Structural properties of pegged timber connections as affected by end distance

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Abstract

This study investigates the influence of end distance on the mechanical behavior of wood-dowel or 'pegged' joints, commonly used in traditional mortise-and-tenon joinery. Static tensile tests were performed on double shear joints, connected with a single 1-inch-diameter northern red oak peg, loaded parallel to the grain of the center member. Specimens were prepared from three species commonly used to build timber-frame homes in the northeastern United States: Douglas-fir, eastern white pine, and northern red oak. Load deformation data (joint stiffness, proportional limit, 5percent offset yield load and ultimate load) were analyzed using analysis of variance techniques to gauge influence of varying end distance. It was found that in no case did reduction of end distance significantly influence joint stiffness. Eastern white pine and northern red oak joints showed no significant reduction in tensile capacity when end distance was reduced to one half of the end distance required for full design load specified by the *National Design Specification® for Wood Construction®* (NDS-97). Joints with end distances shorter than this, however, showed the potential for undesirable abrupt and catastrophic failures. Douglas-fir joints showed significant reduction in yield strength at 67 percent of the full design end distance and displayed abrupt failures even at 100 percent of the required NDS-97 end distance.

Traditional timber frame structures are commonly built using large heavy timbers connected with mortise-and-tenon joinery secured with wood pegs. In restoring and renovating these historic structures, or for the design of new structures where traditional timber framing methods are desired, a complete understanding of the mechanical behavior of these wood-pegged connections is necessary.

Most of the existing research on wood connections, however, has been conducted using steel-bolted wood joints. In fact, the design procedure for wood connections described in the current *National Design Specification® for Wood Construction* (NDS-97) (1) is based on the European yield model (14) that was developed using steel bolts. Nevertheless, much of this research has contributed to the advancement of wood peg research, including topics such as wood member bearing strength (13,22,23), joint modeling (18,19), and multiple bolted joints (17).

Research that pertains specifically to wood-dowel connections, on the other hand, is somewhat limited. Brungraber (8) was the first to conduct experimental tests on individual joints as well as a few full size timber frames. Based on joint behavior, he proposed a three spring model and further used this model in a two-dimensional finite element analysis to predict the frame behavior. Good results were reported. In 1992, Brungraber

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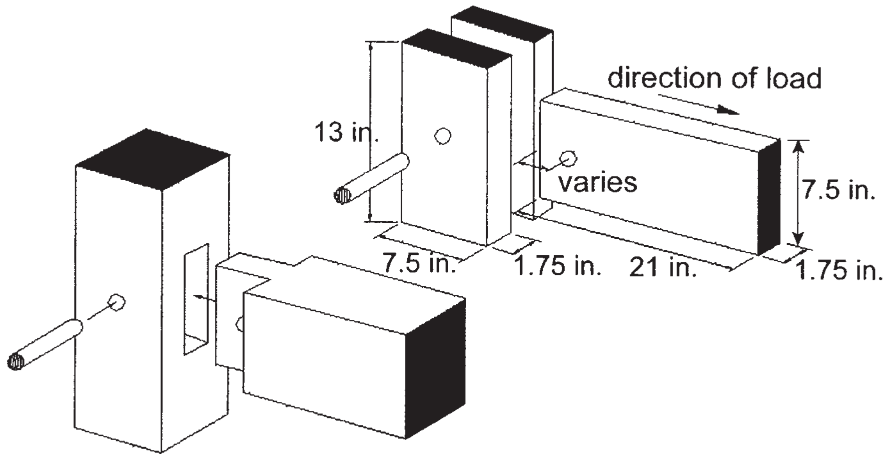

Figure 1. — True mortise-and-tenon and simulated mortise-and-tenon joint.

Figure 2. — Riehle test machine setup.

(6) compared historic and contemporary joinery methods and proposed revisions to and refinement of the NDS models. Specifically, he suggested the need for full-scale tests to better define the value of yield stress in pegs and to justify a reduction in end and edge distance values mandated by NDS-97.

