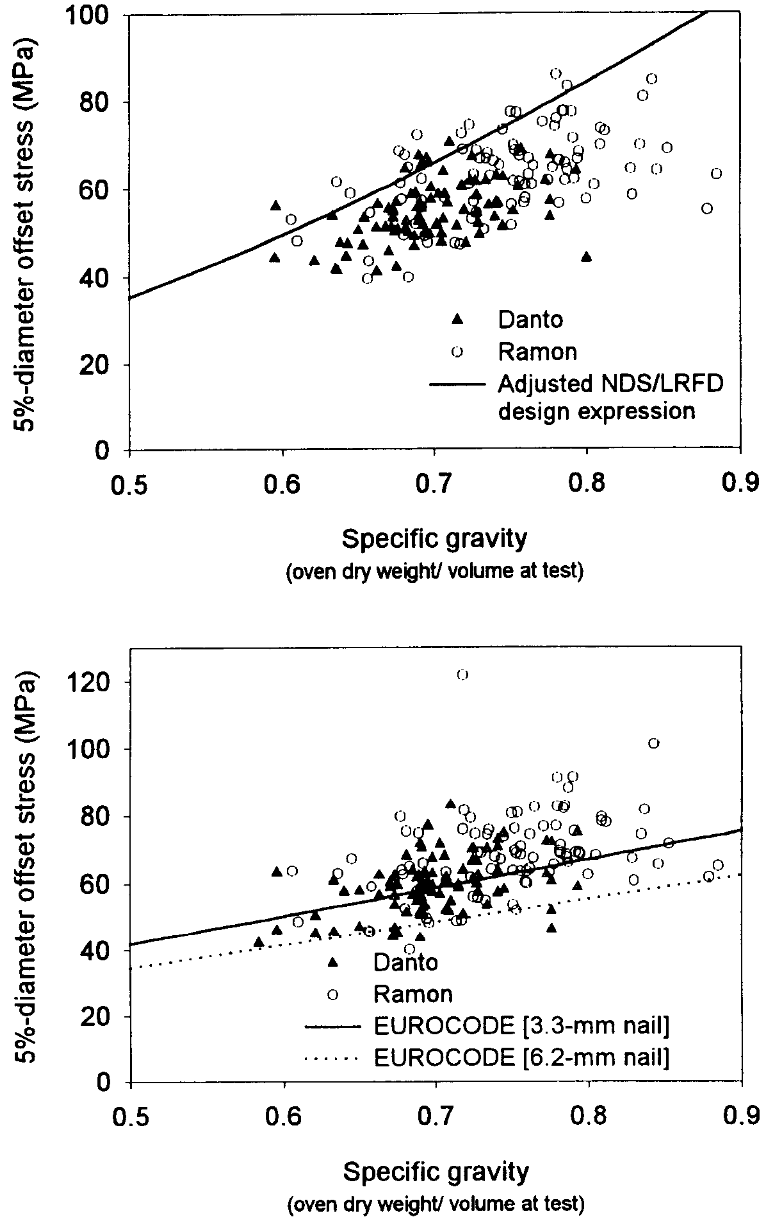

Figure 8. — Comparison of Danto and Ramon results with current nail-bearing design expressions adjusted to represent average experimental response: a) NDS/LRFD expression; and b) proposed EUROCODE expression.