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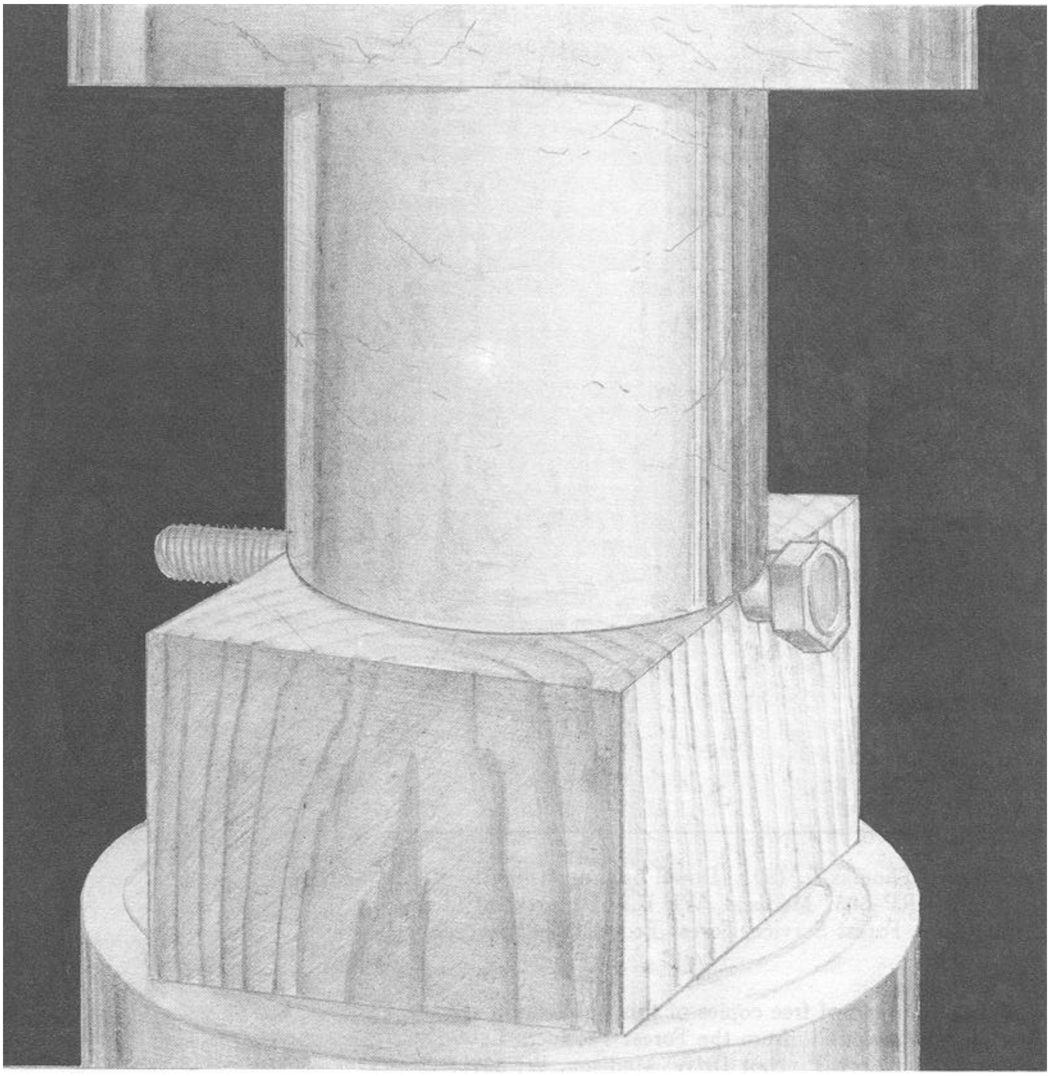
Dowel Bearing Strength

Thomas L. Wilkinson



Abstract

The European Yield Model has been proposed as a base for setting design values of laterally loaded dowel-type connections. This study investigated one input property for the model, the dowel bearing strength. Effects of specific gravity, dowel diameter, and loading direction were studied for bolts and nails. Results showed that bearing strength for bolts loaded parallel to grain is related to specific gravity; for bolts loaded perpendicular to grain, bearing strength is related to specific gravity and bolt diameter. Bearing strength for nails is related to specific gravity only.

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Dowel Bearing Strength

Thomas L. Wilkinson, Research General Engineer
Forest Products Laboratory, Madison, Wisconsin

Introduction

The European Yield Model (EYM) (Johansen 1949) has been proposed as a base for setting the design capacity of laterally loaded nail, bolt, and screw connections; that is, dowel-type connections. The EYM incorporates connection geometry, dowel yield stress, and dowel bearing strength to predict the yield load for a connection.

Dowel bearing strength is the property of connection members that imparts resistance to embedding of a dowel. Whale and Smith (1986) related this property to species density and dowel diameter for bolts and nails. The authors defined bearing strength as the maximum test load. A lower load level for bearing strength has been proposed for connection design provisions in the United States.

