ANALYSIS, DESIGN, AND PERFORMANCE TESTING OF A GATE-LEG TABLE

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Abstract. Gate-leg tables behave differently from conventional tables and have not been studied extensively. To determine the distribution of moments in the main and side frames, structural analyses were conducted on a gate-leg table under different loading scenarios. Potential weak construction points were identified. Back-to-front load performance tests of the tables constructed with mortise-and-tenon and dowel joints were performed and compared. Results show that the strength of mortise-and-tenon joints is superior to the strength of dowel joints. The tables constructed with mortise-and-tenon joints would be ranked just below the "medium-duty" performance level, whereas tables constructed with dowel joints would be ranked just above "light-duty." Strength of dowel joints was closely related to the length of the dowels. Finally, ultimate strength tests were conducted on undamaged joints cut from the frames following the performance testing to determine their in-plane, out-of-plane, and torsional moment capacities. Substantially higher values were obtained for the mortise-and-tenon joints.

Keywords: Gate-leg table, joint test, performance test, structural analysis.

INTRODUCTION

In conventional four-legged tables with rails, the top is supported by four top rails (aprons) that are located near to, and run parallel to, the edges of the top and frame into the sides of the legs. Gate-leg tables, in contrast, are characterized by a main frame that runs beneath the major axis of the top, and for the design considered here, two gate-leg frames that run beneath the minor axis. Since the corners of rectangular tops are not supported by these frames, gate-leg table tops are often made elliptical in shape with the major axis running parallel to the axis of the main frame. Four-legged gate-frame versions do exist, however, in which two gates are hinged near each end of the main frame. These double gates may be folded out to provide support at each corner of a rectangular top.

In conventional tables with rails, in which the rails are joined to the sides of the legs with tenons or dowels, side-thrust forces applied to the table, such as those that occur when a table is pushed across a floor, are resisted by in-plane bending moments generated in the top rails. In contrast, side-thrust forces applied to gate-leg tables may be resisted by in-plane moments generated in the main frame, but they may also be

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resisted by out-of-plane and torsional moments generated in the gate-leg frames. Rational determination of the magnitudes of the moments is complicated by the semi-rigid behavior of the joints and hinges and the structural behavior of the "stopped" hinge on one side of the table.

To determine the distribution of moments in the main and side frames, structural analyses were conducted on a gate-leg table in which the tenons and hinges were treated as individual elements whose properties could be altered to simulate semi-rigid behavior. Cyclic increased load performance tests were also conducted on the tables to determine their resistance to side-thrust forces similar to those that might occur in service. These tests are similar to those described by Eckelman (1977). Finally, ultimate strength tests were conducted on undamaged joints cut from the frames following performance testing to determine their in-plane, out-of-plane, and torsional moment capacities.

MATERIAL AND METHODS

Frame design and construction

The overall design of the table is given in Fig 1. All the members measure 30 × 80 mm in cross-section. The tenons measured 13 × 51 mm in cross-section; the dowels were 12.7 mm dia by either 50.8 or 76.2 mm long. The first set of specimens was constructed of European red pine and the second of southern pine.

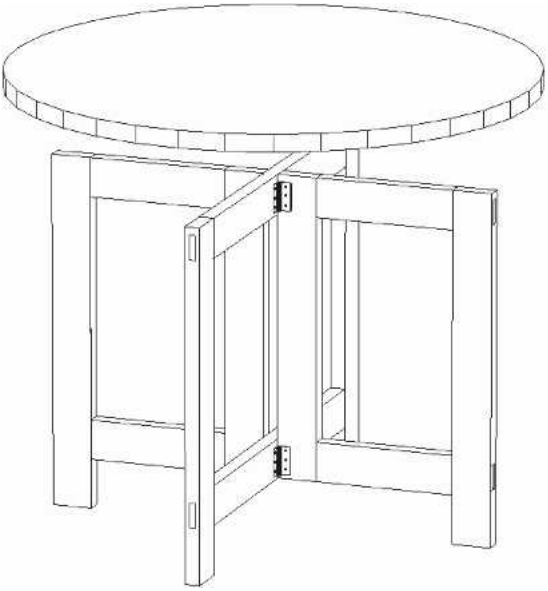

FIGURE 1. Overall design of the table evaluated.

