Screwholding Performance
In Hardwoods and Particleboard

C. A. Eckelman

Abstract

Screw withdrawal tests were carried out on various species of hardwood and particleboard samples in order to evaluate formulas which had previously been developed to predict the holding strength of screws in wood and particleboard type materials. Results of these tests indicate that shear strength parallel to grain is a better predictor of holding strength in solid wood than specific gravity. On the other hand, specific gravity is a good indicator of holding strength in particleboard. Expressions are given in this paper which enable furniture manufacturers to predict the average holding strength of screws in both solid wood and particleboard materials.

Although extensive investigations have been made of the holding strength of screws in wood and particleboard (Fairchild 1927; Cockrell 1933; Johnson 1967), relatively few subsequent efforts have been made to interpret and correlate the results of these studies and put them in a form in which they can readily be used by furniture manufacturers and designers. The Wood Handbook (Anon. 1955), of course, contains formulas for calculating allowable design loads for screws used in conventional building construction. These formulas, however, have certain shortcomings when applied to the problems of furniture construction, so they are not entirely satisfactory for furniture engineering purposes. In the case of particleboard, even less predictive information exists. Presumably, there are no formulas available which can be used to predict the holding strength of screws in particleboard except for one expression published by the National Particleboard Association (Anon. 1968).

Because there was a critical need for formulas which could be used to predict the holding strength of screws as they are used in furniture construction, the author reviewed a number of past studies of screw strength and developed formulas which could be used to fairly represent the results obtained by the various researchers (Eckelman 1973). In the interval since that study was completed an opportunity presented itself to carry out screw withdrawal tests on a number of hardwood samples which were cut from actual furniture frames. These frames were obtained from a relatively wide geographical region and contained material which was typical of the kind and quality used in furniture frame construction. These tests, therefore, afforded the opportunity to evaluate the predictive expressions which had been developed under essentially normal design conditions. In addition, tests were carried out to determine the relationship of the withdrawal strength of screws to depth of embedment in particleboard. This relationship had not previously been reported, hence these tests provided the information needed to formulate more complete equations which express withdrawal strength as a function of screw diameter, depth of embedment, and specific gravity (SG) of the particleboard.

A brief review of the original development of all of the predictive expressions referred to is given in this paper along with the results of the tests which were carried out. For more detailed information about the formulation of these equations, however, the interested reader is referred to the author’s previous paper (Eckelman 1973).

Withdrawal Strength of Screws from Solid Wood Side Grain

In developing expressions to predict the holding strength of screws in wood and wood-base materials, it is first necessary to determine which material property is most closely correlated with holding strength. An analysis of the data presented by Fairchild (1927), for example, indicates that the holding strength of screws in solid wood is closely related to the SG of the wood. It also indicates, however, that holding strength is equally well correlated with the shear strength of the wood. An analysis of the data presented by Cockrell (1933), on the other hand, indicates that shear strength is a better predictor of withdrawal strength than is SG. In both cases, moreover, calculations based on shear strength yield results which agree well with practice, whereas calculations based on SG are not always so consistent. This is particularly true with species such as yellow birch, American beech, and sugar maple which have nearly the same SG yet have

The author is Associate Professor of Wood Science, Dept. of Forestry and Conservation, Purdue Univ., West Lafayette, Ind. This paper was received for publication in July 1974 as Journal Paper No. 5787 of the Purdue Univ. Agri. Expt. Sta.
considerable differences in holding strength. For this reason, it appears advantageous to base formulas that are to be used for furniture design on the shear strength of the wood rather than on SG. This procedure has an added advantage in that it also provides a convenient means of taking the moisture content (MC) of the material into account, since shear strength can readily be adjusted for MC.

Since the tip of a screw is of lesser diameter than the shank portion, its holding power is less, and this "tip effect" must also be taken into account in a predictive formula. If this is not done, such a formula will predict that a screw which completely passes through a board so that the tip protrudes and one which is merely embedded in the full thickness of the board without the tip protruding (Fig. 1) will have the same holding power. But, as will be shown later, this is not true—the screw which has the protruding tip will have the greater holding strength.

