United States
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FPL-RP-513

Strength of Bolted Timber Connections with Steel Side Members

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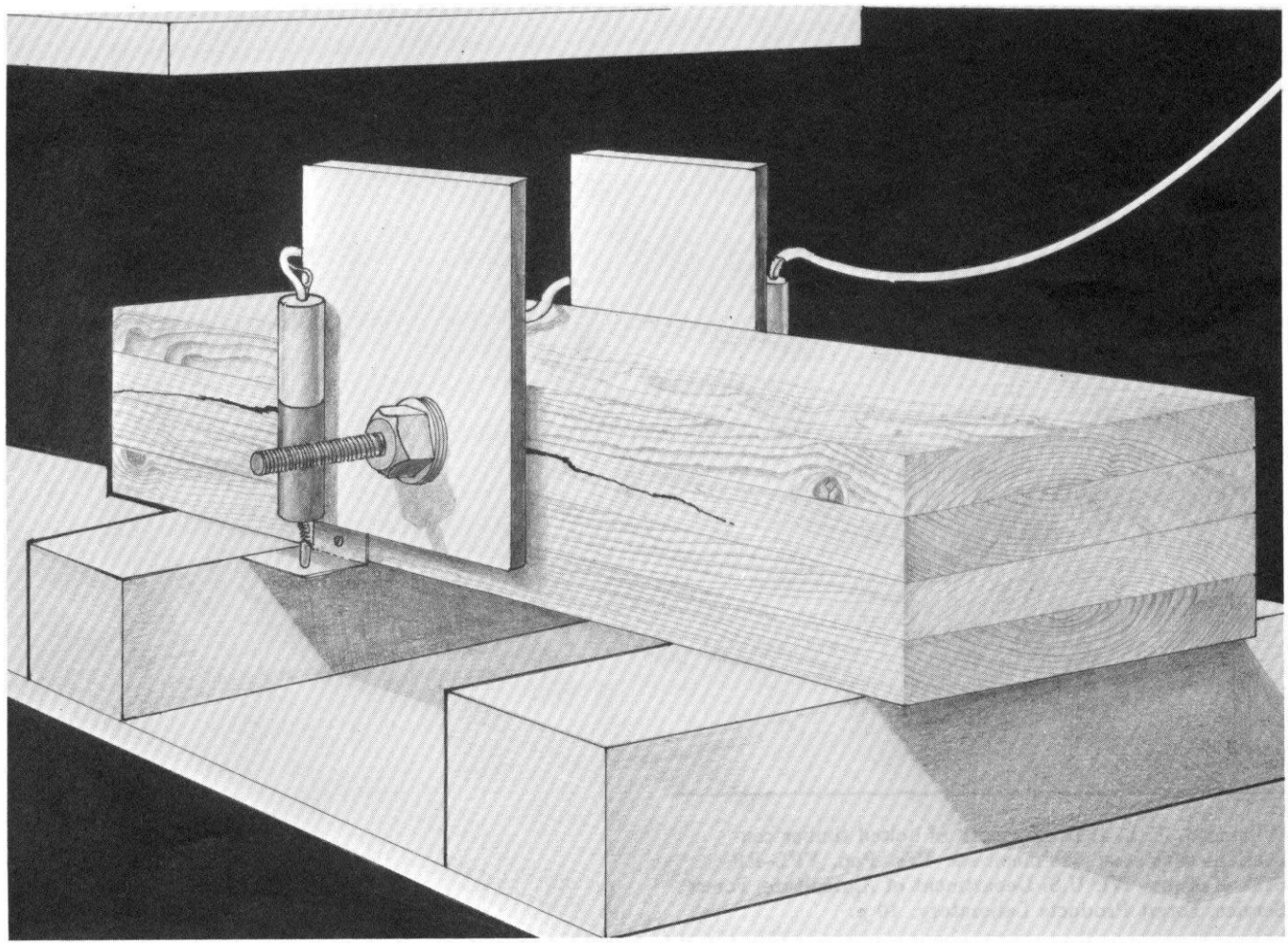

Abstract

This study investigated the properties of bolted timber connections with steel side members. The intent of this study was to determine (1) how well the European Yield Model (EYM) predicts experimental results (2) if there is a difference in results from tension- and compression-loaded specimens, and (3) what the effect is of steel side member thickness. Three bolt diameters and four ratios of main member thickness to bolt diameter were investigated. Connections were loaded both parallel and perpendicular to the gram. Results were compared to predicted results from the EYM. The study revealed that the EYM predicts connection yield load with acceptable accuracy.

Keywords: Bolts, wood connections, European Yield Model, yield load, dowel embedment strength

July 1992

Wilkinson, T. L. 1992. Strength of bolted timber connections with steel side members. Res. Pap. FPL-RP-513. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 10 p.

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Strength of Bolted Timber Connections With Steel Side Members

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Introduction

Historically, design values for bolted timber connections (NFPA 1986) have been based on research conducted by Trayer (1932). Trayer's recommendations were based on an empirical fit of experimental data and thus are limited to the connection geometries evaluated, although Trayer's recommendations have been extrapolated to other geometries by rule of thumb type procedures. Trayer empirically related bolt bearing stress at proportional limit with the ratio of main member thickness to bolt diameter. He further related the bolt bearing stress with the small, clear compressive strength of the wood. His sample sizes were four and five specimens.

Doyle and Scholten (1963) evaluated bolted connections in Douglas-fir with sample sizes of three specimens. Soltis and others (1986) evaluated bolted Douglas-fir connections with wood side members using sample sizes of 16 specimens. Both of these studies found that the previous recommendations from Trayer were still valid.