Structural analysis—modeling of the table understructure

The joints and members of the main frame and two gate-leg frames were labeled for analysis as shown in Figs 2a, 2b, and 3. Joint numbers are enclosed in circles; member numbers are enclosed in brackets.

Structural members measured 30 × 80 mm in cross-section with moments of inertia of 1.276 × 10^6 m^4 and 0.178 × 10^6 m^4. Members and tenons were assumed to have a modulus of elasticity (MOE) of 11.2 GPa and a calculated modulus of rigidity (MOE/20) of 560 MPa.

Each tenon was treated as an individual member that measured 12.7 × 50.8 mm in cross-section by 12.7 mm long. By treating the tenons as individual members, the joints could be treated as semi-rigid. Choice of tenon length was based on estimated vs test deflection of the frame.

Semi-rigid constants for the hinges were also unknown. For purposes of analysis, they were first given the same properties as the tenons. Analyses were then conducted to determine the

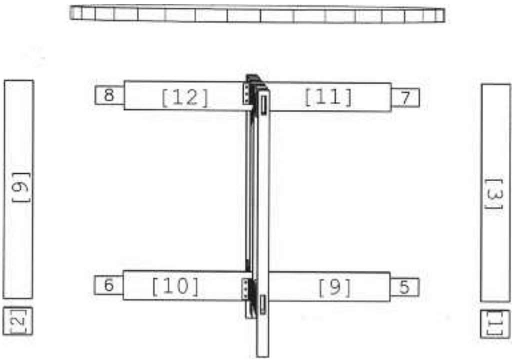

FIGURE 2a. Diagram showing labeling of the main frame. Member numbers are enclosed in parentheses; tenon numbers are not enclosed.

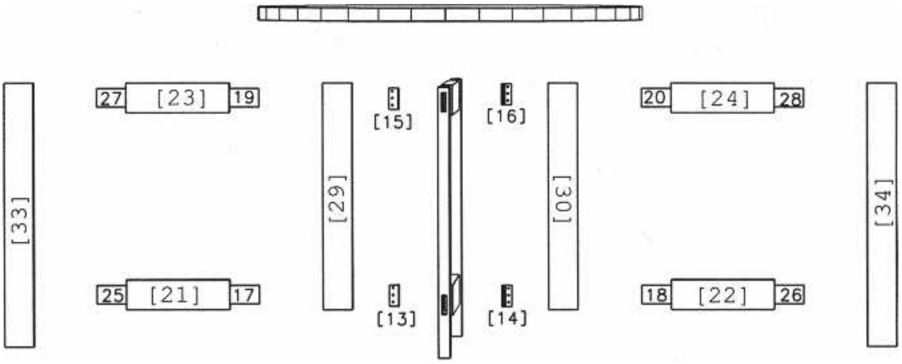

FIGURE 2b. Diagram showing labeling of the gateleg frames. Member numbers are enclosed in parentheses; tenon numbers are not enclosed.

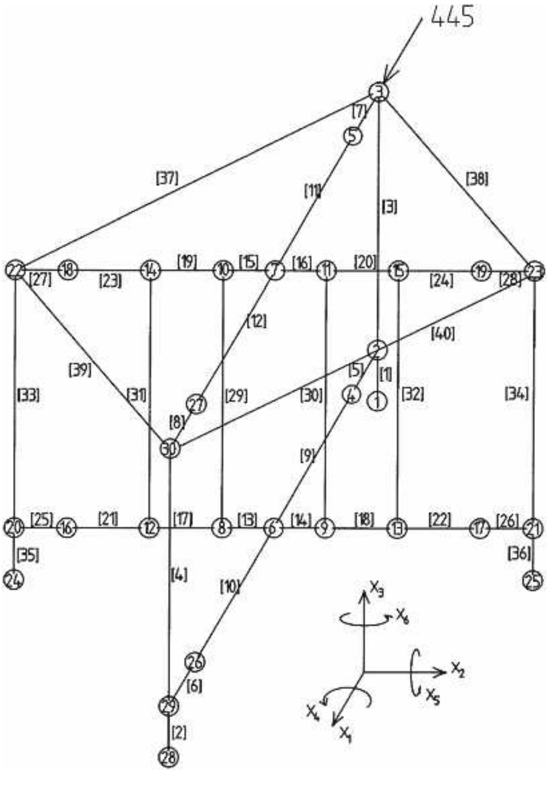

FIGURE 3. Diagram of joint and element numbers. Member numbers are enclosed in brackets; joint numbers are enclosed in circles.

effect of changing their properties on the overall distribution of forces in the frame. These changes were sufficiently small that the properties of the hinges were left unchanged. However, the 1-ends of hinges 13 and 15 (Fig 2b) were released so that these hinges could not resist out-of-plane bending moment, ie, they were free to close as they normally would. In contrast, the 1-ends of hinges 14 and 16 (Fig 2b) were not released to allow them to carry moment—as occurs when the gate-leg is wedged against the main frame.

