The use of performance tests in evaluating joint and fastener strength in case furniture

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C.A. Eckelmann

Abstract
Cyclic performance tests were carried out on sample furniture cases constructed with sheet metal screws to determine joint strength, stiffness, and durability as a function of number of screws, screw diameter, screw length, and screw position. Test results indicate that cyclic stepped load performance tests provide an effective way of evaluating case joint performance. Screw length significantly affected case strength and durability with larger diameter screws (e.g., #14). Length was less important with smaller screws (e.g., #10) because they tended to fail in fatigue. Results also tended to indicate that the most efficient way to strengthen a case was to concentrate fasteners near the open face of the case. Maximum fastener strength was obtained when fasteners were placed no closer than 3.5 inches from one another.

Case-type furniture is one of the most important categories of furniture produced and used today. It is used extensively in homes and offices for storage and has become essential to maintaining order in both settings. The use of cases can be dated to over 3,000 years ago — several well-preserved samples were found in the tomb of Tutankhamen (4). Numerous periodic and regional styles of various functional designs have subsequently emerged.

Until the last three decades, the structural characteristics of cases have not been scientifically investigated. Investigation would have led to rational design procedures and, therefore, sounder, more durable products. In general, such procedures require structural theories and analytical procedures to determine the magnitude and distribution of the forces acting within the furniture and the accompanying deflections of the joints and members.

Research carried out since 1955 has resulted in methods of analysis that allow the stiffness (deflection) of a case to be readily determined. However, research has not been carried out that allows the joints to be analyzed and designed on a rational basis. For example, there are no design methods that determine the number and size of dowels or screws that should be used to attach the sides of a case to a top or bottom.

Given the importance of this topic, both to the furniture industry in terms of efficiency of design and to users in terms of improvements in lifestyle, research was undertaken to first develop a performance test method that could be used to determine the strength and durability of cases in an unambiguous manner and to then use the test method developed to evaluate case strength effects related to the size and placement variables of one type of fastener, namely, screws.

The objective of this research was to develop a specific performance test that could be used to determine the strength and durability of cases and to then use this test to investigate the effect of specific factors on the strength and stiffness of cases. The factors examined were:

1) How screw diameter and screw length affect the rigidity of cases under repeated racking forces;
2) How the number of screws in a case joint affects overall case rigidity; and
3) How screw location affects case rigidity.

Methods and Materials
Cases constructed with 12 screw configurations were evaluated. The general configuration of the sample cases is shown in Figure 1. All cases were 24 inches long, 24 inches wide, and 16 inches deep, so that the cases were geometrically symmetrical. The top, bottom, and side panels of the cases were constructed of 3/4-inch-thick particleboard; the rear panels were constructed of 1/8-inch-thick masonite board.

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Pan head, zinc-plated, type-A sheet metal screws were used in fabricating the sample cases. A total of 12 types of screw configurations were included with 3 replicates for each type. The dimensions and number of screws used in the joints of each of the 12 samples are given in Table 1. Construction details of the various joints used in fabrication of the cases follows.

**Cases with three screws along the joint**

The two outermost screws were placed at points 1 inch from the ends; the third screw was placed at the center of the edge. Screw placement is shown in Figure 2. The screws used in these three-screw cases included #10 screws, 2 inches long; #12 screws, 2 and 2.5 inches long; and #14 screws, 1.5, 2, 2.5, and 3 inches long. It was anticipated that tests of these cases would demonstrate the effect of screw size and length on case performance.

**Cases with four screws per joint**

There were two types of joints included in these four-screw cases. Screw placement is shown in Figure 3. One of the types had all four screws evenly spaced along the edge of the joint. The other had unevenly spaced screws, i.e., the screws were placed at points 1, 4, 8, and 15 inches along the edges. In effect, the screws were concentrated near the open face of these cases. The screws used were #12, 2.5 inches long. This pattern was used in order to investigate the effect of screw location on case stiffness.

**Cases with two, five, and seven screws along the joint**

The placement of screws in these specimens is shown in Figure 4. In this type of joint, screws were evenly spaced along the edge of the joint. The screws used were #12, 2.5 inches long. It was anticipated that these cases and the three- and four-screw cases previously described would demonstrate the effect of the number of screws on case performance.

In all samples, the rear panels were attached to the rear edges of the top, bottom, and side panels with glue and nails. This was done to ensure that the rear of each case was quite rigid to eliminate unwanted variables that might affect results.