Kessel and Augustin (15,16) investigated the structural behavior of joints with oak pegs. Kessel conducted full-scale tests on oak and spruce mortise-and-tenon joints with two octagonal oak pegs to provide tension design criteria. His tests varied end and edge distances, peg spacing, peg diameter, connection angle, and member dimensions such as overall cross-sectional area and tenon thickness. Kessel recommended a minimum end distance of 1.5 peg diameters for both oak and spruce joints. Because of differences in the design process, these values have not been accepted in practice in the United States; however, the results do suggest that the minimum end distances specified by the NDS are conservative.

Other research in the area includes tests on pegs, bearing capacity tests, and modeling of joints and frames. Brungraber and Morse-Fortier (7) conducted research on double and single shear joints with variations in direction of loading relative to the grain of the side members, growth ring orientation of the peg, and number of pegs in the joint. Tests on peg bending strength and bearing capacity were also performed. Schmidt and MacKay (21) conducted material property tests on joints and worked towards using the European yield model to predict the strength of all-wood connections. They presented additional failure modes including that referred to as relish failure (i.e., shear failure of the wood directly behind the peg in the tenon). Church and Tew (11) studied the effects of peg diameter, peg-hole clearance, specimen grain orientation, and species on bearing strength of red oak and Douglas-fir specimens when pegged with white oak dowels. Research by Bulleit et al. (9,10) has included both analytical and empirical evaluation of traditional timber connections to establish accurate models for single joints as well as entire frames. With commercially available structural analysis software, joints and frames were modeled mathematically and design forces were predicted. Finally, in 1997, a comprehensive report was prepared by Schmidt and Daniels (20) that outlines material tests and a limited number of joint tests using white oak pegs. Based on their results, they recommended a design procedure for all-wood mortise-and-tenon connections.

The foregoing studies do not fully address the matter of an appropriate end distance for wood pegs, other than to express a need for further investigation to assess the suitability of the NDS requirements. In designing for the full capacity of a joint, NDS-97 (assuming steel dowels) prescribes a minimum end distance equal to five times the diameter of the dowel in hardwoods and seven times the diameter of the dowel in softwoods. It is generally known that oak pegs have lower bending strength and stiffness than steel bolts. Consequently, the load to develop full capacity of the joint (i.e., the load to induce dowel failure, as opposed to mortise or tenon failure) is less for wood pegs than for steel bolts. As such, it is speculated that the end distance required to develop this full capacity would therefore be less for wood pegs than for steel bolts, making the end distance requirements of NDS-97 overly conservative for all-wood joints.

The objective of the current study is to expand the knowledge base for this subject by exploring the influence of end distance on the tensile behavior (specifically stiffness, proportional limit, yield load, and ultimate load) of mortise-and-tenon wood pegged joints using three commonly used species: eastern white pine, Douglas-fir, and red oak. The experimental observations and results presented herein will augment the current experimental database for all-wood connections.

Materials and methods

Tensile tests with varying end distances were performed on simulated mortise-and-tenon joints. Three pieces of nominal 2 by 8 were arranged to represent a traditional mortise-and-tenon joint, commonly used for connecting 6- by 8-inch posts and beams (**Fig. 1**). A single 1-inch-diameter northern red oak peg was used to make the connection. The strength data of these simulated mortise-and-tenon joints may indeed be a

Table 1. — Physical properties of joint components.

Species	Component	Count	Specific gravity Mean	Specific gravity COV	Moisture content Mean	Moisture content COV
					(%)	
Eastern white pine	Mortise	96	0.38	10.7	10.8	26.7
	Tenon	48	0.38	9.8	11.5	27.3
Douglas-fir	Mortise	90	0.52	16.2	10.4	12.1
	Tenon	45	0.48	11.4	10.3	6.5
Northern red oak	Mortise	80	0.72	6.0	16.6	25.0
	Tenon	40	0.72	6.2	16.0	20.9
Northern red oak	Pegs	133	0.76	9.2	9.8	6.3

