Chapter VI

Design of Furniture Joints

Introduction

The design of the joints in a furniture frame is perhaps the most important step in the entire design process. Even though the members may have more than enough strength to carry the forces imposed upon them, if the joints are too weak, the structure may still fail. It is probably safe to say that more structural failures occur in furniture because of weak joints than from any other single cause. It is important, therefore, that the joints used in the construction of a particular piece of furniture be scientifically designed so that they can safely carry the forces imposed upon them in service.

The literature of furniture joint design is limited. Investigations have been made of the ultimate strength of various types and sizes of joints, but with a few exceptions, no attempts have been made to derive design formulas from this data. One of the problems faced in trying to develop design equations is that the data reported by various investigators are often too incomplete to permit such deductions to be made. In addition, there are usually so many variables involved that the data collected by one researcher cannot be compared with those obtained by another. Still, enough information is available that a number of generalizations can be made. Furthermore, even when this is not possible, the values obtained by the various researchers may often be used as reliable indicators of the strength that can be obtained from a particular type of joint.

In discussing the joints used in furniture construction, it is necessary to make a clear distinction between the terms fasteners and joints. Staples, nails, screws, and dowel pins are all examples of fasteners. When any of these fasteners are used to join two or more members together, they form what is termed a joint. Two dowel pins, for example, are commonly used to join a seat rail to a back post in a chair. The joint that is formed by these fasteners is properly referred to as a “two-pin moment-resisting dowel joint.” Each type of fastener has its own unique strength characteristics such as ultimate withdrawal strength and shear strength, and ideally, we would like to be able to design a complete joint from a consideration of the strength of the individual fasteners used in its construction. Whenever possible, this practice will be followed in the design procedures presented here.

Dowel Joints

Because of their favorable cost and production characteristics, dowel pins long have been a favorite connector of the furniture industry. They are uniquely simple in design and require only drilling operations to form a joint. When force-fitted or driven into a hole they form joints that have high initial strength, require no clamping, and with reasonable care, need not be cured before handling. Dowel pins are also self-aligning and locate parts for further assembly without the use of jigs. Furthermore, they
can be used to join parts of almost any shape that come together at nearly any angle subject only to the condition that matching surfaces of sufficient size can be found to place the dowel holes (Willard, 1964).

Although dowel pins are used to construct a wide variety of joints, which may resist axial, shear, bending moment, and torsional forces, the dowel pins themselves are ordinarily subjected only to shear and axial forces. Single pins may occasionally be subjected to torsional forces, but this practice should be avoided. An example that shows dowel pins loaded both axially and in shear is given in Figure 6-1. As can be seen in this illustration, even though the loading produces a bending moment that acts upon the seat rail to back post joint, the individual dowel pins are subjected only to shear and axial forces.

Ideally, we would like to be able to design all types of dowel joints on the basis of the axial and shear properties of the individual dowel pins used in their assembly. Usually, however, this cannot be done because our knowledge of the factors that affect their behavior is too limited. In particular, the strength and stiffness characteristics of these joints, which are needed for the precise engineering design of furniture, have never been theoretically defined. Empirically based formulas have been developed, however, that may be used to obtain reasonable estimates of their properties. A number of these equations are presented in the discussion that follows. It must be remembered, however, that these expressions are often based on a limited number of tests and are intended only to provide estimates of joint strength that must necessarily be used with care and discretion rather than accepted allowable design strength values.

Solid Wood

Single Pin Joint Strength

Withdrawal Strength of Dowels from Side Grain

Experiments have shown (Eckelman, 1969) that the average withdrawal strength of a dowel pin from the side grain surface of a wood member, Figure 6-2, can be predicted by means of the expression

\[ F_2 = 0.834 \times D \times L^{0.89} \left( 0.95 \times S_1 + S_2 \right) \times a \times b \times c \]  

(6-1)

where

- \( F_2 \) = ultimate withdrawal strength of the dowel in pounds;
$D = \text{diameter of the dowel in inches};$

$L = \text{depth of penetration of the dowel in the member in inches};$

$S_1 = \text{shear strength of the wood member parallel to the grain, psi};$

$S_2 = \text{shear strength of the wood dowel parallel to the grain, psi};$

$a = 1.0 \text{ for polyvinyl resins with at least 60 percent solids content}
\text{ or gap-filling urea-formaldehyde adhesives}$

$= 0.9 \text{ for polyvinyl adhesives with less than 60 percent solids}$

$= 0.85 \text{ for animal glues}$

$b = \text{correction factor for dowel-hole clearance}$

$= 1.0 - (9.1 \cdot d) \text{ where } d \text{ is the difference measured in inches between}$

$\text{the dowel and dowel hole diameters for urea formaldehyde adhesives}$

$= 1.0 - (17.1 \cdot d) \text{ for polyvinyl acetates}$

$= 1.0 - (1.8 \cdot d) \text{ for animal glues}$

$c = 1.0 \text{ for plain (smooth surface) dowels}$

$= 0.9 \text{ for spiral-groove and multi-groove dowels (Eckelman and Hill, 1971)}$

According to this expression, the withdrawal strength of a dowel is proportional to its diameter. Thus, a 7/16-inch diameter dowel should be 16.7 percent stronger than a 3/8-inch diameter dowel and a 1/2-inch diameter dowel 33 percent stronger. What is perhaps more striking is that a 1/2-inch diameter dowel is only twice as strong as a 1/4-inch diameter dowel.

Similarly, withdrawal strength is nearly but not quite directly proportional to depth of embedment of the dowel in the side wood member. For practical purposes, it is reasonable to consider withdrawal strength to be essentially proportional to embedment since deviations are not large for small incremental changes in length. Thus, a 7/16-inch diameter dowel with a 1-1/4 inch depth of penetration would be expected to have 25 percent more strength than the same dowel with a 1-inch depth of penetration (the actual value would be about 22 percent).

Likewise, withdrawal strength is directly proportional to the weighted average of the shear strengths parallel to the grain of the woods of which the dowel and joint are constructed. Thus, a joint constructed with a dowel made of sugar maple, which has a shear strength of 2,330 psi at 12 percent moisture content, would be expected to have considerably more strength than a joint constructed with a white birch dowel that has a shear strength of only 1,210 psi.

Figure 6-2. Diagram showing a dowel inserted into the side, or, face grain of a member. Withdrawal strength of the dowel may be estimated by means of equation (6-1).
The use of this equation can be greatly simplified by calculating values of $0.834D^{0.89}$ for various dowel diameter-length combinations and tabulating them as has been done in Table 6-1. Values of $a$ and $b$ can also be determined for various adhesives and dowel-hole clearance combinations as has been done in Table 6-2. Under these conditions, equation 1 can be re-written as

$$F_2 = A \times (0.95 \times S_1 + S_2) \times B \times c \quad (6-2)$$

where $A = 0.834D^{0.89}$; $B = a \times b$; and the remaining symbols have the same meanings as previously defined.

