Rational design of multi-dowel corner joints in case construction

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Abstract

Although dowel joints are widely used in the construction of case furniture, little information is available about the additive effects of dowels on the ultimate bending strength of multi-dowel joints or optimum dowel spacing. Bending strength tests were carried out on 6.75-, 9-, 11-, and 14-inch-wide specimens that were constructed with 2 to 5 dowels in order to evaluate these effects. Specimens were tested both in compression and tension. Test results indicate that maximum strength per dowel is obtained when dowels are spaced at least 3 inches apart. Results also indicate inherent differences in strength between joints loaded in tension and compression. The strength of joints loaded in compression is presumably related to the internal bond strength of the board, whereas the strength of joints loaded in tension is presumably related to the tensile strength of the board.

The efficient design of case-type furniture constructed with dowels requires specific design information on the bending strength of multi-dowel corner joints. Several investigations have been made on corner joints that have yielded pertinent design information.

Englesson (5) investigated the strength of five types of corner joints constructed with particleboard: butt dowel joints, a mitered joint with an included plastic angle, a mitered joint with dowels, a simple miter joint, and a miter joint with a spline. Of the joints tested, the mitered joint with spline gave the best results followed by the doweled miter. In the case of joints 100 mm (3.937 in.) wide constructed with three 8-mm-diameter (0.315-in.) by 32-mm-long (1.26-in.) dowels, Englesson obtained bending strengths for 19-mm-thick (0.748-in.) boards that were 47.3 percent stronger than those constructed with 16-mm-thick (0.630-in.) boards. However, bending strength values per dowel were lower than those subsequently reported by other researchers. The lower values obtained by Englesson likely resulted from the close spacing of the dowels in the specimens.

Similarly, in tests carried out on corner joints constructed with 16- and 19-mm-thick particleboard, Bachmann and Hassler (2,3) found that delamination of the free edge of the face member in a corner joint was the principal source of failure in many of the joints they tested. When the exposed free edge of the face member was covered with mahogany veneer, however, the bending strength increased by over 200 percent. They also carried out tests with corner joints constructed with more than one dowel. Specifically, they carried out tests with 100-mm-wide corner joints constructed with one 8-mm-diameter dowel, 200-mm-wide (7.87-in.) joints constructed with two dowels, 300-mm-wide (11.81-in.) specimens constructed with three dowels, and 400-mm-wide (15.75-in.) specimens constructed with four dowels. For all practical purposes, the strengths of the dowels in the multiple dowel joint were additive. This work is particularly noteworthy because it indicates a 100-mm spacing is sufficient to allow for the development of the full bending strength of 8-mm-diameter dowels.

Albin et al. (1) carried out extensive tests on corner joints constructed with adhesive and mechanical fasteners to determine their ultimate strength and to evaluate the proper method of testing such joints. Of particular importance for future testing, they obtained significantly higher values with miter-type joints when the joints were loaded in compression as opposed to tension. Also of interest, the authors carried out tests on joints 400 mm wide constructed with four dowels. Joints constructed with 19-mm-wide boards and four...
10- by 30-mm-dowels (0.394- by 1.181-in.) gave bending strength values of up to 45 percent greater than joints constructed with 16-mm-wide boards and 8- by 30-mm-dowels. Depths of penetration of the dowels in the faces of the boards were 15 mm (0.591 in.) and 12 mm (0.472 in.) for the 19- and 16-mm boards, respectively. The interacting effects of board thickness, dowel diameter, and depth of penetration cannot be separated from one another, but these results do provide an indication of the increase in strength that can be expected from more robust constructions.

There has not been enough research on establishing direct relationships between board properties and joint strength. However, Albin et al. (1) found that joint strength was strongly influenced by the type of particleboard used. Similarly, Wang (8) found that bending strength of corner joints constructed with particleboard was strongly related to board density.