The moisture content (MC), specific gravity (SG), internal bond strength (IB), modulus of rupture (MOR), and modulus of elasticity (MOE) were determined for the material from which each case was constructed after performance testing was completed. All tests were carried out in accordance with appropriate ASTM standards (1-3). Test specimens were randomly selected and cut from the sample cases.

![Figure 1. — General configuration of the sample cases used in this study.](image)

![Figure 2. — Placement of screws in the three-screw cases.](image)

<table>
<thead>
<tr>
<th>Joint configuration</th>
<th>Screw gage</th>
<th>Screw length</th>
<th>No. of screws per joint</th>
<th>Spacing</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>#10</td>
<td>2</td>
<td>3</td>
<td>Even</td>
</tr>
<tr>
<td>2</td>
<td>#12</td>
<td>2</td>
<td>3</td>
<td>Even</td>
</tr>
<tr>
<td>3</td>
<td>#12</td>
<td>2.5</td>
<td>3</td>
<td>Even</td>
</tr>
<tr>
<td>4</td>
<td>#14</td>
<td>1.5</td>
<td>3</td>
<td>Even</td>
</tr>
<tr>
<td>5</td>
<td>#14</td>
<td>2</td>
<td>3</td>
<td>Even</td>
</tr>
<tr>
<td>6</td>
<td>#14</td>
<td>2.5</td>
<td>3</td>
<td>Even</td>
</tr>
<tr>
<td>7</td>
<td>#14</td>
<td>3</td>
<td>3</td>
<td>Even</td>
</tr>
<tr>
<td>8</td>
<td>#12</td>
<td>2.5</td>
<td>2</td>
<td>Even</td>
</tr>
<tr>
<td>9</td>
<td>#12</td>
<td>2.5</td>
<td>4</td>
<td>Even</td>
</tr>
<tr>
<td>10</td>
<td>#12</td>
<td>2.5</td>
<td>4</td>
<td>Not even</td>
</tr>
<tr>
<td>11</td>
<td>#12</td>
<td>2.5</td>
<td>5</td>
<td>Even</td>
</tr>
<tr>
<td>12</td>
<td>#12</td>
<td>2.5</td>
<td>7</td>
<td>Even</td>
</tr>
</tbody>
</table>
Performance test apparatus

Cases were mounted in a framework for testing in a manner similar to that described in a previous document (5). Two air cylinders were used to apply loads to the case in opposite directions. Reaction brackets were placed diagonally at the bottom to produce counter forces to prevent the case from sliding. Figure 5 illustrates how these forces acted on the case. Two straps were then passed over the edges and connected to the rod end of each air cylinder; the other ends of the straps were fastened to the cases with nails.

Other equipment used to carry out performance tests in this study included: 1) pressure regulators to control and adjust the magnitude of the loads; 2) a system to control the cyclic rate of loading; 3) a predetermined counter to count the number of cycles completed and to stop the test when a preset number of cycles had been reached; 4) a force dynamometer with a 1,000-pound load capacity to calibrate the force exerted by the air cylinders; and 5) speed control valves to regulate air flow to prevent impact loading.

Performance test procedures

A discussion of the cyclic stepped load test proce-

Figure 3. — Placement of screws in the four-screw cases.

Figure 5. — Diagram of the forces acting on the cases in the performance tests.

Figure 4. — Placement of screws in the 2-, 5-, and 7-screw cases.
TABLE 2. — Physical and mechanical properties of particleboard.

<table>
<thead>
<tr>
<th></th>
<th>Average</th>
<th>Coefficient of variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture content</td>
<td>8.2%</td>
<td>14.6</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>0.7</td>
<td>1.8</td>
</tr>
<tr>
<td>Internal bond</td>
<td>101.7 psi</td>
<td>10.0</td>
</tr>
<tr>
<td>Modulus of elasticity</td>
<td>422,940.0 psi</td>
<td>7.3</td>
</tr>
<tr>
<td>Modulus of rupture</td>
<td>1,965.2 psi</td>
<td>9.7</td>
</tr>
</tbody>
</table>

Procedure followed in this study is provided by Eckelman (5,6). The test was begun at the 50-pound load level. Loads were increased in increments of 50 pounds after 25,000 cycles had been completed at each previous load level. The rate of loading was 20 cycles per minute. Testing was discontinued when visible damage occurred that might have affected the strength of the case.

