Load capacity and deflection characteristics of large wooden dowels loaded in double shear

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Abstract

Tests were conducted to determine the load capacity of large wood dowels loaded in double shear. Results of the tests indicate that dowels may be expected to fail "gradually"in a stepwise manner—during which time the joint continues to carry substantial load—rather than fail suddenly in a catastrophic mode. Ultimate load capacity of such joints is nearly proportional to dowel diameter raised to the 1.5 power and material MOR raised to the 0.6 power. Only weak relationships exist between plate thickness and load capacity. A 5 percent deviation point occurs at about 2/3 of the ultimate load capacity of the joint. Load displacement curves for the joints are essentially sigmoid in shape with an initial curvilinear stiffening phase followed by a linear response, and finally ending in a curvilinear "yielding" phase. Stiffness of the joints is nearly proportional to the diameter of the dowels. Semirigid connection factors for the joints ranged from about 2.0×10^{-5} for 1.5-inch diameter dowels to 9×10^{-6} in/lbf for 4-inch diameter dowels. Joint displacement at the 5 percent deviation point ranged from 0.10 inches for the 1.5 inch diameter dowels to 0.182 inches for the 4-inch dowels.

In the construction of light timber frames with round mortise and tenon joints, the tenons on the ends of members are often loaded in double shear by the constructions into which they frame. The tenons on the ends of ceiling purlins, for example, may be loaded in double shear when they are used as the pins in spliced ceiling joist or tie beam connections (**Fig. 1**).

Research has been reported on the load capacity of 0.75-, 1-, and 1.25-inch diameter wood dowels (or, pegs) loaded in double shear in traditional rectangular mortise and tenon joints in the oft-cited works of Schmidt and Daniels (1999), Sandberg et al. (2000), Schmidt and Scholl (2000), along with Burnett et al. (2003) and Miller (2004), among others. Results of these studies indicate that the load capacity of a 1-inch dowel might be expected to lie in the 3,000 to 4,000 pound-force (lbf) range. Further, Church and Tew (1997) found that grain orientation of the peg had only a slight effect on strength, but that highest strength was obtained when the pegs were loaded in the radial direction. Sandberg et al. (2000) obtained greatest capacity for red oak pegs when they were loaded in the tangential direction but concluded that grain orientation had little effect on the strength of the other species tested. They also found that moderate variations in hole size had little effect on strength. Schmidt and Daniels (1999) found that in traditional rectangular mortise and tenon construction the shear capacity of the peg is highly dependent on the gap between the mortise and the rectangular tenon that frames into it—which indicates that gaps between the main member and splice plates should be minimized. They also presented an empirical expression for estimating the shear strength of 1-inch white oak dowels as a function of specific gravity. Miller (2004) likewise presented a simple power curve expression for estimating dowel bearing strength.

The use of wood dowels (of similar size) as cross pins in other joints including splice joints has been reported by Karlsen (1967). He discussed the effect of splice plate thickness on the distribution of stresses in cross pins and indicated that the use of thick splice plates produces a more uniform stress distribution in the center member. He also indicated that the smaller the dowel diameter, the lower the forces tending to spread apart the walls of the dowel seat.

Information was not found, however, on the performance of larger diameter dowels loaded in double shear although infor-

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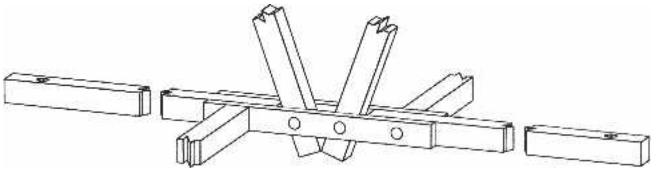

Figure 1. — Example of double shear splice joint in tie beam connection.

mation does exist on the performance of somewhat similar Kubel dowel connectors (Kollmann 1936, 1955). The information that exists, however, in effect applies to short dowels loaded in single shear (Wood Handbook 1940, 1955) with the grain direction of the dowel perpendicular to its longitudinal axis.

