Designing high quality furniture with wood composites

by Carl A. Eckelman
Professor of Wood Science, Purdue University, West Lafayette, Indiana

Abstract
Modern furniture designs require the use of wood composites with high strength properties. It is necessary, therefore, for the furniture manufacturer to systematically assess the physical properties requirements of the boards he uses and for the board producers to provide meaningful physical properties data for the boards they produce. Of particular interest, allowable design stress values are needed for wood composites, or, at the least, statistical tolerance limits. In addition, published values for the creep characteristics of the commercial boards is critically needed. In this paper, the physical properties requirements of various furniture constructions are discussed, along with the relationship of fastener-holding strength to board properties. In general, it is shown that boards with high strength and performance characteristics are needed to satisfy modern furniture design requirements.

Modern furniture designs impose ever-increasing performance demands on the properties of the materials used in their construction. This is particularly true in the case of furniture constructed of wood composites. New design systems such as the 32-mm system for kitchen cabinets require that the boards perform as unsupported structural members. In addition, relatively small fasteners are used to hold large panels together so that joint forces are high. Wood composites are also used increasingly as unsupported structural members in tabletops, shelves, and other flat panel applications. If such furniture is to give satisfactory service, it is essential that furniture manufacturers select and purchase only those boards which can meet the high performance and uniform quality requirements of modern furniture. Historically, failure to follow this procedure has resulted in such spectacles as conference tables with a 3-inch sag, shelves and case tops and bottoms with unsightly deflections, desktops with a sway-back appearance, cases with fasteners torn loose at the corners, and so on.

Board properties most important to furniture manufacturers include: 1) modulus of rupture (MOR), ultimate bending strength; 2) modulus of elasticity (MOE), stiffness; 3) internal bond strength (IB), force required to pull the board apart; 4) creep resistance, the tendency of the board to continue to deflect with time; 5) impact strength, the ability of the board to resist sudden impact forces without breaking; and 6) modulus of rigidity (G), the resistance of the board to twisting forces. Nonstrength properties are also important such as the shrinking and swelling characteristics and the surface smoothness of the board.

A factor equally important as average mechanical strength properties is the range of strength properties that must be expected in any shipment of boards. A quoted average value of 3,500 psi for MOR may be misleading if the minimum value to be expected from that lot of boards may be as low as 1,000 or 1,500 psi. For this reason, furniture manufacturers should not specify boards in terms of average values. Rather, they should specify minimum values. Technically, however, it is essentially impossible for board producers to guarantee minimum strength properties. A technique that is widely used in other fields and could be used with composites is to specify what are known as “statistical tolerance limits” for the properties of the boards. Two statements are embodied in such tolerance limits. The first statement expresses the degree of confidence in the statement to be made about the strength properties of the board. The second statement expresses the anticipated properties of the board. Thus, a tolerance limit for a board product might state that a manufacturer is “90 percent confident that 95 percent of the boards in a given shipment may be expected to have a MOR equal to or exceeding some value, such as 3,000 psi.”

To provide tolerance limits for boards, producers must regularly sample and test their production material – most producers already do this since the average strength values published for their boards are pre-
that the creep modulus for particleboard loaded to 20 percent of ultimate strength for 15 days amounts to about 0.65E where E is the MOE of the board. Similarly, a study carried out by Dinwoodie, et al. (4), indicates that the creep modulus of particleboard loaded to 30 percent of ultimate for a period of 2 years may be taken as 0.47E.

These two values provide some indication of the intermediate and long-term deflection of particleboard as a function of the MOE. Notice that these factors apply to particleboard loaded to only 20 and 30 percent, respectively, of ultimate strength; these factors should not be applied to boards which are more heavily loaded. In particular, it should be remembered that particleboard loaded to 50 percent of its ultimate strength may be expected to fail in about 1 year (7).

The important point to be remembered, however, is that if a furniture manufacturer is to design shelves rationally, there must be reliable quantitative information concerning the creep characteristics of the board used. Logically, this information must necessarily be provided by the board producers.

