Out-of-Plane Strength and Stiffness Of Dowel Joints

Carl A. Eckelman

Abstract

The rational design of furniture as an engineered structure with specified strength characteristics requires that methods be available for systematically designing the joints. Of particular concern are dowel joints loaded in flatwise bending since neither their strength nor stiffness characteristics have been investigated and yet they are often heavily loaded in bending. To evaluate these characteristics, 60 dowel joint specimens were constructed of black walnut and tested in flatwise bending. The joints were assembled with 3/8-inch-diameter plain sugar maple dowels and a gap-filling urea-formaldehyde resin. Ten joints each were constructed with rails of the following thicknesses: 3/4, 1, 1-1/4, and 1-1/2 inches. Similarly, 10 joints with rails 3/4 inch thick were assembled with gaps between rail and post of 1/16 and 1/8 inch. A set of edgewise bending specimens was included in the study to provide a basis of comparison between edgewise and flatwise bending characteristics.

Results of the tests indicated that the strength of the joints could be predicted by means of the formula

\[ F_c = \frac{(D^3/16)S + F(W-D)}{2} \]

where \( F_c \) refers to the ultimate bending strength of the joint, pound-inches; \( D \) is the diameter of the dowel, inches; \( F_c \) is the ultimate withdrawal strength of the dowels, pounds; \( S \) is the MOR of the material of which the dowels were constructed, and \( W \) is the thickness of the rail, inches. Values predicted by this expression agreed within 2 percent of observed test values over the range of rail widths evaluated. Joints were quite flexible in flatwise bending as compared to edgewise bending; specifically, joints with 3/4-inch-thick rails were 14 times more flexible. Joint stiffness was closely related to tightness of fit of the joint; i.e., the tighter the fit between rail and joint, the stiffer the joint.

Dowel joints are perhaps the most popular method of joining members together in wood furniture frame construction. The strength of these joints is somewhat limited relative to the strength of the joined members, so unless they are properly designed, they may be the weakest part of a furniture frame. In a typical furniture frame, dowel joints may be subjected to axial, shear, torsional, and/or bending forces (4). Bending forces are usually of most concern, however, because their magnitude may easily exceed the maximum theoretical resistance of a particular joint configuration. An example of a dowel joint which is often highly loaded in bending is the two-pin side rail to back post joint in a common side chair, Figure 1. Ordinarily, the rail and post are turned on edge in this type of construction to allow for the greatest possible dowel spacing and, therefore, the greatest strength. Sufficient research (3) has been carried out on joints of this configuration to predict their strength with reasonable accuracy, and they may be designed, therefore, to meet specified in-service strength requirements.

Dowel joints are also regularly used in frame constructions in which the members are loaded in bending in the flatwise or out-of-plane position, Figure 2. Intuitively, the bending strength of such joints would be

The author is Associate Professor of Wood Science, Dept. of Forestry and Natural Resources, Purdue Univ., Lafayette, Ind. This paper was received for publication in October 1978.

AUGUST 1979
design purposes. Two questions were of primary concern. First, what is the ultimate bending strength and stiffness of joints normally used in furniture construction. Second, what are the effects of loose joint construction on these characteristics.

Materials

All specimens were constructed of black walnut which had been conditioned to a moisture content (MC) of 6 percent. The joints were assembled with 3/8-inch-diameter plain sugar maple dowels and a gap-filling urea-formaldehyde adhesive. Dowel and hole diameters varied slightly, but dowel-hole diameter differences averaged less than 0.005 inch (7). Joint configurations are illustrated in Figures 3 through 6. Eight groups of 10 specimens each were tested. A brief description of the characteristics of each group and the reason for its inclusion in the study are given below.

Withdrawal strength, Group 1, Figure 3.—The material was selected at random from an initial supply of black walnut lumber. Purpose of the test was to determine the expected withdrawal strength of dowels expected to be less than that of edgewise joints loaded in-plane. The lack of quantitative data concerning their performance presents a serious problem in the strength design of such frames. Such data are necessary for design purposes since neither the strength nor rigidity of the frame as a whole can be predicted with equations.