Purpose and objectives

A limited number of tests were conducted to obtain initial estimates of the longitudinal load capacity of parallel plate joints constructed with 1.5-, 2-, 3-, and 4-inch diameter wood dowels when loaded in double shear. Specific objectives were to obtain estimates of the load-carrying capacities of the dowels as they relate to tenon diameter and wood species, to identify the modes of failure of the dowels, and to evaluate the effect of splice plate thickness on ultimate load capacity and mode of dowel failure.

Specimen construction

The specimens used in these tests were similar to those used by Sandberg et al. (2000). Specimens were constructed with tenons approximately 1.5, 2, 3, and 4 inches in diameter. An illustration of a typical specimen is given in **Figure 2**. Note that the grain of the side plates and center members is parallel to the load. Thus, the seats for the dowels in both the side plates and center member are loaded in compression parallel to the grain. Specimens were constructed with combinations of center members and side plates whose thicknesses were equal to 100, 150, or 200 percent of the dowel diameter so that there were nine possible center member vs. side plate combinations for each dowel diameter—although not all possible combinations were constructed, and a few other variations also existed. Three specimens of each specific construction were tested. Specimen construction schedules are given in **Table 1**.

Holes were bored in the plates with Forstner bits. Dowels were cut with deep hole saws or were turned on a metal cutting lathe so that the dowels were nearly circular in shape. All dowels were cut slightly undersized to provide a "snug"—as opposed to force—fit in the holes. In so far as possible, dowels were aligned so that loads were applied parallel to the tangential planes of the dowels. This alignment provides for "worst case" displacement since MOE in the tangential direction is less than in the radial.

Most of the specimens were constructed of kiln-dried yellow-poplar (*Liriodendron tulipifera*) because of its ready availability in all needed sizes and the ease with which the larger dowels could be machined with available equipment; however, limited numbers of specimens were constructed of white ash (*Fraxinus americana*), sugar maple (*Acer saccharum*), shagbark hickory (*Carya ovata*), southern yellow pine (*Pinus sp.*), Douglas-fir (*Pseudotsuga menziesii*), and red oak (*Quercus rubra*).

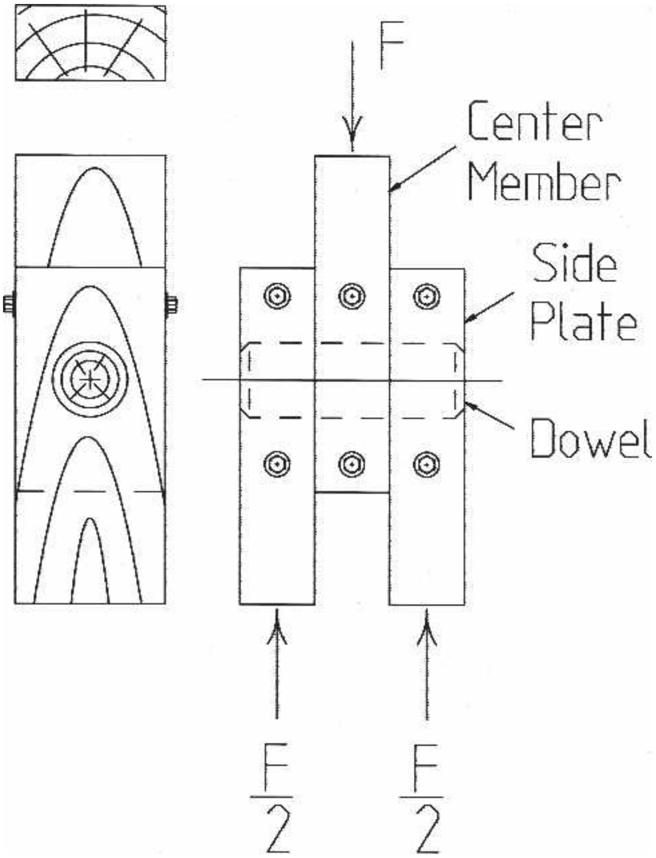

Figure 2. — Illustration of typical specimen and method of loading used to determine load capacity of dowels loaded in double shear.

Many of the dowels contained juvenile wood because most of the dowels were cut from timbers that had been sawn to include the heart of the tree. A notable exception was the shagbark hickory, which was cut from old slow-growth material. All material was stored indoors. Nominal moisture content of the specimens was 8 percent at the time of test.