What magnitude of mechanical properties should the furniture manufacturer expect to be able to buy in the present market? In the case of particleboard, a good stiffness value might be 500,000 psi; a good bending strength value might be 3,500 to 4,000 psi; and a good IB value might be at least 120 psi (1). In the case of medium density fiberboard (MDF), a slightly lower value for MOE of about 400,000 might be expected.

In the case of particleboard, the long-term deflection of a panel under the worst anticipated load conditions should not be more than twice its initial deflection.

The importance of the board properties listed above can perhaps best be illustrated by actual furniture and fastener examples.

**Dowels**

The ultimate holding strength of 3/8-inch diameter dowels embedded in the face of MDF and particleboard under optimum gluing conditions may be predicted by using Equation [2]. This expression indicates that face holding strength is strongly related to both the IB strength of the board and to the depth of embedment of the dowel. As an example, the face withdrawal strength of a 3/8-inch diameter dowel embedded 5/8-inch in a piece of particleboard or MDF which has an IB strength of 120 psi can be calculated with Equation [3].

This is a rather high value which can be obtained only under optimum construction conditions, but it does indicate the potential strength that can be obtained with dowel joints in MDF and particleboard. If, however, the board had an IB strength of only 60 psi, the holding strength of the dowel would be reduced to (60/120)0.85 x 608, or 337 pounds. As can be seen, the holding strength of the dowel in the board with the lower IB strength has been greatly reduced.

The importance of using boards with high IB strengths becomes even clearer if a more practical design problem is considered in which the depth of penetration is reduced.

In many modern cabinet systems, the effective depth of penetration of the dowel in the face of the boards is often no more than 3/8 inch. For this depth of penetration, the holding strength of the dowel in a board with an IB of 120 psi would be (0.375/0.625)0.85 x 608, or 394 pounds. For the board with an IB strength of 60 psi, however, the holding strength of the dowel would amount to only (0.375/0.625)0.85 x 337, or 217 pounds.

---

**Equation [1]**

\[
E' = E/(1 + (\gamma_c - \gamma_s)/\gamma_s) = E/(1 + \gamma_c/\gamma_s)
\]

where:

- \(E\) = creep modulus [psi]
- \(E'\) = modulus of elasticity [psi]
- \(\gamma_c\) = inelastic deflection owing to creep [in.]
- \(\gamma_s\) = initial elastic deflection [in.]
- \(\gamma_t\) = total deflection [i.e., \(\gamma_s + \gamma_c\)]

---

**Equation [2]**

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

where:

- \(f_s\) = withdrawal strength of the dowel [lb.]
- \(IB\) = internal bond strength of the board [psi]
- \(D\) = diameter of the dowel [in.]
- \(L\) = depth of embedment of the dowel in the face of the board [in.]

---

**Equation [3]**

\[
f_s = 28(0.5)^{0.6}(120)^{0.85}(0.625)^{0.85} = 610 lbs.
\]
it is remembered that these values may be expected only under optimum conditions and that production line joints may have considerably less strength. It is not difficult to visualize that if such a joint were given a sharp jolt in service, it would likely fail. Clearly, the strength of a joint that can be produced in this type of construction is limited. Therefore, it is essential that such furniture be constructed with boards of high IB strength in order to obtain the highest holding strengths possible.

**Screws**

The holding strength of screws in the face of MDF and particleboard may be predicted by using Equation [4]. Similarly, the holding strength of screws in the edge of MDF may be predicted by using Equation [5]. It should be noted that this second expression does not hold for particleboard that has a coarse core and overall stratified structure.

Both of these expressions clearly illustrate that holding strength is directly related to the IB strength of the board. To demonstrate the importance of high IB strength to the holding strength of screws, let us calculate the holding strength of a No. 10 sheet metal type screw embedded 1/2 inch deep in the face of an MDF board which has an IB strength of 150 psi. Substituting the appropriate values into the first of the two above expressions results in Equation [6].