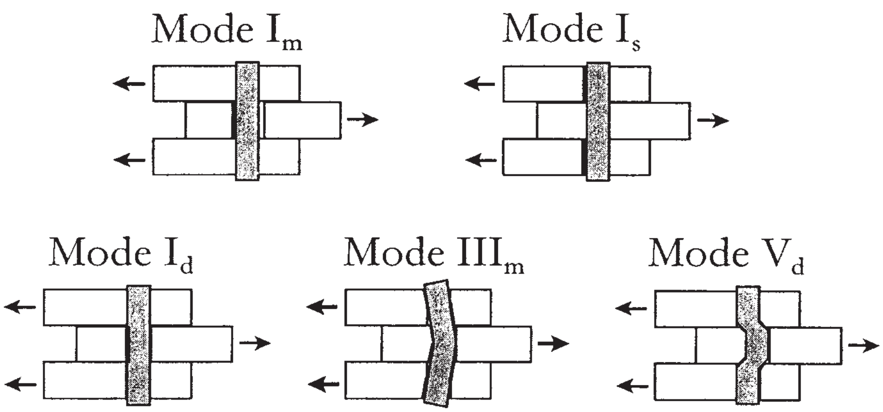

Figure 3. — Observed failure modes (reproduction from Schmidt and Daniels 1999).

conservative approximation for that of the real joint since the enclosed configuration of the real joint would tend to resist the tenon splitting that was frequently observed at reduced end distances, as discussed in the results section.

Benson Woodworking generously donated green, rough-sawn 2- by 8-inch boards of three species for the mortises and tenons (eastern white pine, Douglas-fir, and northern red oak) as well as a supply of 1-inch-diameter northern red oak pegs. All lumber was kiln-dried and trimmed to uniform dimensions. The 21-inch-long tenon members were selected from lengths of board that were essentially clear for at least 12 inches. Pin knots, small amounts of wane, and other minor defects were allowed only outside the center one-third region of the board. The 13-inch-long mortise sides were selected from boards that had no defects in the center one-third region where the peg hole would eventually be located.

End distances corresponding to 100, 67, 50, 40, 33, 30, and 14 percent of the required end distance for full design capacity per the NDS (7D for softwood and 5D for hardwood, where D is the peg diameter) were tested. The end distance test schedules for each species are different as they were decided as the tests proceeded based on experimental observations. Up to 10 replications for each joint configuration were tested: a total 133 tests in all. Mode of failure was recorded for each test.

Figure 2 illustrates the test setup. A 7/8-inch-wide by 3/8-inch-deep dado groove was cut 2 inches from the bottom of each side of the tenon piece to accept the grip apparatus. The peg holes were made to match the diameter of the peg as closely as possible, with a 1-inch-diameter forstner bit in a drill press. All joints were assembled by hand.

The test method was established using ASTM D 5652-95 Standard Test Methods for Bolted Connections in Wood and Wood-Base Products (3) as well as ASTM D1761-88 Standard Test Methods for Mechanical Fasteners in Wood (2). Tests were performed using a Riehle testing machine with a capacity of 60,000 pounds under deflection control mode. Load and deformation were recorded with a uniform crosshead rate of 0.035 in./min. It was assumed that strain within the grip apparatus was negligible at the load level applied in this study. Each specimen was pre-loaded to approximately 100 pounds, to minimize the slack in the setup from the initial seating of the specimen in the grips.

Results and discussion

Physical property data

A summary of the physical material properties data for the individual components for each species tested is provided in **Table 1**. Moisture content (ovendry method [4]) and specific gravity (method A - [5]) were both measured from a small cube cut near the peg hole for each piece. The moisture content of both softwoods averaged around 11 percent, with an average coefficient of variation (COV) of 27 percent for eastern white pine and 9 percent for Douglas-fir. The moisture content of the northern red oak was somewhat high, however, at about 16 percent. Both moisture content and specific gravity of the pegs (pooled for all tests) were very consistent. The pegs averaged 12.3 rings per inch with a COV of 38 percent. Despite taking great care to avoid end checks when kiln-drying, 42 percent of the Douglas-fir specimens contained tenon end splits that could be attributed to tenon failure. This fact may indeed bias the data, however, it is also representative of the drying behavior of Douglas-fir and should not be neglected.