The National Design specification (NFPA 1986) recognizes no difference between parallel- and perpendicular-to-grain loading of small-diameter dowels, such as nails, but does recognize such a difference for large-diameter dowels, such as bolts. Soltis and others (1987) showed that the point where no difference between parallel- and perpendicular-to-grain loading occurs is a function of dowel diameter and species specific gravity. Thus establishment of dowel bearing strength requires knowledge about the effects of specific gravity, dowel diameter, and loading direction.

The research reported here focused on the effect of species specific gravity, dowel diameter, and loading direction on dowel bearing strength as defined in the United States. The study included bolts and nails of various diameters and several hardwood and softwood species.

Procedure

No standard test method exists for evaluating dowel bearing strength. As part of this study, several specimen sizes, hole sizes, and loading procedures were investigated. One test method for bolts and another for nails were selected as giving repeatable, reliable results. The results reported for this study were obtained us ing these methods. Future plans are to establish an American Society for Testing and Materials (ASTM) standard test method after some additional testing.

Bolt Specimens

The series of tests conducted with bolts is summarized in Table 1. The effect of specific gravity was evaluated using 3/4-in. (19-mm) bolts and seven species. The effect of bolt diameter was determined with Southern Pine using bolt diameters from 1/4 in. (6 mm) to 1-1/2 in. (38 mm). Specimens were loaded parallel and perpendicular to grain. A total of 240 specimens were tested.

The type of specimen used is schematically shown in Figure 1. Average dimensions are given in Table 1. The different dimensions were a result of our effort to establish a standard test method. We believe that these differences did not affect the results because all specimens had uniform crushing failures under the bolt. Sufficient thickness was selected so that the results were not affected by such wood characteristics as growth rings. The hole diameter was 1/16 in. (1.6 mm) larger than the bolt diameter.

The moisture content of all material was between 10 and 12 percent.

Nail Specimens

The series of tests conducted with nails is summarized in Table 2. The effect of specific gravity was evaluated using 0.162-in.- (4.1-mm-) diameter (16d) nails on five species. The effect of nail diameter was determined with Douglas Fir using 0.148-in.- (3.8-mm-), 0.162-in.- (4.1-mm-), and 0.225-in.- (5.7-mm-) diameter (10d, 16d, and 40d) nails. Specimens were loaded parallel and perpendicular to gram. A total of 139 specimens were tested.

The type of specimen was similar to that shown in Figure 1. Average dimensions are given in Table 2. The different dimensions were a result of establishing a standard test method. Sufficient width and length were needed to prevent premature splitting; because the splitting tendency is species dependent, different dimensions were needed for different species. Nails were driven through a lead hole equal to 50 percent of the nail diameter. This was accomplished by clamping two pieces of wood together, drilling the lead hole in the seam of the abutting pieces, and driving the nail before unclamping. This produced a half hole with a surface characteristic produced by a driven nail.

The moisture content of all material was between 10 and 12 percent.

Loading Procedure

Bolts and nails were embedded in the. half holes of the specimens. The dowel was uniformly loaded along its length. A load-embedment curve was recorded on an *xy* recorder up to maximum load. Embedment was measured by the movement of the movable crosshead of the testing machine using a linear variable differential transformer (LVDT). Specimens were loaded at a constant rate of the crosshead of approximately 0.04 in/min (1 mm/min).

Results

Three loads were recorded for each specimen: (1) the proportional limit load, (2) the 5-percent offset load, and (3) the maximum load. Average loads are described in Tables 3 and 4.

Of the recorded loads, the 5-percent offset load was of the most interest because this load has been used to define dowel bearing strength and yield load of dowel-type connections. The 5-percent offset load was obtained by offsetting the initial slope of the load-deformation curve by 5 percent of the dowel diameter and locating the load at which the offset intersects the curve (Fig.2). In some instances, the offset did not intersect the curve before the maximum load was reached. In these cases, the maximum load was used as the 5-percent offset load. The dowel bearing strength was obtained by dividing the 5-percent offset load by the dowel diameter and the specimen thickness. Average values of the dowel bearing strength are given in Tables 3 and 4 as 5-percent offset stress.

Analysis

Bolts

To establish the relation between bolt bearing strength F_e and specific gravity based on ovendry weight and volume at 12 percent moisture content, G_{12}, several equations were fitted to the data for 3/4-in. (19-mm) bolts, combining all species. For parallel-to-grain loading, the best fit equation (r^2 = 0.55) (Fig. 3) was

$$\text{Parallel} \qquad F_e = 11{,}830\, G_{12} \tag{1}$$

For perpendicular-to-grain loading, the best fit equation (r^2 = 0.50) (Fig. 4) was

$$\text{Perpendicular} \qquad F_e = 7{,}670\, G_{12}^{1.45} \tag{2}$$

To establish the relation between bolt bearing strength and bolt diameter D, equations were fitted to the Southern Pine data for various bolt diameters. For parallel-to-grain loading, the bolt bearing strength was multiplied by a factor of $0.56/G_{12}$ to eliminate the effects of specific gravity. The best fit equation (r^2 = 0.35) (Fig. 5) was

$$\text{Parallel} \qquad F_e = 10{,}770\, G_{12} D^{-0.15} \tag{3}$$

For perpendicular-to-grain loading, the bolt bearing strength was multiplied by ($0.54/G_{12}^{1.45}$) to eliminate the effects of specific gravity. The best fit equation (r^2 = 0.71) (Fig. 6) was

