United States
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Paper
FPL-RP-524

Bolted Connection Strength and Bolt Hole Size

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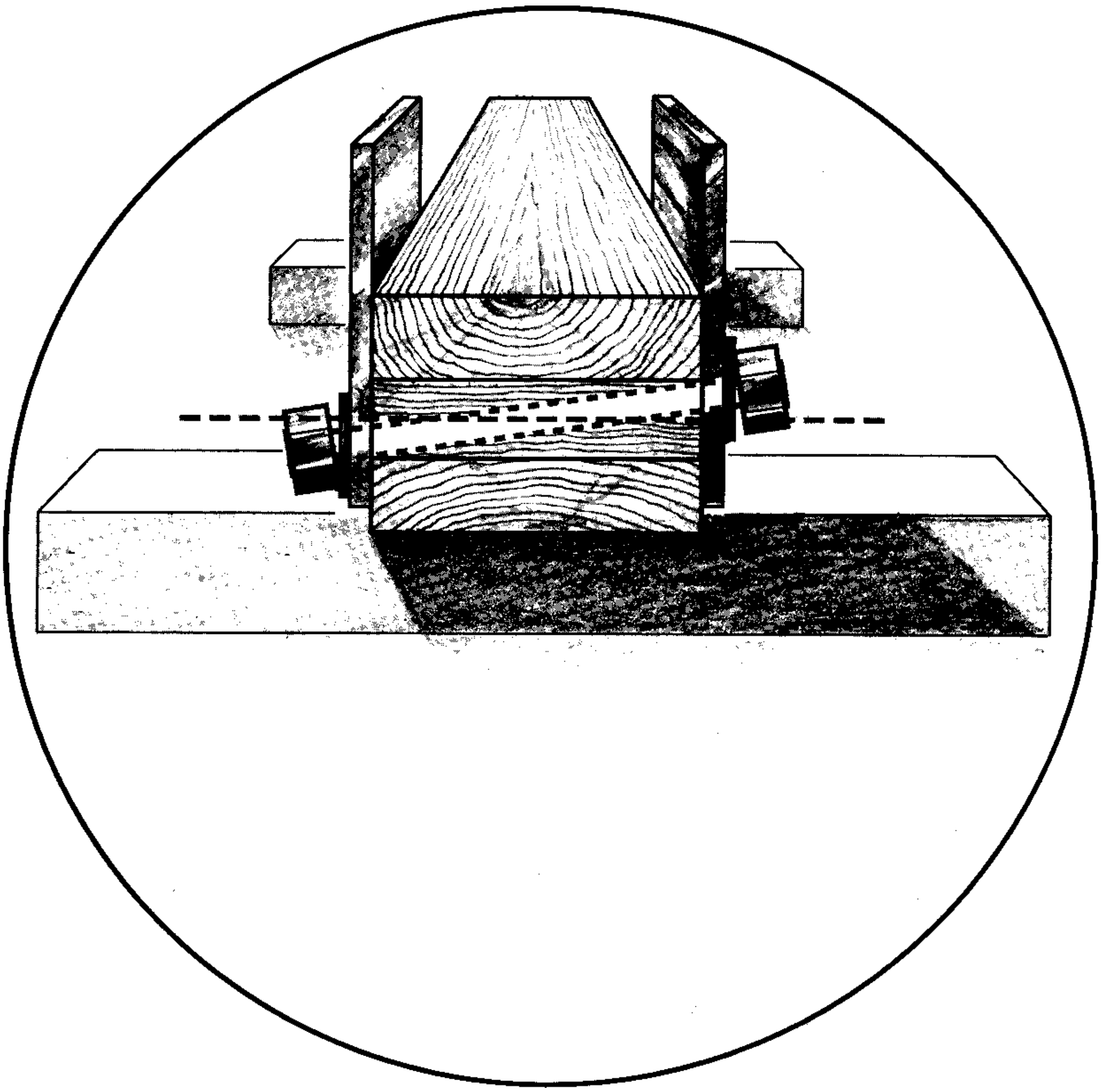

Abstract

This study investigated the effects of oversized bolt holes on the properties of bolted connections with steel side members. The intent of the study was to determine (1) how well the European Yield Model (EYM) predicts experimental results for connections with oversized bolt holes and (2) how the load-deformation behavior of connections is affected by oversized and/or misdrilled holes. Variables included bolt hole size, angle of hole relative to member surface, and orientation of load relative to wood grain. The study revealed that the EYM predicts connection yield load for connections with oversized bolt holes with acceptable accuracy. Results indicated little difference in yield load or maximum load with increased bolt hole size. Results indicated a reduction in load of up to 21 percent with increased bolt hole size and an additional reduction of up to 63 percent when holes were drilled at a 2° angle from perpendicular to the member surface.

Keywords: Bolt, wood connection, European Yield Model, yield load, bolt hole, dowel bearing strength

August 1993

Wilkinson, T.L. 1993. Bolted connection strength and bolt hole size. Res. Pap. FPL-RP-524. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 9 p.

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Bolted Connection Strength and Bolt Hole Size

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Introduction

In recent code developments, the European Yield Model (EYM) proposed by Johanson (1949) has been adopted as the base for predicting the strength of bolted connections. The EYM can predict the strength for various connection geometries and material combinations for two- and three-member connections. Soltis and others (1986) found that the EYM explains much of the observed behavior of bolted timber connections. McLain and Thangjitham (1983) also found that the EYM predicts bolted connection performance. Wilkinson (1992) found that the EYM predicts connection yield load defined by the 5-percent offset load with acceptable accuracy. These studies indicated that the EYM can be a useful model to predict behavior for single-bolted connections.