Observed failure modes

The observed modes of failure were consistent with the five modes outlined in Schmidt and Daniels (20), illustrated in **Figure 3**. Modes I_m and I_s are attributed to primarily mortise-and-tenon failure; modes I_d, III_m, and V_d are associated with peg bearing, peg bending failure with a single flexural hinge, and peg shear/bending failure, respectively. As expected, joint failure associated with peg failure (i.e., the latter three modes) provided a ductile response. This is attributed to the gradual crushing of the peg (a compression perpendicular-to-grain

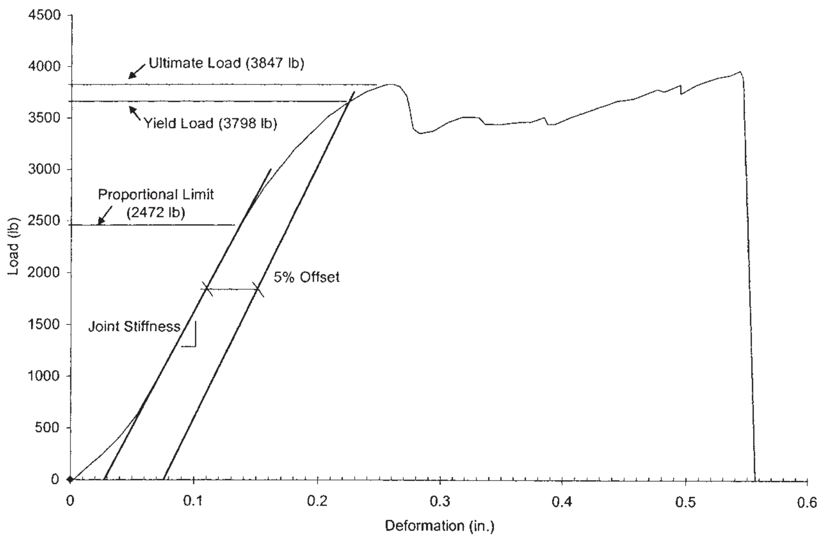

Figure 4. — Sample load versus deformation plot for Douglas-fir joint (7-inch end distance).

Table 2. — Failure mode summary.

% of required end distance for full design capacity per NDS-97	Fraction of results attributed entirely to peg failure		
	Eastern white pine	Douglas-fir	Northern red oak
100	9/9	7/10	10/10
67	- -	7/10	- -
50	12/12	2/10	9/10
40	8/10	2/10	3/10
33	5/9	0/5	- -
30	2/6	- -	3/10
14	0/3	- -	- -

failure mechanism), which is known to be a nonlinear, ductile response (12). This crushing occurred generally in combination with a ductile bending response of the peg.

In contrast, failures associated with mortise or tenon failure produced an abrupt, brittle response, as a result of perpendicular-to-grain tensile as well as shear stresses. Failure observed in the tenon was similar for all tests. Typically, the first event was a split from the top of the peg hole to the end of the tenon. This usually resulted in a small relaxation of load in the joint. Many joints then regained their initial stiffness and the load increased. Eventually, this type of failure led to cleavage of the tenon beyond the peg hole. At this point, many joints experienced a partial relish failure in which only one side of the relish failed.

A ductile failure is the preferred failure mode for design of joints, particularly in response to seismic or hurricane forces. A ductile response helps to mitigate damage as well as to provide more notice in the case of ultimate collapse. **Table 2** shows the fraction of results that were attributed entirely to ductile peg failure in terms of the percentage of required end distance for full design capacity per NDS-97. For example, all tests with an end distance of 7D for eastern white pine failed in a ductile manner as a result of peg failure (i.e., no splitting of mortise or tenon members was observed). This is an expected result as full design capacity by NDS-97 is based on the assumption of peg failure. Northern red oak provided similar results. Douglas-fir, however, failed in the tenon 3 times out of 10 at full end distance. It is speculated that this is a result of the relatively high incidence of tenon end checks noted for Douglas-fir. This result may also imply that full capacity of a Douglas-fir joint is not achieved with an end distance of 7D. Further testing would be required to substantiate this assertion. For all species, **Table 2** clearly shows an increasing probability of mortise or tenon failure with decreasing end distance.