It was anticipated that splitting of the ends of the main member and side plates might occur as the dowels flattened (ovalized) and exerted an outward thrust on the side walls of the mortises. To prevent such splitting, the specimens were reinforced with either 3/8-inch or 1/2-inch diameter crossbolts as shown in **Figure 2**.

Method of test

The specimens were loaded in compression as shown in **Figure 2**. Initially, the joints were clamped together with pipe clamps during placement in the testing machine; the clamps were subsequently loosened when loads were applied to the specimens. Rate of loading was 0.1 inches per minute. Load head deflection was measured with a 0.001 inch digital dial gage. Testing was continued until a fracture occurred that was accompanied by a substantial non-recoverable drop-off in load.

Results and discussion

Results of the tests are given in **Table 1** and are presented graphically in **Figure 3**. Behavior of the dowels during the tests was relatively uniform. Typically, following an initial

Table 1. — Specimen description and average test results—ultimate load, 5 percent deviation load, and semirigid connection factor—3 specimens each.

Dowel			Center member		Side plate		Ult. load	SD	5% deviation load	Slope reg. coeff.		Z-values
Diam.	Leng.	Species[a]	Thick.	Species[a]	Thick.	Species[a]				a_0	a_1	
-----(in)-----			(in)		(in)		------------(lbf)------------			(in)	(in/lb)	(in/lbf)
1.5	9	Y-Pop	2	Y-Pop	3	Y-Pop	5,957	670	3,200	0.005	2.2×10^{-5}	2.5×10^{5}
1.5	9	Y-Pop	2.25	Y-Pop	3	Y-Pop	5,073	541	3,200	0.016	2.2×10^{-5}	2.9×10^{-5}
1.5	9	Y-Pop	3	Y-Pop	3	Y-Pop	5,503	730	3,600	0.010	1.8×10^{-5}	2.3×10^{-5}
1.5	5.5	R Oak	1.5	Y-Pop	2	Y-Pop	8,580	243	5,200	0.014	1.4×10^{-5}	1.9×10^{-5}
1.5	7	R Oak	1.5	Y-Pop	3	Y-Pop	8,667	181	5,200	0.010	1.5×10^{-5}	1.8×10^{-5}
1.5	6	R Oak	2.25	Y-Pop	2	Y-Pop	8,613	172	7,200	0.011	$1. \times 10^{-5}$	1.3×10^{-5}
1.5	8.25	R Oak	2.25	Y-Pop	3	Y-Pop	7,983	225	7,200	0.015	1.4×10^{-5}	1.7×10^{-5}
1.5	9	R Oak	3	Y-Pop	3	Y-Pop	8,503	327	7,200	0.018	1.3×10^{-5}	1.6×10^{-5}
1.5	9	S Map	3	Y-Pop	3	Y-Pop	8,100	590	6,000	0.035	1.5×10^{-5}	2.3×10^{-5}
2	10	Y-Pop	2	Y-Pop	4	Y-Pop	9,083	679	5,000	-0.0001	1.8×10^{-5}	1.8×10^{-5}
2	11	Y-Pop	3	Y-Pop	4	Y-Pop	10,050	866	8,000	0.013	1.6×10^{-5}	1.8×10^{-5}
2	12	Y-Pop	4	Y-Pop	2	Y-Pop	8,033	231	6,000	0.025	1.9×10^{-5}	2.5×10^{-5}