These previous studies evaluated connections in which the bolt hole was 1/16 in. larger than the bolt diameter, the largest bolt hole allowed by the National Design Specification (NFPA 1991). (See Table 1 for SI conversion factors.) Holes were always drilled perpendicular to the member surface. In practice, bolt holes may be enlarged and misdrilled, which may affect single-bolted connection behavior. For more than one bolt in a row, Wilkinson (1986) showed that enlarged bolt holes, such as oversized and misdrilled bolt holes, can greatly affect the load distribution among bolts in the row. This can result in a few bolts carrying most of the load and others carrying very little load.

Objectives

This report presents data for single-bolted timber connections with steel side plates and various sizes of bolt holes. Additional data are presented for connections with various sizes of bolt holes drilled at an angle to the member surface. Load-deformation behavior of connections is compared, and EYM-predicted loads are compared to experimental results where applicable. The objectives were to determine (1) how well the EYM predicts experimental results for connections with oversized bolt holes and (2) how the load-deformation behavior of connections is affected by oversized and/or misdrilled bolt holes.

Table 1—SI conversion factors

English unit	Conversion factor	SI unit
inch (in.)	25.4	millimeter (mm)
pound-force (lbf)	4.448	newton (N)
pound-force per square inch (lbf/in^2)	6.895	Pascal (Pa)

European Yield Model

The EYM provides an analytical method for predicting the strength of a two- or three-member dowel-type connection. This model was originally developed in Europe (Johanson 1949) and is based on equilibrium equations resulting from the free body diagram of a bolt in a wood member. McLain and Thangjitham (1983), Wilkinson (1992), and Soltis and others (1986) found good agreement between EYM-predicted and experimental data sets.

The EYM assumes that the capacity of a bolted connection is attained when either (1) the compressive strength of the wood beneath the bolt is exceeded (Mode I or II yielding) or (2) one or more plastic hinges develop in the bolt (Mode III or IV yielding). These assumptions provide for several modes of yielding depending on connection member dimensions, member strength, bolt diameter, and bolt strength. For three-member connections, the yield load Z_y is the smallest value given by the following equations.

Mode I,

$$Z_y = D t_m F_{em} \quad (1a)$$

Mode I.

$$Z_y = 2 D T_S F_{es} \quad (1b)$$

Mode III_s

$$Z_y = \frac{2 D t_m F_{em}}{R_t(2+R_e)}\left[\sqrt{\frac{2(1+R_e)}{R_e} + \frac{2 F_y (2+R_e) R_t^2}{3 F_{em}(t_m/D)^2}} - 1\right] \quad (1c)$$

Mode IV

$$Z_y = 2 D^2 \sqrt{\frac{2 F_y F_{em}}{3(1+R_e)}} \quad (1d)$$

where

R_e is F_{em}/F_{es},

R_t t_m/t_s,

t_m thickness of main member (in.),

t_s thickness of side member (in.),

F_{em} dowel bearing strength of main member (lbf/in^2),

F_{es} dowel bearing strength of side member (lbf/in^2),

F_y bending yield strength of bolt (lbf/in^2), and

D bolt diameter (in.).

Methods

Specimens

Three-member connections loaded both parallel and perpendicular to the grain were evaluated. Each connection consisted of a wood main member and steel side members fastened with a single bolt.

Bolt diameter was 3/4 in. The steel bolts were SAE Grade 2. Bolts were long enough to prevent bearing on the threads. Nuts were finger-tight at time of test.

Ratios of main member thickness to bolt diameter (t_m/D) were 3.0, 6.75, and 10.25. Steel side member thickness was 3/8 in.

The main members were cut from Douglas Fir glulam beams constructed of L2 or better laminating stock. The beams had three 1-1/2 in.-thick laminations. All wood members had a moisture content of approximately 12 percent.

The bolt hole diameters were 13/16, 7/8, and 1 in. For an additional set of specimens per bolt hole diameter, the hole was drilled at a 2° angle from perpendicular to the member surface, tilted perpendicular to the applied load, so that the load was not applied uniformly along the bolt length under initial loading. Bolt holes were drilled parallel to glue lines. Bolt holes in the steel side members were 13/16 in. for all specimens.

Twenty replications were created for each combination of variables for a total of 360 parallel-to-grain and 360 perpendicular-to-grain loaded specimens.

The connection configurations were made to exceed National Design Specification (NFPA 1991) requirements for end and edge distance. For parallel-to-grain loading, the distance from the bolt to the end of the main member was 7.5 times the bolt diameter; for perpendicular-to-grain loading, the distance exceeded 4.25 times the bolt diameter. Edge distance equaled or exceeded 1.5 times the bolt diameter for both loadings. For perpendicular-to-grain loading, the distance between supports was 13.5 in. This distance was three times the depth of the main member, as specified by ASTM D1761-88 (ASTM 1990).

Experimental Procedure

The test procedures for parallel-to-grain loading (Fig. 1) and perpendicular-to-grain loading (Fig. 2) generally followed those given in ASTM D1761-88 (ASTM 1990). Tension loading was used for the parallel-to-grain specimens and compression loading for the perpendicular-to-grain specimens. No preload was used to set the bolts. The applied load was deformation controlled at 0.050 in./min. The tests were terminated at member failure.

Deformation was measured using a linear variable differential transducer (LVDT). Load-deformation values were continuously recorded until failure. Deformations were measured to an accuracy of ±0.001 in.