Had this screw been inserted in a board with a much lower IB strength of only 60 psi, its withdrawal strength would have been \( \frac{60}{150}^{0.85} \times 427 \), or 196 pounds. Use of the board with the lower IB strength, accordingly, reduces the holding strength of the screw by over 50 percent.

In contrast to the strong relationship between holding strength and IB strength, the above expressions indicate that the holding strength of screws in MDF is only weakly related to the diameter of the screw. Furthermore, realistically, the diameter of the screw used in a given application cannot likely be varied over a wide range, whereas boards with a wide range of IB strengths could potentially be used. In general, therefore, optimum holding strength is not likely to be obtained through the enlightened choice of a specific mechanical fastener but rather through the choice of boards with high IB strengths.

**Threaded metal inserts**

The holding strength of threaded metal inserts in the face of MDF and conventional particleboard may be predicted by using Equation [7]. This expression indicates that the holding strength of threaded metal inserts in MDF and particleboard is related primarily to the depth of insertion of the fastener into the board; it is only weakly related to either diameter or the IB of the board. Furthermore, the expression indicates that the holding strength to be expected from inserts is, in fact, limited relative to the size of the fastener. As an example, the holding strength of a 1/2-inch diameter insert embedded 1/2 inch deep in an MDF board which has an IB strength of 170 psi is found using Equation [8]. This value is comparable to that previously calculated for a 3/8-inch diameter dowel embedded 5/8 inch deep in a board with an IB of only 120 psi. Had a board been used which has an IB strength of only 80 psi, the holding strength of the fastener would amount to only \( \frac{80}{170}^{0.85} \times 561 \), or 384 pounds. Therefore, even though the relationship is relatively weak, the difference in holding strength to be obtained from boards with high IB strengths compared to boards with low IB strengths is quite significant.

**Shear deflection**

The midspan deflection of a simply supported uniformly loaded shelf is given in Equation [9]. As can be seen, the deflection of a shelf is directly related to its geometry and to the material properties of the board, specifically the MOE of the board. Ordinarily, the geometry of the board is fixed by aesthetic considerations. As a result, deflection must be controlled through the use of boards with appropriate MOE properties. To illustrate, the midspan deflection of a shelf which is 30 by 8 by 3/4 inches, has an MOE of 350,000 psi, and is loaded to a relatively light load level of only 1.67 lb./in. (20 lb./ft.), can be found in Equation [10]. The deflection over span ratio, \( y/L \), for this shelf amounts to 0.18/30, or, 1/168. In general, an acceptable \( y/L \) ratio for quality furniture amounts to 1/360. For less demanding situations where deflection cannot be readily observed and compared to straight line, a ratio of 1/180 may be acceptable. Above the greatest ratio that the human eye will accept is perhaps 1/165 to 1/150 [9]. Deflection/span ratios greater than this will judged totally unacceptable by nearly any observer. Hence, it can be seen that the deflection is too great to be acceptable in furniture.

The deflection of the above shelf can be improved either by increasing its thickness (which will likely result in an unsightly shelf) or by using a board with a high MOE. If, for example, a commercially available MDF board is used which has a vertised MOE of 600,000 psi, the deflection would be reduced to \( \frac{350,000/600,000}{0.18} \), or 0.10 inch. The \( y/L \) ratio for this deflection amounts to 0.10/30, or 1/300, which is acceptable.

\[
\text{Equation [4]} \quad f = 39(150)^{0.85}D^{0.5}[L - D/3]^{1.25}
\]

where:
- \( D \) = diameter of the screw (in.)
- \( L \) = depth of embedment of the screw (in.)