Of particular interest in the analysis were a) the torsion forces acting on the mortise-and-tenon (or dowel) joints, and b) the shear forces and bending moments acting on the hinges. Also of interest were the out-of-plane bending moments acting on the mortise-and-tenon (or dowel) joints and, to a lesser degree, the in-plane forces acting on these joints.

Four load cases were considered in conducting structural analyses of the understructure of the table as listed below.

Case 1. A back-to-front load of 445 N was applied to the center-rear edge of the top along the centerline of the main frame (positive x_1-direction of the main frame) with the legs of the gate-leg frames restrained in the x_1-and x_3-directions and the front and rear legs of the main frame restrained in the x_3-direction. Purpose of this loading was to determine the out-of-plane and torsional moments acting on the hinges and tenons (dowels) of the hinged frame.

Case 2. A back-to-front load of 445 N was applied to the center-rear edge of the top along a line parallel to the centerline of the table (positive x_1-direction) with the front leg of the main frame restrained in the x_1-direction and the rear leg in the x_3-direction. Purpose of this analysis was to determine the in-plane bending forces acting on the joints of the main frame.

Case 3. A sidesway load of 445 N was applied to the center-left edge of the top along the axis of the gate-leg frames (along the positive x_2-axis of the hinged frame) with the front and rear legs of the main frame restrained in the x_2- and x_3-directions and the left and right legs restrained in the x_3-direction. Purpose of the analysis was to determine the out-of-plane and torsional moments acting on the joints of the unhinged main frame.

Case 4. A sidesway load of 445 N was applied to the center-left edge of the top along the axis of the hinged frame (along the positive x_2-axis of the hinged frame) with the right leg of the hinged frame restrained in the x_2-and x_3-directions and the front, rear, and left legs in the x_3-direction. Purpose of this analysis was to determine the in-plane bending forces acting on the joints of the gate-leg hinged frames.

Performance tests—front to back load test on tops

Four tables were tested; two were constructed of red pine with mortise-and-tenon joints, and two were constructed of southern pine with dowel joints. Each table was mounted for testing as shown in Fig 4 (Eckelman 1977). Screws were used to attach the table top to the top rails at four points, 50 mm from the ends of each rail.

Testing was started at the 222-N load level and increased in increments of 222 N after 25,000 cycles had been completed at each preceding load level until 778 N was reached. At this point, the load was increased by 111 N and testing continued for another 25,000 cycles. This load increment was then used until failure occurred.

Joint tests

Following performance testing of the frames, undamaged joints were cut from the frames and tested individually in a universal testing machine. Joints were supported for testing as shown in Figs 5a through 5g. In-plane tests were conducted on both T- and L-shaped joints. Half of the L-shaped joints were tested in compression (decreasing angle between legs of joint) and half in tension (increasing angle between legs). Torsion tests were conducted on both L- and T-shaped joints. Finally, out-of-plane bending tests were conducted on both T- and L-shaped joints.

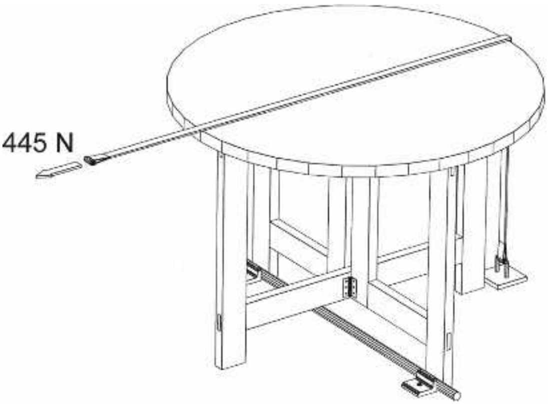

FIGURE 4. Test arrangement for performance testing of table.