The EYM requires the measurement of dowel bearing strength. This property was determined by uniformly loading a bolt in a half-hole (Fig. 3). One specimen was obtained for each connection from a section of the glulam beam directly adjacent to the main member. Bolt holes, the same size as those in the connection, were located in the same laminations as the connection bolt holes. A load-deformation curve was obtained using the movement of the movable head of the testing machine as a measure of deformation. The head movement was measured with an LVDT.

Bolt bending yield strength was determined from bending tests (Fig. 4). Approximately 10 bolts of each of the two longer lengths were tested. Bolts were loaded at the center of the span. Spans were 5-1/4 in. and 8-3/16 in., the longest spans that could be used for the various bolt lengths without bearing on the threads. A load-deflection curve was obtained using the movement of the movable head of the testing machine measured with an LVDT as a measure of deflection,

The dowel bearing strength of the steel side members was not measured. This property was developed based on American Institute of Steel Construction, Inc. specifications (AISC 1970).

Specific gravity and moisture content were determined for each bolted connection. Specimens were taken from a section of the glulam beam directly adjacent to each main member that contained laminations with bolt holes.

Definition of Yield Load

The yield load as given by the EYM may be defined as any load on the load-deformation curve. One proposed definition of yield load is the maximum load. Another approach, originally suggested by Harding and Fowkes (1984), defines the yield load as the intersection of the load-deformation curve with a straight line parallel to the initial portion of the load-deformation curve and offset a distance of 5 percent of the fastener diameter from the origin of the load-deformation curve. This 5-percent offset approach was selected as the definition of yield load for this study and by the National Design Specification (NFPA 1991).

Using the 5-percent offset yield load has several advantages compared to using the maximum load. For connections with large t_m / D ratios, the EYM equations predict a Mode III_s yielding. The typical load-deformation curve shows three stages of yielding as indicated by three distinctive slopes (Figure 5a). The third stage is caused by the restraint imposed by the bolt head and nut, thus producing a Mode IV yielding. By using the 5-percent offset load, yield load is defined in the region of Mode III_s yielding.

For perpendicular-to-grain loading, a drop in load often occurs before the maximum load is reached (Fig. 5b). This is due to a fracture failure mode, which is not handled by the EYM. The 5-percent offset approach defines yield at a load before this initial drop in load occurs.

With yield load defined on a 5-percent offset basis, the other input properties in the EYM equations should also be defined on the same basis. In this study, the dowel bearing strength of the connection members and the bending yield strength of the bolts were determined on the basis of a 5-percent offset load.

Results

Results of the connection tests are summarized in Table 2. Values of yield load (based on 5-percent offset) for specimens with holes drilled parallel and perpendicular to the member surface and maximum load for all specimens are presented along with the deformation at each load. It was not possible to obtain yield loads for connections where the hole was drilled at a 2° angle from perpendicular to the surface because of the typical shape of the load-deformation curve (Fig. 6). The initial loading period of these specimens brought the full length of the bolt into bearing on the bolt hole. The results indicate little difference in yield load or maximum load with increased bolt hole size, but deformation generally increased with increased bolt hole size. Maximum load was apparently reduced when holes were not drilled perpendicular to the member surface.

Since yield loads could not be obtained for specimens with holes drilled at a 2° angle from perpendicular to the member surface, we decided to use load at the yield load deformation for connections with 13/16-in. bolt holes to compare all specimens. This type of comparison may serve to indicate a serviceability limit for such connections. The data in Table 3 indicate how much the connection load would be reduced if the connection deformation were restricted to that for 13/16-in. bolt hole connections. Results indicated a reduction in load of up to 21 percent with increased bolt hole size and an additional reduction of up to 63 percent when holes were drilled at a 2° angle from perpendicular to the member surface. These effects were increased with increased t_m / D ratio: 4 percent for t_m / D = 3.00 compared to 21 percent for t_m / D = 10.25 for a l-in. hole. The reduction in load was greater for parallel-to-grain loading than for perpendicular-to-grain loading—63 percent compared to 39 percent for a l-in. hole at a 2° angle from perpendicular to the surface.

Table 4 presents the results of the dowel bearing strength tests along with the average moisture content and specific gravity of the bearing specimens and bolted connection specimens. The dowel bearing strength was based on a 5-percent offset load. Results indicated a slight decrease (approximately 400 lbf/in^2) in dowel bearing strength with increased hole diameter.

The average bending yield strength of the bolts was 79.26×10^3 lbf/in^2) with a coefficient of variation of

1.3 percent. The bending yield strength was based on a 5-percent offset load. The plastic section modulus ($D^3/6$) was used to calculate the bending yield strength. Published elastic yield strength for these bolts is 57×10^3 lbf/in^2.

Analysis

One purpose of the study was to see how well the EYM predicted the experimental results for connections with oversized bolt holes. For input in the EYM equations, the experimental dowel bearing strength was averaged over all t_m/D ratios for each bolt hole size. The dowel bearing strength of the steel side members was not measured. The side members were low carbon steel, with an assumed yield stress of 36×10^3 lbf/in^2. The yield stress was increased by 35 percent to account for stress concentrations, as given by the American Institute of Steel Construction, Inc. (AISC 1970), to arrive at an allowable bearing stress of 48×10^3 lbf/in^2. This allowable bearing stress was used as the dowel bearing strength of the steel side members. The AISC currently recommends an allowable bearing stress of 69×10^3 lbf/in^2, which would increase the predicted yield load by 5 percent for Mode III_s yielding while not changing the predicted yield load for Mode I, yielding. Other input variables were as measured.