This study's purpose was to obtain estimates of the strength and stiffness of dowel joints in flatwise bending. These estimates would be of practical use for
from the black walnut material used in construction of the other specimens.

*Edgewise bending strength, Group 2, Figure 4.*—These specimens were tested to determine the edgewise or in-plane bending strength and stiffness of two-pin, moment-resisting dowel joints constructed of the same material as that used in the flatwise bending specimens. Purpose of the test was to provide the values needed to permit a comparison of the flatwise stiffness and bending strength of dowel joints, with edgewise stiffness and bending strength. Dowel length was 2 inches and depth of embedment was 1 inch in both rail and post.

*Flatwise bending strength, tight and loose joints, Groups 3, 4, and 5, Figure 5.*—These specimens were evaluated to determine the effect of an open joint on strength and flexibility. All three sets of joints were constructed with 3/4-inch-thick rails. The specimens of Group 3 were constructed with the joint between the rail and post closed; those of Group 4 had a 1/16-inch gap between the rail and post; and those of Group 5 had a 1/8-inch gap. Rail width in all three cases was 3 inches. All three sets of specimens were constructed in such a way that the dowels penetrated 1 inch into the rail and 3/4 inch into the post; lengths of the dowels used, accordingly, were 1-3/4, 1-13/16, and 1-7/8 inches. Dowels were 1-1/2 inches apart.

*Flatwise bending strength, variable rail thickness, Groups 6, 7, and 8, Figure 6.*—Purpose of this test was to
evaluate the effect of rail thickness on joint strength and stiffness in flatwise bending. In each case the rail was 3 inches wide; rail thicknesses were 1, 1-1/4, and 1-1/2 inches for Groups 6, 7, and 8, respectively. The specimens of Group 3 provided data on rails 3/4 inch thick since they were also of tight construction. In all cases, the dowels penetrated 1 inch into the end grain of the rail and 3/4 inch into the side grain of the post.

Test Methods

The dowel withdrawal tests were carried out using the equipment shown in Figure 7. Each end of the loading apparatus was attached to a ball seat in the testing machine so that loads were applied along the axis of the dowels free of eccentricity. Moderate loading rates of about 400 pounds per minute were used in testing the specimens (6).

All bending strength tests were carried out using the loading jig shown in Figure 8. Flatwise bending specimens were attached to the front of the column, whereas in-plane specimens were bolted to its side. Vertical loads were applied to the rail of each specimen exactly 12 inches in front of the post so that the bending force applied to a joint was equal to 12 times the applied load. Rate of loading for the in-plane bending specimens was about 25 pounds per minute; for the flatwise bending specimens it was about 10 pounds per minute. Rotation of the rail relative to the post was measured indirectly by means of a dial gage and holding bracket shown in Figure 9.

Results and Discussion

Results of all the tests are given in Table 1. The withdrawal strength of the dowels in sample Group 1 was 1,632.5 pounds. As was stated previously, this first set of tests was carried out to establish dowel withdrawal strength values for the material used in the remainder of the tests.

In the case of specimen Group 2—the edgewise bending specimens—the average bending strength was 3,060 pound-inches (lb.-in.). Previous research (3) carried out with sugar maple specimens indicated that the bending strength of this type of joint could be predicted by means of the expression

$$F_r = F_d (d_c / d_s)$$  \[1\]

where $F_r$ is the bending strength of the joint, pounds; $F_d$ is the withdrawal strength of the dowels, pounds; $d_c$ is the distance between dowel centers, inches; $d_s$ is the distance from the dowel center to the adjacent outside edge of the rail; i.e., for a symmetrical dowel arrangement $d_s = (w - d_c / 2$ where $w$ is the width of the rail. For the specimens of Group 2, $d_c = 1-1/2$ inches and $d_s = (3 - 1-1/2) / 2$, or 3/4 inch. Furthermore, from Table 1 we see that $F_d$ is 1,632.5 pounds. Substituting these values into Equation [1] and solving gives a predicted bending strength of 3,061 pound-inches. The close agreement between the predicted and the test value in this study provides additional support for the hypothesis that the bending strength of such joints can be reliably predicted.