2	12	Y-Pop	4	Y-Pop	3	Y-Pop	9,233	525	6,000	0.049	1.5×10^{-5}	2.5×10^{-5}
2	12	Y-Pop	4	Y-Pop	4	Y-Pop	9,667	275	7,000	0.059	2.2×10^{-5}	3.4×10^{-5}
2	10	D-fir	4	Y-Pop	3	Y-pop	11,930	3,537	na[b]	na	na	na
2	11	D-fir	4	Y-pop	3.5	Y-pop	12,767	929	na	na	na	na
2	10	W Ash	2	Y-Pop	4	Y-Pop	13,333	1,283	8,000	0.027	1.1×10^{-5}	1.5×10^{-5}
2	11	W Ash	3	Y-Pop	4	Y-Pop	13,917	480	9,000	0.015	9.8×10^{-6}	1.2×10^{-5}
2	12	W Ash	4	Y-Pop	4	Y-Pop	13,967	701	9,000	0.037	9.3×10^{-6}	1.5×10^{-5}
2	12	W Ash	4	Y-Pop	4	Y-Pop	18,283	1,151	13,000	0.027	1.0×10^{-5}	1.3×10^{-5}
2	12	S Map	4	Y-Pop	4	Y-Pop	14,750	1,994	11,000	0.027	1.1×10^{-5}	1.5×10^{-5}
2	9	S Hick	2	Y-Pop	4	Y-Pop	12,900	1,905	8,000	0.024	1.1×10^{-5}	1.5×10^{-5}
2	15	S Hick	4	Y-Pop	4	Y-Pop	12,350	2,330	9,000	0.040	1.0×10^{-5}	1.7×10^{-5}
3	12	Y-Pop	3	Y-Pop	4.5	Y-Pop	19,483	2,650	9,000	0.010	7.5×10^{-6}	9.6×10^{-6}
3	12	Y-Pop	4.5	Y-Pop	3	Y-Pop	20,850	3,748	11,000	0.023	8.1×10^{-6}	1.1×10^{-5}
3	21	Y-Pop	4.5	Y-Pop	6	Y-Pop	23,050	1,311	16,000	0.040	9.0×10^{-6}	1.0×10^{-5}
3	12	Y-Pop	6	Y-Pop	3	Y-Pop	23,917	2,816	17,000	0.054	8.0×10^{-6}	1.0×10^{-5}
3	21	Y-Pop	6	Y-Pop	4.5	Y-Pop	23,275	1,590	18,000	0.054	7.9×10^{-6}	1.2×10^{-5}
3	21	Y-Pop	6	Y-Pop	6	Y-Pop	21,017	3,262	17,000	0.044	7.5×10^{-6}	1.1×10^{-5}
3	11	SYP	4	SYP	5.4	SYP	18,650	2,990	na	na	na	na
3	11	D-fir	4	SYP	5.5	SYP	20,980	1,240	na	na	na	na
3	18	S Map	6	Y-Pop	6	Y-Pop	25,550	2,298	20,000	0.035	8.0×10^{-6}	1.1×10^{-5}
3	18	S Hick	6	Y-Pop	6	Y-Pop	22,500	1,323	16,000	0.018	1.1×10^{-5}	1.3×10^{-5}
4	9.5	Y-Pop	3	Y-Pop	3.25	Y-Pop	19,033	2,577	10,000	0.016	1.1×10^{-5}	1.4×10^{-5}
4	10.25	Y-Pop	3	Y-Pop	3.63	Y-Pop	16,200	346	10,000	0.047	1.2×10^{-5}	1.8×10^{-5}
4	12	Y-Pop	4	W Ash	4	W Ash	20,700	1,300	10,000	0.033	9.5×10^{-6}	1.4×10^{-5}
4	21	Y-Pop	4	W Ash	7.81	W Ash	28,500	6,062	14,000	0.018	7.3×10^{-6}	9.3×10^{-6}
4	21	Y-Pop	6	W Ash	7.5	W Ash	37,750	5,443	22,000	0.039	6.7×10^{-6}	9.4×10^{-6}
4	21	Y-Pop	7.8	W Ash	7.8	W Ash	33,467	2,540	28,000	0.020	6.2×10^{-6}	7.3×10^{-6}
4	11	SYP	4	SYP	3.5	SYP	35,400	5,370	na	na	na	na
4	12	SYP	4	W Ash	4	W Ash	33,800	1,442	16,000	0.038	5.7×10^{-6}	9.2×10^{-6}
4	21	S Map	5.8	W Ash	7.63	W Ash	43,750	6,493	26,000	0.034	7.8×10^{-6}	9.8×10^{-6}
4	18.5	S Hick	6	W Ash	6.25	W Ash	35,067	3,312	24,000	0.042	6.1×10^{-6}	8.8×10^{-6}

[a] W Ash = white ash, D-fir = Douglas-fir, S Hick = shagbark hickory, Oak = red oak, S Map = sugar maple, Y-Pop = yellow-poplar.