Previous research by Zhang (9) yielded pertinent information on the strength of corner joints constructed with single dowels. Specifically, this research showed that dowels should be embedded 1 inch in 3/4-inch-thick butt members in order to obtain optimum bending strength. In addition, bending strength in 3/4-inch-thick particleboard increased as the depth of embedment in the face member increased from 1/4 to 5/8 inch and also as dowel diameter increased from 1/4 to 3/8 inch. In general, for single dowel joints, the length of the fractured plug was from 1-7/8 to 3-5/8 inches wide for compression tests and from 1 to 2-3/4 inches wide for tension tests.

These previous studies provide valuable basic design information on the strength of multi-dowel corner joints and information on the maximum strength that can be obtained from joints constructed with a single fastener. However, designers must also have information on the additive effects of dowels on the bending strength of multi-fastener joints and, in particular, the effect of dowel spacing on joint strength. The objectives of this study were to evaluate the additive effects of dowels on the ultimate bending strength of multi-dowel corner joints as a function of spacing and to find the optimum spacing for multi-dowel joints.

**Description of specimens**

The general configuration of the specimens used in the multi-dowel corner joint tests is shown in Figure 1. All the specimens were constructed of 3/4-inch-thick particleboard. Each specimen consisted of two principal structural members (a face member and a butt member), dowels, and wax paper. The face member measured 6-1/4 by 3/4 inches in cross section, whereas the butt member measured 5-1/2 by 3/4 inches; thus, when the two parts were joined together along the length of the member, a symmetrical joint resulted. Member lengths of 6.75, 9, 11, and 14 inches were used in the study.

In preparing the specimens, 4- by 8-foot full-size sheets of particleboard were first cut into face and butt member strips. These strips were subsequently sequentially cut into desired member lengths on a 6.75-, 9-, 11-, and 14-inch repeating pattern basis. Members for joints were randomly selected from this common supply. Samples for moisture content, specific gravity, internal bond strength, modulus of rupture, and modulus of elasticity determinations were randomly cut from sections between member lengths.

Multi-groove yellow birch dowels (5/16 in. diameter) were used in assembling the specimens. A supply of dowels (1-5/8 in. long) was first cut from cleanly machined multi-groove dowel rods with no loose or torn surface fibers. Approximately 250 dowels were then randomly selected from this common supply to be used in joint construction. The maximum and minimum diameters of some 50 dowels randomly

![Figure 1. General configuration of the specimens used in the multi-dowel corner joint tests.](image1)

![Figure 2. Diagram showing the placement of dowels in the four specimens, where: W = 6.75, 9, 11, and 14 inches.](image2)
TABLE 1. — Description of the specimens and the modes of failure in multi-dowel joint tests.

<table>
<thead>
<tr>
<th>No. of dowels</th>
<th>Type of loading</th>
<th>Length of specimen (in.)</th>
<th>Dowel spacing (in.)</th>
<th>No. of specimens</th>
<th>Mode of failure</th>
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<tr>
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<td>Compression</td>
<td>9</td>
<td>4.5</td>
<td>5</td>
<td>Far apart</td>
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<tr>
<td>3</td>
<td>Compression</td>
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<td>3</td>
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<td>Continuous</td>
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<tr>
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<td>9</td>
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<td>5</td>
<td>Overlap</td>
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<tr>
<td>5</td>
<td>Compression</td>
<td>9</td>
<td>1.8</td>
<td>5</td>
<td>Strong overlap</td>
</tr>
<tr>
<td>2</td>
<td>Compression</td>
<td>14</td>
<td>7</td>
<td>5</td>
<td>Far apart</td>
</tr>
<tr>
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<td>14</td>
<td>4.67</td>
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<td>Far apart</td>
</tr>
<tr>
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<td>Compression</td>
<td>14</td>
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<td>Far apart</td>
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<td>5</td>
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</tr>
</tbody>
</table>

selected from these 250 were measured and recorded. Both maximum and minimum diameters were measured.