The flatwise bending strengths of the specimens of Groups 3, 4, and 5 are shown graphically in Figure 10. The tight joints were over twice as strong as the joints.
with either 1/16- or 1/8-inch gaps. Furthermore, there was little practical difference between the strength of these latter two types of joints. These results clearly demonstrate that bending strength is highly dependent on the quality of joint construction; i.e., how well the parts fit together.

The bending strengths of the specimens in Groups 3, 6, 7, and 8 are given graphically in Figure 11. As was expected, the bending strength of the joints in flatwise bending was much less than in edgewise bending. Nevertheless, the magnitudes of the bending strengths of the well-made joints indicate that they would make a significant contribution to the overall strength of several types of furniture frames, and it is worthwhile, therefore, to ensure that they are properly constructed.

It is also noteworthy that there is a regular stepwise increase in bending strength as the width of the rail is increased by 1/4-inch increments. The orderly behavior of these joints suggested that some type of empirical expression similar to Equation [1] might be developed to predict the bending strength of these joints.

In developing such an expression, it was assumed that the internal resisting moment generated in the joint was equal to the sum of the bending resistances developed in the dowels themselves plus the resisting moments of the couples formed by the tensile forces, $T$, acting along the axes of the dowels and the resultant compressive forces, $C$, acting on the heel of the rail (Fig. 12). Under these assumptions, the ultimate bending strength of the joint is limited by both the ultimate bending strength and the ultimate withdrawal strength of the dowels. As a first approximation, the ultimate bending strength of the dowels may be found by means of the standard flexure formula. Furthermore, the ultimate resisting moment of each of the couples is equal to the ultimate withdrawal strength of a dowel multiplied by the moment arm of the couple. The ultimate

---

**TABLE 1.** Average ultimate withdrawal (Group 1) and bending strength (Groups 2-8) of the specimens.

<table>
<thead>
<tr>
<th>Group No.</th>
<th>Sample Size</th>
<th>Mean Strength</th>
<th>Std. Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>1,632.5 lb.</td>
<td>149.2 lb.</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>3,960.0 lb-in.</td>
<td>526.8 lb-in.</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>908.4 lb-in.</td>
<td>46.4 lb-in.</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>444.9 lb-in.</td>
<td>77.4 lb-in.</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
<td>391.2 lb-in.</td>
<td>38.4 lb-in.</td>
</tr>
<tr>
<td>6</td>
<td>10</td>
<td>1,060.0 lb-in.</td>
<td>55.4 lb-in.</td>
</tr>
<tr>
<td>7</td>
<td>10</td>
<td>1,215.6 lb-in.</td>
<td>137.4 lb-in.</td>
</tr>
<tr>
<td>8</td>
<td>10</td>
<td>1,376.4 lb-in.</td>
<td>155.0 lb-in.</td>
</tr>
</tbody>
</table>

---

**Figure 9.** Diagram of dial gages and brackets used to measure the rotation of the rail relative to the post.

**Figure 10.** Graph showing effect of closeness of fit between rail and post on out-of-plane bending strength of dowel joint.

**Figure 11.** Graph showing relationship of rail thickness to out-of-plane bending strength of dowel joint.
strength of the joint, therefore, may be predicted by means of the expression

\[ F = 2(\pi D/32)S_t + 2(F_r)d \]  \hspace{1cm} \text{Equation [2]}

where \( F \) is the ultimate bending strength of the joint, pound-inches; \( D \) is the diameter of the dowel, inches; \( S_t \) is the modulus of rupture (MOR) of the material of which the dowels were constructed, pounds per square inch; \( F_r \) is the ultimate withdrawal strength of the dowels, pounds; and \( d \) is the moment arm of the couple, inches. All of these values are known or may be readily calculated except for the moment arm, \( d \).