\[
\text{Equation [5]} \quad f = 18.4(150)^{0.85}(L - D/3)^{1.25}
\]

\[
\text{Equation [6]} \quad f = 39(150)^{0.85}(0.190)^{0.50}(0.50 - 0.190/3)^{1.25}
\]

\[
\text{Equation [7]} \quad f_s = 121.5(150)^{0.5}L^{0.5}
\]

\[
\text{Equation [8]} \quad f = 121.5(1700)^{0.5}(0.50)^{0.5}(0.50) = 561 \text{ lbs}
\]

\[
\text{Equation [9]} \quad y = 5qL^4/[384E(wr^2/12)]
\]

where:
- Simply supported span
- \( y \) = deflection at midspan (in.)
- \( q \) = linear load (lb./in. of shelf length)
- \( L \) = shelf span (in.)
- \( E \) = modulus of elasticity (psi)
- \( w \) = width (in.)
- \( t \) = thickness (in.)

\[
\text{Equation [10]} \quad y = 5(1.67)(30)^4/[384(350,000)(8.75)^2/12] = 0.18 \text{ in.}
\]
might be acceptable for short-term loading. It is necessary, however, to take the creep of the board into account. A rule of thumb suggested by the producer for the above board which may be used to take its long-term deflection, or creep, into account is to calculate long-term deflection as equal to double the short-term deflection \(8\). Hence, a shelf constructed with this board would not be acceptable on a long-term basis since its deflection after a period of use would amount to \(2 \times 0.10\), or 0.20 inch, and its \(y/L\) ratio would be 0.2/30, or 0.0066 which is unacceptable.

Clearly, the thickness of the shelf must be increased if deflection is to be held to acceptable limits. If, for example, the thickness of the shelf were increased to 1 inch, the midspan deflection would be reduced to \((0.75/1.125) \times 0.18\), or 0.08 inch. The \(y/L\) ratio for this deflection amounts to 0.08/30, or 0.133, which would be acceptable. From an aesthetic viewpoint, however, the shelf would likely be unsightly and unacceptable. If a 7/8-inch-thick shelf were used instead of a 1-inch-thick shelf, the deflection would amount to \((0.75/0.875) \times 0.18\), or 0.113 inch, which has an \(y/L\) ratio of 1/255. Again, on a long range basis, this design would not be acceptable.

Such calculations could be continued indefinitely, but, in general, what they would show is that conventional particleboard and MDF are likely to be satisfactory in shelving only if they are limited in use to lightly loaded, relatively short shelves. If, for example, the length of a shelf is increased from 30 to 36 inches, its deflection will double; i.e., its deflection will increase by a factor of \(36/30\) or 2.07. In general, therefore, where shelves are to be heavily loaded or where long spans are to be used, it may be necessary to use one of the oriented strand type of boards which have MOE in excess of 1 million psi. Realistically, however, before these boards can be used by the furniture manufacturers, the smoothness of the board surfaces must be improved.

The deflection characteristics of particleboard and MDF shelving are improved when the top and bottom surfaces are veneered. The stiffness added to the shelf by the veneer may be calculated by the method of equivalent sections \(5\). Unless the veneer is of substantial thickness, however, the contribution of the veneer faces may be quite limited.

Summarizing the use of particleboard and MDF in shelving, it is difficult to obtain satisfactory performance even when the highest quality boards are used. Boards with low MOEs, therefore, should be avoided. Finally, in order to satisfy deflection criteria in heavily loaded shelving or in relatively long shelving and still keep shelf thickness within acceptable aesthetic limits, it may be necessary to use one of the oriented strand type boards, provided that the producers are able to manufacture boards with satisfactory surface smoothness.

### Tables

An inordinate number of problems arise with tabletops and desktops which tend to take on a swayback appearance in service. These problems arise primarily in those types of designs in which the tops are unsupported by rails, and in the case of desks, where the pedestals are hung from the tops. A few design calculations readily illustrate the causes of these problems.

The deflection of tabletops which are supported only at the ends or the corners may be calculated, as a first approximation, by means of beam formulas. For a top subjected to a point load at midspan, the corresponding deflection at this point is given by Equation [12].