RESULTS AND DISCUSSION

Results and discussion of frame analyses

Case 1. Maximum torsional moments of 32.7 N · m act on tenons [17] and [25] of the lower left rail (Fig 3). Similarly, a maximum torsional moment of 18 N · m acts on the hinge connect-

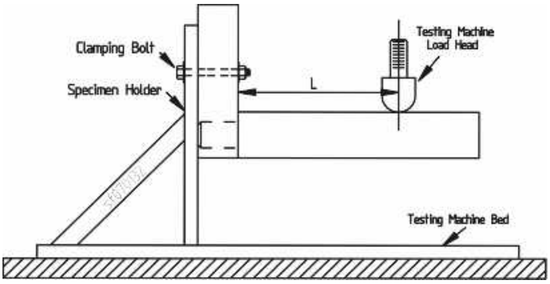

FIGURE 5a. In-plane bending moment: L-joint out.

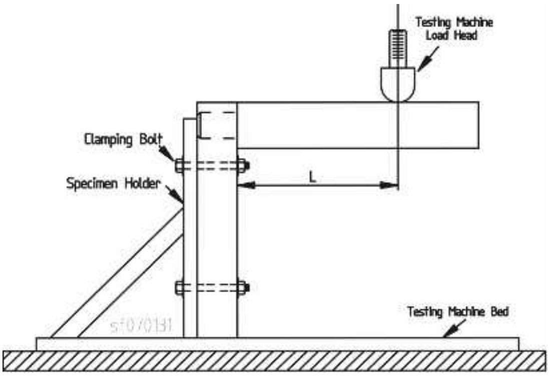

FIGURE 5b. In-plane bending moment: L-joint in.

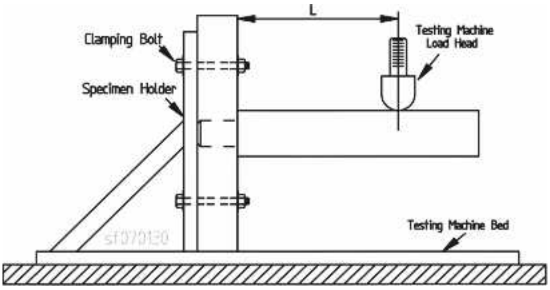

FIGURE 5c. In-plane bending moment: T-joint.

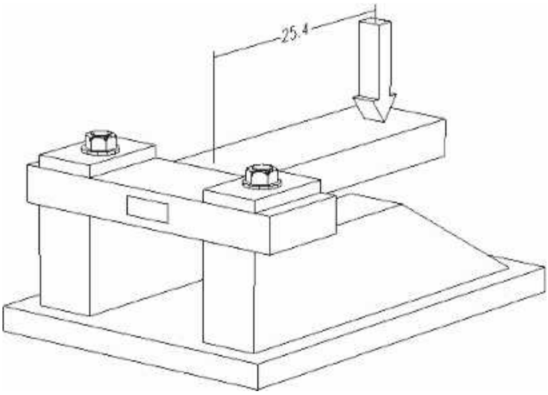

FIGURE 5d. Out-of-plane bending moment: T-joint.

ing the lower rail of the left gate-leg frame to the lower rail of the main frame.

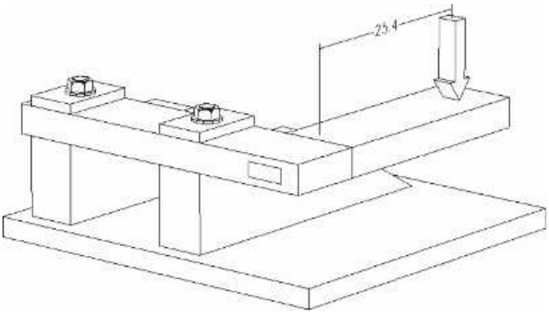

FIGURE 5e. Out-of-plane bending moment: L-joint.

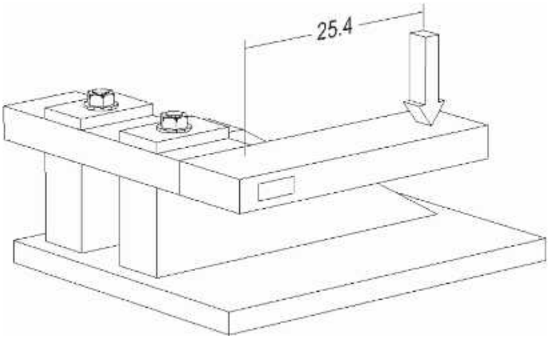

FIGURE 5f. Torsional moment: L-joint.