Previous research \((1, 5)\) indicated that the withdrawal strength of dowels from the side grain of wood is proportional to their depth of embedment in the wood raised to the 0.89 power. The depth of embedment of the dowels in the side grain members of the specimens in Groups 3, 6, 7, and 8 was \( 3/4 \) inch compared to 1 inch for the specimens in Group 1. Since the dowels in Group 1 had an average withdrawal strength of 1,632.5 pounds, those in Groups 3, 6, 7, and 8 would be expected to have a mean withdrawal strength of \((0.75)^{0.89}/(1)^{0.89}\times 1,632.5\), or 1,264 pounds. The MOR of sugar maple (15,800 psi at 12\% MC) may be found in the Wood Handbook \((8)\). Transforming this value to 6 percent MC gives 19,448 pounds per square inch when it is assumed that the response of sugar maple to changes in MC is similar to that of yellow birch \((8)\). Substituting these values into Equation [2] along with the ultimate bending strength of each of the specimen groups in turn and solving for \( d \), we obtain values of 0.2800, 0.3357, 0.4012, and 0.4653 inch for \( 3/4 \), 1, 1-1/4, and 1-1/2-inch-thick rails, respectively. These results dictate that the results, as previously defined, must be treated as though they act at a point very nearly midway between the lower edge of the dowel and the adjacent edge of the rail (Fig. 12). This distance may be calculated by means of the expression

\[ d = (W + D)/4 \]

where \( W \) is the thickness of the rail and \( D \) is the diameter of the dowel. Equation [2], therefore, may be rewritten as

\[ F = \frac{\pi D}{16}S_t + F_r(W + D)/2 \]  \hspace{1cm} \text{Equation [3]}

This expression gives the following estimates of bending strength for the joints tested.

<table>
<thead>
<tr>
<th>Rail thickness (in.)</th>
<th>Predicted bending strength (lb. -in.)</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3/4</td>
<td>912.4</td>
<td>0.44</td>
</tr>
<tr>
<td>1</td>
<td>1,070.4</td>
<td>1.94</td>
</tr>
<tr>
<td>1-1/4</td>
<td>1,228.4</td>
<td>1.05</td>
</tr>
<tr>
<td>1-1/2</td>
<td>1,386.4</td>
<td>0.72</td>
</tr>
</tbody>
</table>

The close agreement noted between predicted and test results provides encouragement for the use of Equation [3]. It must be remembered, however, that Equation [3] is not unique and other expressions could be fitted to the data that would give equally good results. Additional tests are obviously needed to determine if this expression holds for joints constructed with some other size of dowel.

Results of the rotation studies are given in tabular form in Table 2. To obtain these results, deflection data were first transformed to rotational values by means of the expression

\[ \phi = \frac{\gamma}{a^{1/2}w/2} \]  \hspace{1cm} \text{Equation [4]}

where \( \phi \) is the rotation of the rail relative to the post, radians; \( \gamma \) is the deflection of the dial gage, inches; \( w \) is the width of the rail, inches; and \( a \) is the distance of the dial gage above the rail, 2 inches.

Regression curves were fitted to each set of rotation versus load data to determine the simplest form of expression, from a practical design point of view, which could be used to represent the data. It was found that all of the data could be represented satisfactorily by the simple linear expression, \( \phi = ZF_r \). This is a quite useful result since it reduces the data to a form that is most compatible with present analytical methods. The constant, \( Z \), describes the stiffness of each joint. \( Z \) values for each set of rotation data are given in Table 2.
TABLE 3.—Internal bending forces acting on the ends of members 3 and 6 of the frame shown in Figure 1 when the stiffness of joint C is progressively reduced.