$$\text{Perpendicular} \qquad F_e = 5{,}570\, G_{12}^{1.45} D^{-0.5} \tag{4}$$

The correlation between bearing strength parallel to grain and bolt diameter was very weak. Because the diameter of most bolts used in the United States is in the range of 1/2 in. (13 mm) to 1 in. (25 mm), where the effect of diameter is apparently minimal (Fig. 5), the effect of diameter on bearing strength parallel to grain was deemed insignificant. Thus, Equation (1) gives the combined effect of specific gravity and bolt diameter on bearing strength parallel to grain. The effect of diameter on bearing strength perpendicular to grain was significant. Thus, Equations (2) and (45) were combined to give the effect of specific gravity and bolt diameter on bearing strength perpendicular to grain. The final relations are

$$\text{Parallel} \quad F_e = 11{,}830\ G_{12} \qquad (5)$$

$$\text{Perpendicular} \quad F_e = 6{,}620\ G_{12}^{1.45} D^{-0.5} \qquad (6)$$

These results differ from those of Whale and Smith (1986). These authors found a diameter effect for parallel-to-grain loading They also found a difference between hardwoods and softwoods for perpendicular-to-grain loading. Whale and Smith defined the yield load as the maxinmm test load, whereas we used the 5-percent offset load. Our study also combined more species than did the Whale and Smith study.

Nails

To establish the relation between nail bearing strength and specific gravity, several equations were fitted to the data for 0.162-in.- (4.1-mm-) diameter nails, combining all species. For parallel-to-grain loading, the best fit equation (r^2 = 0.65) (Fig. 7) was

$$\text{Parallel} \quad F_e = 16{,}710\ G_{12}^{1.55} \qquad (7)$$

For perpendicular-to-grain loading, the best fit (r^2 = 0.48) (Fig. 8) was

$$\text{Perpendicular} \quad F_e = 11{,}330\ G_{12}^{1.47} \qquad (8)$$

These correlations were fairly weak. Because the difference between nail connections loaded parallel or perpendicular to grain has not been traditionally recognized, we decided to combine the data for the two loading directions. The beat fit equation (r^2 = 0.52) (Fig. 9) for the combined data was

$$F_e = 18{,}400\ G_{12}^{1.84} \qquad (9)$$

To establish the relation between nail bearing strength and nail diameter, equations were fitted to the Douglas Fir data for three nail diameters. Because the effect of specific gravity was not affected by loading direction, parallel- and perpendicular-to-grain data were combined to examine the diameter effect. The nail bearing strength was multiplied by $0.38/G_{12}^{1.84}$ to eliminate the effect of specific gravity. The best fit equation (r^2 = 0.08) (Fig. 10) was

$$F_e = 36{,}719\ G_{12}^{1.84}\ D^{0.31} \qquad (10)$$

The effect of diameter was insignificant. Therefore, Equation (9) describes the relation between nail bearing strength and specific gravity.

This result again differed from that of Whale and Smith (1986). These authors found a difference between parallel- and perpendicular-to-grain loading for nails. Again, the yield load was defined differently in our study than in the Whale and Smith study.

Comparison of Nail and Bolt Relations

As a part of the effort to establish a standard test method, a few additional tests were performed to enplain the difference between the relations of small-diameter bolts and large-diameter nails. The results of Soltis and others (1987) had indicated that no difference should have occurred.

The equations for bolts and nails indicate that a bolt loaded parallel to grain would have a higher bearing strength than a nail of the same diameter for a specific gravity less than 0.60. For perpendicular-to-grain loading, the bolt and nail equations are nearly equal for a diameter, around 1/4 in. (6.4 mm) over most of the specific gravity range.

Nails were tested in driven holes, and bolts were tested in oversized holes. Three series of tests were conducted with 1/4-in. (6.4-mm) dowels in Southern Pine loaded parallel to grain to determine if the hole size or condition of the hole surface could explain the difference between bolt and nail test results. The hole was 9/32 in. (7.1 mm) in one series and 1/8 in. (3.2 mm) in another series. Specimens for these two series were prepared by drilling the hole and then cutting through the center of the hole. Specimens for the third series of tests were prepared by drilling a 3/16-in. (4.8-mm) lead hole, driving a pointed 1/4-in. (6.4-mm) dowel through the hole, removing the dowel, and then cutting through the center of the hole. These test results are summarized in Table 5. Bearing strength and maximum load were the same when the hole diameter was less than or greater than the dowel diameter. However, the bearing strength and maximum load for driven dowels were about 80 percent that for undriven dowels. This difference agrees closely with the difference between bolt and nail equations.