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. These studies indicated that the EYM can be a useful model to predict connection behavior for single-bolted connections.

Most investigations of bolted timber connections have used small sample sizes that do not allow the calculation of reliable statistical properties of the distribution of connection properties. In the future, design loads for bolted connections may be derived using reliability-based design procedures, which would require distribution properties.

Most studies have reported only proportional limit loads for bolted timber connections. For future design procedures, other connection properties may need to be known. These properties include maximum load and connection deformation information. Deformation data would be useful in setting serviceability limits for connections in a reliability-based design procedure. Deformation data are also needed for predicting the load distribution among bolts in multiple bolt connections in procedures such as that developed by Lantos (1969).

Objective

This paper presents data for single-bolted timber connections with steel side members. Input data for use with the EYM are also presented and EYM-predicted loads are compared to experimental results. The objectives were to determine (1) how well the EYM predicts experimental results, (2) if results from tension-loaded specimens differ from results from compression-loaded specimens, and (3) what the effect is of steel side member thickness.

European Yield Model

The EYM provides an analysis method to predict the strength of a two- or three-member dowel-type connection. It 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. The method has been examined by McLain (1983) and Soltis (1986). Both found general agreement between 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 (Modes III or IV yielding).

These assumptions provide for several modes of yielding depending on connection member dimensions, member strength, and bolt strength. For three-member connections, the yield load Z_y is the smallest value given by the following equations.

Mode I,,,

$$Z_y = D t_m F_{em} \tag{1a}$$

Mode I,

$$Z_y = 2 D t_s F_{es} \tag{1b}$$

Mode III,

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

Mode IV

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

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 (lb/in^2),

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

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

D bolt diameter (in.).

(Conversion factors are 1 in. = 25.4 mm; 1 lb/in^2 = 6.89 kPa.)

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.

Three bolt diameters, 1/2 in. (12.7 mm), 3/4 in. (19.0 mm), and 1 in. (25.4 mm), were used. 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, 5.125, 6.75, and 10.25 for each bolt diameter. Steel side member thickness was 1/4 in. (6.4 mm), 3/8 in. (9.5 mm), and 1/2 in. (12.7 mm) for the 1/2-in. (12.7-mm) bolts; 3/8 in. (9.5 mm) for the 3/4-in. (19.0-mm) bolts; and 1/2 in. (12.7 mm) for the 1-in. (25.4-mm) bolts.

The wood main members were cut from Douglas-fir glulam beams constructed of L2 or better grade laminating stock. Specimens with 1/2-in. (12.7-mm) bolts had two laminations, those with 3/4-in. (19.0-mm) bolts had three laminations, and those with 1-in. (25.4-mm) bolts had four laminations. All laminations were 1-1/2 in. (38.1 mm) thick. Bolt holes 1/16 in. (1.6 mm) greater than the bolt diameter were drilled parallel to the glue lines. All wood members had a moisture content of approximately 12 percent.

Twenty replications were created for each combination of variables for a total of 240 parallel-to-grain loaded specimens and 240 perpendicular-to-grain loaded specimens.

The connection configurations were made to exceed National Design Specification (NFPA 1986) requirements for end and edge distance. The distance from the bolt to the end of the main member was 7.5 times the bolt diameter for parallel-to-grain loading. The distance from the bolt to the loaded edge exceeded 4.25 times the bolt diameter for perpendicular-to-grain loading. Edge distance equaled or exceeded 1.5 times the bolt diameter for both loadings. For perpendicular-to-grain loading, the distance between supports was 9 in. (230 mm) for specimens with 1/2-in. (12.7-mm) bolts, 13.5 in. (340 mm) for specimens with 3/4-in. (19.0. mm) bolts, and 18 in. (460 mm) for specimens with 1-in. (25.4-mm) bolts. These distances were 3 times the depth of the main member, as specified by ASTM D1761-88 (ASTM 1990).

In addition to the main series of teats, 20 parallel-to-grain loaded specimens were evaluated using compression loading instead of tension loading. These specimens used 3/4-in. (19.0-mm) bolts and a t_m/D of 6.75. Two additional groups of 20 parallel-to-grain loaded specimens each were evaluated with 1/2-in. (12.7-mm) bolts and steel side member thicknesses of 3/8 in. (9.5 mm) and 1/2 in. (12.7 mm). For these two groups the t_m/D was 5.125.

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 with the parallel-to-grain loaded specimens except for one group, which used compression loading. The applied load was

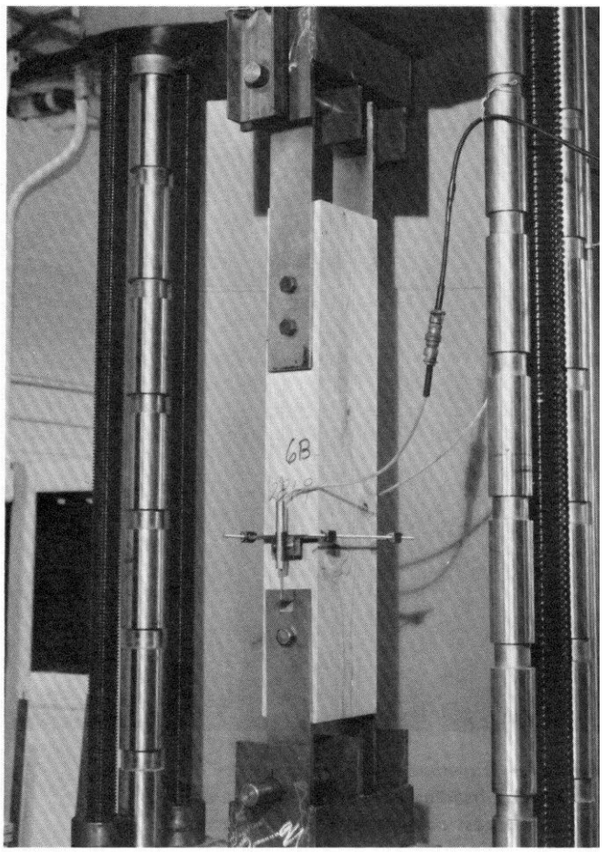

Figure 1—Experimental arrangement for loading bolted connections parallel to grain.

deformation controlled at either 0.035 or 0.050 in/min (0.89 or 1.27 mm/min). The tests were terminated when failure occurred.