To illustrate the use of this equation, let us calculate the withdrawal strength of a 3/8-inch diameter yellow birch dowel embedded one inch in the side grain of a sugar maple member. Let us assume that a plain dowel is used, that the dowel-hole clearance is 0.005 inches, and that the dowel is held in place with a gap-filling urea-formaldehyde resin. The moisture content of the material is assumed to be 7 percent.

Referring to Table 6-1, it is seen that the length-diameter ratio for this dowel is 0.31. From Appendix 6-1, we see that the shear strengths, $S(12)$, at 12 percent moisture content, $mc(12)$, for sugar maple and yellow birch are 2,330 and 1,880 pounds per square inch (psi), respectively. These values can be converted to equivalent shear stress values, $S(x)$, at any lower moisture content level, $mc(x)$, by means of the formula

$$S(x) = S(12) \times [1 + 0.03 \times (12 - mc(x))] \quad (6-3)$$

Carrying out this operation to obtain the shear strength for sugar maple at 7 percent moisture content gives

$$S(7) = 2,330 \times [1 + 0.03 \times (12 - 7)] = 2,330 \times 1.15 = 2,680 \text{ psi}$$

, and for yellow birch,

$$S(7) = 1,880 \times 1.15 = 2,162 \text{ psi}$$

From Table 6-2, we see that the adjustment factor for a urea-formaldehyde adhesive with a 0.005-inch dowel-hole clearance is 0.96. Substituting these values into equation (6-2) yields

$$F_2 = 0.31 \times (0.95 \times 2,680 + 2,162) \times 0.96 \times 1.0 = 1,401 \text{ lb}.$$  

Limiting Length over Depth Ratios

Experiments have shown that strength does not continue to increase with length when the depth of penetration over diameter ratio exceeds about 4 to 1. The strength of a quarter-inch diameter dowel, for example, does not continue to increase for depths of penetration greater than one for 21295.0 6-2

<table>
<thead>
<tr>
<th>Dowel-Diameter (in.)</th>
<th>Depth of Dowel Embedment</th>
</tr>
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<tbody>
<tr>
<td>1/4</td>
<td>1/2 3/4 1 1-1/4 1-1/2 1-3/4 2</td>
</tr>
<tr>
<td>3/8</td>
<td>.17 .24 .31 .38 .45</td>
</tr>
<tr>
<td>7/16</td>
<td>.20 .28 .37 .45 .52 .60</td>
</tr>
<tr>
<td>1/2</td>
<td>.23 .32 .42 .51 .60 .69 .77</td>
</tr>
</tbody>
</table>

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inch. This restriction should be observed in calculating the strengths of longer dowels

Effect of Gluing Conditions

Although important differences exist in the withdrawal strengths that can be obtained from the several common woodworking adhesives, essentially any of the adhesives may be used to form excellent dowel joints. In the special case of PVA adhesives, however, those adhesives with higher solids content (60 percent) may be expected to give significantly better results.

Adequate gluing is essential for maximum dowel withdrawal strength. In particular, it must be understood that the strength of a dowel joint depends on the quality of the bond formed between the dowel and the walls of the hole. Certainly, a small amount of glue injected into the bottom of the hole cannot be expected to produce strong joints. Both the walls of the hole and the sides of the dowel should be liberally coated with adhesive. At the least, the walls should be thoroughly coated.

Effect of Tightness of Fit

A close fit between the dowel and the hole is essential for the development of high withdrawal strength with all adhesives but especially so with PVA adhesives. Clearance between the dowel and the dowel hole should be kept as close to zero as possible.

When less than optimum gluing conditions are used, it has been shown (Konjer, Vorholt, and Gerhardt; 1986), that snug-fitting 5/16-inch (8 mm) diameter dowels [that are up to 0.008 inches (0.2 mm) oversize in the case of softwoods and up to 0.004 inches (0.1 mm) oversize with hardwoods] give higher strength values with PVA adhesives than do undersize dowels. The reason cited for this phenomenon is that the tight fitting dowels result in better glue distribution along the sides of the dowels (only 0.1 ml of glue was used in each dowel hole).

Effect of Dowel Surface

Under ideal conditions, the strongest joints are produced with plain dowels since withdrawal strength is proportional to the undisturbed surface area of a dowel. In the factory, however, spiral-groove or multi-groove dowels may produce better results. Also, the grooves will allow entrapped air in the hole to be released. In general, multi-groove and spiral-groove dowels may be expected to give equally good results (Eckelman and Hill, 1971). Dowels with fine grooving should be preferred over those with coarse grooving—because withdrawal strength is proportional to surface area, the less the surface is disturbed, the stronger the joint.

Effect of Shear Strength of Woods

To obtain a feeling for the potential withdrawal strength of dowels, let us calculate the withdrawal strength of a 3/8-inch diameter sugar maple dowel from the side grain surface of a sugar maple member. Assume
that the dowel pin is embedded one inch in the member and that the joint has been assembled with a high solids content PVA with zero dowel-hole clearance. Further, assume that the moisture content of the material is 12 percent.

Substituting the appropriate values into equation (6-1) and solving gives

\[ F_2 = 0.313 \times (0.95 \times 2,330 + 2,330) = 1,422 \text{ lb}. \]

Had a white birch dowel been used, which has a shear strength of 1,210 psi, the corresponding withdrawal strength would have been

\[ F_2 = 0.313 \times (0.95 \times 2,330 + 1,210) = 1,072 \text{ lb}. \]

In this case, the one joint is 33 percent stronger than the other, yet the only thing changed is the species of wood of which the dowel was constructed.

Product Engineering Considerations

Clearly, it is advantageous to use dowels cut from woods with high shear strengths—provided that the joints are well made. (If the joints are poorly made with inadequate gluing, it is unlikely that wood species will significantly affect strength). A joint made with a high shear strength wood such as white oak (with a shear strength of 2,000 psi), for example, will have greater strength than a joint made with a wood such as yellow poplar. Specifically, the withdrawal strength of a sugar maple dowel from a white oak member would be

\[ F_2 = 0.313 \times (0.95 \times 2,000 + 2,330) = 1,324 \text{ lb}, \]

whereas the withdrawal strength of the same (sugar maple) dowel from a yellow poplar member would be

\[ F_2 = 0.313 \times (0.95 \times 1,90 + 2,330) = 1,083 \text{ lb}. \]

This result confirms what was expected, namely, that stronger joints can be made with white oak than with yellow poplar. More importantly, however, the value of using dowels with high shear strengths is clearly demonstrated. Further, it might be noted that the withdrawal strength of a white birch dowel from a yellow poplar member would be only

\[ F_2 = 0.313 \times (0.95 \times 1,190 + 1,210) = 733 \text{ lb}. \]

This example clearly demonstrates the range of values that can be obtained with various combinations of woods used for dowels and members.