Conversion of Bolt and Nail Equations

In the U.S. codes, specific gravity G_d is based on ovendry volume and ovendry weight. In our equations, specific gravity G_{12} is based on volume at 12 percent moisture content. In ASTM Standard D2395 (ASTM 1990), the relation between these two specific gravity values is expressed as

$$G_{12} = \frac{G_d}{1 + 0.108\ G_d} \qquad (11)$$

In the codes, G_d ranges from 0.31 to 0.75. Using the average value of 0.53 in Equation (11) gives the following approximate relation:

$$G_d \cong 1{,}067\ G_{12} \quad (12).$$

Equation (12) was used to convert Equations (5), (6), and (9) from specific gravity G_{12} to specific gravity G_d. The resulting relations for bolts and nails are

Bolts

$$\text{Parallel} \quad F_e = 11{,}200\ G_d \quad (13)$$

$$\text{Perpendicular} \quad F_e = 6{,}100\ G_d^{1.45} D^{-0.5} \quad (14)$$

Nails

$$F_e = 16{,}600\ G_d^{1.84} \quad (15)$$

Conclusions

Within the limits of the test program, the results suggest the following relation of dowel bearing strength to specific gravity and dowel diameter:

1. Bearing strength for bolts loaded parallel to grain is dependent upon specific gravity only (see Eq. (13)).
2. Bearing strength for bolts loaded perpendicular to grain is dependent upon specific gravity and bolt diameter (see Eq. (14)).
3. Bearing strength for nails is dependent upon specific gravity (see Eq. (15)) and is independent of loading direction and nail diameter.
4. The difference between nail and bolt results is in part due to the bearing surface: bolts bear on smooth bole surfaces whereas nails bear on surfaces produced by driving the nails.

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Table 1—Bolt tests

Species group	Bolt diameter (in.)[a]	Sample size	Grain direction	Specimen dimensions (in.)		
				Length	Width	Thickness
Douglas Fir	3/4	20	Parallel	4.00	4.50	2.25
			Perpendicular	3.25	6.00	2.25
Southern Pine	3/4	10	Parallel	7.50	7.27	1.52
			Perpendicular	7.50	7.27	1.52
Spruce–Pine–Fir	3/4	10	Parallel	7.50	5.43	1.50
			Perpendicular	7.50	5.43	1.50
Sitka Spruce	3/4	10	Parallel	4.04	4.00	1.50
			Perpendicular.	4.00	3.46	1.50
Red Oak	3/4	10	Parallel	3.47	3.44	1.50
			Perpendicuiar	3.44	3.46	1.50
Yellow Poplar	3/4	10	Parallel	7.49	7.38	1.50
			Perpendicular	7.01	6.94	1.50
Aspen	3/4	10	Parallel	5.08	5.50	1.38
			Perpendicular	5.14	5.12	1.38
Southern Pine	1/4	10	Parallel	2.49	2.32	0.69
			Perpendicular	2.40	2.44	0.49
Southern Pine	1/2	10	Parallel	4.99	5.00	1.50
			Perpendicular	3.56	3.75	0.94
Southern Pine	1	10	Parallel	7.38	7.30	1.50
			Perpendicular	7.18	7.38	1.50
Southern Pine	1-1/2	10	Parallel	7.25	7.25	1.50
			Perpendicular	7.25	7.25	150

[a] 1 in. = 25.4 mm.

Table 2—Nail tests

Species group	Bolt diameter (in.)	Sample size	Grain direction	Specimen dimensions (in.)[a]		
				Length	Width	Thickness
Douglas Fir	0.162	10	Parallel	2.00	2.00	0.71
			Perpendicular	2.00	2.00	0.72
Southern Pine	0.162	10	Parallel	1.97	2.08	0.65
			Perpendicular	2.07	1.96	0.71
Spruce–Pine–Fir	0.162	10	Parallel	2.01	2.07	0.69
			Perpendicular	2.03	1.97	0.69
Yellow -Poplar	0.162	10	Parallel	1.95	1.88	0.59
			Perpendicular	1.94	1.94	0.56
Aspen	0.162	10	Parallel	1.85	1.90	0.60
			Perpendicular	1.90	1.94	0.63
Douglas Fir	0.148	10	Parallel	2.00	2.00	0.71
			Perpendicular	2.00	2.00	0.71
Douglas Fir	0.225	9	Parallel	3.19	3.13	1.49
			Perpendicular	3.47	3.60	1.49

[a] 1 in. = 25.4 mm.