In the previous study conducted by the author (Eckelman 1973) it was found that after these factors had been taken into account, the results obtained by two of the principal investigators in this field, Fairchild (1927) and Cockrell (1933), could then be fairly represented by the regression expression:

\[ F_w = 3.20D(L-D)^{0.4}S_e \]  

[1]

Where \( F_w \) = withdrawal strength in pounds from side grain

\( D \) = Shank diameter of the screw in inches

\( D = 0.06 + 0.013N \) where \( N \) is the screw gage or number.

\( L \) = depth of embedment of the threaded portion of the screw

\( S_e \) = shear strength of the wood parallel to the grain at current MC

The multiple correlation coefficient for this expression along with the corresponding coefficients for the other expressions developed in this paper are given in Table 2. In this expression, a correction is made for tip effect by subtracting one full screw diameter, \( D \), from the depth of embedment, \( L \), of the threaded portion of the screw in the wood. Thus, the corrected or effective depth of penetration in Equation [1] is represented by the quantity \( (L-D) \). In those cases where the tip of the screw passes completely through a member and protrudes, the quantity \( (L-D)^{0.4} \) is accordingly used in Equation [1] rather than \( (L-D)^{0.4} \).

To further evaluate the merits of this expression, screw withdrawal tests were carried out on 110 hardwood samples which were cut from actual furniture frames. The intent here, as previously stated, was not to select samples from a closely controlled material source but rather from actual production line parts which had come from a broad spectrum of sources. The thicknesses of the samples varied somewhat, but most of the material was about 7/8 inches thick. Two number 10, type A sheet metal screws were embedded in each of the samples as shown in Figure 1. One of the screws was embedded the full thickness of the sample, whereas the other screw was driven completely through until the tip protruded approximately 1/4 inch. Pilot holes, 1/8 inch in diameter, were drilled for all screws. The species makeup of the specimens is given in Table 1.

All withdrawal tests were carried out using the equipment shown in Figure 2. After a test was

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**Table 1.** LIST OF SPECIES AND NUMBER OF SPECIMENS OF EACH INCLUDED IN THE TEST. EACH SAMPLE USED IN THESE TESTS WAS CUT FROM AN ACTUAL FURNITURE FRAME. IN NO CASE WAS THERE MORE THAN ONE SAMPLE CUT FROM ANY SINGLE MEMBER IN A FRAME, THE EXACT SOURCES OF THE MATERIAL USED IN THE FRAMES IS UNKNOWN, BUT THE FRAMES WERE RECEIVED FROM WIDELY SCATTERED GEOGRAPHIC LOCATIONS.

<table>
<thead>
<tr>
<th>Species</th>
<th>Number of specimens</th>
</tr>
</thead>
<tbody>
<tr>
<td>White Ash</td>
<td>1</td>
</tr>
<tr>
<td>Basswood</td>
<td>1</td>
</tr>
<tr>
<td>Amer. Beech</td>
<td>4</td>
</tr>
<tr>
<td>Amer. Elm</td>
<td>3</td>
</tr>
<tr>
<td>Red Elm</td>
<td>4</td>
</tr>
<tr>
<td>Rock Elm</td>
<td>1</td>
</tr>
<tr>
<td>Hackberry</td>
<td>3</td>
</tr>
<tr>
<td>Shegbark Hickory</td>
<td>3</td>
</tr>
<tr>
<td>Magnolia</td>
<td>4</td>
</tr>
<tr>
<td>Soft Maple</td>
<td>3</td>
</tr>
<tr>
<td>Hard Maple</td>
<td>1</td>
</tr>
<tr>
<td>Red Oak</td>
<td>13</td>
</tr>
<tr>
<td>White Oak</td>
<td>7</td>
</tr>
<tr>
<td>Yellow-Poplar</td>
<td>4</td>
</tr>
<tr>
<td>Sweetgum</td>
<td>44</td>
</tr>
<tr>
<td>Tupelo</td>
<td>12</td>
</tr>
<tr>
<td>Black Walnut</td>
<td>2</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>110</strong></td>
</tr>
</tbody>
</table>