The holes for the dowels were drilled in a symmetrical pattern along the length of the face member at a distance of 3/8 inch from one edge (perpendicular to the face). Corresponding holes were drilled into one edge of the butt member. The drilling patterns are given in Figure 2.

Holes were drilled with precision wood drilling bits at a speed of 2,160 rpm (6.7). A rapid feed rate was used to avoid charring the walls of the holes.

Nominal hole depth in the face member was 5/8 inch. Nominal hole depth in the butt member was 1-1/16 inches; i.e., the holes were drilled 1/16 of an inch deeper than the desired depth of dowel embedment to allow for variations in dowel length.

All specimens were assembled with a polyvinyl acetate emulsion adhesive with 65 percent solids content. Double gluing techniques were used, in which both the walls of the holes and sides of the dowels were liberally coated with glue prior to insertion of the dowels. Excess adhesive was used as recommended by Eckelman (4). The dowels were first inserted into the face members to ensure that the dowels were embedded to the required depth. In all samples, a piece of wax paper was included between the two members to prevent the face from adhering to the butt member. During assembly, samples were randomly selected to measure the depths of dowel embedment in face and butt members. All specimens were allowed to cure for at least 1 week before testing.

Design of study

A total of 70 specimens was constructed and tested; 35 were tested in compression and 35 were tested in tension. The dowels were symmetrically placed in all the specimens used. For example, in the case of a 9-inch specimen constructed with two dowels, the dowels were placed at points 2-1/4 inches from each end of the joint so that the distance between the dowels was 4-1/2 inches. The lengths of the specimens, the number of specimens used, and the number of dowels used in each size of specimen are shown in Table 1.

![Diagram showing apex loading (tension) of a specimen. The letter "R" refers to the reaction force.](image)

Both apex loading (tension) and side loading (compression) as shown in Figures 3 and 4 were used in evaluating the joints. Joint strength was defined as the bending force at failure. Ultimate load values were converted to corresponding bending force values by means of the expression $M_c = 3.359 F_{lb.-in.}$, where $M_c$ is the moment arm of the moment arm is defined as shown in Figure 4 for compression loading; and by the expression $M_t = 1.945 F_{lb.-in.}$, where the moment arm is defined as shown in Figure 3 for tension loading, where $M_c$ and $M_t$ are the ultimate bending load in compression and tension, respectively, and $F$ is the applied force (lb.).

The 9- and 14-inch wide specimens were tested in compression; the 6.75- and 11-inch wide specimens were tested in tension. Dowel spacings varied from 1.8 to 7 inches in compression and from 1.35 to 5.5 inches in tension.

Testing

All tests were carried out on a Tinius Olsen universal testing machine. A rate of loading of 0.25 inch per minute was used in all tests. Time to failure varied
from 0.5 to 1.5 minutes. Loads were applied as shown in Figures 3 and 4. In the tension test setup, the bottom of each of the two legs of the joints were placed on rollers on the bed of the testing machine so that the two joint members were free to move outwardly and free of restraint as the joint was loaded. In the case of the shorter specimens, loads were applied to the top of the joint through the load head of the testing machine. In the case of the longer specimens, loads were applied through a steel l-beam, which could be positioned along the top edge of the joint to ensure that loads were applied uniformly along the length of the joint.

In the compression tests, the specimens were positioned in the testing machine so that loads were applied to one leg of a specimen while the other leg rested on the bed of the testing machine as shown in Figure 4. The line of action of the load, therefore, passed through the outside bottom edge of both legs. Again, loads were applied to the edge of the specimen through a small l-beam to ensure that the entire length of a specimen was uniformly loaded.