Deformation was measured using linear variable differential transducers. Load-deformation values were continuously recorded until failure occurred. Deformations were measured to an accuracy of ±0.001 in. (0.025 mm).

Minor Tests

A wood property needed for input in the EYM is the 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 were located in the same laminations as the bolt hole in the connection. A load-deformation curve was obtained using the movement of the movable head of the testing machine as a measure of deformation.

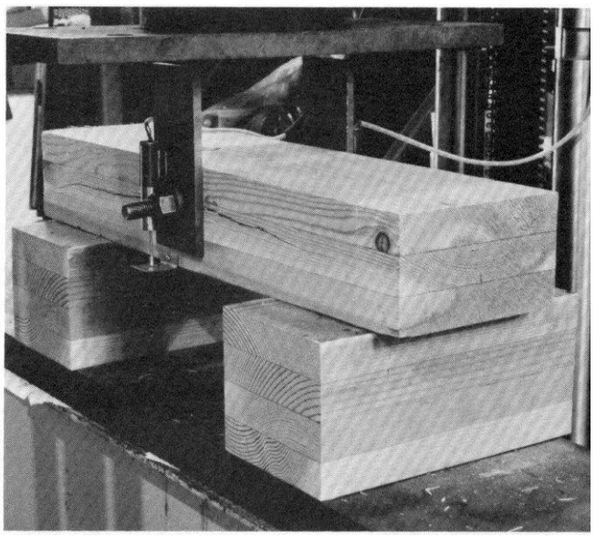

Figure 2—Experimental arrangement for loading bolted connections perpendicular to grain.

Bolt bending yield strength was determined from bending tests of bolts (Fig. 4). Bolts were loaded at the center of the span. Spans of 2-13/16 in. (71 mm), 3-3/4 in. (95 mm), and 5-15/32 in. (139 mm) were used with 1/2-in. (12.7-mm) bolts; 3-3/4 in. (95 mm), 5-1/4 in. (133 mm), and 8-3/16 in. (208 mm) with 3/4-in. (19.0-mm) bolts; and 7 in. (177 mm) and 11 in. (279 mm) with l-in. (25.4-mm) bolts. These were the longest spans that could be used for the various length of bolts without bearing on the threads. A load-deflection curve was obtained using the movement of the movable head of the testing machine as a measure of deflection. Approximately 10 bolts of each diameter and length were tested.

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

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 has been selected as the definition of yield load for this study.

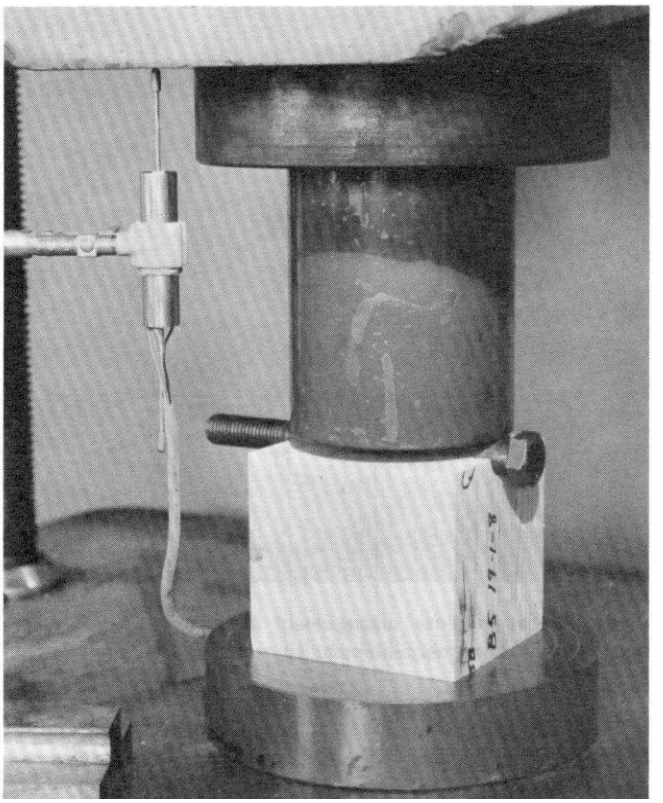

Figure 3—Experimental arrangement for determining dowel embedment strength.