[b] na = not available.

increase in joint stiffness, the joints exhibited a linear load displacement response until a series of audible fractures occurred. After each audible fracture, a fall-off of load occurred, which was subsequently regained as cross head movement continued. This phenomenon repeated itself until a robust fracture resulted—at which point a non-recoverable fall-off in load occurred. Bending failures of the dowels originated either at midlength of the dowel or adjacent to a side plate. Exceptions to this behavior occurred when the dowel either contained hidden defects at midlength or contained brash wood. Longitudinal shear failures occurred in a number of dowels with low length over diameter ratios—most notably in the 4-inch diameter dowels with length over diameter ratios of 3 or less.

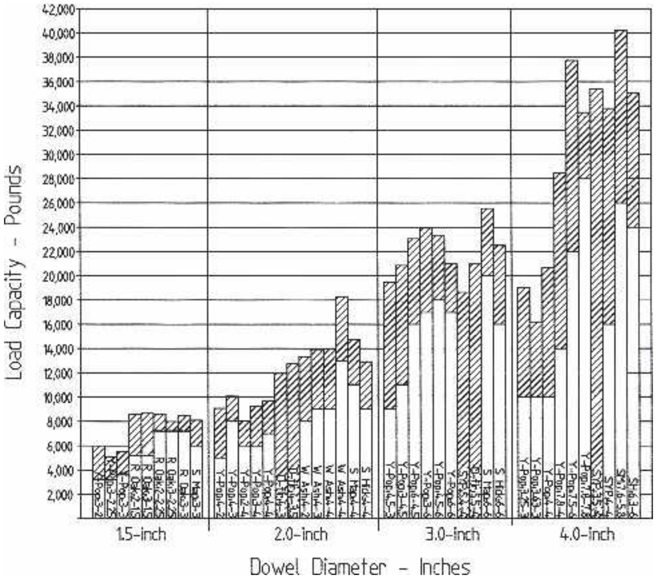

Figure 3. — Load capacity of dowel joints included in test. Hatched area: ultimate load; unhatched area: 5 percent deviation point capacity. Vertical numbers are side plate-center member thickness.

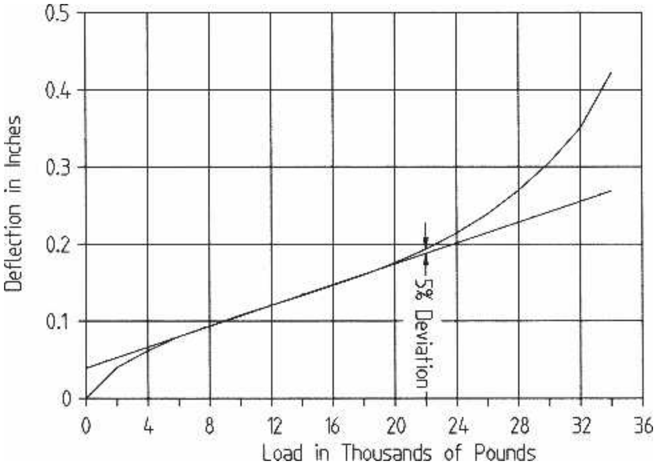

Figure 4. — Deflection characteristics of 4-inch diameter sugar maple dowel joint.

To evaluate the effects of dowel diameter and plate thickness on joint strength, an expression of the form $F = a_o D^{a1} C^{a2} P^{a3} S^{a4}$ was fitted to the test results where F refers to ultimate load capacity, lbf; D is dowel diameter, inch; C and P are center member and side plate thicknesses, respectively, inch; and S refers to Wood Handbook MOR (adjusted for moisture), psi. Other expressions were also investigated, but the above curve gave the highest correlation values—in keeping with the findings of Miller (2004). Regression analyses gave coefficients of 15.0, 1.477, 0.161, −0.021, and 0.575 for a_0, a_1, a_2, a_3, and a_4, respectively, with $R^2 = 92.83$ percent. Thus, this result indicates that ultimate load capacity was proportional to dowel diameter raised to about the 1.5 power and MOR raised to about the 0.6 power, but there was essentially no, or only a very weak, relationship between load capacity and center member or side plate thicknesses. Subsequent analyses of specific dowel diameter classes produced similar center member and side plate relationships.