It is also informative to calculate the withdrawal strength of a white birch dowel from a sweetgum member (shear strength = 1,600 psi) since that combination frequently occurs in practice. Withdrawal strength for this case would be

\[ F_2 = 0.313 \times (0.95 \times 1,610 + 1,210) = 854 \text{ lb}. \]

Sample Problem
Calculate the withdrawal strength of a 7/16-inch diameter multi-grooved yellow birch dowel from the side grain of red oak. The dowel is embedded 1-1/4 inches in the oak; moisture content is 7 percent; dowel hole clearance is 0.002 inches; and the adhesive is PVA with 62 percent solids content.

\[
F_2 = 0.834 \times (7/16) \times (1.25)^{0.89} \times (0.95 \times 1,780 + 1,880) \times 1.15 \\
1.0 \times [1.0 - (17.1 \times 0.002)] \times 0.9 = 1,588.6 \text{ lb.}
\]

Withdrawal Strength of Dowel Pins From End Grain Surfaces

The withdrawal strength of dowel pins from end grain surfaces, Figure 6-3, can be calculated in the same manner as for side grain surfaces except that the constant, 0.95, in equation (6-1) is deleted. Carrying out this operation gives

\[
F'_2 = 0.834 \times D \times L^{0.89} \times (S_1 + S_2) \times a \times b \times c
\]

for the withdrawal strength of dowel pins from end grain surfaces, or, in simplified form

\[
F'_2 = A \times (S_1 + S_2) \times B \times C
\]

Referring to the previous example, it is seen that the predicted withdrawal strength of a 3/8-inch diameter yellow birch dowel embedded one inch in the end grain of a sugar maple specimen under the conditions previously listed would be

\[
F'_2 = 0.31 \times (2,680 + 2,162) \times 0.961 \times 1 = 1,441 \text{ lbs.}
\]

In this case, therefore, withdrawal strength from the end grain surface was \[
\left[\frac{1,441 - 1,401}{1,401}\right] \times 100\% = 2.86\%
\]

or 2.86 percent greater than from the side grain surface.

Withdrawal Strength of End Grain to Side Grain Joints

The withdrawal strength of a single-pin end to side grain joint can be calculated by means of either equation (6-2) or (6-5) depending on which gives the least value. As an example, consider the joint shown in Figure 6-4a. The moisture content of the material is 6 percent so that the shear strength of the sugar maple, equation (6-3), is

\[
S(6) = 2,330 \times [1 + 0.03(12 - 6)] = 2,749 \text{ psi ,}
\]

whereas that of the yellow birch is

\[
S(6) = 1,880 \times [1 + 0.03 \times (12 - 6)] = 2,218 \text{ psi}
\]

If we calculate the withdrawal strength by means of equation (6-2), the predicted strength is

\[
F'_2 (\text{side grain}) = 0.31 \times (0.95 \times 2,749 + 2,218) = 1,497 \text{ lbs.}
\]
If, however, we use equation (6-5) we obtain

\[ F_2(side\ grain) = 0.31 \times (2,749 + 2,218) = 1,540 \text{ lbs}. \]

Obviously, the joint will fail at the lesser value, so that the estimated strength should be 1,497 pounds.

In this case, the dowel pin connection in the side grain member was weaker than the connection in the end grain member so that the strength of the joint must be based on the withdrawal strength of the dowel from the side grain surface. If, on the other hand, the end grain connection had been the weaker of the two, design calculations would have to be based on withdrawal strength of the dowel from end grain. To illustrate this principle, let us calculate the withdrawal strength of the joint shown in Figure 6-4b, which is identical to the joint just considered, except that the end grain member is constructed of American elm rather than sugar maple. The shear strength of the American elm at 6 percent mc is

\[ S(6) = 1,510 \times [1 + 0.03 \times (12 - 6)] = 1,782 \text{ psi} \]

so that the withdrawal strength of the dowel from the end grain of this member would be

\[ F_2(elm) = 0.31 \times (1,782 + 2,218) = 1,240 \text{ lbs}. \]

The estimated strength of the joint is, therefore, 1,240 pounds and not 1,497 pounds as side grain calculations indicate. As can be seen from this example, the withdrawal strength from both the side and end grain surfaces should always be checked to see which is the least.

**Withdrawal Strength of Side Grain to Side Grain Dowel Joints**

The withdrawal strength of a side grain to side grain joint of the type

![Diagram](Image)

Figure 6-4. Calculation of withdrawal strengths of yellow birch dowels. The dowel on the right will withdraw from the end grain of the American elm rather than the side grain of the sugar maple because of the difference in shear strength of the two woods.

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shown in Figure 6-5 can be calculated by means of equation (6-2) in which the value of \( S_1 \) is taken as the lesser of the shear strengths of two members joined together. For the joint shown, the shear strength of American beech at an assumed moisture content of 8 percent is

\[
S(8) = 2,010 \times [1 + 0.03 \times (1,208)] = 2,251 \text{ psi},
\]

whereas that of the sweetgum is

\[
S(8) = 1,600 \times [1 + 0.03 \times (12 - 8)] = 1,792 \text{ psi},
\]

Consequently, the shear strength value for sweetgum should be used in calculating the strength of the joint rather than the value for American beech. In calculating the strength of this joint, we must first find the shear strength of white birch (paper birch) dowels at 8 percent mc. Carrying out this operation gives

\[
S(8) = 1,210 \times [1 + 0.03 \cdot (12 - 8)] = 1,355 \text{ psi}
\]

Substituting the appropriate remaining values into equation (6-2) gives the proper withdrawal strength, i.e.,

\[
F_2 = 0.28 \times (0.95 \times 1,792 + 1,355) = 856 \text{ lbs}.
\]

Withdrawal of End Grain to End Grain Joints

End grain to end grain joints such as the one shown in Figure 6-6 occur when it is necessary to join two members together longitudinally. The strength of such joints can be estimated by means of equation (6-5) provided that \( S_1 \) is taken as the lesser shearing strength of the two members. For the joint shown, for example, it can be seen from Appendix 6-1 that the shearing strength of the sweetgum is less than that of oak; hence the joint should be designed on the basis of the sweetgum member. To find the strength of this joint we must first find the shearing strengths of the white birch dowel and the sweetgum member at the current moisture content. At an assumed moisture content of 7 percent, the shear strengths of white birch and sweetgum are

\[
S(7) = 1,210 \times [1 + 0.03 \times (12 - 7)] = 1,392 \text{ psi},
\]

\[
S(7) = 1,600 \times [1 + 0.03 \times (12 - 7)] = 1,840 \text{ psi},
\]

respectively. Substituting the shear strengths along with the length-diameter and clearance-adhesive factors for animal glue from Table 6-1 and Table 6-2 respectively, into equation (6-5) gives the appropriate withdrawal strength, namely,

\[
F_2 = 0.37 \times (1,840 + 1,392) \times 0.85 = 1,018 \text{ lbs}.
\]
Two-pin Moment-Resisting Dowel Joints

T-Shaped Joints

In modern furniture construction, two-pin moment-resisting dowel joints are used more than any other type to give strength and rigidity to furniture frames. Probably the most common example of the use of this joint is the side rail to back post joint in chairs. Research results (Eckelman, 1971a) indicate that the bending moment resistance of these joints can be predicted by means of the expression

\[ F_4 = F_2 \times d \]  \hspace{1cm} (6-6)

where \( F_4 \) = the ultimate bending moment resistance of the joint, in-lb; \( F_2 \) = the withdrawal strength of the dowel loaded in tension, lb.; and \( d \) = the internal lever arm, inch.