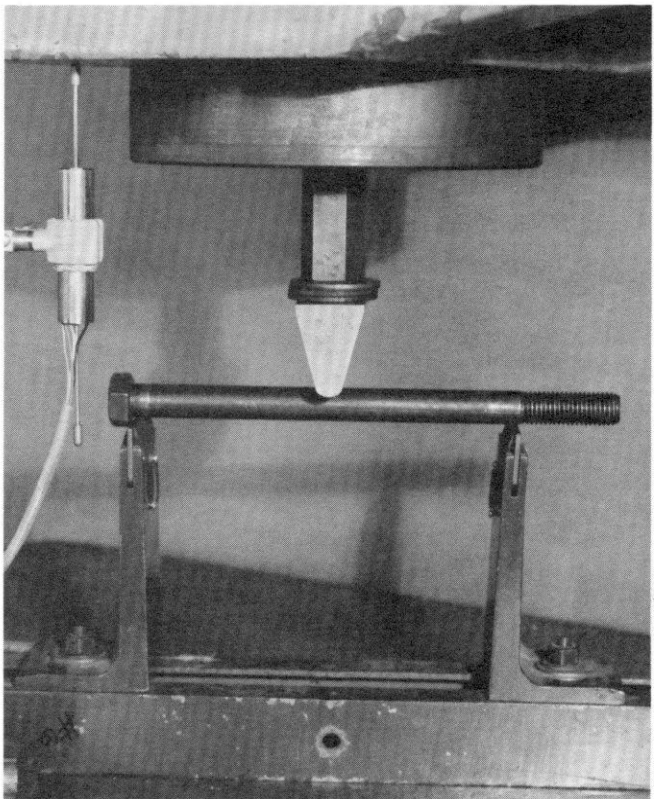

Figure 4—Experimental arrangement for determining bolt bending yield strength. The span was the longest possible without bearing on threads.

The 5 percent offset yield load has several advantages over using the maximum load. For connections with large t_m/D ratios, the EYM equations predict a Mode III. yielding. The typical load-deformation curve (Fig. 5) shows three stages of yielding. 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, there is often a drop in load before the maximum load is reached (Fig. 6). 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 have been determined on the basis of a 5 percent offset load.

Results

Results of the connection teats for specimens loaded in tension are summarized in Table 1. Values of proportional limit load, yield load (based on 5 percent offset), and maximum load are presented along with the deformation at each load. The initial slope of the load-deformation curve is also presented. These results indicate that the yield load was less variable than the proportional limit load and generally less variable than the maximum load.

Table 2 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. Apparently specimen thickness had no effect on the bearing strength. The bearing strength perpendicular to the grain decreased as the diameter increased. This same effect was noted by Trayer (1932). There was no diameter effect for parallel-to-grain loading.

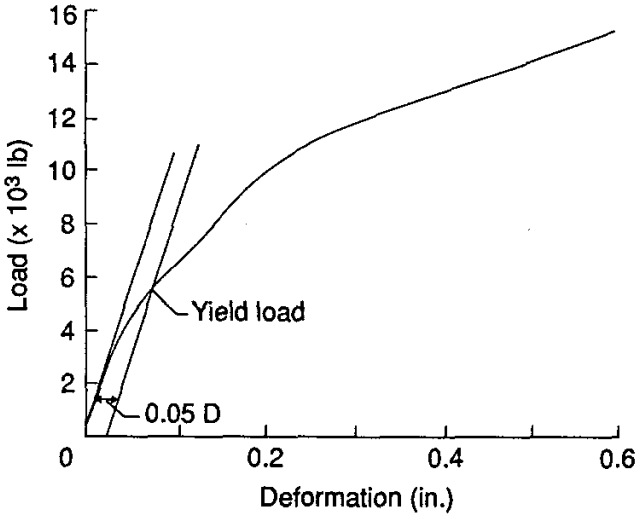

Figure 5—Typical load-deformation curve for a bolted connection loaded parallel to grain with t_m /D ratio of 10.25. D = 1/2 in. (12.7 mm) (1 in. = 25.4 mm; 1 lb = 4.45 N).

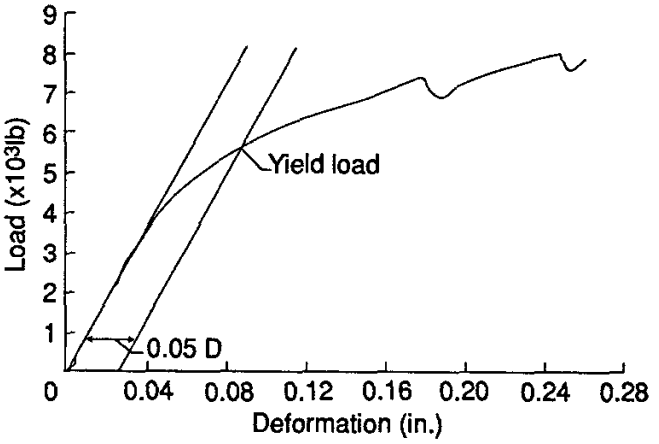

Figure 6—Typical load-deformation curve for a bolted connection loaded perpendicular to grain with t_m /D ratio of 5.125. D = 3/4 in. (19.0 mm) (1 in. = 25.4 mm: 1 lb = 4.45 N).

Table 3 gives the bending yield strength of the bolts. The load for calculating the yield strength was obtained by offsetting the initial slope of the load-deflection curve by 5 percent of the bolt diameter and taking the load where the offset slope intersected the curve. If the offset did not intersect the curve, the maximum load was used. The yield strength was calculated by

$$\text{Bending yield strength} \frac{1.5\ PL}{D^3} \qquad (2)$$

where

P is 5 percent offset load (lb),

L span (in.), and

D bolt diameter (in.).

This equation uses the plastic section modulus $(D^3/6)$. The results in Table 3 indicate that the bending yield strength decreased as bolt diameter increased.

Tables 4 and 5 compare the specimens loaded in compression with those loaded in tension. Apparently the two types of loading do not significantly differ except that more deformation at maximum load was obtained with compression loading.