Table 3—Bolt test results

Species group			Specific gravity[b]		Proportional limit load (lb)[c]		5-percent offset load (lb)[c]		Maximum load		5-percent offset stress (lb/in^2)[d]	
			Mean	COV	Mean	COV	Mean	COV	Mean	COV	Mean	COV
Douglas Fir	3/4	Parallel	0.46	0.11	5,103	0.21	9,104	0.09	9,274	0.08	5,339	0.09
		Perpendicular	0.46	0.08	1,804	0.24	3,403	0.18	4,071	0.16	2,016	0.18
Southern Pine	3/4	Parallel	0.56	0.09	4,805	0.13	6,866	0.11	6,931	0.11	6,027	0.10
		Perpendicular	0.52	0.08	1,828	0.19	3,099	0.13	4,239	0.12	2,720	0.13
Spruce-Pine-Fir	3/4	Parallel	0.41	0.11	2,407	0.28	4,422	0.20	4,499	0.19	3,927	0.20
		Perpendicular	0.41	0.11	749	0.18	1,811	0.21	2,816	0.20	1,607	0.21
Sitka Spruce	3/4	Parallel	0.36	0.02	4,371	0.13	5,970	0.05	6,014	0.05	5,307	0.05
		Perpendicular	0.36	0.02	1,386	0.10	2,273	0.03	2,957	0.05	2,020	0.03
Red Oak	3/4	Parallel	0.58	0.05	6,972	0.10	8,699	0.08	8,758	0.08	7,732	0.08
		Perpendicular	0.58	0.05	3,366	0.09	5,207	0.07	5,890	0.08	4,628	0.07
Yellow Poplar	3/4	Parallel	0.49	0.03	5,520	0.09	6,936	0.05	7,164	0.04	6,165	0.05
		Perpendicular	0.49	0.03	2,571	0.08	3,750	0.08	5,166	0.10	3,333	0.08
Aspen	3/4	Parallel	0.37	0.03	2,869	0.14	3,670	0.07	3,763	0.06	3,559	0.07
		Perpendicular	0.37	0.03	1,380	0.09	2,170	0.03	2,476	0.03	2,104	0.03
Southern Pine	1/4	Parallel	0.59	0.08	1,128	0.16	1,358	0.14	1,404	0.12	7,874	0.16
		Perpendicular	0.49	0.02	295	0.16	473	0.20	615	0.20	3,842	0.19
Southern Pine	1/2	Parallel	0.56	0.09	3,444	0.21	5,090	0.05	5,215	0.04	6,787	0.05
		Perpendicular	0.56	0.09	1,248	0.15	1,946	0.10	2,387	0.16	4,147	0.06
Southern Pine	1	Parallel	0.56	0.09	6,565	0.09	9,371	0.02	9,371	0.02	6,246	0.02
		Perpendicular	0.56	0.09	1,917	0.03	3,051	0.03	3,569	0.04	2,034	0.03
Southern Pine	l-1/2	Parallel	0.56	0.09	10,971	0.14	12,590	0.15	12,590	0.15	5,596	0.15
		Perpendicular	0.56	0.09	2,786	0.15	4,741	0.10	4,741	0.10	2,107	0.10

[a] 1 in. = 25.4 mm.
[b] Specific gravity based on volume at 12 percent moisture content and ovendry weight. COV is coefficient of variation.
[c] 1 lb = 4.45 N.
[d] 1 lb/in^2 = 6.89 kPa.

Table4—Nail test results

Species group	Bolt diameter (in.)[a]	Grain direction	Specific gravity[b]		Proportional limit load (lb)[c]		5-percent offset load (lb)[c]		Maximum load		5-percent offset stress (lb/in^2)[d]	
			Mean	COV	Mean	COV	Mean	COV	Mean	COV	Mean	COV
Douglas Fir	0.162	Parallel	0.39	0.02	333	0.20	476	0.18	579	0.19	4,146	0.18
		Perpendicular	0.38	0.02	279	0.18	382	0.21	479	0.17	3,289	0.21
Southern Pine	0.162	Parallel	0.50	0.03	435	0.13	547	0.08	565	0.08	5,205	0.08
		Perpendicular	0.40	0.06	191	0.17	340	0.20	539	0.11	2,960	0.22
Spruce-Pine-Fir	0.162	Parallel	0.40	0.06	352	0.10	453	0.09	495	0.10	4,068	0.10
		Perpendicular	0.37	0.07	205	0.08	288	0.07	358	0.08	2,581	0.07
Yellow Poplar	0.162	Parallel	0.49	0.02	409	0.16	582	0.11	752	0.07	6,090	0.11
		Perpendicular	0.49	0.02	269	0.15	362	0.08	533	0.13	3,970	0.08
Aspen	0.162	Parallel	0.37	0.03	232	0.14	320	0.11	475	0.07	3,283	0.11
		Perpendicular	0.37	0.03	159	0.12	228	0.10	357	0.18	2,243	0.10
Douglas Fir	0.148	Parallel	0.38	0.04	257	0.11	349	0.15	377	0.16	3,294	0.15
		Perpendicular	0.38	0.04	293	0.28	398	0.22	499	0.23	3,762	0.22
Douglas Fir	0.225	Parallel	0.39	0.03	1,035	0.17	1,457	0.12	1,668	0.13	4,355	0.12
		Perpendicular	0.39	0.03	921	0.08	1,279	0.07	1,541	0.07	3,827	0.07

[a] 1 in. = 25.4 mm.
[b] Specific gravity based on volume at 12 percent moisture content and ovendry weight. COV is coefficient of variation.
[c] 1 lb = 4.45 N.
[d] 1 lb/in^2 = 6.89 kPa.

Table 5—Effect of hole size and condition on bearing strength parallel to grain for southern Pine dowels

Hole diameter (in.)[a]	Hole condition	5-percent offset load (lb)[b]		Maximum load (lb)[b]	
		Mean	COV	Mean	COV
9/32	Smooth undriven	3,097	0.10	3,146	0.09
1/8	Smooth undriven	3,119	0.10	3,131	0.10
3/16[c]	Rough driven[d]	2,452	0.06	2,536	0.05

[a] 1 in. = 25.4 mm.
[b] 1 lb = 4.45 N. COV is coefficient of variation.
[c] Lead hole.
[d] Dowel was driven in lead hole and removed before cutting through hole to form half hole.