The internal lever arm, \( d \), is further defined by the expression

\[ d = d_1 + (d_2 / 2) \]  \hspace{1cm} (6-7)

where \( d_1 \) = the spacing between dowel hole centers, and \( d_2 \) = the distance from the center of the dowel loaded in compression to the corresponding outside compression edge of the rail. These relationships are further illustrated in Figure 6-7.

This expression indicates that the bending moment resistance of a dowel joint is related to a) the withdrawal strength of the dowel, b) the width of the rail, and c) the spacing of the dowels within the rail. The most overlooked of these factors is dowel spacing within the joint. Many times dowels are spaced one inch on centers, for example, when they could be spread much further apart.

To demonstrate the use of the expressions, consider a joint consisting of a sugar maple rail, 3 inches wide, that is joined to a sugar maple back post by two, 3/8-inch diameter by 2-inch long sugar maple dowels and assembled with a gap-filling urea-formaldehyde resin, Figure 6-8. Assume the dowel-hole clearance is zero and dowel penetration in both rail and post is one inch. If we assume that the moisture content of the maple is 7 percent, then its shear strength would be

\[ S(7) = 2,330 \times [1 + 0.03 \times (12 - 7)] = 2,680 \text{ psi} \]

The withdrawal strength of the dowel according to equation (6-2) would be

\[ F_2 = 0.31 \times (0.95 \times 2,680 + 2,680) \times 1 \times 1 = 1,620 \text{ lbs.} \]

Assuming that the dowels are symmetrically spaced 1 inch apart, Figure 6-8a, in the beam, the internal lever arm, \( d \), is

\[ d = 1 + \frac{1}{2} = 1 \frac{1}{2} \text{ inch} \]

The bending moment resistance, denoted by \( F_4 \), is then calculated by means of the expression

\[ F_4 = F_2 \times d = 1,620 \times (1 \frac{1}{2}) = 2,430 \text{ in-lb} \].
Had the holes been spaced 1-1/2 inches apart in the beam, Figure 6-8b, the internal lever arm would be
\[ d = 1\tfrac{1}{2} + \left(\tfrac{1}{4}\right) / 2 = 1\tfrac{1}{2} + \tfrac{1}{8} = 1\tfrac{3}{8} \text{ inch}, \]
and the bending moment resistance of the connection would increase to
\[ F_4 = 1,620 \times 1\tfrac{3}{8} = 3,038 \text{ in-lb}. \]

Similarly, for a 2-inch dowel spacing, Figure 6-8c, the internal lever arm is
\[ d = 2 + (\tfrac{1}{4}) / 2 = 2\tfrac{1}{4} \text{ in} \]
so that the bending moment resistance of the joint, \( F_4 \), is
\[ F_4 = 1,620 \times (2\tfrac{1}{4}) = 3,645 \text{ in-lb}. \]

Note that the bending moment resistance of the joint was increased 1-1/2 times simply by increasing the dowel spacing from 1 to 2 inches. There is probably no other way in which the strength of a joint can be so easily increased.

Similar calculations can be carried out for other beam sizes. The strength of a 2-1/2-inch beam, Figure 6-8d, with dowels identical to those used before but with a 1-1/2 inch dowel spacing would be
\[ F_4 = 1,620 \times (1\tfrac{1}{2} + \tfrac{1}{4}) = 2,835 \text{ in-lb}. \]

Thus, the calculations show that joint C is substantially stronger in bending than either joint (a) or joint (b) owing only to the greater spacing of the dowels. Furthermore, even though the width of the rail of joint (d) is less than that of joint (a), joint (d) is stronger than joint (a) because its dowel spacing is greater.
As a last example, consider a joint constructed with a 3-inch wide elm rail and elm post and two, 3/8-inch diameter by 1-1/2-inch long maple dowels, spaced 1 inch apart, Figure 6-9. If we assume a moisture content of 7 percent, then the shear strength of the elm is

\[ S(7) = 1,510 \times \left[ 1 + 0.03 \times (12 - 7) \right] = 1,737 \text{ psi} \]

and that of the maple is

\[ S(7) = 2,330 \times \left[ 1 + 0.03 \times (12 - 7) \right] = 2,680 \text{ psi} \]

Assuming 0.75-inch penetration in each member, the withdrawal strength of the dowels may be calculated by means of equation (6-2); i.e.,

\[ F_2 = 0.24 \times (0.95 \times 1,737 + 2,680) = 1,039 \text{ lb.} \]

The moment arm, \( d \), is

\[ d = 1 + \frac{1}{2} = 1\frac{1}{2} \]

so that the bending moment resistance, \( F_4 \), is

\[ F_4 = 1,039 \times 1\frac{1}{2} = 1,559 \text{ in} - \text{lb} \]

This problem demonstrates that the bending moment resistance of a two-pin joint is dependent on the species of wood used as well as dowel spacing and size. This joint constructed of American elm, for example, has less strength than joint (a) of Figure 6-8.

Problems
1. Consider the joint shown in Figure 6-10. Let us assume that the members of this joint are constructed of American elm that has a moisture content of 7 percent. The dowels are 7/16-inch diameter spiral-grooved yellow birch; depth of embedment is 1-1/4 inches. Dowel hole clearance is zero; adhesive is PVA with a 62 percent solids content. Rail width is 2-1/2 inches; dowel spacing is 1-1/2 inches. Find the bending moment resistance of the joint.