Table 6 shows the effect of steel side member thickness. For the 1/2-in. side members, 80 percent of one side member was bearing on bolt threads. This would account for the slightly lower proportional limit and yield loads for this plate thickness.

Analysis

One purpose of the study was to see how well the EYM predicted the experimental results. For input in the EYM equations, the experimental dowel bearing strength was averaged over all t_m/D ratios for each bolt diameter. 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 36,000 lb/in^2 (248.2 MPa). The yield stress was increased by 35 percent to account for stress concentrations, as given by American Institute of Steel Construction, Inc. (AISC) (1970), to arrive at an allowable bearing stress of 48,600 lb/in^2 (335.1 MPa). This allowable bearing stress was used as the dowel bearing strength of the steel side members. The AISC presently recommends an allowable bearing stress of 69,600 lb/in^2 (479.9 MPa), which would increase the predicted yield load by 5 percent for Mode III, yielding while not changing the predicted yield load for Mode I, yielding. Other input variables were as measured.

Figures 7, 8, and 9 compare the EYM-predicted yield loads with experimental yield loads for parallel-to-grain loading. Figures 10, 11, and 12 give comparisons for perpendicular-to-grain loading. In practically all cases there appears to be general agreement between EYM-predicted loads and experimental results. Notice that the EYM predicts only Mode I, and Mode III_s yielding. This was one of the reasons 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.

Table 1—Summary of bolted connection properties for tension-loaded connections ($t_m/D = 0.5$)[a]

Bolt diameter (in.)	t_m/D	Load (lb)			Deformation (in.)			Initial slope (lb/in)
		Proportional limit	Yield	Maximum	Proportional limit	Yield	Maximum	
		Average[b]	Average	Average	Average	Average	Average	Average
				Parallel to grain				
1/2	3.000	3,060 (8.7)	4,560 (9.3)	4,850 (8.7)	0.022 (19.1)	0.060 (11.7)	0.130 (41.5)	129,150 (22.1)
	5.125	4,070 (13.8)	6,450 (12.7)	7,940 (18.9)	0.045 (39.6)	0.094 (15.0)	0.155 (31.5)	91,810 (13.1)
	6.750	3,320 (18.2)	5,460 (10.9)	11,970 (13.3)	0.026 (23.6)	0.068 (9.7)	0.376 (32.5)	128,810 (14.0)
	10.250	3,530 (10.0)	5,700 (11.9)	14,800 (12.6)	0.039 (25.1)	0.087 (20.0)	0.628 (21.6)	94,700 (16.7)
3/4	3.000	4,230 (18.0)	8,020 (11.8)	8,830 (13.4)	0.022 (23.9)	0.079 (13.4)	0.209 (50.0)	214,680 (27.4)
	5.125	6,630 (11.8)	12,540 (9.9)	17,960 (13.8)	0.036 (24.2)	0.102 (14.0)	0.270 (38.2)	210,380 (20.0)
	6.750	6,880 (12.1)	13,040 (10.9)	24,580 (11.7)	0.042 (18.9)	0.113 (9.5)	0.455 (38.9)	185,940 (13.4)
	10.250	6,760 (13.9)	13,030 (11.6)	28,260 (9.2)	0.039 (16.2)	0.107 (9.4)	0.656 (20.7)	204,580 (16.2)
1	3.000	9,173 (12.7)	13,630 (9.5)	13,710 (9.1)	0.054 (22.2)	0.124 (11.6)	0.124 (26.5)	237,100 (21.7)
	5.125	11,290 (15.9)	24,550 (11.9)	31,560 (18.6)	0.048 (25.1)	0.138 (13.1)	0.237 (39.8)	333,720 (7.3)
	6.750	10,280 (7.0)	22,350 (11.3)	38,190 (15.7)	0.056 (16.3)	0.156 (11.1)	0.612 (35.3)	237,790 (8.9)
	10.250	13,850 (12.5)	26,320 (8.4)	39,950 (18.6)	0.062 (18.0)	0.159 (10.7)	0.477 (42.5)	267,060 (9.3)
				Perpendicular to grain				
1/2	3.000	1,550 (24.1)	2,830 (21.3)	3,590 (22.7)	0.034 (33.0)	0.081 (14.4)	0.186 (39.4)	56,760 (23.2)
	5.125	1,810 (16.1)	3,130 (15.7)	5,380 (15.9)	0.041 (29.4)	0.091 (15.5)	0.305 (35.3)	50,460 (20.9)
	6.750	2,220 (11.9)	3,580 (13.8)	7,080 (10.3)	0.055 (24.2)	0.111 (15.1)	0.372 (28.2)	43,080 (12.5)
	10.250	3,720 (42.7)	5,790 (33.6)	12,230 (12.6)	0.114 (40.3)	0.200 (32.9)	0.610 (25.2)	35,340 (30.9)
3/4	3.000	2,020 (25.5)	3,820 (19.5)	5,270 (14.1)	0.036 (38.0)	0.100 (16.9)	0.271 (34.1)	69,410 (26.3)
	5.125	3,220 (20.1)	5,810 (16.4)	8,590 (18.2)	0.047 (27.0)	0.115 (12.4)	0.326 (32.1)	82,910 (20.7)
	6.750	4,260 (12.4)	7,480 (10.6)	12,200 (13.2)	0.064 (22.6)	0.136 (11.3)	0.400 (21.8)	90,440 (11.1)
	10.250	5,100 (20.3)	9,440 (14.7)	22,060 (7.9)	0.064 (28.2)	0.153 (15.4)	0.606 (14.9)	81,660 (13.7)
1	3.000	3,580 (17.4)	7,120 (11.5)	10,520 (11.8)	0.054 (30.2)	0.145 (12.7)	0.427 (35.5)	84,460 (15.8)
	5.125	5,430 (20.8)	11,450 (15.3)	16,280 (10.4)	0.052 (32.2)	0.151 (14.5)	0.392 (37.7)	122,170 (22.5)
	6.750	7,230 (20.3)	12,770 (17.6)	20,970 (10.0)	0.085 (24.1)	0.186 (13.1)	0.499 (22.7)	103,980 (17.1)
	10.250	7,750 (21.4)	11,860 (22.3)	29,780 (11.6)	0.088 (22.3)	0.192 (24.6)	0.757 (14.5)	85,310 (25.0)