Figures 7 and 8 compare EYM-predicted yield loads with experimental yield loads for parallel-to-grain and perpendicular-to-grain loading, respectively. In all cases, there appears to be general agreement between EYM-predicted loads and experimental results. Notice that the EYM predicts only Mode I_m and Mode III_s yielding. This was one reason for selecting the 5-percent offset load as the definition of yield load because it eliminates the apparent Mode IV yielding caused by end restraint on the bolt.

Concluding Remarks

This study investigated the properties of bolted connections with steel side members with oversized bolt holes of various diameters. The study included a set of specimens with oversized bolt holes drilled at a 2° angle from perpendicular to the member surface. Three t_m/D ratios were investigated, and connections were loaded both parallel and perpendicular to the grain. The major findings were as follows:

1. Increased bolt hole size had little effect on yield load or maximum load but generally increased deformation.
2. Maximum load was reduced when holes were drilled at a 2° angle from perpendicular to the member surface.
3. For 1/16-in. oversized hole connections, load was decreased up to 21 percent; for larger bolt holes, load was decreased up to 63 percent, when holes were drilled at a 2° angle from perpendicular to the surface. The decrease in load was greater for larger t_m/D ratios.
4. Hole diameter and angle of hole had a greater effect for parallel-to-grain compared to perpendicular-to-grain loading.
5. The European Yield Model (EYM) predicted bolted connection yield load with acceptable accuracy.

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Table 2—Summary of **connection properties**[a]

t_m/D	Hole size (in.)	Load (× 10^3 lbf)		Deformation (in.)	
		Yield	Maximum	Yield	Maximum
		Parallel to grain			
3.00	13/16	8.02 (11.8)	8.83 (13.4)	0.079 (13.4)	0.209 (50.0)
	7/8	7.77 (15.8)	8.10 (15.2)	0.086 (11.8)	0.159 (76.0)
	1	8.21 (12.8)	8.69 (14.7)	0.092 (14.3)	0.190 (49.0)
	At 2°				
	13/16		8.31 (13.4)		0.156 (53.9)
	7/8		8.66 (11.4)		0.190 (51.9)
	1		8.47 (15.0)		0.183 (33.6)
6.75	13/16	13.04 (10.9)	24.58 (11.7)	0.113 (9.5)	0.455 (38.9)
	7/8	13.01 (14.4)	24.61 (10.3)	0.116 (18.8)	0.497 (28.7)
	1	12.92 (9.5)	23.49 (13.9)	0.124 (13.4)	0.478 (38.2)
	At 2°				
	13/16		23.87 (8.9)		0.568 (30.5)
	7/8		23.03 (11.7)		0.494 (23.7)
	1		20.56 (23.3)		0.395 (45.0)
10.25	13/16	13.03 (11.6)	28.26 (9.2)	0.107 (9.4)	0.656 (20.7)
	7/8	11.74 (7.7)	32.40 (15.1)	0.108 (8.1)	0.837 (22.0)
	1	11.36 (8.2)	29.45 (12.0)	0.131 (10.4)	0.769 (19.9)
	At 2°				
	13/16		27.24 (23.9)		0.792 (34.1)
	7/8		28.45 (19.5)		0.798 (26.5)
	1		28.91 (15.4)		0.807 (24.3)
		Perpendicular to grain			
3.00	13/16	3.82 (19.5)	5.27 (14.1)	0.100 (16.9)	0.271 (34.1)
	7/8	3.69 (19.7)	6.07 (11.2)	0.110 (16.0)	0.412 (25.8)
	1	3.39 (20.8)	5.37 (13.6)	0.116 (19.8)	0.340 (32.9)
	At 2°				
	13/16		5.26 (10.8)		0.333 (33.4)
	7/8		5.13 (16.6)		0.293 (36.7)
	1		4.61 (15.8)		0.268 (37.3)
6.75	13/16	7.48 (10.6)	12.20 (13.2)	0.136 (11.3)	0.400 (21.8)
	7/8	6.91 (18.9)	12.38 (12.0)	0.139 (18.1)	0.402 (24.8)
	1	7.35 (16.1)	12.55 (11.5)	0.156 (10.8)	0.381 (24.1)
	At 2°				
	13/16		12.19 (12.2)		0.422 (20.4)
	7/8		11.89 (12.9)		0.387 (18.6)
	1		11.36 (15.5)		0.394 (29.9)
10.25	13/16	9.44 (14.7)	22.06 (7.9)	0.153 (15.4)	0.606 (14.9)
	7/8	9.97 (16.4)	20.27 (10.0)	0.172 (17.0)	0.531 (23.5)
	1	8.86 (21.8)	20.86 (13.8)	0.183 (30.1)	0.576 (18.0)
	At 2°				
	13/16		21.19 (17.7)		0.634 (24.3)
	7/8		20.14 (13.2)		0.619 (25.1)
	1		19.13 (10.7)		0.619 (15.4)

[a] t_s = 3/8 in.; D = 3/4 in. t_m D is ratio of main member thickness to bolt diameter. Average values based on sample size of 20 specimens; coefficient of variation in parentheses, expressed as percentage. See Table 1 for SI conversion factors.

Table 3—Ratio of average loads at fixed deformation equal to yield load-deformation for connections with 13/16-in. bolt holes[a]

Hole size (in.)	Ratio of loads at various t_m/D values[b]					
	3.00 (0.079 in.)	6.75 (0.113 in.)	10.25 (0.107 in.)	3.00 (0.100 in.)	6.75 (0.136 in.)	10.25 (0.153 in.)
13/16	1.00	1.00	1.00	1.00	1.00	1.00
7/8	0.94	0.97	0.90	0.92	0.92	0.98
1	0.96	0.93	0.79	0.78	0.90	0.83
At 2°						
13/16	0.91	0.63	0.49	0.90	0.90	0.71
7/8	0.93	0.56	0.46	0.83	0.88	0.73
1	0.71	0.54	0.36	0.68	0.81	0.61

[a] Average values based on sample size of 20 specimens.
[b] Yield deformation values are in parentheses.