The shear strength of yellow birch at 7 percent moisture content is equal to 1,880\times(1.15) = 2,162 psi; that of American elm is 1,510\times(1.15) = 1,736.5 psi. Substituting the appropriate values into equation (6-1) gives a withdrawal strength of

\[ F_2 = 0.45 \times (0.95 \times 1,736 + 2,162) \times (1 \times 1 \times 0.9) = 1,543.5 \text{ lbs}. \]

The bending moment resistance of the joint is then found by substituting the appropriate values into equation (6-6) and solving

\[ F_4 = F_2 \times \left[ \frac{1}{2} + \frac{1}{2} \right] = 1,543.5 \times 1\frac{1}{4} = 2,700 \text{ in} - \text{lb} \]

2. To illustrate the importance of dowel spacing, consider the remaining joints shown in Figure 6-10. Width of the rail in the remaining three cases shown is 3 inches. In the first case, dowel spacing is 1 inch; in the second, spacing is 1-1/2 inches; and in the third, spacing is 2 inches. Find the bending moment resistances of the joints.

The internal moment arm is 1.5 inches in the first case, 1.875 in the second, and 2.25 inches in the third case. The joint with dowels spaced 1-1/2 inches apart, therefore, is \( (1.5 + 0.75/2)/(1 + 0.5) \), or 25 percent stronger than the joint with dowels placed 1 inch apart; similarly, the joint with the dowels placed 2 inches apart is 2.25/1.5, or, 50 percent stronger.
As can be seen, the strength of the joint can be dramatically increased simply by spreading the dowels as far apart as possible.

3. Calculate the bending moment resistances of the three joint constructions shown in Figure 6-11. Assume that the main members are constructed of white ash that has a moisture content of 8 percent.

The plain 3/8-inch diameter dowels are constructed of white paper birch and have a one inch depth of embedment. Dowel-hole clearance is 0.005 inches; the adhesive is PVA with 40 percent solids content.

Ans. 1,595; 1,241; and 1,063 lb-ins.

Figure 6-10. Configuration of the joints described in Problem 1.

L-Shaped Corner Joints

The strength values predicted by the previous expressions hold only for “T”-sections such as the side rail to back post joint in a chair. When one member frames into another to form an “L”-type joint, such as the side rail to front leg joint in a side chair (where the leg does not extend significantly above the side rail), the strength of the joint may be considerably less owing to splitting of the top of the member. This type of ac-
tion may also occur with other types of joints such as mortise and tenon. To help eliminate such splitting, the dowels should penetrate as deeply as possible into the side grain member.

**Out of Plane Bending Moment Resistance of Dowel Joints**

Tests (Eckelman, 1979) indicate that the out of plane bending moment resistance of two pin dowel joints, Figure 6-12, may be estimated by means of the expression

\[ F_4 = \left( \frac{3.14 \times D^3}{16} \right) \times S_4 + \left( \frac{t + D}{2} \right) \times F_2 \text{ in-lb} \quad (6-8) \]

where
- \( F_4 \) = the ultimate bending moment resistance of the joint, in-lb;
- \( D \) = the diameter of the dowels, inches;
- \( S_4 \) = the modulus of rupture of the wood of which the dowels are constructed, psi;
- \( F_2 \) = the withdrawal strength of a dowel, lb.;
- \( t \) = the thickness of the rail, in; Figure 6-12.

Maximum strength and stiffness are obtained when a close fit is secured between the two mating members. Bending moment resistance was found to decrease by over 50 percent in one set of tests when the gap between rail and post was increased to 1/16 inch (Eckelman, 1979).

To illustrate the use of equation (6-8), consider a joint similar to that shown in Figure 6-12. Assume that the members are constructed of black walnut which has a moisture content of 6 percent. The members are 1-1/2 inches thick and are joined together with 3/8-inch diameter plain sugar maple dowels; depth of penetration into the side grain member is 3/4 inches; dowel-hole clearance is 0.005 inches; the adhesive is a gap-filling urea-formaldehyde.

Withdrawal strength of the dowels from the side grain of the main members would be

\[ F_2 = 0.242 \times (0.95 \times 1.825 + 2.330) \times 1.18 \times \left[ 1.0 - (9.1 \times 0.005) \right] = 1,108 \text{ lbs.} \]

The modulus of rupture of sugar maple at 6 percent is equal to 15,800x1.24 = 19,592 psi. Substituting the appropriate values into equation (6-8) gives

\[ F_4 = \left( \frac{3.14 \times (0.375)^3}{16} \times 19,592 \right) + \left( 1,108 \times \frac{1.5 + 0.375}{2} \right) = 1,241 \text{ in-lb}. \]

As can be seen, the bending moment resistance is not as great as that of in-plane type joints; however, the strength of the joints is certainly significant and can provide sufficient strength for many design situations.

**Problems**

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Calculate the flatwise bending moment resistance of a joint similar to that shown in Figure 6-12 in which the main members are constructed of sugar maple that has a moisture content of 7 percent. The plain dowels are 3/8-inch diameter yellow birch; penetration in the side grain of the one member is 3/4 inches; dowel-hole clearance is zero; the adhesive is PVA with 62 percent solids content.

The withdrawal strength of the dowels, $F_2$, is

$$ F_2 = 0.834 \times (0.375) \times (0.75)^{0.89} \times [0.95 \times 1,880 + 2,330] \times 1.15 = 1,146 \text{ lb}. $$

The flatwise bending moment resistance of the joint is

$$ F_4 = 3.14 \times [(0.375)^3 / 16] \times [15,900 \times 1.20] + [1,146 \times (1.0 + 0.375) / 2] = 984 \text{ in-lb} $$

### Shear Strength of Two-pin End-to-Side Grain Dowel Joints

In many types of furniture construction, dowel joints are heavily loaded in shear by horizontal and vertical forces, Figure 6-13. The ends of the front rail in a sofa, for example, may be joined to the stumps with dowels; these joints may be loaded in vertical shear by the seat loads and in horizontal shear by the front-to-back spring loads. The top rail of a sofa is another example of a member whose ends must ordinarily be designed to carry shear loads. When one or more people lean backwards in a sofa, these loads are transmitted as shear forces to the dowel pins which are used to connect the top rail to the end posts.

Because dowel joints are so often used to transmit shear, it is necessary that a rational means be available for designing them to meet service needs. To date, however, it has not been possible to relate shear strength to the usual material and geometrical joint parameters. The maximum shear strength of a dowel joint might be expected to be limited by the lateral shear or crushing strength of the dowel pins used in its construction. Research carried out by the author (Eckelman, 1971b), however, indicates that the dowels themselves seldom fail in shear. Rather, what ordinarily happens is that the ends of the members split. Furthermore, such factors as dowel spacing and member cross section (within limits) do not appear to have a predictable effect on joint strength. This result is somewhat contrary to what is expected since it would seem that the thicker and wider the end-grain member (such as the end of a rail) of a joint, the greater should be the shear strength. A possible explanation for this phenomenon is that stress concentrations develop around the holes, and once the ultimate strength of the wood is exceeded at these points, the end of the rail splits regardless of the average stress acting upon it.