Interpretation of results

The results were interpreted in terms of joint stiffness as well as three limit states: proportional limit, 5 percent offset yield load, and ultimate load. A sample load versus displacement plot for Douglas-fir is provided in **Figure 4**, for explanatory purposes. The stiffness modulus was calculated as the slope of the initial linear portion of the curve and each state was determined in accordance with ASTM D 5652-95 Standard Test Methods for Bolted Connections in Wood and Wood-Base Products (3).

The proportional limit was determined as the load at which the curve deviates from the initial linear portion. The yield load was determined by the 5 percent offset method described in the standard. While the ultimate load may be open to interpretation, for this study it was defined as the point at which a decrease in load was not followed immediately by an increase in load at a rate equal to or greater than the slope of the stiffness modulus. This interpretation was developed due to the large number of tests in which an audible crack in either the tenon or the peg was accompanied by a small load reduction, but the curve immediately rebounded, the stiffness of the joint was not compromised, and the capacity of the joint continued to increase. This interpretation applies only to the ultimate load. In the event that this type of a load reduction occurred before the standard proportional limit or yield load as defined above, the proportional limit or yield load was selected at the point of the initial load reduction.

The effect of end distance was analyzed with respect to each of these limit states as well as joint stiffness. **Tables 3, 4,** and **5** show single-factor analysis of variance (ANOVA) results for eastern white pine, Douglas-fir, and northern red oak, respectively. It is noted that, for

Table 3. — ANOVA results for eastern white pine joints.

	End distance (in.)	7.0	3.5	2.8	2.3	2.0	1[a]
	Count	9	12	10	9	6	3
Stiffness	Mean (psi)	13,667.83	13,753.01	12,894.79	12,889.79	13,315.14	13,018.36
	SD (psi)	1,061.27	1,067.32	932.49	958.70	1,038.35	1,197.79
	Mean comparison	Means are not significantly different					
Proportional limit	Mean (lb.)	2,253.33	2,126.58	1,958.80	1,917.78	1,944.50	997.33
	SD (lb.)	199.49	278.75	228.91	338.99	463.21	219.22
	Mean comparison	Means are not significantly different					
5% offset yield load	Mean (lb.)	3,035.56	2,989.67	2,638.10	2,456.67	2,588.67	997.33
	SD (lb.)	222.22	216.18	447.23	510.47	770.49	219.22
	Mean comparison[b]						
Ultimate load	Mean (lb.)	3,274.11	3,197.33	2,889	2,861.22	2,830	1,454.66
	SD (lb.)	231.66	222.40	367.86	306.46	502.56	327.34
	Mean comparison	Means are not significantly different					

[a] Not included in mean comparison: too few data points.
[b] Data transformed to correct for heteroscedastic variance of residuals.

Table 4. — ANOVA results for Douglas-fir joints.

	End distance (in.)	7.0	4.7	3.5	2.8	2.3
	Count	10	10	10	10	5
Stiffness	Mean (psi)	21,356.53	21,606.72	20,546.96	21,564.90	19,834.99
	SD (psi)	949.64	1,273.85	1,381.11	1,581.19	1,502.24
	Mean comparison[a]	Means are not significantly different				
Proportional limit	Mean (lb.)	2,562.60	2,443.30	2,137.00	2,295.30	1,788.40
	SD (lb.)	169.06	463.40	569.24	581.57	578.48
	Mean comparison[a]					
5% offset yield load	Mean (lb.)	3,570.00	3,264.70	2,543.50	2,821.80	1,796.00
	SD (lb.)	251.30	904.59	862.47	955.20	586.74
	Mean comparison[a]					
Ultimate load	Mean (lb.)	3,590.70	3,397.20	2,842.90	2,924.90	2,062.20
	SD (lb.)	262.65	749.87	555.48	812.71	429.50
	Mean comparison[a]					

[a] Data transformed to correct for heteroscedastic variance of residuals.

all cases, the error terms followed a Gaussian distribution as determined using a Kolmogorov-Smirnov test. However, occasionally, where noted, the error terms were deemed heteroscedastic (i.e., the error variance was not constant over all cases) and data transformation was used as a remedial measure.