[a] 1 in. = 25.4 mm; 1 lb = 4.45 N; t_m/D is ratio of main member thickness to bolt diameter.
[b] Averages based on sample size of 20 specimens; coefficient of variation in parentheses, expressed as percent.

Table 2—Summary of dowel bearing strength, moisture content, and specific gravity[a]

Bolt diameter (in.)	t_m/D	Average moisture content[b] (percent)	Average specific gravity (percent)	Dowel bearing strength (lb/in^2) Average[c]
		Parallel to grain		
1/2	3.000	12.1	0.471	5,870 (11.7)
	5.125	10.3	0.465	6,130 (12.1)
	6.750	11.4	0.451	5,950 (9.4)
	10.250	11.9	0.456	5,750 (6.5)
3/4	3.000	11.6	0.456	5,340 (9.1)
	5.125	11.5	0.430	5,230 (8.1)
	6.750	10.9	0.435	5,490 (10.3)
	10.250	13.3	0.432	5,370 (12.9)
1	3.000	9.6	0.445	6,140 (11.1)
	5.125	10.5	0.459	6,310 (7.8)
	6.750	10.4	0.448	6,140 (6.8)
	10.250	10.4	0.472	6,160 (7.5)
		Perpendicular to grain		
1/2	3.000	11.6	0.502	3,240 (22.2)
	5.125	10.9	0.474	2,430 (14.2)
	6.750	11.9	0.451	2,420 (18.2)
	10.250	12.0	0.453	2,380 (14.5)
3/4	3.000	10.9	0.458	2,020 (17.7)
	5.125	11.0	0.442	2,000 (16.1)
	6.750	10.4	0.444	2,590 (18.0)
	10.250	12.8	0.459	2,730 (14.3)
1	3.000	10.1	0.441	2,000 (14.2)
	5.125	11.1	0.452	1,850 (10.8)
	6.750	10.9	0.434	1,790 (18.8)
	10.250	10.9	0.479	1,910 (13.0)

[a] 1 in. = 25.4 mm; 1 lb/in^2 = 6.89 kPa; t_m/D is ratio of main member thickness to bolt diameter.
[b] Averages baaed on sample sizes of 20 specimens.
[c] Coefficient of variation in parentheses, expressed as percent.

Table 3—Bolt bending yield strength[a]

Bolt diameter (in.)	Bending yield strength[b] (1b/in^2)
1/2	85,125
3/4	79,260
1	47,000

[a] 1 in. = 25.4 mm; 1 lb/in^2 = 6.89 kPa.
[b] Based on 5 percent offset load.

Table 4—Load comparison of tension-loaded and compression-loaded bolted connections parallel to grain (D = 3/4 in., t_m/D = 6.75)[a]

Type of load	Load (lb) Tension Average[b]	Load (lb) Compression Average
Proportional limit	6,880 (12.1)	6,850 (11.9)
Yield	13,040 (10.9)	12,940 (15.8)
Maximum	24,580 (11.7)	26,070 (12.7)

[a] 1 lb = 4.45 N; t_m/D is ratio of main member thickness to bolt diameter.
[b] Averages based on sample sizes of 20 specimens; coefficient of variation in parentheses, expressed as percent.

Table 5—Deformation comparison of tension-loaded and compression-loaded bolted connections parallel to grain (D = 3/4 in., t_m/D = 6.75)[a]

Type of load	Deformation (in.) Tension Average[b]	Deformation (in.) Compression Average
Proportional limit	0.042 (18.9)	0.045 (21.2)
Yield	0.113 (9.5)	0.114 (14.0)
Maximum	0.455 (38.9)	0.584 (24)

[a] 1 in. = 25.4 mm; t_m/D is ratio of main member thickness to bolt diameter.
[b] Averages based on sample sizes of 20 specimens; coefficient of variation in parentheses, expressed as percent.

Table 6—Effect of steel side member thickness on bolted connection load when loaded parallel to grain (D = 1/2 in., t_m/D = 5.125)[a]

Steel thickness (in.)	Sample size[b]	Average load (lb) Proportional limit	Yield	Maximum
1/4	20	4,070	6,450	7,940
3/8	19	3,980	6,780	8,340
1/2	18	3,430	6,180	8,000

[a] 1 in. = 25.4 mm; 1 lb = 4.45 N; t_m/D is ratio of main member thickness to bolt diameter.
[b] Number of specimens.