**Table 2.** MULTIPLE CORRELATION COEFFICIENTS \( r^2 \), FOR THE CORRESPONDING EQUATIONS GIVEN IN THE TEXT.

<table>
<thead>
<tr>
<th>Equation No.</th>
<th>( r^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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</tr>
<tr>
<td>3</td>
<td>0.95</td>
</tr>
<tr>
<td>4</td>
<td>0.93</td>
</tr>
<tr>
<td>7</td>
<td>0.90</td>
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<td>9</td>
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<tr>
<td>12</td>
<td>0.98</td>
</tr>
<tr>
<td>13</td>
<td>0.78</td>
</tr>
</tbody>
</table>

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![Figure 1. Diagram showing examples of screws with fully embedded tip and protruding tip.](image-url)
completed, the sample was immediately weighed and overried so that its MC could be determined.

An analysis of the data from the tests carried out indicated that the screws driven completely through the specimens had 16 percent greater withdrawal strength, on the average, than those that were simply embedded to the full depth of the wood. This result clearly demonstrates that a tip effect exists and should be taken into account in a predictive expression.

To evaluate the convention of subtracting one full diameter of the screw from the embedded length to arrive at an effective depth of penetration, Equation [1] was written in the form:

$$F_e = 3.204D(L - aD)^{1/4}S,$$

where $a$ is a constant in order to predict the withdrawal strength, $F_e$, of screws fully embedded in the wood, and in the form:

$$F_p = 3.204D(L)^{1/4}S,$$

in order to predict the withdrawal strength, $F_p$, of screws with tips driven completely through the samples. Forming the ratio of these two expressions, and solving for $a$ gives:

$$a = 1 - (F_p/F_e)^{6/3}L/D$$  [2]

Carrying out this operation on each of the pairs of values obtained for each wood sample and averaging the results gives $a = 0.80$. This result indicates that subtracting a full diameter, i.e., letting $a = 1.0$, from the embedded length of the threaded portion of the screw gives an estimate that is conservative for this particular set of specimens. It must be remembered, however, that the constant, $a = 1.0$ utilized in Equation [1] is an average value which applies to any of the comprehensive collection of length-diameter classes included in the Fairchild data, whereas the value, $a = 0.80$, is a specific value which strictly applies only to number 10 screws embedded about 7/8 inch in wood. Furthermore, if we assume that the average thickness of the samples was 7/8 inch, then the loss of predicted strength noted in using a value of 1.0 instead of 0.8 in Equation [1] for number 10 screws is only about 4 percent. From a practical point of view, this is not a serious reduction, and the results of these tests tend to justify the practice of using the single general constant, $a = 1.0$, rather than a number of local constants.

An analysis of these same test results was next made to determine whether SG or shear strength was the better predictor of withdrawal strength with regard to these samples. In order to do this, two comparable regression expressions, one based on shear strength and the other based on SG, were fitted to the results reported by Fairchild (1927). The expression developed for SG was:

$$F_s = 17,700D^{1.166}(L - D)^{0.707}G_s^{1.345}$$  [3]

where $G_s$ = the specific gravity of the wood based on oven-dry weight-oven-dry volume. All of the other symbols have the same meanings as previously defined. The regression expression developed to predict withdrawal strength based on shear strength and fitted to the same data was:

$$F_s = 13.16D^{1.155}(L - D)^{0.702}S_s^{0.440}$$  [4]
where all of the symbols have the same meanings previously defined in Equation [1]. Predicted values for the withdrawal strengths of the screws from the 110 samples were then calculated using both Equations [3] and [4] and compared with the observed test results by means of the statistic:

$$\frac{1}{n} \sum \frac{y-y'}{y} \times 100 \text{ percent}$$  \[5\]

where $y$ = the observed test value in each of the tests and $y'$ = the predicted value. This statistic gives the average difference between observed and predicted values in percent based on predicted strength. All shear strength and SG values for the various species used in Equations [3] and [4] were taken from the Wood Handbook and corrected to the appropriate MC of the samples. The intent here was to make these comparisons under the same conditions that would be faced by a designer. In other words, calculations were to be based on published values which would be available to a designer rather than on exact experimental values obtained for each specimen. Furthermore, certain species were necessarily grouped. All red oaks, for example, were treated as northern red oak, all white oak species as white oak, all hard maple as sugar maple, all soft maples as red maple, and all true hickories as shagbark hickory. Results of this analysis indicated that the average difference (Equation [5]) between observed and predicted values based on SG calculations (Equation [3]) was $+20.2$ percent compared to a difference of $+13.1$ percent when calculations were based on shear strength (Equation [4]). These results, accordingly, tend to support the supposition that shear strength is a better predictor of withdrawal strength than is SG.