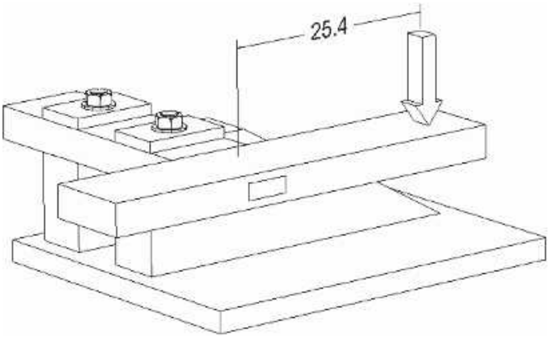

FIGURE 5g. Torsional moment: T-joint.

Importantly, a maximum out-of-plane moment of 55.3 N · m acts on the 9-end of tenon [18], which connects the lower rail of the right hand gate-leg [22] to the interior post [30]. Likewise, an out-of-plane moment of 38.8 N · m acts on the stopped hinge [14]. The out-of-plane moment acting on the end of tenon [18] is 160% greater than the out-of-plane moments acting on any other tenon. Hence, this tenon (joint) would be expected to be the first to fail at higher load levels. Furthermore, additional analyses indicate that if the ends of tenon [18] are released in the x_{4}-, x_{5}-, and x_{6}-directions (see Fig 3), the out-of-plane moment acting on the 23-end of tenon [28] at the 445 N level increases to 150.2 N · m. Hence, under Case-1 loading, the joint represented by tenon [18] normally would be expected to fail first followed by the immediate failure of the joint represented by tenon [28].

Case 2. A maximum bending moment of 87.1 N · m acts on tenon [6], which connects the lower rail of the main frame to the front leg. The magnitude of this bending moment is 35% greater than the next largest moment, 64.6 N · m, which acts on the 5-end of tenon [7]. Given the magnitude of the difference of moments, tenon [6] would normally be expected to fail first under higher Case-2 loading.

Since the length of the tenons is greater than their depth, the rail-to-post joints would be expected to fail owing to fracture of the tenons—rather than withdrawal of the tenons from the posts. If an MOR of 82.7 MPa is assumed for these members, the tenons would be expected to have an ultimate bending moment capacity, *m*, of

$$\begin{aligned} m &= 82{,}700{,}000 \times 0.013 \times 0.051 \times 0.051/6 \\ &= 466\ \mathrm{N \cdot m} \end{aligned} \tag{1}$$

that is sufficient to resist a repetitive side thrust load of 890 N applied to the top of the table. Actual test values for the joints ranged from about 293.8 N · m for L-shaped joints to 485.8 N · m for a T-shaped joint.

Cases 3. The maximum out-of-plane moment, 94.3 N · m, occurs at the center of the bottom rail, ie at the junction of members [9] and [10]. These two members in reality constitute a single element with a cross-section of 30 × 80 mm. Calculating the stress, σ, acting on the section gives

$$\sigma = \frac{6 \times 94.3}{0.080 \times 0.030 \times 0.030} = 7.86\ \mathrm{MPa}, \tag{2}$$

which is small relative to the MOR of the frame material. Similarly, the bending moments acting on the tenons joining the rails to the legs amount to 9.5 N · m. The corresponding stress, σ, developed in a tenon with cross-section of 12.7 × 50.8 mm amounts to

$$\sigma = \frac{6 \times 9.5}{0.0508 \times 0.0127 \times 0.0127} = 7.07\ \mathrm{MPa}. \tag{3}$$

Although the stress in the tenon itself is low, the joint should, in fact, be designed as an out-of-plane mortise-and-tenon (or dowel) joint since the walls of the mortise may split before the tenon fractures.