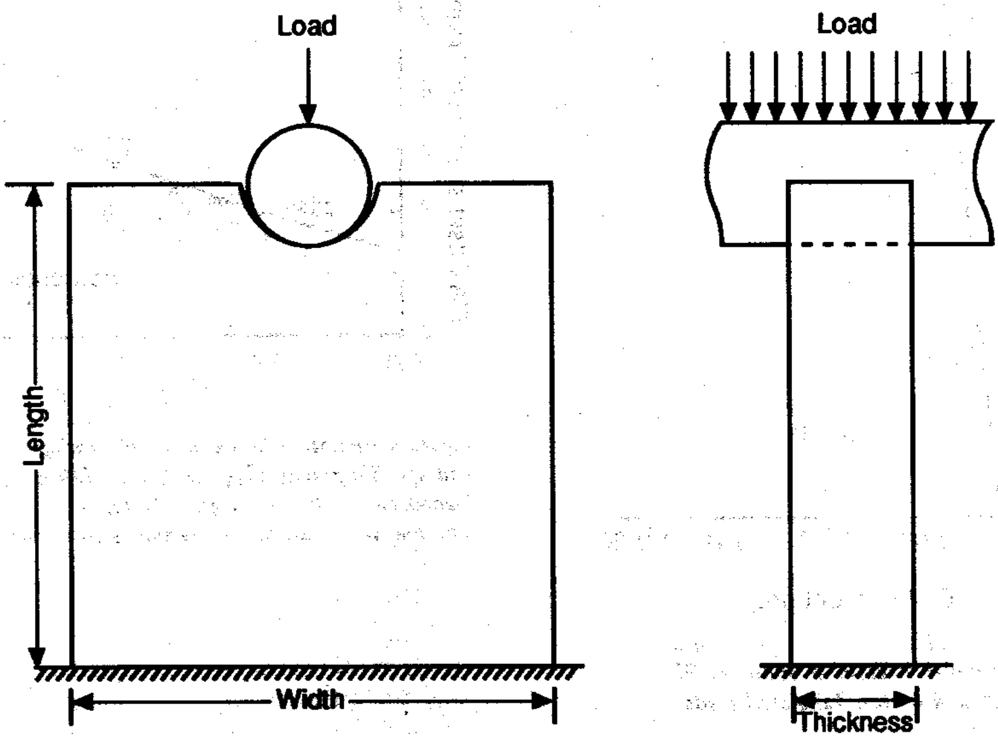

Figure 1—Schematic of bolt test specimen. A similar specimen was used for nail, except that the nail hole was made by driving the nail in a lead hole.

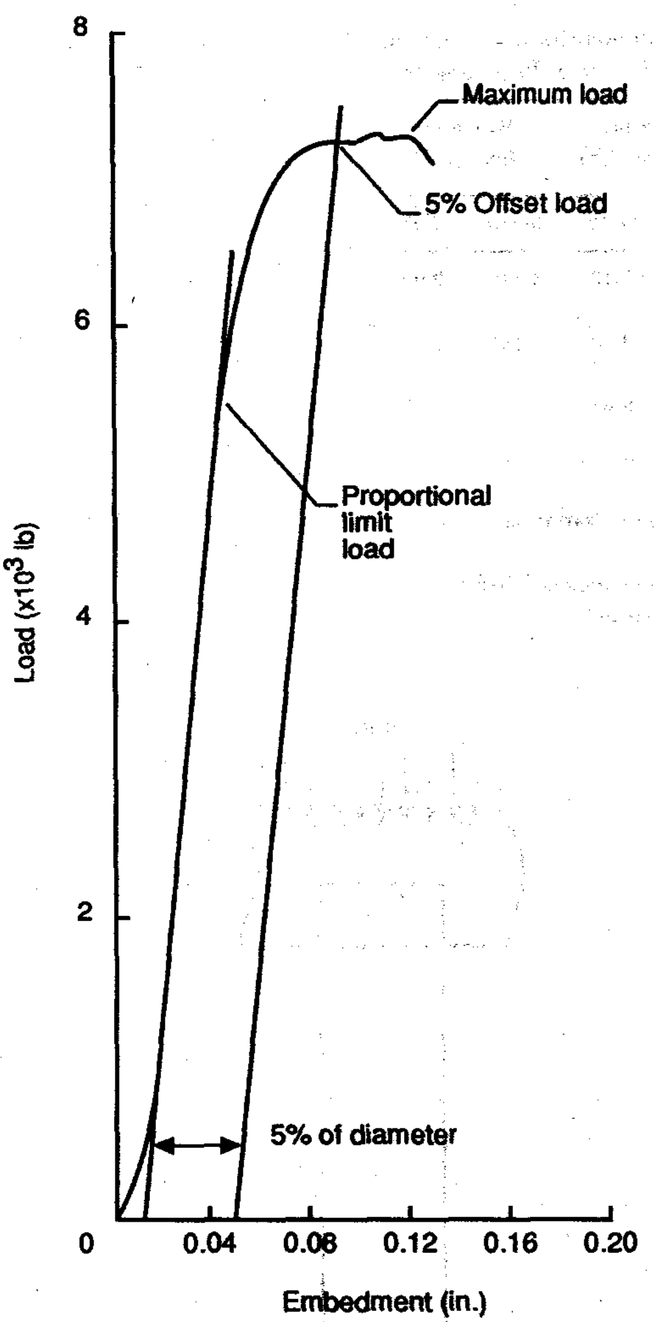

Figure 2—Typical load-embedment curve for a 3/4-in. (19-mm) bolt loaded parallel to grain in Southern Pine (1 in. *= 25.4 mm; 1 lb = 4.45 N). Tabulated loads* are indicated on the curve.