The test data were next used to further evaluate the accuracy of the predictions made by Equation [1]. This expression, it should be noted, differs from Equation [4] in that it was based on the combined data of Fairchild (1927) and Cockrell (1933). Predicted withdrawal values were calculated for each pair of screws and then compared to observed results by means of the statistic previously discussed (Equation [5]). The average difference between observed and predicted values for screws which had their tips protruding was $+5.9$ percent. The comparable difference for those screws which were embedded to the full depth of the wood was $+9.9$ percent so that the overall average difference for the two cases was $+7.9$ percent. From a practical point of view, this represents a rather close agreement between predicted and observed values. Although Equation [1] could be modified to increase predicted values by $7.9$ percent, it is not felt that such a change is justified on the basis of the data presented here, and any such modifications, if warranted, should be based on the results of future studies.

Since it was previously stated that the formula presented in the Wood Handbook for the withdrawal strength of screws from the side grain of solid wood was not entirely satisfactory for the problems of furniture design, it is interesting to compare predicted and observed results obtained using this formula with those obtained using Equation [1]. Modifying the formula given in the Wood Handbook to take length into account and to give ultimate rather than allowable values (i.e., eliminate the specified factor of safety of 6) gives an expression of the form:

$$F_w = 14.220 DU G^2$$  \[6\]

where the symbols have the same meanings as previously defined. Using this formula, the average differences between observed and predicted values for protruding and fully embedded screws were $+52.6$ and $+29.9$ percent, respectively. When these values are compared to those obtained using Equation [1], considerable support is provided for the conclusion that Equation [1] is a better predictor of screw strength for furniture construction problems than is the Wood Handbook expression.

End Grain

Regression analyses of the results obtained by Fairchild (1927) and Cockrell (1933) indicate (Eckelman 1975) that the average ultimate withdrawal strength of screws from the end grain of solid wood can be predicted by means of the expression:

$$F_w = 8.75D^{0.44}(L-D)^{0.44}$$  \[7\]

where $F_w$ = withdrawal strength from end grain in pounds.

In order to evaluate this expression, number 10, type A sheet metal screws were embedded 1-inch deep in the end grain surface of 10 samples each of sugar maple, red oak, and yellow poplar. The withdrawal strengths of the screws were then determined using a test set up similar to that shown in Figure 2. Predicted values were calculated using Equation [7] and then compared to observed values by means of the average difference statistic, Equation [5]. The average difference between observed and predicted values amounted to $-6.4$ percent; i.e., Equation [7] under-predicted the withdrawal strength by 6.4 percent. Again, this represents a rather close agreement between predicted and observed values. It is not felt that a change in Equation [7] to account for the differences noted is justified unless further research indicates that it is needed.

It is interesting to again calculate the values predicted by the Wood Handbook and compare them with observed results. The convention described in that document is to calculate end grain withdrawal values as equal to 75 percent of side grain values. Carrying out this operation by means of Equation [6] for sugar maple, red oak, and yellow poplar, averaging the test results for each of the species, and substituting the appropriate values into Equation [5] gives differences of $8.0$, $-9.8$, and $59.7$ percent, respectively, between predicted and observed values for these species. Again, the calculations based on shear strength appear to give better estimates of withdrawal strength than those based on SG, particularly in the case of yellow-poplar.