Table 4—Summary of dowel bearing strength, moisture content, and specific gravity'

Hole size (in.)	Moisture content (× 10[3] lbf/in[2])			Specific gravity			Dowel bearing strength (× 10[3] lbf/in[2])[b]		
	3.00	6.75	10.25	3.00	6.75	10.25	3.00	6.75	10.25
					Parallel to grain				
13/16	11.6	10.9	13.3	0.456	0.435	0.432	5.34 (9.1)	5.49 (10.3)	5.37 (12.9)
7/8	11.7	11.1	13.2	0.454	0.432	0.432	4.84 (10.0)	5.04 (15.5)	5.13 (11.4)
1	11.8	11.0	13.2	0.448	0.429	0.436	4.92 (11.7)	4.55 (13.3)	4.99 (8.3)
At 2°									
13/16	11.9	11.5	13.4	0.456	0.428	0.443	5.20 (12.2)	4.91 (14.2)	4.84 (10.0)
7/8	12.0	11.6	13.4	0.468	0.427	0.432	4.83 (14.7)	4.99 (7.9)	5.09 (10.0)
1	11.2	10.9	13.2	0.447	0.428	0.427	4.75 (11.8)	4.96 (12.5)	4.94 (9.3)
					Perpendicular to grain				
13/16	10.9	10.4	12.8	0.458	0.444	0.459	2.02 (17.7)	2.59 (18.0)	2.73 (14.3)
7/8	11.1	10.9	12.8	0.448	0.443	0.450	1.83 (20.7)	1.96 (17.0)	2.20 (13.1)
1	11.0	10.5	12.9	0.500	0.447	0.461	1.63 (18.6)	1.86 (16.8)	2.21 (19.9)
At 2°									
13/16	10.9	10.5	12.8	0.467	0.445	0.445	2.07 (12.4)	2.23 (19.1)	2.51 (9.9)
7/8	11.0	10.7	12.8	0.462	0.441	0.447	1.91 (19.9)	2.04 (14.2)	2.51 (17.1)
1	10.9	10.6	12.9	0.448	0.438	0.456	1.69 (16.2)	1.95 (22.9)	2.03 (17.1)

Average properties for various t_m/D ratios

[a] Average values based on sample sizes of 20 specimens.
[b] Coefficient of variation in parentheses, expressed as percentage.

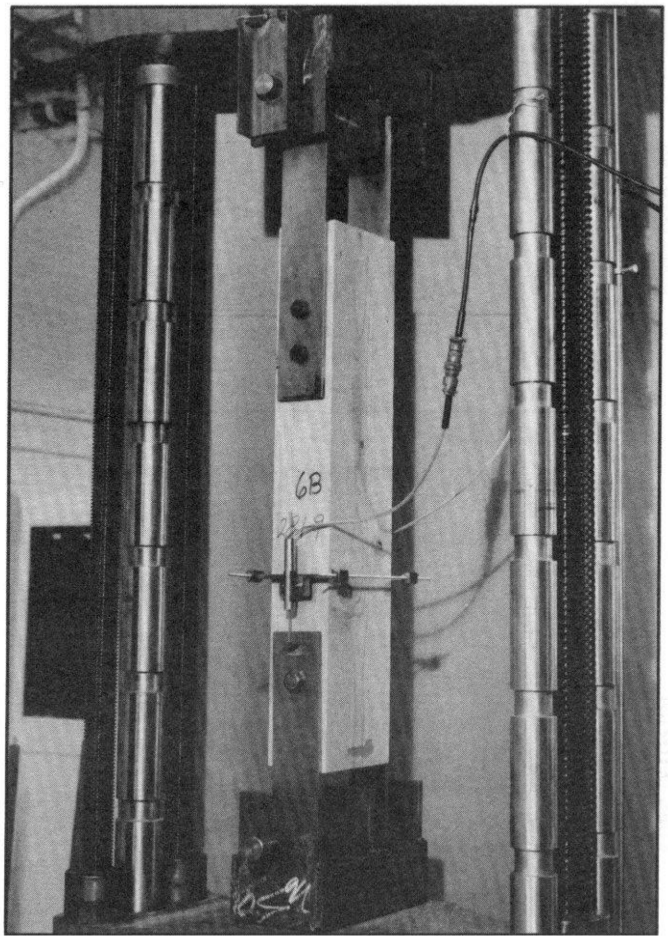

Figure 1—Experimental arrangement for loading bolted connections parallel to grain. (M87 0201-2)

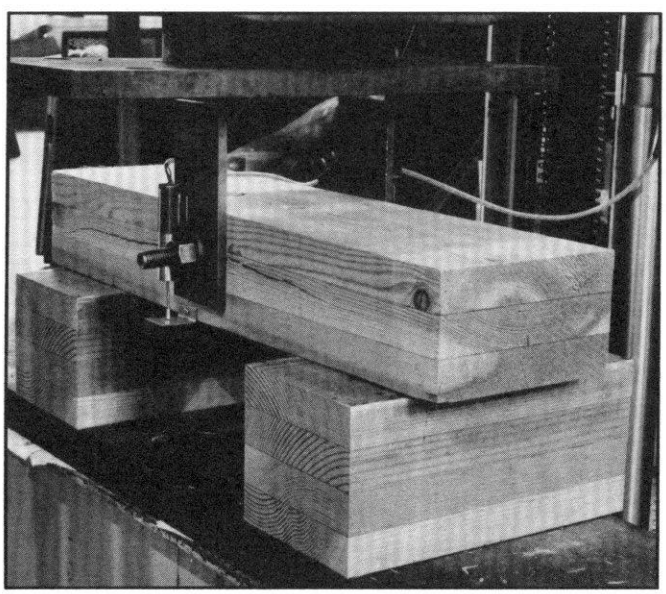

Figure 2—Experimental arrangement for loading bolted connections perpendicular to grain. (M88 0010-10)