If an object such as a 50-pound typewriter were placed on the top at midspan, the expected deflection of the top would amount to 0.004 \(\times 50\), or 0.20 inch. This amounts to a \(y/L\) ratio of 1/360 which would be acceptable. If, however, this load remains on the table, the top must be expected to deflect an amount equal to twice its original value, or 0.4 inches. The \(y/L\) ratio would now amount to 1/180 which would not be acceptable. What these calculations show is that if an acceptable \(y/L\) ratio for this table is to be preserved, its long-term load carrying capacity is limited to 25 pounds. In reality, the weight of the top itself must also be taken into account since it will significantly contribute to the deflection of the top. Given the above considerations, it is not difficult to see why numerous problems arise with unsupported tabletops and desktops, and in the latter case, in those tops in which the pedestals are attached to and supported by the top itself.

In the previous example, a top thickness of 1.25 inches was assumed. Had a thickness of 1.375 inches been assumed, the midspan deflection would have been reduced according to the ratio \((1.25/1.375)^3\) or 0.75; i.e., the deflection would have been only 75 percent as great as predicted above. On the other hand, had a thickness of 1 inch been used, the deflection would increase by the ratio \((1.25/1)^3\) or 1.95; i.e., the deflection would be nearly twice as great as calculated above. It is not difficult to see why many problems have occurred in this type of construction when thinner boards are used. Finally, to use an extreme case, if a 3/4-inch-thick board were used (as is occasionally done), the deflection would be almost five times as great as with the 5/4-inch board.

Similarly, it was assumed that the board had an MOE of 400,000 psi. Had a board been used with an MOE of 600,000 psi, the deflection would have been only two-thirds as great. In like manner, if a board with an MOE of 1 million had been used, the deflection would have been halved. On the other hand, had a board with an MOE of 250,000 psi been used, the deflection would have increased by a factor of 1.6.

Clearly, the structural demands of tables with unsupported tops are difficult to satisfy even with the best of board materials. Fur-

---

**Equation [11]**

\[
y = F_L^{3/4}(48EI)
\]

where:

- \(F_L\) = magnitude of the point load (lb.)

**Equation [12]**

\[
y = 1^{[72/90(48[400,000][30 \times 1.25/12)] = 0.004\text{ in.}}
\]
Furniture manufacturers should choose board materials carefully, therefore, to ensure that they obtain those boards with optimum stiffness and creep characteristics.

In considering the use of composites in tabletops, it is also necessary to consider the strength of the top. In the case of the table discussed above, the bending stress acting at the center of the top, as a first approximation, is given by Equation [13].

For a 1-pound load, the stress acting at midspan in the sample table would be that found in Equation [14].

If a 200-pound person were to sit on the table, the corresponding stress at midspan would amount to 200 \times 2.3, or, 461 psi. It should be noted that the corresponding midspan deflection would amount to 0.004 \times 200, or 0.8 inch. Note that if two such people were to sit on the table, the value could be doubled to 922 psi, and, in fact, depending on how the table might be used, or abused, internal stresses could be developed which might be dangerous. The least strength to be expected from the boards becomes very important for this reason. In tests carried out by the author, a top with a specified MOR of 2,400 psi was found to have an actual MOR of only 1,200 psi. Although it might have appeared safe to use this board on the basis of its published values, its use would, in fact, be quite questionable in a top of this design.

Frames

For a number of years, attempts have been made with varying success to use various composites in chair and sofa frames. Where this material is used for decorative, nonstructural purposes, there should be little problem in its use. Where it is used for structural purposes, however, considerable discretion should be exercised. This follows because there are no published allowable design stress values for these materials. Furthermore, as discussed above, no information is published concerning the weakest material to be expected in a given batch of board. Furthermore, the impact strength of these materials as compared to solid wood is quite low so that they are at risk when they are used to replace long slender solid wood members. The problems encountered in the use of these materials are readily demonstrated by example.