Face Withdrawal

Extensive studies (Johnson 1967; Anon. 1968) have been made of the withdrawal strength of screws from particleboard, but the lengths of embedment used have generally been limited to either $5/8$ or $2/3$ inch so
that insufficient information has been available to formulate a reliable relationship between depth of embedment and withdrawal strength. In order to obtain this information, tests were carried out on 60 specimens which had screws embedded in them to depths ranging from 1/2 to 1-3/4 inches. These samples were constructed of two 7/8-inch-thick pieces of medium density, homogeneous hardwood fiberboard which were glued together. The two pieces joined together were as closely matched as possible with respect to density so that the resulting specimen was of uniform density. A single number 10, type A sheet metal screw was inserted into each specimen. Ten each of the samples had screws driven into them to depths of 1/2, 3/4, 1, 1-1/4, and 1-3/4 inches. These screws were then withdrawn from the samples by means of the equipment shown in Figure 2. A regression expression of the form:

$$F_t = a_0 D^{1/3}(L-aD)^{1/3}G_s$$  \[8\]

where fitted to the results obtained where

- $F_t =$ withdrawal strength from the face of the board in pounds
- $a_0$, $a_1$, ..., $a_6 =$ the regression coefficients
- $G_s =$ SG of the material based on oven dry weight
- and volume at current MC.

Since only a single screw diameter was used in the tests described here, the relationship of withdrawal strength to screw diameter; i.e., $a_1 = 1/2$, was first determined from an analysis of the data presented by Johnson (1927) so that only the coefficients $a_0$, $a_2$, $a_3$, and $a_4$ remained to be determined. After carrying out several analyses in order to reduce the coefficients to their simplest form without seriously affecting the predictive power of the expression, the following formula was developed:

$$F_t = 3700D^{1/3}(L-D/3)^{1/3}G_s$$  \[9\]

Additional tests were then carried out to evaluate the reasonableness of the factor used in Equation [9] to correct for tip effect; i.e., $D/3$. The samples used in these tests were constructed of a single layer of the same material used in the previous tests. Each of the samples had two screws embedded in it. One screw was driven completely through the specimen so that the tip protruded, whereas the other screw was embedded to the full thickness of the specimen. In order to evaluate the correction factor for tip effect, the results of withdrawal tests carried out on these specimens were again analyzed using equation [5] as was previously done for the solid wood samples. The average value determined for the constant $a$ was 0.334 which agrees closely with the value of 0.333 used in Equation [9]. This result indicates that the correction factor, $D/3$, was the most appropriate one to use with regard to these specimens, when the quantity $(L-aD)$ is raised to the 5/4 power. It should be noted here, however, that these factors are interrelated so that, had a different power been used, the value of the constant $a$ would also have changed.

The results obtained by Johnson (1967) were then re-examined to obtain an expression which would apply to particleboard rather than fiberboard. In carrying out these analyses, the following relationship based on Equation [9] was used:

$$F_t = a_0 D^{1/3}(L-D/3)^{1/3}G_s$$  \[10\]

so that only the coefficient $a_0$ remained to be found. The final form of the regression expression fitted to the data was:

$$F_t = 2655D^{1/3}(L-D/3)^{1/3}G_s$$  \[11\]

where $F_t$ refers to withdrawal strength from the face of particleboard. In these expressions it was assumed that the relationship of withdrawal strength to depth of embedment was the same for both particleboard and fiberboard; just as it was assumed in Equation [9] that the relationship to diameter was the same for both materials. These assumptions remain to be experimentally validated, but considering the similarity of the two materials, they appear to be reasonable approximations to make at this time.

Tests were then carried out to see how well this expression would predict the withdrawal strength of screws from a type of particleboard which was in common use; namely, a 1/2-inch-thick, homogeneous, softwood board. In these tests, 10 each of 7 different manufacturer's types of number 8 screws were embedded the full thickness of the particleboard, and 10 each were also driven through the board. Withdrawal tests were again carried out using the equipment shown in Figure 2. Predicted withdrawal values were then calculated using Equation [11] and compared to the observed values by means of the statistic given in Equation [5]. The average predicted values were 2.2 percent less than observed values when screws were fully embedded and 3.6 percent less when the screws penetrated the samples which gives a combined average of $-2.9$ percent. These results accordingly indicate a rather good agreement.