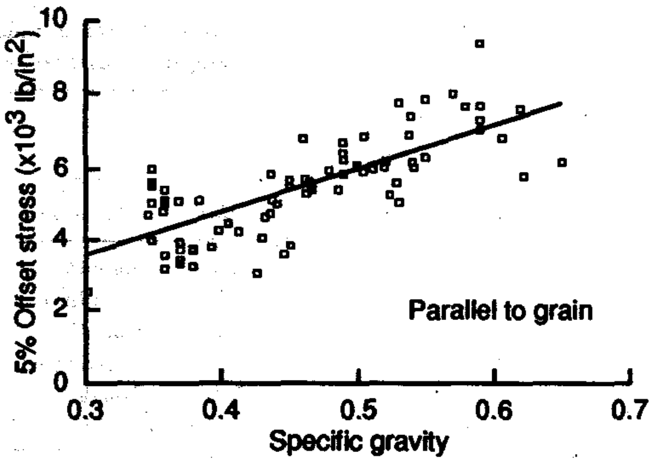

Figure 3—Relation betwen dowel bearing stength and specific gravity G_{12} for 3/4-in. (19-mm) bolts loaded parallel to grain (1 lb/in^2 = 6.89 kPa).

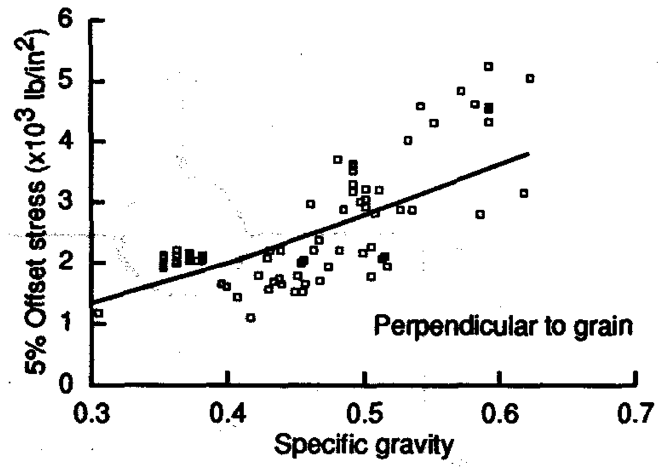

Figure 4—Relation between dowel bearing strength and specific gravity G_{12} for 3/4-in. (19-mm) bolts loaded perpendicular to grain (1 lb/in^2 = 6.89 kPa). The low values are from specimens from one board.

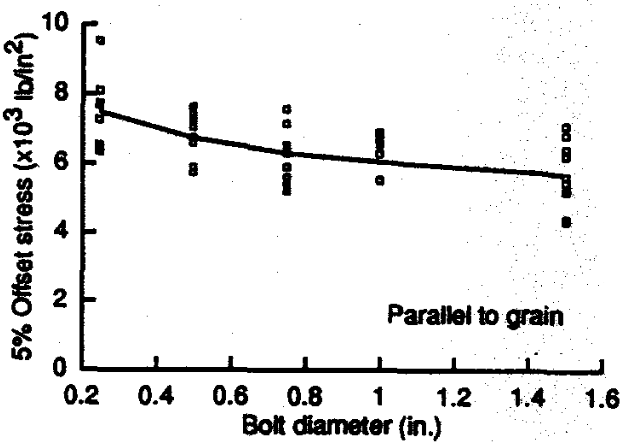

Figure 5—Relation between dowel bearing strength and bolt diameter for Southern Pine loaded parallel to grain (1 in. = 25.4 mm; 1 lb/in^2 = 6.89 kPa). Bolt bearing strength multiplied by a factor of 0.56/G_{12}.

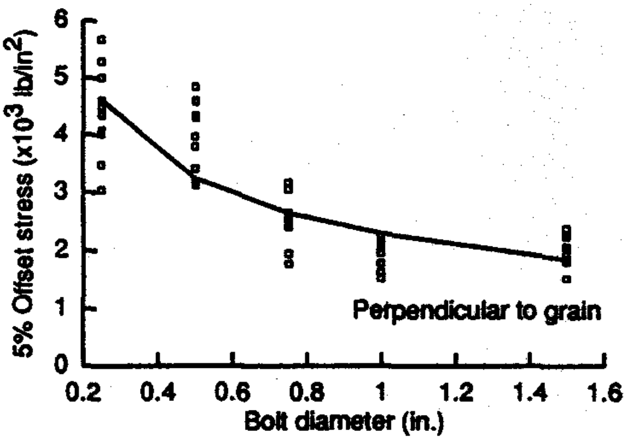

Figure 6—Relation between dowel bearing strength and bolt diameter for Southern Pine loaded perpendicular to grain (1 in. = 25.4 mm; 1 lb/in^2 = 6.89 kPa). Bolt bearing strength multiplied by a factor of 0.56/G_{12}.