TABLE 3. — Performance test results and types of failure observed.

<table>
<thead>
<tr>
<th>Case*</th>
<th>Ultimate load (lb.)</th>
<th>No. of cycles completed</th>
<th>No. of broken screws</th>
<th>Panel break</th>
<th>Location*</th>
</tr>
</thead>
<tbody>
<tr>
<td>#10, 2-in. (3)</td>
<td>175, 175, 175</td>
<td>129,958, 132,796, 120,468</td>
<td>1, 1, 1</td>
<td>-</td>
<td>TR1, BL1</td>
</tr>
<tr>
<td>#12, 2-in. (3)</td>
<td>200, 175, 225</td>
<td>154,508, 139,665, 185,845</td>
<td>2, - , 1</td>
<td>Top panel, Top panel, Bottom panel</td>
<td>TL1, BL1, TR1</td>
</tr>
<tr>
<td>#12, 2.5-in. (3)</td>
<td>150, 175, 175</td>
<td>105,300, 125,046, 136,123</td>
<td>1, 1, 1</td>
<td>-</td>
<td>TR1, BL1</td>
</tr>
<tr>
<td>#14, 1.5-in. (3)</td>
<td>225, 225, 225</td>
<td>175,358, 175,007, 177,926</td>
<td>- , - , -</td>
<td>Top, bottom panel, Top, bottom panel, Top, bottom panel</td>
<td>TRa, BLa, TRa, BLa, TRa, BLa</td>
</tr>
<tr>
<td>#14, 2-in. (3)</td>
<td>225, 200, 200</td>
<td>187,806, 151,490, 150,016</td>
<td>- , - , -</td>
<td>Left panel, Bottom panel, Bottom panel</td>
<td>BL1, BL1, BL2</td>
</tr>
<tr>
<td>#14, 2.5-in. (3)</td>
<td>225, 175, 225</td>
<td>194,200, 144,531, 179,413</td>
<td>2, 1, 1</td>
<td>Bottom panel</td>
<td>TL1, BL1, BL1, TR1</td>
</tr>
<tr>
<td>#14, 3-in. (3)</td>
<td>225, 275, 225</td>
<td>188,192, 232,234, 197,449</td>
<td>1, - , 1</td>
<td>Left panel</td>
<td>BL1, BL1</td>
</tr>
<tr>
<td>#12, 2.5-in. (4)</td>
<td>175, 200, 175, 200</td>
<td>133,639, 150,267, 141,693, 150,041</td>
<td>3, 1, 1, 1</td>
<td>-</td>
<td>BL1, TL1, TR1</td>
</tr>
<tr>
<td>#12, 2.5-in. (4)</td>
<td>200, 250, 225</td>
<td>152,270, 200,041, 196,958</td>
<td>4, 1, 2</td>
<td>-</td>
<td>TL1, BL1, TR1, TR2</td>
</tr>
<tr>
<td>#12, 2.5-in. (2)</td>
<td>175, 150, 175</td>
<td>135,838, 116,901, 143,788</td>
<td>2, 1, 1</td>
<td>-</td>
<td>BL1, TR1</td>
</tr>
<tr>
<td>#12, 2.5-in. (5)</td>
<td>225, 250, 250</td>
<td>180,346, 208,596, 216,924</td>
<td>1, 1, 2</td>
<td>-</td>
<td>BL1, BL1</td>
</tr>
<tr>
<td>#12, 2.5-in. (7)</td>
<td>250, 225, 250</td>
<td>200,121, 195,504, 214,303</td>
<td>2, 2, 2</td>
<td>-</td>
<td>TR1, BL1, BL2</td>
</tr>
</tbody>
</table>

* The number in parentheses indicates how many screws were used in each corner joint; an apostrophe indicates uneven spacing within the joint.

* The locations where screws broke or panels broke are: TR = top right corner; TL = top left corner; BR = bottom right corner; BL = bottom left corner; a = whole area of the joint. The number specifies the part of the connection where failure occurred in terms of the position where the screw was set in the connection starts from open face.
TABLE 4. — Average number of cycles completed by three-screw cases.