Results and discussion

Moisture content of the particleboard averaged 9.04 percent with a standard deviation of 0.13 percent, specific gravity averaged 0.71 with a standard deviation of 0.008, and internal bond strength averaged 98.0 psi with a standard deviation of 20.6 psi. Moisture content of the dowels averaged 9.5 percent with a standard deviation of 0 percent. The modulus of rupture of the material averaged 2,000 psi with a standard deviation of 193.2 psi and the modulus of elasticity averaged 400,000 psi with a standard deviation of 29.120 psi.

Diameters of holes in face members averaged 0.312 inch with a standard deviation of 0.001 inch. Diameters of holes in the butt members averaged 0.313 inch with a standard deviation of 0.002 inch.

The average diameter of the dowels was 0.319 inch with a standard deviation of 0.001 inch. The depth of embedment of the dowels in the face members averaged 0.596 inch with a standard deviation of 0.036 inch. The depth of dowel embedment in the butt members averaged 1.030 inch with a standard deviation of 0.036 inch.

Average bending moments are given in Figures 5 and 6. The modes of failure are listed in Table 1 and are illustrated in Figure 7.

![Diagram showing loading of the sides (compression) of a specimen.](image)

Figure 4. — Diagram showing loading of the sides (compression) of a specimen.

![Average bending moment of specimens as a function of number of dowels used in the specimens with: (a) length of 11 inches and (b) length of 14 inches.](image)

Figure 5. — Average bending moment of specimens as a function of number of dowels used in the specimens with: (a) length of 11 inches and (b) length of 14 inches.
Mode of failure

The mode of failure in the compression and tension specimens differed in the manner in which the wall of the face member fractured. In the case of the specimens loaded in compression, a "plug" of material was pulled from the wall in a direction perpendicular to the plane of the wall. Failure of the wall was initiated along the free edge of this member. Resistance to failure, presumably, was related to the internal bond strength of the board. In the case of specimens loaded in tension, a "plug" of material was pulled free from the plane of the wall. In effect, therefore, a tension failure was initiated in the surface material of the wall. Resistance to failure, accordingly, was presumably related to the tensile strength of the board.

In addition to these differences in failure, three clearly definable types of specimen failure occurred in both the compression and tension tests with respect to the length of the failure zones. In the first type, the edge of the face member fractured; the fractured areas overlapped. In the second type, the edge of the face member fractured; the fractured areas just touched one another without overlapping. In the third type, the edge of the face member fractured; the fractured areas did not overlap.

As can be seen in Table 1 and Figure 7, the 9-inch specimens constructed with three dowels exhibited a continuous mode of failure. This implies that the zone of failure for each dowel was 3 inches for specimens in the compression test. The 11-inch specimens constructed with four dowels also had a continuous mode of failure. This implies that the length of failure for each dowel was 2-3/4 inches for specimens in the tension tests. Also, it was found that the average length of failure was 3 inches for specimens in the compression tests with a non-overlapping type of failure, and was 2-3/4 inches in the tension tests.

Effects of dowel spacing

In the case of specimens that exhibited non-overlapping failure, Figure 5 shows that the bending moments increased as the numbers of dowels increased in both the 11-inch (tension) and the 14-inch

Figure 6. — Average bending moment of specimens as a function of the number of dowels used in the specimens with: (a) length of 6-3/4 inches and (b) length of 9 inches.

Figure 7. — Diagram illustrating the modes of failure of the specimens.
(compression) specimens. This suggests that maximum strength is obtained with the continuous mode of edge failure shown in Figure 7. In the case of specimens with overlapping failures, Figure 6 shows that total bending moment increased as the number of dowels increased in specimens with lengths of 6-3/4 and 9 inches, but the bending moment per dowel decreased as the number of dowels increased because the area of overlap increased. This implies that in order to obtain maximum bending moment per dowel, a continuous mode of edge failure must be obtained. Overall, a 2-3/4- to 3-inch dowel spacing was found to provide optimum joint strength.