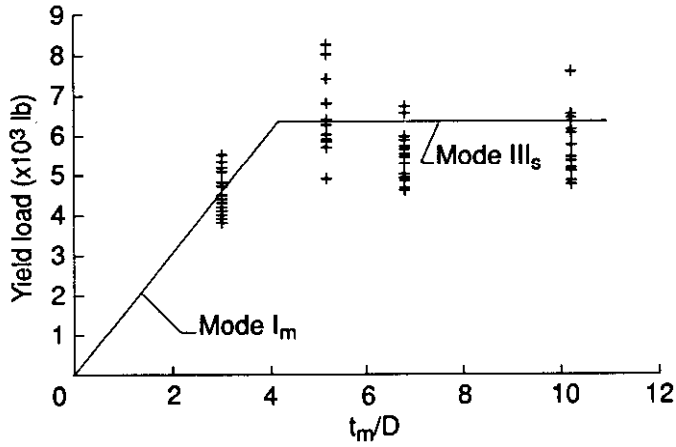

Figure 7—Experimental and EYM-predicted yield loads for bolted connections with 1/2-in. (12.7-mm) bolts loaded parallel to grain. t_m /D is ratio of main member thickness to bolt diameter. F_{em} = 5,920 lb/in^2 (40.8 MPa); F_{es} = 48,600 lb/in^2 (335.1 MPa); F_y = 85,120 lb/in^2 (586.9 MPa); and t_s = 1/4 in. (6.4 mm). (For yield load conversion, 1 lb = 4.45 N.)

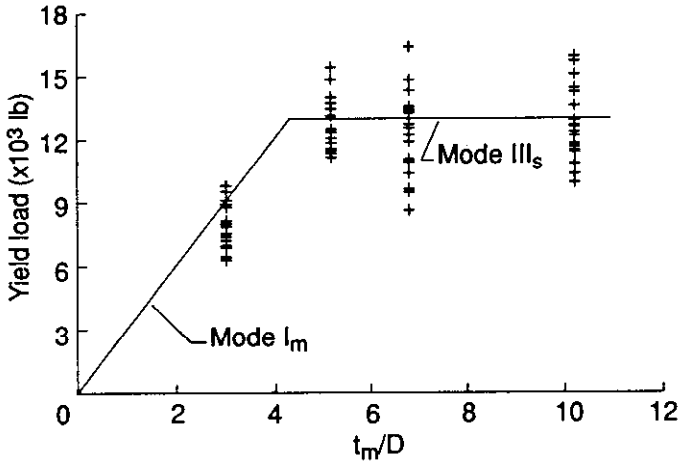

Figure 8—Experimental and EYM-predicted yield loads for bolted connections with 3/4-in. (19.0-mm) bolts loaded parallel to grain. t_m /D is ratio of main member thickness to bolt diameter. F_{em} = 5,360 lb/in^2 (37.0 MPa): F_{es} = 48,600 lb/in^2 (335.1 MPa); F_y = 79,260 lb/in^2 (546.5 MPa); and t_s = 3/8 in. (9.5 mm). (For yield load conversion, 1 lb = 4.45 N.)

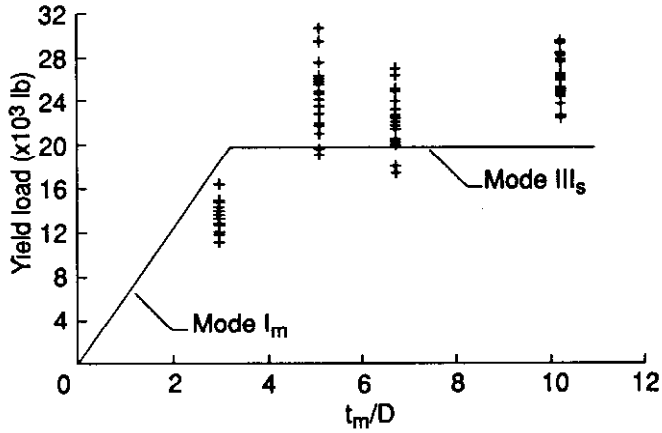

Figure 9—Experimental and EYM-pedicted yield loads for bolted connections with 1-in. (25.4-mm) bolts loaded parallel to grain. t_m /D is ratio of main member thickness to bolt diameter. F_{em} = 6.190 lb/in^2 (42.7 MPa); F_{es} = 48,600 lb/in^2 (335.1 MPa): F_y = 47,000 lb/in^2 (324.1 MPa); and t_s = 1/2 in. (12.7 mm). (For yield load conversion, 1 lb = 4.45 N.)

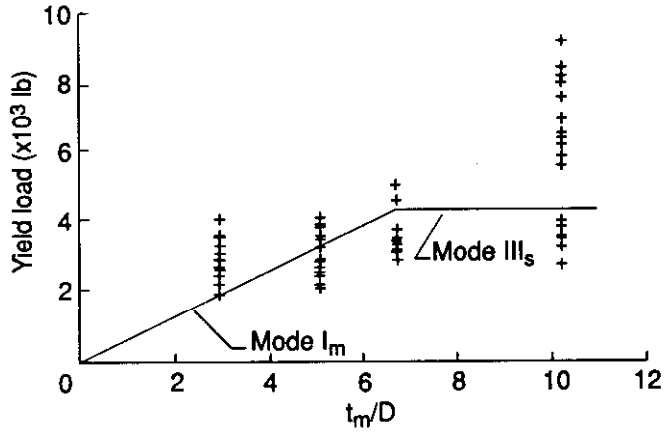

Figure 10—Experimental and EYM-predicted yield loads for bolted connections with 1/2-in. (12.7-mm) bolts loaded perpendicular to grain. t_m /D is ratio of main member thickness to bolt diameter. F_{em} = 2,620 lb/in^2 (18.1 MPa); F_{es} = 48,600 lb/in^2 (335.1 MPa); F_y = 85,120 lb/in^2 (586.9 MPa); and t_s = 1/4 in. (6.4 mm). (For yield load conversion, 1 lb = 4.45 N.)