<table>
<thead>
<tr>
<th>$Z$ (rad./lb-in)</th>
<th>$f_{BC}$ (lb-in)</th>
<th>$f_{CB}$ (lb-in)</th>
<th>$f_{DE}$ (lb-in)</th>
<th>$f_{ED}$ (lb-in)</th>
<th>$f_{CB}$ semirigid</th>
<th>$f_{CB}$ rigid</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>-471.86</td>
<td>-676.73</td>
<td>-115.25</td>
<td>-115.99</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>1.0 x 10^-4</td>
<td>-474.35</td>
<td>-672.36</td>
<td>-116.36</td>
<td>-116.92</td>
<td>99.4</td>
<td></td>
</tr>
<tr>
<td>1.0 x 20^-3</td>
<td>-495.44</td>
<td>-663.45</td>
<td>-125.80</td>
<td>-124.79</td>
<td>93.9</td>
<td></td>
</tr>
<tr>
<td>1.0 x 10^-2</td>
<td>-624.10</td>
<td>-810.24</td>
<td>-172.80</td>
<td>-172.80</td>
<td>60.6</td>
<td></td>
</tr>
<tr>
<td>1.0 x 10^-3</td>
<td>-806.88</td>
<td>-90.26</td>
<td>-265.22</td>
<td>-241.02</td>
<td>13.3</td>
<td></td>
</tr>
<tr>
<td>1.0 x 10^-4</td>
<td>-852.59</td>
<td>-10.26</td>
<td>-285.68</td>
<td>-258.07</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>1.0 x 10^-5</td>
<td>-857.86</td>
<td>-1.01</td>
<td>-288.04</td>
<td>-280.04</td>
<td>0.15</td>
<td></td>
</tr>
<tr>
<td>1.0 x 10^-6</td>
<td>-856.30</td>
<td>0.10</td>
<td>-288.28</td>
<td>-280.24</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>1.0 x 10^-7</td>
<td>-858.40</td>
<td>0.01</td>
<td>-288.30</td>
<td>-280.36</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

*Z* constant describing the stiffness of joint C (radians per pound-inch), *f* Bending forces are denoted by the symbol *f*. The letters in parenthesis following the symbol indicate the member on which the force is acting. In addition, the first letter indicates the end of the member on which the force is acting. Thus, the complete symbol $f_{BC}$ refers to the internal bending force acting on the C-end of member BC.

0.0 indicates a perfectly rigid joint.

The effect of the flexibility of a specific joint on the distribution of forces in a furniture frame is difficult to predict since the magnitude of the forces at any point is a function of the stiffnesses of essentially all of the members and joints in the frame. This effect can, perhaps, be illustrated best by means of a specific example. Consider the chair side frame shown in Figure 1. Let us consider the effect of the stiffness of joint C upon the distribution of forces in the remainder of the frame. Varying the stiffness of joint C and carrying out an analysis of the distribution of forces in the frame (2, 4) gives the results shown in Table 3. As can be seen, for a $Z$ value of $10^{-6}$ radians per pound-inch (rad./lb-in.), joint C still carries 93.9 percent of the bending force it would carry if it were rigid. For $Z$ values of $10^{-5}$, $10^{-4}$, and $10^{-3}$ radians per pound-inch, it carries 60.6 percent, 13.3 percent, and 1.5 percent respectively. Thus, the joint has lost most of its rotational resistance at a $Z$ value of $10^{-4}$ radians per pound-inch. This result is of considerable practical importance since it implies that joints with this degree of flexibility may, for many practical purposes, be treated as though they were pinned (this conclusion is supported by the analysis of several other frames (4)). Such an assumption makes it possible to analyze several types of furniture frames as determinate rather than indeterminate structures. Ordinarily, the savings in time and computational effort resulting from the use of a simplified analytical model are considerable.

**Conclusions**

Results indicate that close-fitting dowel joints have substantial strength in flatwise bending. A high proportion of strength is lost, however, if the members are not fitted together closely. Behavior of the joints tested was well ordered; specifically, there was a regular stepwise increase in the strength of the joints as the thickness of the rail was increased by 1/4-inch increments. The bending strength of the joints could be predicted by the expression

$$F_c = \pi D^2/16S_PW(W+D)/2$$

Whether this expression holds for joints constructed with dowels other than 3/8 inch in diameter remains to be verified by experiment.

The flexibility of the joints in flatwise bending was much greater than for in-plane bending. Three-quarter-inch rails with tight joints were 1.42 times more flexible in flatwise bending than the in-plane specimens; similarly, 1-1/2-inch rails with tight joints were 4.7 times more flexible than the in-plane specimens. The "loose" joints were from 35 to 40 times more flexible. Because of their flexibility, such joints would not be expected to have significant bending resistance in a frame.

**Literature Cited**