Analysis of data

Regression curves were fitted to the test data to analyze the effects of the various joint parameters on bending strength and to obtain functional relationships between bending strength and various joint parameters that might be used for practical design purposes. In general, it is assumed that bending strength per dowel decreases when dowel spacing becomes less than some critical value and that bending strength per dowel ceases to increase, on the other hand, when dowel spacing exceeds some critical value, then this relationship may be expressed by a regression curve of the form:

\[ y = aN^b \left( \frac{1}{c(W/2N + d)^2 + e} \right) \]  

where:
- \( y \) = the ultimate bending moment (lb.-in.)
- \( N \) = the number of dowels in the joint
- \( W \) = the width of the joint (in.)
- \( a, b, c, d, e \) = the regression coefficients

The term \( W/2N \) represents one-half the distance between adjacent dowels. Thus, in a symmetrical joint, \( W/2N \) refers to the distance from an outermost dowel to the edge of the board.

With limited data, it is useful to set \( c = 1 \) to keep the values of \( a \) and \( e \) relatively small. With this simplification and with minor adjustments of coefficients to simplify the expression, the following expression was obtained for the joints loaded in tension:

\[ y = 1187N^{0.750} \left( \frac{1}{(W/2N - 2.000)^2 + 5.000} \right) \]  

where:
- \( r^2 = 0.8990 \)

This expression did not hold for the compression tests, however, which were best fitted by a simple power expression:

\[ y = 174(N)^{0.9} \left( \frac{1}{(W/2N)^{0.6}} \right) \]  

where:
- \( r^2 = 0.9289 \)

These expressions predict that bending strength will increase in proportion to the number of dowels used raised to the 0.75 power in the case of joints loaded in tension and to the 0.9 power for joints loaded in compression.

To provide additional information concerning the overall relationships between the various joint parameters and bending strength, the test results reported for multidowel joints were combined with those previously reported by Zhang (9) for single dowel joints. Results of the regression analyses of the combined test results yielded the following expression for joints loaded in tension:

\[ 3800(N)^{0.75} \left( \frac{1}{(W/2N - 2)^2 + 5} \right) (D)^{0.5} (L)^{1.25} \]  

where:
- \( D \) = dowel diameter
- \( L \) = depth of embedment of the dowel in the face member
- \( r^2 = 0.9860 \)

Results of the regression analysis for joints loaded in compression again yielded a simple power expression:

\[ 558(N)^{0.95} \left( \frac{1}{(W/2N)^{0.057}} \right) (D)^{0.5} (L)^{1.25} \]  

where:
- \( r^2 = 0.9799 \)

These expressions further predict that bending strength is proportional to the diameter of the dowels used raised to the 0.5 power and to the depth of insertion of the dowels in the face member raised to the 1.25 power. This implies that depth of insertion is much more important than dowel diameter.

Equations [4] and [5] provide a means of estimating the bending strengths of selected corner joints within the range of joints tested as a function of number of dowels used, dowel diameter, and depth of insertion. This assumes that the joints are constructed of 3/4-inch-thick particleboard with an internal bond strength of 98 psi.

Conclusions

Test results indicate that maximum strength per dowel is obtained in multi-dowel corner joints when the spacing between dowels is at least 3 inches. The study also showed that maximum strength with the boards used in the study could be obtained when dowels were inserted at least 1 inch deep into the edge of the butt member because failure always occurred in the face member.

Results also indicate that joints exhibit different behavior when loaded in tension as opposed to compression. Bending strength per dowel was found to be proportional to the number of dowels used raised to the 0.75 power in tension but to the 0.9 power for joints loaded in compression. Furthermore, the physical mode of failure for joints loaded in tension is different from for joints loaded in compression. The bending strength of joints loaded in compression is presumably related to internal bond strength of the board, whereas the bending strength of joints loaded in...
tension is presumably related to the surface tensile strength of the board.

The relationships of bending strength to board thickness and to internal bond strength remain to be resolved. The effect of reinforcing the free edge of the face members with veneer or perhaps resin also deserves further study.

References