The load vs. displacement curves for the joints were sigmoid in shape. Initially, the joints stiffened rapidly as load was applied until the deflection vs. load response became linear. This linear behavior continued over the central portion of the curve until micro fractures in the dowel caused a rapid increase in displacement/load ratios. The typical shape of a displacement curve is shown in **Figure 4**.

The term "yielding" has been used by several authors to describe the nonlinear load-displacement behavior of pegged joints at load levels above the linear response region. Schmidt et al. (1996), for example, discussed the use of "yield model" theory in the design of pegged connections. Several researchers (Church and Tew 1997) used a 5 percent offset load procedure to define the yield point of pegged joints. Owing to the use of larger diameter dowels along with the use of several wood species in this study, a slightly different procedure was used to define the load capacity of the joints at a 5 percent "deviation" point. Curves were first plotted for the average values of each set of joint displacement data. Straight lines were then fitted to the data corresponding to the central linear portions of the load-displacement curves. The load at which a test displacement curve deviated from its corresponding fitted straight line by 5 percent was then regarded as the "yield" load for the dowel joint set. These values, though based on an arbitrarily selected deflection value, provide a basis for comparing the "useable" load capacity of the dowels. Overall, it was found that the load at 5 percent deviation averaged about 2/3 as great as the ultimate load. The 5 percent point for a 4-inch diameter sugar maple dowel is shown in **Figure 4**.

The slopes of the linear portions of the load-displacement curves are given in **Table 1**. The semirigid connection factors, here labeled Z-values (Lothers, 1960), for the joints are also given. An examination of the values obtained for yellow-poplar indicated that the Z-values could be estimated by the expression $Z = 4.114 \times 10^{-5}\, ID^{0987}$ in/lbf (R^2 equals 63.16%), which for convenience may be simplified to $Z = 4 \times 10^{-5}\, ID$ (with R^2 equal to 63.15%). This latter relationship gives first estimates of Z-values of 2.667×10^{-5}, 2.0×10^{-5}, 1.333×10^{-5}, and 1.0×10^{-5} in/lbf for joints with 1.5-, 2-, 3-, and 4-inch diameter dowels, respectively. These values should be regarded only as first estimates of stiffness connection factors since values for specific wood samples and wood species may differ substantially. The test values for the 2-inch yellow-poplar dowels, for example, averaged 2.4×10^{-5} in/lbf, whereas the values for higher density species were considerably smaller.

As previously discussed, radial orientation of the dowel with respect to direction of load may give higher load values; additionally, it could also affect the displacement characteristics of a joint. The modulus of elasticity of yellow-poplar in the radial direction, for example, is more than double its MOE in the tangential direction. Shrinking and swelling in service could also be a factor. Shrinking and swelling of yellow-poplar, for example, is only 56 percent as great in the radial direction as in the tangential. These factors may be outweighed by Poisson's ratio considerations, however. Thus, a dowel oriented in the radial direction would be expected to exert a greater force on the sidewalls of a mortise than one oriented in the tangential direction and thus increase the propensity of the mortised member to split.

Conclusions

Dowel joints loaded in double shear, constructed with defect free dowels, may be expected to fail "gradually" in a stepwise manner—during which time the joint continues to carry substantial load—rather than fail suddenly in a catastrophic mode. Ultimate load capacity of such joints is nearly proportional to dowel diameter raised to the 1.5 power and material MOR raised to the 0.6 power. Only weak relationships exist between plate thickness and load capacity. A 5 percent deviation point occurs at about 2/3 of the ultimate load capacity of the joint. Displacement curves for the joints are essentially sigmoid in shape with an initial curvilinear stiffening phase followed by a linear response, and finally ending in a curvilinear "yielding" phase.

Overall, joint stiffness was nearly proportional to dowel diameter. Semirigid connection factors for the joints ranged from about 2.0×10^{-5} for 1.5-inch diameter dowels to 9×10^{-6} in/lbf for 4-inch diameter dowels. Joint displacement at the 5 percent deviation point ranged from 0.10 inches for the 1.5-inch diameter dowels to 0.182 inches for the 4-inch dowels.

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