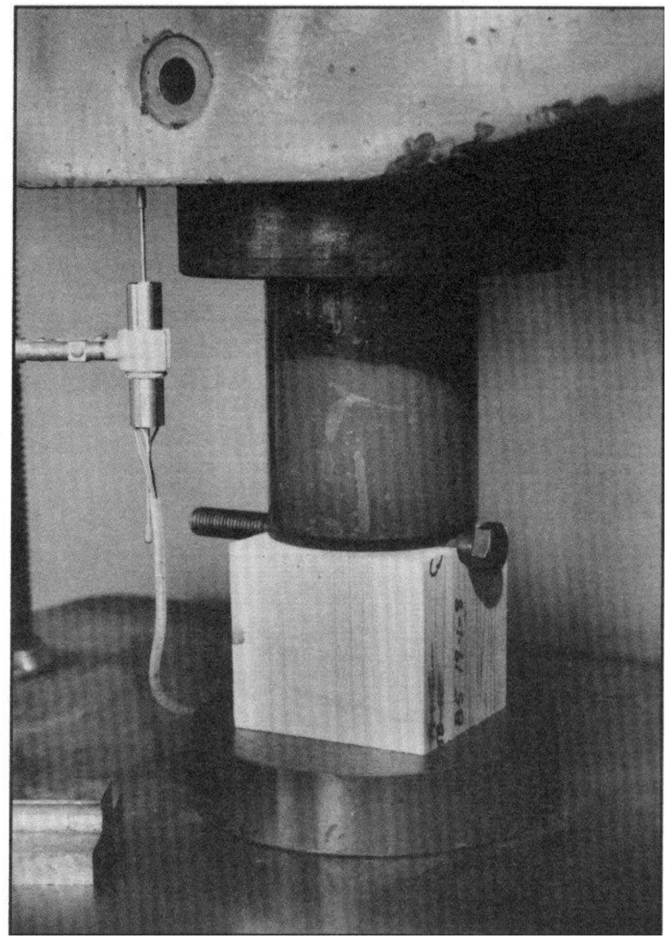

Figure 3—Experimental arrangement for determining dowel bearing strength. (M87 0201-6)

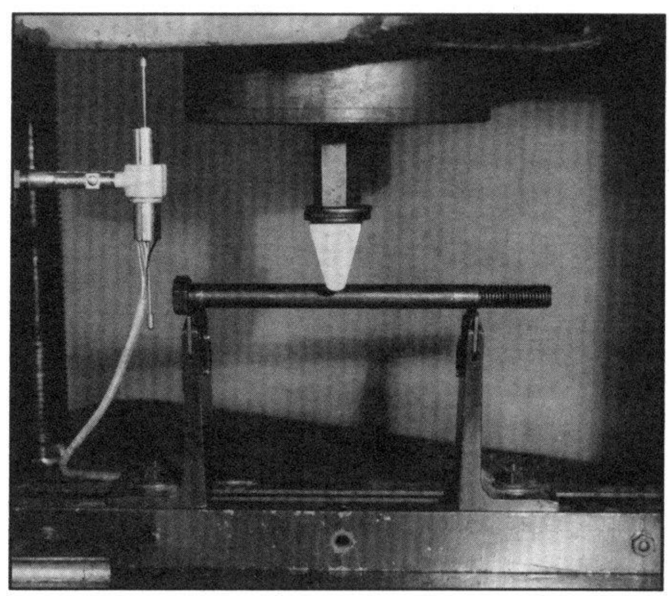

Figure 4—Experimental arrangement for determining bolt bending yield strength. The span was the longest possible without bearing on threads. (M87 0201-8)