Looking first at joint stiffness, it was found that in no case did reduction of end distance significantly influence joint stiffness at a 0.05 level of significance. From a mechanical perspective, this would imply that the initial mechanisms of failure (presumably initial wood embedment and peg bending) are always the same and are independent of end distance.

With respect to proportional limit, only Douglas-fir showed a significant difference in the mean values. The fact that the proportional limit, being the point of incipient yield, was influenced by end distance may indicate that the mechanisms of initial failure for Douglas-fir are due to micro-fractures in the mortise and tenon. It is noted that, for this case, the data were first transformed to stabilize the variances whereby each observation received a weight that was the reciprocal of the estimated variance for that group. This data transformation was done to correct for heteroscedasticity as determined using Bartlett's test. A Tukey-Kramer comparison test was then used to identify end distances that differed significantly from one another. It is speculated that the differences among the standard deviations of the data sets were a result of the presence of different failure mechanisms (i.e., tension perpendicular-to-grain and shear of the tenon or mortise material) early on in the test.[1]

End distance was found to have a significant influence on 5 percent offset yield loads for all species tested. This is of particular importance because 5 percent offset yield load is the measure by which the NDS determines joint strength. For eastern white pine data, no significant difference was apparent between the mean values for end distances 7D and 3.5D at a 0.05 percent level of significance. This result could imply that a critical end distance of 7D, set by NDS, is overly conservative by a factor of two for this species. However, it is cautioned that a larger database would be required to confirm this in order to rule out the probability of undesirable brittle mortise or tenon failure. For northern red oak joints, the variances of the error terms were found to be homoscedastic. Using the Tukey-Kramer multiple comparisons

[1]ANOVA assumes that the data are sampled from populations with identical SDs. Bartlett's test suggests that the differences among the SDs is not significant.

Table 5. — ANOVA results for northern red oak joints

	End distance (in.)	5.0	2.5	2.0	1.5
	Count	10	10	10	10
Stiffness	Mean (psi)	18,456.72	19,110.26	18,982.12	19,697.29
	SD (psi)	1,653.63	1,937.23	1,790.55	870.54
	Mean comparison	Means are not significantly different			
Proportional limit	Mean (lb.)	2,577.60	2,560.20	2,277.70	2,122.70
	SD (lb.)	365.76	335.77	543.53	533.58
	Mean comparison	Means are not significantly different			
5% offset yield load	Mean (lb.)	3,498.60	3,455.00	2,685.70	2,420.80
	SD (lb.)	361.13	461.69	752.14	846.33
	Mean comparison				
Ultimate load	Mean (lb.)	3,607.60	3,657.30	3,694.90	3,319.20
	SD (lb.)	335.08	433.63	326.98	473.44
	Mean comparison	Means are not significantly different			