<table>
<thead>
<tr>
<th>Screw length (in.)</th>
<th>Screw gauge</th>
<th>#10</th>
<th>#12</th>
<th>#14</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>130.743</td>
<td>160.006</td>
<td>163.104</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>122.823</td>
<td>172.714</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>205.958</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Results and Discussion**

The average MC, SG, MOE, MOR, IB of the particleboard are given in Table 2.

**Mode of failure and evaluation of tests**

In general, two types of failure were observed during testing, screw fracture and breaking or splitting of the panel material. A complete list of modes of failure is given in Table 3. As anticipated, the major type of failure was fracture of the screws closest to the open face of the case. In most cases, broken screws were found in the upper right corner, bottom left corner, or both; i.e., in those corners where the ends of the boards underwent bending in an outward direction. Only six cases had broken screws at the top left corner or bottom right corner where the connections bent inward. The screws usually broke at the point where the two panels abutted one another.

When larger diameter screws were used, the panels tended to fracture. Presumably, this resulted because the larger screws have more resistance to bending under repeated bending forces. Panel breakage, as opposed to screw fracture, was found mostly in cases constructed with #14 screws. In cases constructed with these screws, screw fracture and panel fracture occasionally occurred concurrently at the front or middle part of the bottom panel. Only one case constructed with 2-inch #12 screws failed due to fracture of the top panel at the left corner near the open face.

It is worthwhile to note that all cases constructed with 1.5-inch #14 screws failed abruptly due to fracture of the material at a load level of 225 pounds. Ordinarily, the top right and bottom left corners first failed when the top and bottom panels split at the points where the screws were driven into their edges.

Although fracture of one or more screws was the principal type of failure in cases constructed with smaller screws, the variety of locations where fracture occurred, along with the fact that the test also caused other modes of failure, indicate that the test is effective in detecting performance strength properties. Because ultimate failure occurred due to accumulated damage over a period of time, the actual failure point was difficult to define precisely. Therefore, testing was stopped when deflection significantly increased. This usually occurred when a screw fractured. By stopping the test at this point, it was possible to observe the fractured screws or the damaged panels before the case completely collapsed and destroyed the details surrounding the failure.

**Diameter and length effects**

Table 4 details the average number of cycles completed by the three-screw cases. The effects of screw diameter and length on case performance are not clearly defined. Because the types of failure observed in cases constructed with #14 screws were considerably different from those observed in cases constructed with #10 or #12 screws, the measure of performance for these cases was, presumably, also different.

As can be seen from Table 4, the average cycles completed by cases with 2.5-inch #12 screws and by cases with 2-inch #10 screws were about the same. However, both were significantly less than the number of cycles completed by cases made with 2-inch #12 screws. The strength of cases constructed with smaller screws (#10 or #12) appeared to be dominated by the screws' inherent resistance to fatigue as long as the length of the screws was sufficient, because most of these cases failed because the screws fractured. Another possible cause for these differences in the difference between the properties of the board materials. Some of the particleboard used in fabricating cases with three 2-inch #12 screws had higher MOE and MOR values than the particleboard used in fabricating cases with three 2.5-inch #12 screws. Also, the MOE and MOR values of the particleboard of cases constructed with three 2-inch #10 screws were higher than those of cases constructed with either three 2- or 2.5-inch #12 screws.

Most cases constructed with 1.5- or 2-inch #14 screws failed due to panel breakage. When the length of #14 screws was 2.5 inches, cases failed because both the screws and the panels failed. Two of three cases constructed with 3-inch #14 screws failed because the screws fractured. This close relationship between screw length and failure type indicates that the bending moment needed to break the screw was a key factor in case performance. It should be noted that the effects of screw length may be quite substantial with regard to static strength of the case even though the cyclic load test results did not differ substantially; i.e., the static strength of a case constructed with 2.5-inch #14 screws might be significantly greater than that of a case constructed with 1.5-inch #14 screws.

**TABLE 5.** — The average number of cycles completed by cases with two, three, four, five, and seven 2.5-inch #12 screws and their spacing in each connection.

<table>
<thead>
<tr>
<th>No. of screws</th>
<th>Average no. of cycles completed</th>
<th>Screw spacing (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>132.175.67</td>
<td>14</td>
</tr>
<tr>
<td>3</td>
<td>128.823</td>
<td>7</td>
</tr>
<tr>
<td>4</td>
<td>160.006*</td>
<td>7</td>
</tr>
<tr>
<td>5</td>
<td>155.857*</td>
<td>4.67</td>
</tr>
<tr>
<td>6</td>
<td>182.069*</td>
<td>3</td>
</tr>
<tr>
<td>7</td>
<td>203.595.33</td>
<td>3.5</td>
</tr>
</tbody>
</table>

* Screw spacing shows the distance between two screws nearest the open faces.