The maximum torsional moment acting on the frame, which occurs in the bottom rail, amounts to 10.7 N · m. This moment is sufficient to develop a longitudinal shear force, τ, in the tenons of the lower rail of 4.57 MPa, ie,

$$\begin{aligned} \tau &= \frac{15 \times 0.08 + 9 \times 0.0299}{5 \times 0.08 \times 0.08 \times 0.0299 \times 0.0299} \times 95 \\ &= 4.88\ \mathrm{MPa} \end{aligned} \tag{4}$$

As can be seen, for higher loadings above 890 N, the shear strength of the wood in the tenons (parallel to the grain) could be exceeded; however, torsion tests of joints cut from the frame gave an average ultimate torsional moment of about 113 N · m. This result indicates that the tenons are reinforced by the walls of the mortise. Presumably, therefore, much larger ultimate torsional moment values are developed by the joint than would be estimated by the above expression.

Case 4. The maximum in-plane bending moment of 59 N · m occurs on the 21-end of tenon [26]; likewise, a maximum bending moment of 3.7 N · m occurs on the 11-end of hinge [16].

Performance tests

The first red pine table with mortise-and-tenon joints failed after 20,000 cycles had been completed at the 890-N load level. Cause of failure was fracture of the bottom rail to interior post joint of the right hand gate-leg frame (joint [9], tenon member [18]) followed by immediate failure of the leg-to-top rail joint (joint [19], tenon member [28]).

The second red pine table with mortise-and-tenon joints failed after 5,000 cycles had been completed at the 1001-N load level. Cause of failure was yielding of the hinge used to connect the interior post of the right hand gate-leg frame (member [14]) to the lower rail of the main frame. This hinge is "stopped" so that out-of-plane moments acting on the hinge cause the "leaf" of the hinge to bend as the hinge in essence tries to pry the screws loose from the top and bottom rails of the main frame.

The first southern pine table with dowel joints failed after 20,527 cycles had been completed at 778 N. Cause of failure was fracture of the bottom rail to interior post joint of the right hand gate-leg frame (joint [9], tenon member [18]) followed by immediate failure of the leg-to-top rail joint (joint [19], tenon member [28]).

The second southern pine table with dowel joints, failed after 470 cycles had been completed at 667 N. Cause of failure was fracture of the bottom rail to interior post joint of the right hand gate-leg frame (joint [9], tenon member [18]) followed by immediate failure of the leg-to-top rail joint (joint [19], tenon member [28]).

Although the mechanical properties of the wood could be a factor, failure of the dowel joints at lower load-levels than those obtained with mortise-and-tenon joints likely indicates that the dowel joints inherently have less out-of-plane bending moment and torsional moment capacity than do the comparable mortise-and-tenon joints. One possible explanation for this result is that the dowels were shorter than the tenons and hence produced greater perpendicular-to-grain forces on the walls of the dowel holes than did the tenons on the walls of the mortise. In addition, the out-of-plane bending resistance of the dowels would be expected to be less than that of the tenons. Finally, the torsional forces acting on the joint may have also caused greater perpendicular-to-grain forces to act on the wall of the dowel hole at the lower end of the post.

In comparison with performance tests conducted on other tables (Eckelman 1977), the tables constructed with mortise-and-tenon joints would be ranked just below the "medium-duty" performance level, whereas the tables constructed with dowel joints would be ranked just above "light-duty."

Results of joint tests

Results of the joint test are given in Tables 1 and 2. As can be seen from these results, substantially higher values were obtained with the mortise-and-tenon joints. One reason for this is that the tenons fully penetrated the member in which they were embedded. In like manner, it was clear from testing that the bending moment and torsional capacity of the dowel joints were closely related to the length of the dowels. Thus, the

TABLE 1. *Results of tests on mortise-and-tenon joints.*

Joint loading configuration	Ult. load (N)	Moment arm (m)	Ultimate torsion capacity (N · m)	Ultimate moment capacity (N · m)
Fast Grown				
In-Plane				
L-in	1378.9	0.254		350.3
L-in	1390.1	0.254		353.1
L-out	1467.9	0.254		372.8
T	1000.8	0.457		457.6
T	1078.7	0.254		274.0
Torsion				
L-torsion	482.6	0.254	122.6	
L-torsion	449.3	0.254	114.1	
Tee-torsion	467.1	0.254	118.6	
Slow Grown				
In-Plane				
L-in	1979.5	0.254		502.8
L-in	1045.3	0.254		265.5
L-out	1365.6	0.254		346.9
L-out	1112.1	0.254		282.5
Out-of-Plane				
L-	467.1	0.254		118.6
L-	511.5	0.254		129.9
T-	645.0	0.254		163.8
T-	511.5	0.254		129.9
Torsion				
L-	347.0	0.254	88.1	
L-	355.9	0.254	90.4	
T-	320.3	0.254	81.3	
T-	311.4	0.254	79.1	