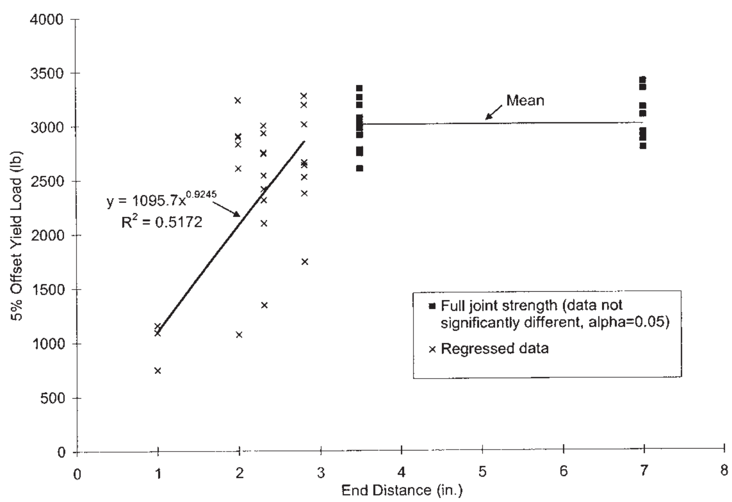

Figure 5. — Five percent offset yield load versus end distance for eastern white pine joints.

test, no significant difference was established between the mean values for the 5D and 2.5D test data. Although reducing the end distance by one half without any influence on strength level may appear conservative from a design perspective, it is cautioned that one test from the latter data set did experience brittle failure. For Douglas-fir, there was a significant difference in means at 7D and 4.7D, with a high percentage of brittle failure, even at 7D.

The high frequency of tenon splitting observed for the Douglas-fir sample may be a consequence of several points specific to this study. The failure mode of tenon splitting was linked to the high incidence of drying checks noted for Douglas-fir. Also, the simulated mortise-and-tenon joint setup may have contributed to more tenon splits than would be observed for a real joint. In a real mortise-and-tenon joint, the encasing of the tenon could reduce its tendency to split.

The 5 percent offset yield load is believed to have better repeatability for determining joint strength than either the proportional limit or the ultimate load (24). As previously alluded to, it is also used in establishing the criteria for the European Yield Model. To understand the general relationship between yield load and end distance, graphs were plotted for each species in **Figures 5**, **6,** and **7**. It is presupposed that the curve should plateau when the end distance is sufficient to develop full joint strength. Therefore, it was assumed that in all cases, the maximum end distance tested did indeed develop full joint strength and that the data that did not differ significantly from this could be pooled. Consequently, a horizontal line representing the mean of grouped data was drawn. A curve was then regressed through the remaining data to observe the general trend of the data below full joint strength. For the eastern white pine tests, a power series best fit the data with an r^2 of 0.52. Douglas-fir and northern red oak data sets produced regression curves with poor coefficients of determination (r^2 = 0.16 and 0.03, respectively). To fully capture the trend of the data and thereby establish a true critical end distance (i.e., the distance for which a greater length would imply only ductile peg failure) for any one of these species, a larger database is required. Drawing on the results of this preliminary investigation, however, it is advised that future tests should focus on end distances between 100 and 40 percent of that for full design capacity.

Conclusions

An experimental program was conducted to investigate joint stiffness as well as three limit states (proportional limit, 5 percent offset yield load, and ultimate load) as they vary with end distance. Tests were performed on double shear joints, connected with a single 1-inch-diameter northern red oak peg, loaded in tension parallel to the grain of the main member. Three different species were used as mortise-and-tenon components: eastern white pine, Douglas-fir, and northern red oak. Findings are as follows:

- In no case was joint stiffness significantly influenced by end distance (at a 0.05 level of significance).
- A general increase in data variability as end distance decreased was observed. This was attributed to the introduction of new failure mechanisms as end distance was reduced.
- The 5 percent offset yield data from the eastern white pine and northern red oak tests suggest that the end distance does not significantly affect joint capacity ($\alpha = 0.05$) until it is reduced to, at least, 50 percent of the NDS-97 requirement for full design capacity. Although this may make the NDS-97 requirement appear conservative, undesirable abrupt failure was