In the case of sofa frames, the front rail of a sofa with a 78-inch front opening might be as small as 4 inches deep. Ordinarily, this member would be constructed of 15/16-inch-thick sweet gum or red oak. A recommended practice with MDF is to use material 3/4 inch thick. If one assumes a nominal loading of three 125-pound vertical loads acting at the third points of the rail, then the bending force acting at midspan of the rail is given in Equation [15]. Substituting the appropriate values into Equation [15] results in Equation [16]. As can be seen, this is a relatively high value relative to the expected strength of the board materials. In the case of some composites, it would be almost as great as the ultimate strength of the board. Also, it would not have the impact strength of solid wood so it could be readily broken if subjected to a sharp sudden impact load.

Perhaps more importantly, however, if the sofa is constructed with sinusoidal-type springs, these springs will impose substantial front to back forces on the front rail. It would not be uncommon, for example, if 18 seat springs were used to construct the seat foundation. Each of these springs, as installed, will exert a front to back force of about 35 pounds on the rail. Therefore, the total front to back force exerted on the rail, even when the sofa is not in use, will amount to at least 35 \times 18, or, 630 pounds. Under these conditions, the rail would be expected to creep an excessive amount with time even though the front rail may be well braced with stretchers. Ordinarily, the fabric tends to hide the normal curvature that occurs, but the degree of curvature expected in this case might be too great. Furthermore, a few preliminary calculations will quickly reveal that the magnitudes of the stresses generated by the springs are sufficient to cause the rail to fail in out-of-plane bending.

In the case of chairs, entire piece side frames have been cut from sheets of MDF. The back legs and back posts in these frames have been as small as 2 inches in depth. In general, it would appear that these frames could be readily broken by impact loads, but beyond this point it is necessary to look at what might occur if someone leans backward in a chair. If, for example, a 200-pound user leans backward to a single of 30 degrees in a chair which has 4-inch legs, the bending force exerted on the leg to rail joint would be expected to be 100(1/2)(16), or 800 psi. For a leg with 3/4-inch thick by 2 inches deep, the corresponding internal resisting stresses are found in Equation [17]. When the consequences of a failure in a critical part as this is considered, this appears to very high level of stress for such parts. Furthermore, if the lowest strength to be expected from the boards is from which this parts are cut cannot be determined, questions must necessarily be raised about safety of such parts.

Conclusions

In order to satisfy the high strength, stiffness, creep resistance, and fastener-holding requirements of modern furniture design, it is important that furniture manufacturers first assess the end-use requirements of their designs and then carefully select and purchase only those boards with properties which will meet those requirements. In many cases, it will be found that even the boards with the highest properties are only marginally satisfactory for demanding furniture constructions. It is particularly important that manufacturers obtain information on the following:

\[
\sigma_s = 6F_vL/[4wt^2]
\]

\[
\text{where:}
\begin{align*}
\sigma_s & = \text{bending stress acting at midspan} \\
W & = \text{weight of the top [in.]} \\
T & = \text{thickness of the top [in.]} \\
L & = \text{length of the top [in.]} \\
F_v & = \text{load applied at midspan}
\end{align*}
\]

\[
\sigma_s = (672)/[4(30)(1.25)^2] = 2.3 \text{ psi}
\]

\[
\sigma_s = 6(5F_vL/12)/(wt^2)
\]

\[
\sigma_s = 6(5)[125]/[78]/[124][0.75] = 2031
\]

\[
\sigma_s = 6(800)/(0.75[2]^2) = 1600 \text{ psi}
\]
concerning the variability of the properties of the boards. At the minimum, the range of values to be expected should be known before a board is purchased. Statistical tolerance limits provide more useful information and should be required for boards used in exacting situations. The creep characteristics of boards used for shelving, tabletops and desktops, and case tops and bottoms should be known before a board is purchased and used in these applications. Finally, the IB strength of boards is critical to the fastener holding ability of a board. Certainly, this property should be carefully scrutinized before a potential board is considered for applications where high joint strength is essential.

Literature cited