Test results also indicate that two-pin end-to-side grain shear-resisting dowel joints appear to have about equal strength when loaded in either the flat position, Figure 6-13, or the edge position. Again, it appears that once the strength of the wood is exceeded at some point, the end of the rail...
splits. Furthermore, these tests do not indicate any regular relationship of joint strength to ordinary joint geometry parameters such as width and thickness. Since no such relationships can be demonstrated, an engineering design formula has not been developed to predict the strength of these joints. In designing shear resisting dowel joints, it is necessary, accordingly, to rely heavily on a direct interpretation of applicable test results. We can, for example, refer to Figures 6-14a, b, c, and attempt to find a test sample that closely matches the wood species, dowel spacing, and overall geometry of a joint in question and then use the strength value obtained for the test sample as a first estimate of expected joint strength.

An alternative procedure that can be followed is to determine the average shear strength, $F_3$, of the joints reported and then apply a reduction factor to this value to take into account the possible variations in strength that must be expected. The average strength value of the joints tested by the author was 981.1 pounds, and the standard deviation was 222.4 pounds. Let us say that we now wish to determine a lower strength value such that even if we continued our tests indefinitely, we could be 95 percent confident that less than 5 percent of the specimens would be weaker than this lower bound. This lower bound or tolerance limit can be determined (Ostle, 1963) by multiplying the standard deviation by 1.855 (which is the appropriate 95 percent tolerance factor at the 95 percent confidence level) and subtracting the product from 981.1 pounds; i.e.

$$F_3 = 981.1 - (1.855 \times 222.4) = 586.6 \text{ lb} \quad (6-9)$$

where $F_3$ is the shear strength of the joint.

This procedure provides us with an estimate of the strength that can be expected a fixed percentage of the time from two-pin shear connections constructed with 3/8-inch diameter dowels that are embedded 1-inch in the hardwoods indicated. Additional research will presumably indicate the strength values that can be expected with other dowel sizes, and, in particular, with other dowel diameters, but at the present time, the shear strength value previously calculated, i.e., $F_3 = 568.6$ pounds, provides us with the best estimate of the usable strength of this type of joint. It must be remembered, of course, that up to 5 percent of the joints con-
structured might be somewhat weaker. The lowest strength value obtained by the author, however, in testing 170 samples was 606.7 pounds.

Although information is limited, a few recommendations can be given regarding placement of the dowels in the end of a member to best resist shear. Specifically, the shear strength of a joint increases somewhat as the spacing between dowel holes is decreased. Thus, in those cases where it is permissible to do so, the dowels should be placed closer to the center of the rail (i.e., a narrow spacing should be used between dowel holes). In the case of a rail placed on edge which is loaded in vertical shear, such as the front rail in a sofa, the top dowel should not be placed too close to the top edge, or the end of the rail may split out owing to the action of the vertical loads.

Holding Strength of Dowels in Particleboard and Medium Density Fiberboard

**Face Withdrawal**

The face holding strength of yellow birch dowels in medium density fiberboard and common types of particleboard may be predicted (Eckelman, 1990) by means of the expression.

\[
F_2 = 28 \times D^{0.6} \times (IB)^{0.85} \times L^{0.85}
\]

(6-10)

where

- \(F_2\) = face withdrawal strength of the dowel, lb.;
- \(L\) = depth of embedment of the dowel, in.;
- \(IB\) = internal bond strength, psi;
- \(D\) = dowel diameter, in.

When single gluing is used, it must be recognized that strength values will be less than predicted. Similarly, when excess glue is forced into the material surrounding the hole, some increase in strength can be expected; in general, plain- and spiral-groove dowels may give somewhat greater holding strength than multi-groove dowels.

**Edge Withdrawal**

The edge withdrawal strength of dowels may be predicted by means of the expression

\[
F_2(\text{edge}) = 1684 \times D^{0.55} \times L^{0.85}
\]

(6-11)

These expressions indicate that there is a near linear increase in both face and edge withdrawal strength as depth of embedment increases. Face withdrawal is also closely related to internal bond strength in both medium density fiberboard and conventional particleboard. Edge withdrawal strength appears to be independent of internal bond strength.

**Diameter Effects**
The values given in the above expressions are based on limited tests carried out by the author and should be used with discretion; however, they do provide an indication of the effect of dowel diameter on withdrawal strength.

**Effect of Dowel Hole Fit**

The fit of the dowel in the hole has an extremely important effect on withdrawal strength. Englesson and Ostman (1972) showed that a clearance of a few thousandths of an inch does not greatly reduce the static strength of dowel joints, but it does significantly reduce their resistance to cyclic or fatigue loading. Specifically, Englesson (1972) found that dowel joints which were constructed with a force fit or grip fit of 0.1 mm (0.004 in.) lost little of their strength after being subjected to cyclic dynamic loading conditions such as occur in service. Joints constructed with a loose dowel fit, in contrast, lost a significant proportion of their strength when subjected to the same cyclic load conditions. These results tend to indicate that a tight “grip” fit is superior to a loose fit when dowels are used in particleboard construction.

When less than optimum gluing conditions are used, it has been shown (Konjer, Vorholt, and Gerhardt; 1986) that within reasonable limits, tightness of fit has little effect on static withdrawal strength. The reason cited for this phenomenon is that the dowels simply force the adhesive into the surrounding substrate so that a better distribution of adhesive along the sides of the dowel does not result (as is presumably the case with solid wood).

**Effect of Gluing Conditions**

The method of gluing the dowels in the holes has a profound effect on their withdrawal strength from particleboard. Englesson (1972) found that coating the surface of the dowel along with the walls of the hole increased strength appreciably. Specifically, applying glue to the dowels along with the walls of the hole (double gluing) gave an increase in strength of 20 percent over putting glue in the holes alone. It was also found that pre-treatment of the dowels with glue gave results equivalent to coating the dowels with glue just prior to their insertion in the holes. Furthermore, it was found that joint strength could be increased appreciably by filling the holes with adhesive so that the glue is forced into the surrounding middle layer of the board by hydraulic action when the dowel is forced into the hole. Even better results are obtained in edge withdrawal than in face withdrawal when this practice is followed.

It is important to understand that dowel joints are adhesive joints—they are not mechanical joints. Joint strength is proportional to the area of the dowel bonded to the walls of the hole and to the quality of that bond. Maximum strength is obtained, therefore, when both the walls of the hole and the surface of the dowel are fully coated with adhesive. A slightly weaker joint is obtained if the walls of the holes alone are covered with adhesive. Very little strength is obtained, however, if a small amount of adhesive is simply “squirted” into the bottom of the hole so that
little bonding occurs between the sides of the dowel and the walls of the hole. Additional strength is obtained when excess adhesive is used because the glue is forced into the surrounding substrate as the dowel is forced into the hole - provided that there is a snug dowel/hole fit.