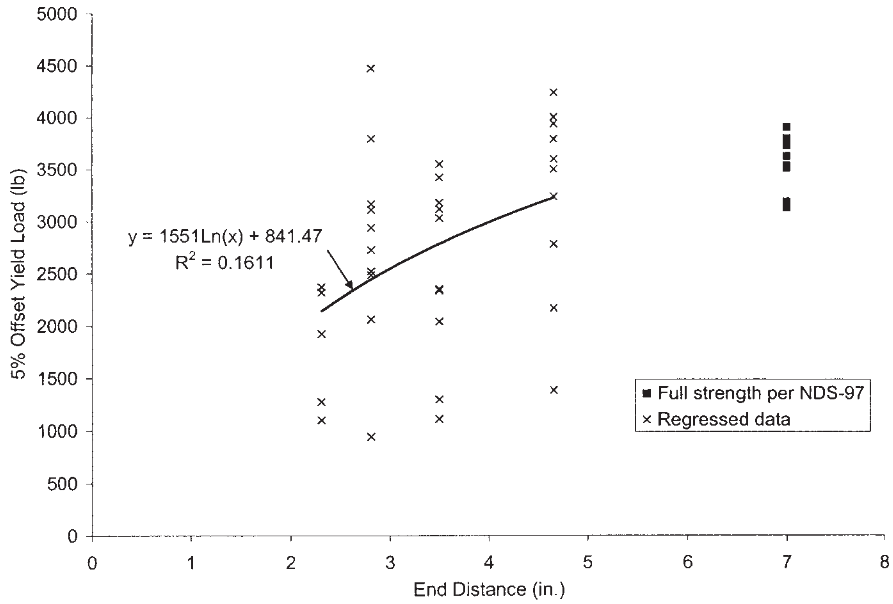

Figure 6. — Five percent offset yield load versus end distance for Douglas-fir joints.

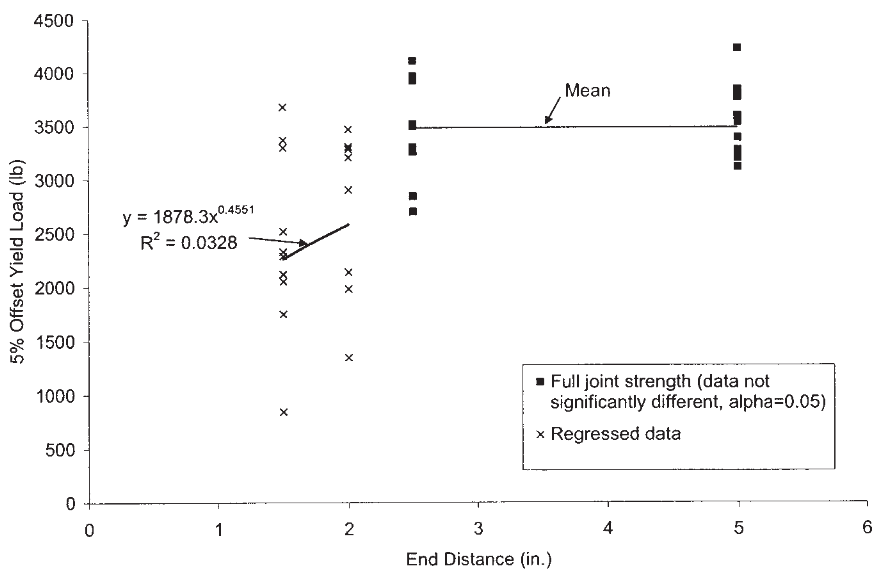

Figure 7. — Five percent offset yield load versus end distance for northern red oak joints.

observed at least once at this 50 percent reduced end distance. Further to the point, 30 percent of the Douglas-fir specimens with full end distance failed by a brittle tenon split. Although potentially controllable, for cases where ductility is of highest importance, (i.e., seismic design) the adequacy of the NDS 7D end distance requirement for Douglas-fir is questioned.

In summary, to establish exactly where the critical end distance (i.e., end distance for which only ductile peg failure) occurs would require an extensive test program. Based on the observations made in this study, future tests should focus on end distances between 100 and 40 percent of the NDS required end distance for these species. It is further noted that this study was restricted to the evaluation of one joint configuration, whereas minimum spacing requirements per code must account for a wide range of possible joint configurations. There is need for experimental evaluation on other species and joint geometries. The brittle results obtained for Douglas-fir at 100 percent of required NDS end distance indicate that other species with relatively low tensile strength perpendicular to the grain must also be carefully examined.

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