TABLE 2. *Results of dowel joint tests.*

Dowel length (m)	Joint loading configuration	Ult. load (N)	Mom arm (m)	Ultimate torsion capacity (N · m)	Ultimate moment capacity (N · m)
	Fast Grown				
	In-Plane				
	L-in	627.2	0.254		159.3
	L-in	653.9	0.254		166.1
	L-in	649.4	0.254		165.0
	Out-of-Plane				
0.051	L-	244.7	0.254		62.1
0.051	L-	129.0	0.254		32.8
0.051	Tee		0.254		
0.051	Teel	209.1	0.254		53.1
	Torsion				
0.051	L-	467.1	0.254	118.6	
0.051	Tee	542.7	0.254	137.8	
0.051	Tee	547.1	0.254	139.0	
	Slow Grown				
	In Plane				
0.051	L-in	756.2	0.254		192.1
0.051	L-in	711.7	0.254		180.8
0.076	L-in	400.3	0.254		101.7
0.076	L-in	1214.4	0.254		308.5
	Out-of-Plane				
	L-out	925.2	0.254		235.0
	L-out	1254.4	0.254		318.6
	L-out	600.5	0.254		152.5
	L-out	609.4	0.254		154.7
	Torsion				
0.051	L-	711.7	0.254	180.8	
0.051	Tee	313.6	0.254	79.7	
0.051	Tee	582.7	0.254	148.0	
0.076	L-	222.4	0.254	56.5	
0.076	L-	240.2	0.254	61.0	
0.076	Tee	275.8	0.254	70.1	
0.076	Tee	395.9	0.254	100.6	

dowels used in the construction of such joints should be as long as is practical.

CONCLUSIONS

Under the action of a back-to-front load applied along the longitudinal axis of the top rail of the main frame with the gate-legs stopped, the tenon connecting the lower gate-leg frame rail to the interior gate-leg post is the most highly loaded element. Failure of this tenon/joint results in immediate transfer of high out-of-plane moment to the tenon connecting the top rail of the gate-leg frame to the exterior post of the frame. Hence the critical joint for this type of loading is the lower rail to interior-post joint of the gate-leg frame. Similarly, with the gate-legs released but the front leg stopped, the tenon connecting the lower main frame rail to the front leg is subjected to the highest in-plane moment, whereas the tenon connecting the top rail to the back leg is subjected to the second highest in-plane moment. In general, it is important that the top rails of the gate-leg frames be firmly attached to the underside of the top. If brackets are not used, the gate-leg frame should be supported by notched wedges that can resist the side thrust forces applied to the leg.

When a sidesway load is applied along the longitudinal axis of the top rail of a gate-leg frame with the legs of the main frame stopped (in this direction), the maximum out-of-plane moment occurs at the center of the lower main frame rail. For rails of the size used in this study, the resulting internal stresses developed in the rail are relatively low. Torsional moments developed in the tenons connecting the top and bottom rails to the legs could cause longitudinal shear failures in the tenons at loads within anticipated service levels. A close fit of the tenon into the mortise helps to reduce this effect. For the case in which the right leg of the gate-leg frame is stopped with the legs of the main frame released, the tenon connecting the lower rail of the frame to the front leg is subjected to the highest in-plane moment. Likewise, the hinge connecting the top rail of the right gate-leg frame to the side of the top rail of the main frame is subjected to the highest in-plane moment.

Results of the performance tests indicate that these tables should be considered for light-to-medium service categories. This result is to be expected since the lack of side rails prevents effective reinforcement of the legs against side sway forces.

Mortise-and-tenon joints of the size used in construction of the tables should provide satisfactory table performance. Use of shorter tenons could potentially seriously affect table performance, and tables constructed with such tenons should be tested to determine the effect of tenon length on performance.

Substitution of dowel joints for mortise-and-tenon joints deserves further research since substitution of dowels for tenons could be an important production as well as design consideration. Presumably, the largest possible dowels should be used. Dowel diameters could perhaps be equal to one-half the thickness of the member in which it is embedded. Dowel length is particularly important and dowels should be as long as is practical—perhaps at least 50 mm. Finally, the dowels should be constructed of woods with high MOE.

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