**Effect of Dowel Surface**

Tests carried out by Eckelman and Cassens (1985) indicate that plain and spiral groove dowels have somewhat higher holding strengths than do multi-groove dowels—at least when excess glue is used in forming the joint. In these tests 3/8-inch diameter plain, spiral- and multi-grooved dowels were embedded 3/4 inches in the face of particleboard. Dowel hole clearance was zero. Before the joints were assembled, the holes were filled with adhesive and the dowels then forced into the holes so that the adhesive was forced into the material surrounding the holes by hydraulic pressure. In many of the tests carried out, a conical plug of material was pulled loose from the specimen. This indicates that the adhesive had spread into the areas adjacent to the dowel and presumably resulted in greater withdrawal strength. Under these conditions, plain- and spiral-groove dowels gave higher holding strength than multi-groove dowels. This phenomenon occurs because the excessive adhesive escapes more freely through the grooves of the multi-groove dowel than the spiral groove dowel--or around the un-grooved surface of the plain dowel. As a result, more adhesive is forced into the surrounding substrate.

**Adhesives**

In general, highest joint strengths are obtained with high (65 percent) as opposed to low (42 percent) solids content polyvinyl acetate adhesives (PVA). Performance tests should be carried out on finished constructions as well as on individual dowel joints in order to determine the most cost effective adhesive. Dowel joint tests carried out in the laboratory can be used to determine which adhesive will produce the greatest dowel holding strength in a given board. Under production line conditions, however, the advantages of one adhesive over another may not be realized. As a result, a less expensive adhesive which gives lower holding strengths in laboratory tests may be just as effective as more costly adhesives under production line conditions. For this reason tests should always be run both on individual dowel joints and also on fully completed assemblies.

**Case (Corner) Joints**

Tests indicate that when dowels are used to join two pieces of board together to form a corner joint, (e.g., a side to bottom or side to top joint in a case) the joint will actually fail at a lower load level if the edge of the one board is glued to the face of the other. This apparent contradiction can be explained in terms of the difference in stiffness between the dowel joint and the stiffness of the adhesive joint between the two boards. The adhesive joint between the edge of one board and the face of the other will
be much stiffer than the dowel joint formed between these two boards. As a result, the adhesive joint between the face and edge will carry the entire load applied to the joint. This in turn will cause the edge of the other board to begin to delaminate owing to internal bond failure. This action can occur before the dowels have begun to carry a significant portion of the load, and hence the joint will fail before the dowels have been able to perform their function. If the edge of the one board is not glued to the face of the other, however, the dowels apply a tensile force to the board along their full length of embedment, and hence, the tendency of the board to delaminate is greatly reduced.

Problems for Discussion

1a. Find the face withdrawal strength of a 3/8-inch diameter yellow birch dowel embedded 5/8-inch in a piece of particleboard or MDF which has an internal bond strength of 120 psi.

**Soln.**

\[ F_2 = 28 \times (0.5)^{0.6} \times (120)^{0.85} \times (0.625)^{0.85} = 610 \text{ lb}. \]

This is a rather high value which can be obtained only under optimum construction conditions with boards of high internal bond strength, but it does indicate the potential strength that can be obtained with dowel joints in MDF and PBd.

1b. Find the face withdrawal strength of a 3/8-inch diameter yellow birch dowel embedded 5/8-inch in a piece of particleboard or MDF which has an internal bond strength of 60 psi.

**Soln.** If the board had an IB strength of only 60 psi, the holding strength of the dowel would be reduced to

\[ F_2 = 28 \times (0.5)^{0.6} \times (60)^{0.85} \times (0.625)^{0.85} = 338 \text{ lb}. \]

As can be seen, the holding strength of the dowel in the board with the lower IB strength has been drastically reduced.

2a. Find the face withdrawal strength of a 3/8-inch diameter yellow birch dowel embedded 3/8-inch in a piece of particleboard or MDF that has an internal bond strength of 120 psi.

**Soln.** For this depth of penetration, i.e., L = 0.375 in, the holding strength of the dowel in a board with an IB of 120 psi would be

\[ F_2 = 28 \times (0.5)^{0.6} \times (120)^{0.85} \times (0.375)^{0.85} = 395 \text{ lb}. \]

2b. Find the face withdrawal strength of a 3/8-inch diameter yellow birch dowel embedded 3/8-inch in a piece of particleboard or MDF that has an internal bond strength of 60 psi.

**Soln.** For a board with an IB strength of 60 psi, the holding strength of the dowel would amount to

\[ F_2 = 28 \times (0.5)^{0.6} \times (60)^{0.85} \times (0.375)^{0.85} = 219 \text{ lb}. \]

These calculations demonstrate the importance of using boards with high internal bond strengths in those design situations where depth of penetration is limited. Entry corner joints in cabinets are particularly critical, and it is important to obtain the highest strengths possible in these joints.
3. Calculate the withdrawal strength (a) of a 3/8-inch diameter dowel embedded 5/8 inches in the face of a particleboard which has an internal bond strength of 100 psi. What is the withdrawal strength (b) of the dowel from the edge of the board? What is the withdrawal strength (c) from the edge of the board if the depth of penetration is increased to one inch?

Ans.

\[ F_2 = 28x(0.375)^{0.6}x(100)^{0.85}x(0.625)^{0.85} = 521 \text{ lb.} \]

b) 658 lb.;

c) 982 lb.

### Holding Strength of Dowels in Plywood and Oriented Strand Board

#### Table 6-3. Expressions used to estimate the withdrawal strength of yellow birch dowels in the face of various composites. \( D \) refers to dowel diameter, in; \( L \) to depth of penetration, in; and \( W \) to density, lbs/ft\(^2\). \( R^2 \) is the correlation coefficient, "under" and "over" refer to the differences between estimated and test values (%), and \( SD \) refers to the standard deviation of the differences (%).