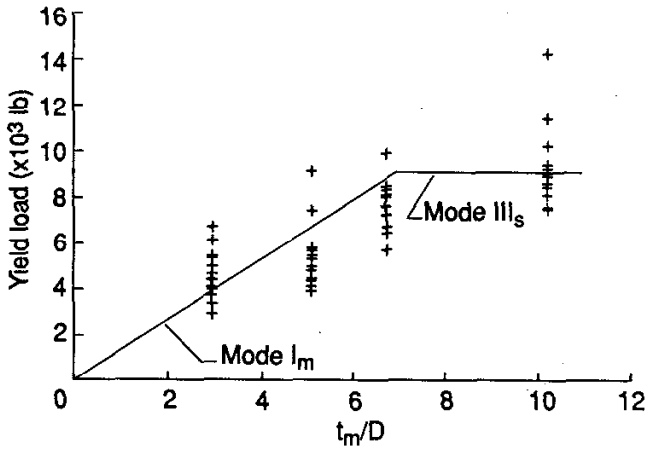

Figure 11—Experimental and EYM-predicted yield loads for bolted connections with 3/4-in. (19.0-mm) bolts loaded perpendicular to grain. t_m /D is ratio of main member thickness to bolt diameter. F_{em} = 2,330 lb/in^2 (16.1 MPa); F_{es} = 48,600 lb/in^2 (335.1 MPa); F_y = 79.260 lb/in^2 (546.5 MPa); and t_s = 3/8 in. (9.5 mm) (For yield load conversion. 1 lb = 4.45 N.)

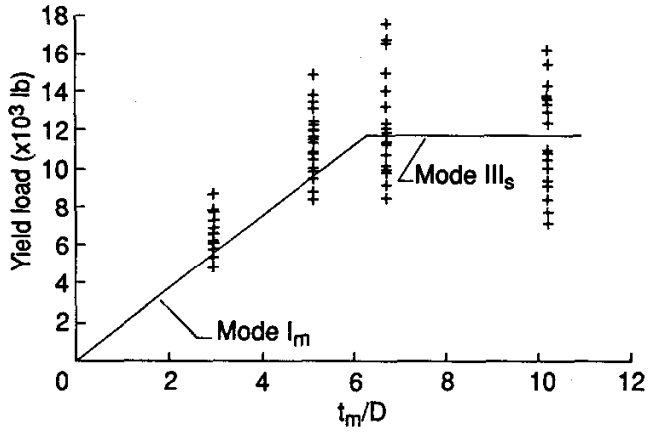

Figure 12—Experimental and EYM-predicted yield loads for bolted connections with 1-in. (25.4-mm) bolts loaded perpendicular to grain. t_m /D is ratio of main member thickness to bolt diameter. F_{em} = 1,890 lb/in^2 (13.0 MPa); F_{es} = 48,600 lb/in^2 (335.1 MPa); F_y = 47.000 lb/in^2 (324.1 MPa); and t_s = 1/2 in. (12.7 mm). (For yield load conversion, 1 lb = 4.45 N.)

Figure 13 compares the experimental effect of steel side member thickness with the effect predicted by the EYM. For this ratio of t_m /D, the EYM predicts a Mode III. yielding and an increase in yield load with

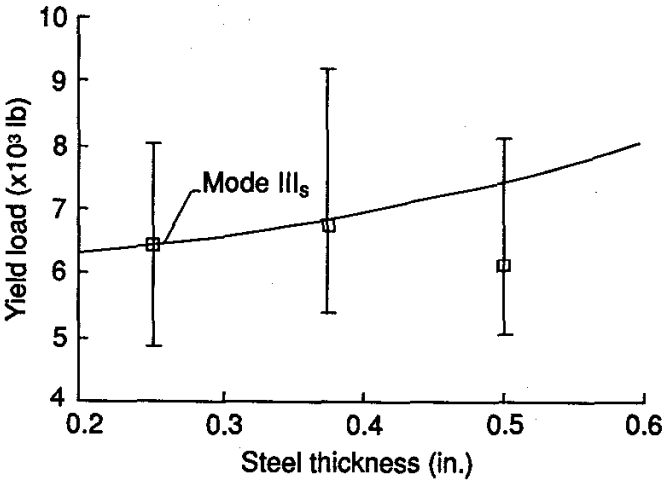

Figure 13—Experimental average yield load and range compared to EYM-predicted effects of steel side member thickness. F_{em} = 6,290 lb/in^2 (43.4 MPa); F_{es} = 48,600 lb/in^2 (335.1 MPa); F_y = 85,120 lb/in^2 (586.9 MPa); D = 1/2 in. (12.7 mm); and t_m /D = 5.125 (1 in. = 25.4 mm; 1 lb = 4.45 N).

increased side member thickness. The results in Figure 13 seem to be in general agreement except for the 1/2-in. (12.7-mm) thickness. One of the side members in these connections was bearing primarily on the bolt threads.

Conclusions

This study investigated the properties of bolted connections with steel side members. Three bolt diameters and four t_m /D ratios were investigated. Connections were loaded both parallel and perpendicular to the grain. Some findings of this study are as follows:

1. A yield load based on a 5 percent offset load is generally less variable than either proportional limit or maximum load.

2. The European Yield Model (EYM) predicts bolted connection yield load with acceptable accuracy. Input properties in the EYM equations should also be based on a 5 percent offset basis.

3. Yield load slightly increases with increased steel member thickness, except when the increased thickness causes the side member to bear on the bolt threads.

4. Connections loaded parallel to the grain by tension or compression loading give the same results.

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