It is interesting at this point to compare the results predicted by this expression with those predicted by the National Particleboard Association (NPA) expression. This latter expression is of the form:

$$F_t = 2743.3+11.32X$$

where $X =$ the density of the board in pounds per cubic foot. A graphical analysis is given in Figure 3. In order to use Equation [11], an MC of 10 percent was assumed in the calculations. The NPA expression, on the other hand does not take MC into account. As can be seen the results agree reasonably well even though the NPA expression is a linear one whereas the expression developed in this study is nonlinear. It must be remembered, however, that the MC assumed in the calculations with the NPA expression has a direct bearing on how well the results agree.

**Edge Withdrawal**

Tests were also carried out to determine the relationship between depth of penetration and the withdrawal strength of screws from the edge of fiberboard. In these tests, 5 each of number 10, type A sheet metal screws were embedded 1/2, 1, and 1-1/2 inches into the edge surface of specimens of homogeneous, hardwood fiberboard which was 7/8-inch thick. Only one screw was driven into each specimen. A 1/8-inch diameter pilot hole was used in all cases. The screws were withdrawn from the specimens using the equipment shown in Figure 2.
Regression analyses were then carried out on the data, and an expression similar to Equation [9] was developed, namely:

$$F_x = 2860D^{1/2}(L-D/3)^{1/2}G_i^2$$ \[12\]

Using the length relationship established in this expression, the results obtained by Johnson (1967) in his study of the edge withdrawal strength of screws in particleboard were then analyzed to obtain a predictive expression for particleboard. The results of the analysis yielded the expression:

$$F_x = 2055D^{1/2}(L-D/3)^{1/4}G_i^2$$ \[13\]

Summary

An analysis of the results reported by several researchers indicates that the withdrawal strength of screws from the side grain of solid wood can be predicted by means of the expression:

$$F_x = 0.20D(L-D)^{1/2}S_i$$ \[1\]

A similar analysis indicates that the average withdrawal strength of screws from end grain surfaces of solid wood can be predicted by the expression:

$$F_x = 6.75D^{1/4}(L-D)^{3/4}S_i$$ \[7\]

In the case of withdrawal tests carried out by the author on several hardwood species which are commonly used in furniture construction, Equation [1] underpredicted the holding strength of screws in side grain by only 7.9 percent, and Equation [7] overpredicted the holding strength of screws in end grain by 6.4 percent. In both cases, the shear strength of the wood was shown to be a “better” predictor of holding strength than SG. It was also shown that these equations are able to predict the withdrawal strength of screws more closely than other available design expressions under the conditions encountered in furniture construction.

The results of screw withdrawal tests carried out on hardwood fiberboard by the author were combined with the results obtained by other investigators for withdrawal strength from particleboard in order to develop expressions to predict the withdrawal strength of screws from the face and edge of particleboard and fiberboard. In the case of particleboard, it was found that the withdrawal strength of a screw from the face of a board could be predicted by the expression:

$$F_y = 2655D^{1/2}(L-D/3)^{1/4}G_i^2$$ \[11\]

and from the edge of a board by:

$$F_y = 2055D^{1/2}(L-D/3)^{1/4}G_i^2$$ \[13\]

Comparable expressions developed for fiberboard were:

$$F_y = 3700D^{1/2}(L-D/3)^{1/4}G_i^2$$ \[9\]

for face withdrawal, and:

$$F_y = 2600D^{1/2}(L-D/3)^{1/4}G_i^2$$ \[12\]

for withdrawal. Values predicted by Equation [11] were compared with those predicted by an expression published by the NPA for number 8 screws embedded 5/8 inch in particleboard, and a relatively close agreement was noted. Furthermore, values predicted by Equation [11] were found to differ from experimental values obtained by the author for number 10 screws embedded 1/2 inch in softwood particleboard by an average of –2.9 percent.

These equations were developed primarily to provide furniture designers with reasonable estimates of the holding strength of screws in wood and wood-base materials. In using these equations, it should be remembered that they are not design formulas, but rather formulas which have been developed to predict average expected ultimate values. Future research will no doubt indicate the changes that are needed in these formulas to improve their predictive accuracy, and experience will indicate the safety factors that must be applied to arrive at allowable design values for use in furniture construction. Even in their present form, however, these formulas do provide a means of putting the information that is presently available concerning the holding strength of screws into a manageable form, and they also provide a means of evaluating new research so that better predictive expressions can be formulated.

**Literature Cited**