<table>
<thead>
<tr>
<th>Material</th>
<th>Expression</th>
<th>( R^2 )</th>
<th>Under</th>
<th>Over</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Face Withdrawal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Douglas-fir Plywood</td>
<td>( y = 64DLW )</td>
<td>81.6</td>
<td>+31</td>
<td>-42</td>
<td></td>
</tr>
<tr>
<td>Southern pine plywood</td>
<td>( y = 55DLW )</td>
<td>79.4</td>
<td>+38</td>
<td>-43</td>
<td>16</td>
</tr>
<tr>
<td>Oriented strand board</td>
<td>( y = 55DLW )</td>
<td>86.8</td>
<td>+28</td>
<td>-40</td>
<td>16</td>
</tr>
<tr>
<td>Hardwood plywood</td>
<td>( y = 44D^{0.5}LW )</td>
<td>+27</td>
<td>-38</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>Edge Withdrawal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Douglas-fir Plywood</td>
<td>( y = 85DLW )</td>
<td>70.5</td>
<td>+44</td>
<td>-31</td>
<td>15</td>
</tr>
<tr>
<td>Southern pine plywood</td>
<td>( y = 75.5DLW )</td>
<td>62.3</td>
<td>+35</td>
<td>-35</td>
<td>17</td>
</tr>
<tr>
<td>Oriented strand board</td>
<td>( y = 179D^2L^{0.5}W )</td>
<td>78.0</td>
<td>+34</td>
<td>-32</td>
<td>16</td>
</tr>
<tr>
<td>Hardwood plywood</td>
<td>( y = 96DW; L=1^* )</td>
<td>68.5</td>
<td>+23</td>
<td>-23</td>
<td>11</td>
</tr>
</tbody>
</table>

### Withdrawal

Research indicates (Eckelman, et al, 2002; Eckelman and Erdil, 2000) that the withdrawal strength of yellow birch dowels in Douglas-fir, Southern yellow pine, and hardwood plywood along with oriented strand board may be estimated ; (Erdil and Eckelman, 2001) by means of the expressions given in Table 6-3. Estimated withdrawal strengths for dowel embedded 3/4 inches in the face of Douglas-fir, Southern yellow pine, and hardwood plywood along with oriented strand board are given in Table 6-4. Estimated withdrawal strengths for dowels embedded 1 inch in the

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edge of the same materials also are given in Table 6-4. These values should be treated as estimates subject to variation rather than as absolute values. Depending on differences in construction, strength differences as great as 50 percent might be expected.

As can be seen in Table 6-3, withdrawal strength depends strongly on dowel diameter. In the case of 3/8-inch diameter dowels, face withdrawal strengths varied from 400 to 800 pounds for 3/4-inch depth of penetration. Likewise, edge withdrawal strengths varied from about 700 to 1500 pounds for 1-inch depth of penetration.

Zhang et al (2003) carried out edge withdrawal tests with equal and unequal depth of penetration of dowels in mating members constructed of "Frame-1" furniture grade, 3/4-inch thick southern yellow pine plywood and 3/8-inch diameter spiral groove white birch dowels. For depths of embedment of 0.5 to 1.5 inches, the following regression curve is obtained for their data

\[ y = 964.7 \times L_p^{0.464} \times L_r^{0.472} \]

with an \( R^2 \) value of 82.8% where \( L_p \) = depth of embedment in the edge of the post (e.g., leg), \( L_r \) = depth of embedment in the end (edge)of the rail. For a 1-inch depth of penetration in post and rail, this expression estimates a withdrawal strength of 964.7 lbs. This compares favorably with the comparable value of 1,042 lbs given in Table 6-4.

**Bending Moment Resistance**

Research (Eckelman et al, 2002) indicates that the bending moment resistance of two-pin moment resisting dowel joints constructed of plywood or oriented strand board may be estimated in a manner identical to that for solid wood. Specifically, the bending moment resistance may be predicted by equation (6-5), which, for convenience has been rewritten in the form below

\[ F_4 = F_2 \left( \frac{d_1 + d_2}{2} \right) \]

where \( F_4 \) is the bending moment resistance, in-lb; \( F_2 \) is the withdrawal strength of the dowel, in; \( d_1 \) = the spacing between dowel hole centers, and \( d_2 \) = the distance from the center of the dowel loaded in compression to the corresponding outside compression edge of the rail, Figure 6-15. This expression has

---

**Table 6-4. Estimated withdrawal strength values of yellow birch dowels embedded in the face and edge of four composites based on the expressions given in Table 6-3.**

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (pcf)</th>
<th>Dowel Diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1/4&quot; 5/16&quot; 3/8&quot; 7/16&quot;</td>
<td></td>
</tr>
<tr>
<td>Face Withdrawal: 3/4-inch of penetration</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Douglas-fir Plywood</td>
<td>32.6</td>
<td>391 489 587 685</td>
</tr>
<tr>
<td>Southern pine plywood</td>
<td>36.8</td>
<td>380 474 569 664</td>
</tr>
<tr>
<td>Hardwood plywood</td>
<td>36.8</td>
<td>580 648 709 767</td>
</tr>
<tr>
<td>Oriented strand board</td>
<td>44.8</td>
<td>462 578 693 809</td>
</tr>
<tr>
<td>Edge Withdrawal: 1-inch depth of penetration</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Douglas-fir Plywood</td>
<td>32.6</td>
<td>693 866 1,039 1,212</td>
</tr>
<tr>
<td>Southern pine plywood</td>
<td>36.8</td>
<td>695 868 1,042 1,216</td>
</tr>
<tr>
<td>Hardwood plywood</td>
<td>36.8</td>
<td>883 1,104 1,325 1,545</td>
</tr>
<tr>
<td>Oriented strand board</td>
<td>44.8</td>
<td>501 783 1,128 1,535</td>
</tr>
</tbody>
</table>

---

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been found to hold over a wide range of rail widths.

To illustrate the use of this expression, let us calculate the bending strength of the joint shown in Figure 6-16. Width of the rail is 5 inches; dowel spacing is 2 inches. The joint is constructed with 3/8-inch diameter dowels that are embedded 1 inch in the edge of the post. Finally, the joint is constructed of southern yellow pine plywood that has a density of 37 pcf.

Referring to Table 6-3, it is seen that the withdrawal strength of a dowel embedded in the edge of Southern yellow pine may be predicted by means of the expression

\[ F = 75.5 \times D \times L \times W \text{ lb} \]

where \( F \) refers to the withdrawal strength of the dowel, lbs; \( D \) refers to the diameter of the dowel, inches; \( L \) refers to the depth of embedment, in; and \( W \) refers to the density of the plywood, pounds per cubic foot (pcf). Substituting the appropriate values into this expression gives

\[ F = 75.5 \times (0.375) \times (37) = 1,048 \text{ lb} \]

The spacing between the longitudinal axes of the dowels is 2 inches so that \( d_1 \) of equation (6-5) = 2; likewise the distance from the longitudinal axis of the lower dowel to the lower edge of the rail is 1.5 inches so that \( d_2 = 1.5 \) inches. Substituting these values into the predictive expression gives

\[ F_4 = 1,048 \times (2 + 1.5 / 2) = 1,048 \times 2.75 = 2,882 \text{ in - lb} \]

A stronger joint would have resulted if the dowels had been spaced 3 inches apart rather than 2 inches. For a 3-inch spacing, \( d_1 = 3 \) inches and \( d_2 = 1 \) inch. Substituting these values into the predictive expression gives

\[ F_4 = 1,048 \times (3 + 1 / 2) = 1048 \times 3.5 = 3,668 \text{ in - lb} \]

As these calculation show, a 27 percent increase in strength was achieved at no expense simply by using a wider dowel spacing.