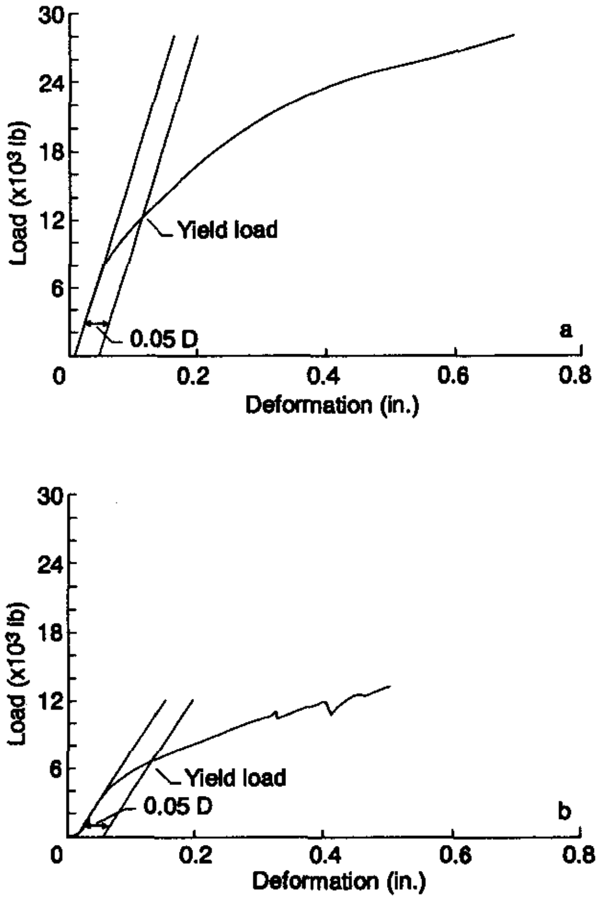

Figure 5—Typical load-deformation curves for bolted connections. t_m/D is ratio of main member thickness to bolt diameter. (a) Connection loaded parallel to grain with t_m/D ratio of 10.25 and 13/16-in. bolt hole (D = 3/4 in.; (b) connection loaded perpendicular to grain with t_m/D ratio of 6.75 and 13/16-in. bolt hole (D = 3/4 in.).

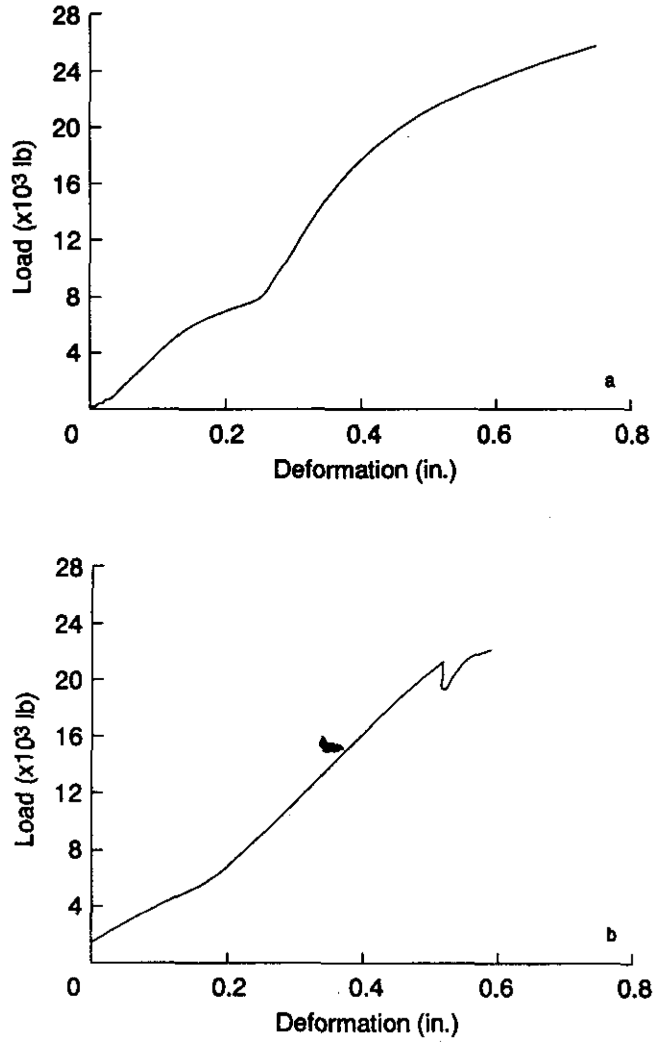

Figure 6—Typical load-deformation curve for bolted connections. (a) Connection loaded parallel to grain with 1-in. bolt hole drilled at a 2° angle from perpendicular to the member surface; (b) connection loaded perpendicular to grain with 1-in. bolt hole drilled at a 2° angle from perpendicular to the member surface (t_m/D = 10.25; D = 3/4 in.).