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Therefore, test results tend to suggest that the
effect of screw length on case performance is
determined by screw diameter. If smaller screws are used,
screw length has less effect on case strength; as screw
diameter increases, the effects of screw length become
increasingly more important.

Screw placement and number of screws

According to structural theory developed for cases,
the fastener closest to the open face is the most heavily
loaded of the fasteners used to attach the side panel
to a top or bottom. In this study, the test results tended
to confirm this hypothesis. Table 5 details the average
cycles completed by cases constructed with two, three,
four, five, and seven 2.5-inch #12 screws along with
the spacing used for each connection.

The differences in the average number of cycles
completed by cases constructed with two, three, and
four screws indicates that adding screws contributed
little to case performance. The length of spacing in
these cases ranged from 4.67 to 14 inches. However,
when the number of screws was increased to five, the
number of cycles increased 42 percent over the four-
screw cases, yet the spacing in these five-screw cases
was reduced by only 1.17 to 3.5 inches.

The performance of seven-screw cases made with
2.5-inch #12 screws (2.33-in. spacing) was no better
than that of five-screw cases made with 2.5-inch #12
screws (3.5-in. spacing). The difference in number of
cycles completed between the two was less than 1
percent.

Test results of four-screw cases made with 2.5-inch
#12 screws (unevenly spaced) indicated that screw
placement had a significant effect on case perform-
ance. The average number of cycles for unevenly
spaced screws was nearly 30 percent more than for
the same cases with even spacing. The number of
cycles from the unevenly spaced four-screw cases was
only 10 percent less than from the five-screw cases.
The effect of screw spacing is evident here because the
spacing of the two screws closest to the open face of a
four-screw case made with 2.5-inch #12 screws was
1/2 inch less than that in a five-screw case.

These test results suggest that the optimum spac-
between screws is about 3 inches and clustering
screws near the open face can effectively improve case
performance. Even though the results of this study
are strongly related to the dimensions of the sample
cases, it is reassuring to find that this spacing is close
to that reported by Rajak (7) in another study. He
proposed that the zone of influence for a screw is 3.5
inches. Thus, it is believed that maximum individual
screw strength would be achieved with a screw spac-
ing of 3 to 3.5 inches in most moderately sized cases.

Case deflection

The change in length of two diagonals of the open
face was measured at the beginning of each load level.
It was anticipated that this practice would demon-
strate the rigidity of the case. The averaged results are
given in Table 6. Although the difference in deflections
between one case and another at a certain load level
was small (a few millimeters), the effects of different
screw types on the stiffness and performance of cases
could still be distinguished.

The initial deflections of the cases were about 0.197
inch. The ultimate deflection, in most of the cases, was
between 1.181 and 1.575 inches. In general, the longer
the screws, the smaller the deflections. A similar
relationship for diameter did not hold; cases with
large-sized screws often had larger deflections than
cases with smaller screws.

The average deflections of four-screw cases made
with 2.5-inch #12 screws with uneven spacing were
smaller than those of cases with screws of the same
size but with even spacing. This indicates that a
clustered screw placement may increase the stiffness
of cases. Minimum case deflections always occurred
in the five- and seven-screw cases made with 2.5-inch
#12 screws.

Conclusions

The most efficient way to strengthen a case is to
concentrate more screws near the front area of the case. The optimum spacing for screws was about 3 to 3.5 inches. The performance of a case with screw spacing less than 3 inches was essentially no better than that of a case with this spacing. However, a wider spacing resulted in a significant decrease in case strength.

Test results also indicated that small-sized screws were likely to break during the cyclic loading process; therefore, the performance of cases with small-sized screws was more dependent on resistance to fatigue than on screw length. On the other hand, the length of the #14 screws was a crucial factor that affected case strength because the length of embedment was related to the bending moment generated in the joint.

It appears the test method used in the study provides a means of evaluating the performance of multifastener joints in a case. The variety of ways in which the cases failed indicated that the method was both unbiased and effective in detecting inherent weakness of a case.

**Literature cited**