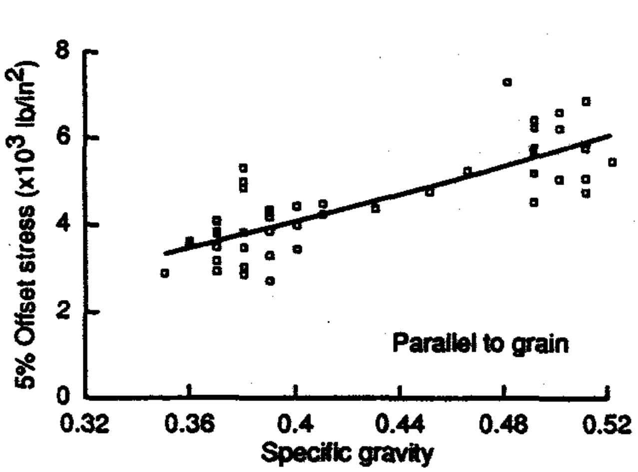

Figure 7—Relation between dowel bearing strength and specific gravity G_{12} for 0.162-in. (4.1-mm) nails loaded parallel to grain (1 lb/in^2 = 6.89 kPa).

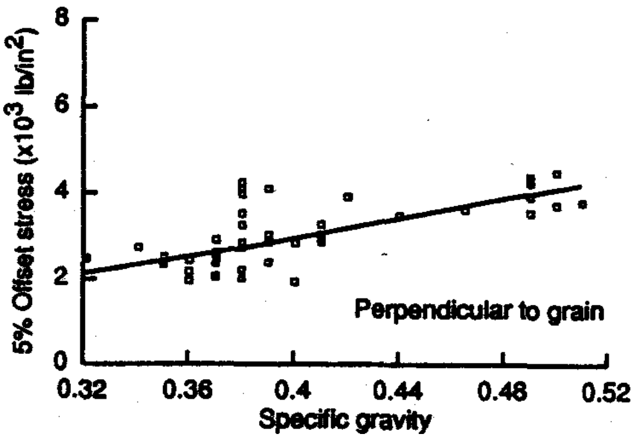

Figure 8—Relation between dowel bearing strength and specific gravity G_{12} for 0.162-in. (4.1-mm) nails loaded perpendicular to grain (1 lb/in^2 = 6.89 kPa).

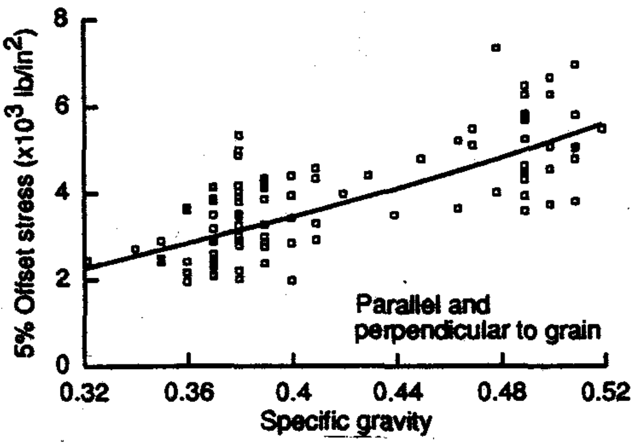

Figure 9—Relation between dowel bearing strength and specific gravity G_{12} for 0.162-in. (4.1-mm) nails, combining both loading directions (1 lb/in^2 = 6.89 kPa).

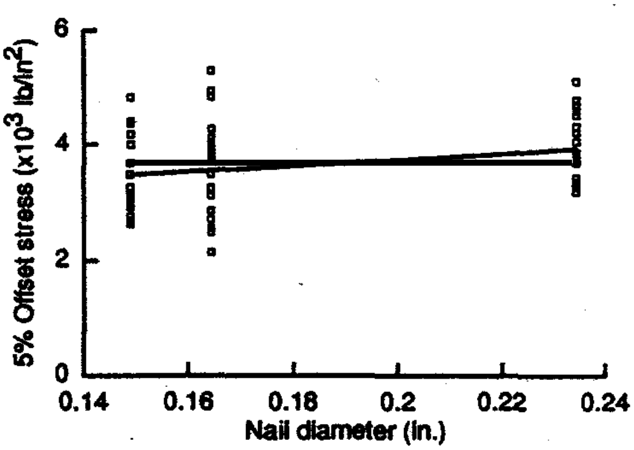

Figure 10—Relation between dowel bearing strength and nail diameter for Douglas Fir for both loading directions (1 in = 25.4 mm: 1 lb/in^2 = 6.89 kPa). Nail bearing strength multiplied by 0.38 $G_{12}^{1.84}$.

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