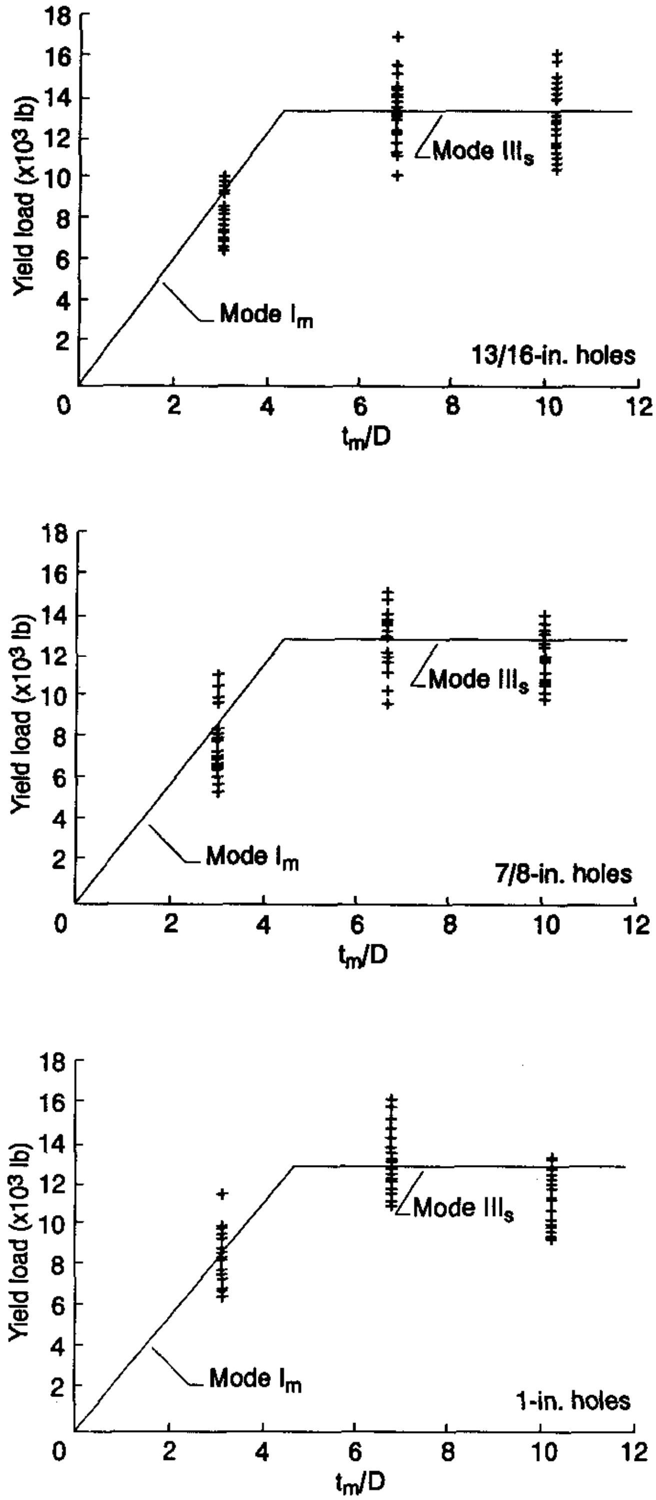

Figure 7 - Experimental and EYM-predicted yield loads for bolted connections with 13/16-in., 7/8-in. and 1-in. bolt holes loaded parallel to grain. D = 3/4-in., F = 48 x 10^3 lbf/in^2. F_y = 79 x 10^3 lbf/in^2. and t_s = 3/8 in. F_{em} = 5.4 x 10^3 lbf/in^2 for 13/16-in. holes, 5.0 x 10^3 lbf/in^2 for 7/8-in. holes, and 4.82 x 10^3 lbf/in^2 for 1-in. holes.

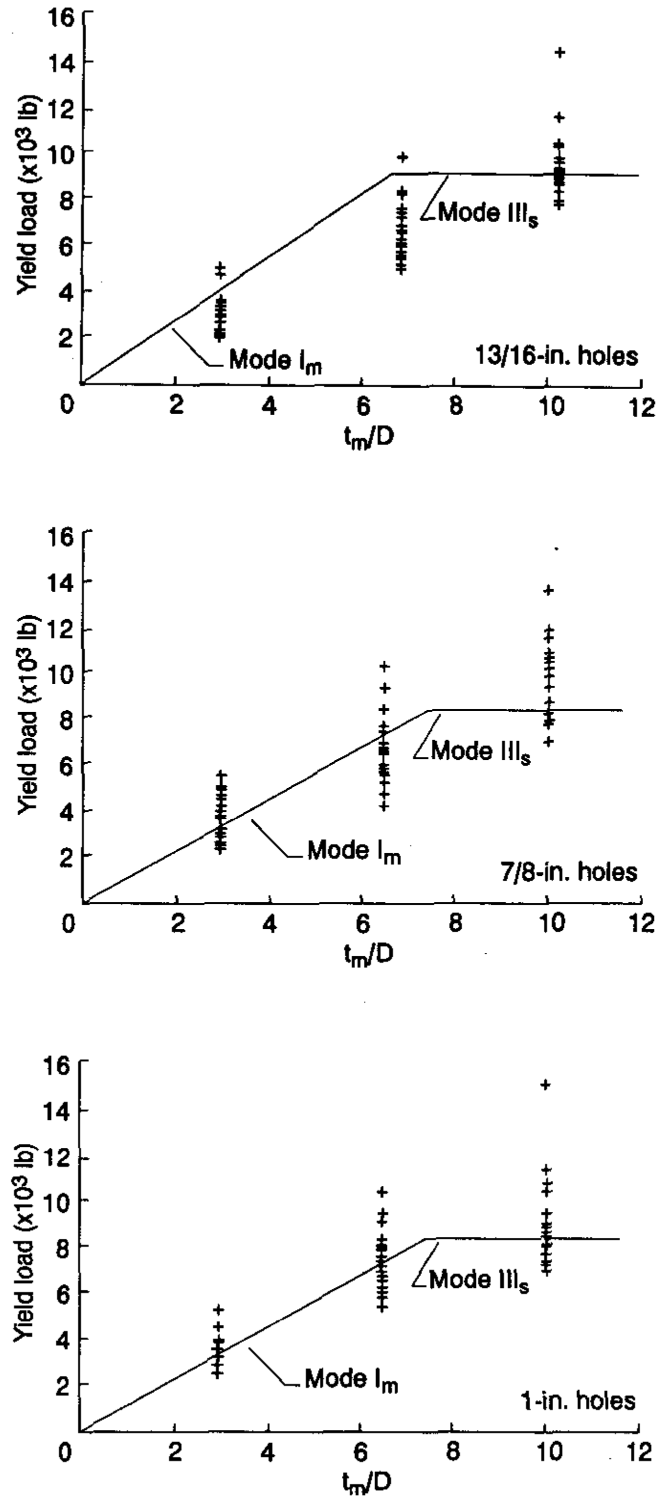

Figure 8 - Experimental and EYM-predicted yield loads for bolted connections with 13/16-in., 7/8-in., and l-in. bolt holes loaded perpendicular to grain. D = 3/4 in., F_{es} = 48,600 lbf/in^2. F_y = 79,260 lbf/in^2, and t_s = 3/8 in. F_{em} = 2.4 x 10^3 lbf/in^2 for 13/16-in. holes. 2 x 10^3 lbf/in^2 for 7/8-in. holes, and 1.9 X 10^3 lbf/in^2 for l-in. holes.

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