Tensile and compressive MOE of flakeboards

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Abstract

Normally pressed gradient-density flakeboards were tested for tensile and compressive modulus of elasticity (MOE). The panels were nonaligned and single-layer aligned. Multiple regression equations were developed for axial MOE versus board specific gravity and ultrasonic wave speed in the direction of mechanical test. These regression equations, along with specific gravity profiles through the panel thickness, were used to calculate predicted effective bending MOE. The regression model found to be most appropriate involved use of logarithmic transformation of the factor and response variables. Tensile MOE of this type of flakeboard apparently exceeds its compressive MOE. Wave propagation speed in the direction of test appears to be a practical measure of alignment, although it is not independent of panel specific gravity. Predicted effective bending MOEs were in reasonably close agreement with measured effective bending MOEs.

The bending modulus of elasticity (MOE) of flakeboards as measured according to ASTM D 1037 (1), sections 11 through 20, is not a true MOE, but rather an effective MOE. This is because the formula used to calculate bending MOE is based on a homogeneous material whereas flakeboard is not homogeneous through its thickness. Almost all flakeboards have a density distribution through their thickness and many flakeboards have different compositions and/or flake alignments at different locations through their thickness. As a result of this inhomogeneity through the panel thickness, true axial MOE (tensile or compressive MOE parallel to the panel surfaces) varies with position through the thickness.

As has been previously explained by Geimer et al. (7), the effective bending MOE (ignoring the effect of interlaminar shear deformation) of a flakeboard is determined by axial MOEs of the layers that compose it and the distances of these layers from the neutral plane. The following equation states this relationship:

$$\text{Effective bending MOE} = \frac{\sum E_i I_i}{\sum I_i}$$  \[1\]

where:

- $E_i$ = axial MOE of the $i^{th}$ layer
- $I_i$ = moment of inertia of this $i^{th}$ layer about the neutral axis

Effective bending MOE, although practically useful, has no theoretical meaning unless qualified by through-the-thickness or “vertical” density or specific gravity (SG) distribution. In contrast, axial MOEs have meaning without such qualification.

Uniform-density boards were made by Geimer (5) to obtain axial MOE data unaffected by density gradient. These boards were obtained by pressing to thickness in an unheated press, and subsequently heating the press. He found that the uniform-density panels had consistently lower tensile MOEs than similar gradient-density panels of equal average density. This finding may be caused, in part, by the fracture of wood structure within flakes, which is caused by exerting high pressure on unheated and hence relatively brittle flakes. Later findings by Geimer et al. (6) indicate that temperature and simultaneous pressure history affects tensile strength of individual flakes after mat-pressing. The data of Carll and Wang (3) suggest that in high-density panels pressed to thickness before heating, wood fracture may negatively influence axial properties parallel to the panel faces. In his 1979 report, Geimer hypothesized that density gradient in itself enhanced axial tensile MOE. This is plausible and could be caused by nonuniform tensile strain at different layers through the thickness of uniform-density panels.
Because tension specimens are loaded by gripping the panel surfaces, tensile strain in surface layers may exceed average tensile strain. Tensile strain measured from the surface may thus be deceptively high. Nonuniform distribution of tensile deformation is more likely to occur in thicker and shorter specimens and in those without the usual (i.e., denser surface layer) density distribution. In specimens from panels with the usual density gradient, the denser, stiffer layers are at the surface; and hence, the surface layers will probably not be stretched much more than the core layers. In contrast, in specimens from panels that have uniform axial MOE through their thickness, surface layers are likely to be strained more than core layers.

It would appear, then, that the tensile MOE data that Geimer obtained from uniform-density flakeboards were low compared with axial tensile MOEs of layers in a normally pressed, gradient-density flakeboard (due either to the fracture of wood structure within flakes or to nonuniform tensile strain during test). His data worked well, however, for predicting effective bending MOE of gradient-density panels with Equation [1]. Because the production of uniform-density panels is difficult, it is expedient to use axial MOE data from normally pressed, gradient-density panels in Equation [1]. Layer tensile data from gradient-density panels were used in this way by Geimer et al. (7) with moderate success. Additional work of this nature would be of value to persons wishing to design panels for effective bending MOE.

Objective

This study was undertaken to obtain axial MOE data from gradient-density boards. Dissecting the panels allowed the tensile MOE of layers as they exist in a normal flakeboard to be measured directly. An additional benefit of measuring tensile MOE of layers is that each panel can yield axial tensile data values at different density or SG levels. Furthermore, tensile MOE tests on layers would not be subject to nonuniformity of tensile strain, due to the thinness of the test specimens. The above benefits were, of course, realized by Geimer et al. (7). In this study, we wanted to compare axial tensile MOEs of different layers with axial tensile or compressive MOEs of full-thickness specimens, something that had not been done before.

A specific objective of this study was to develop multiple regression equations of axial MOE versus specimen SG and flake alignment.

Procedure

Boards measuring 0.5 by 24 by 28 inches (13 by 610 by 711 mm) were made of disk-cut flakes of douglas-fir (Pseudotsuga menziesii) and bigtooth aspen (Populus grandidentata). The flakes were cut 2.5 inches (6.35 cm) long by 0.030 inch (0.762 mm) thick by random width and were run through a fan to break them into narrower flakes that could be aligned. Binder resin was a resol liquid phenolic applied at 5 percent resin solids content (based on oven-dry (OD) wood mass). Wax emulsion was also used and applied at 1 percent wax solids content, also on OD wood mass basis. Mat moisture content (MC) going to the press was targeted at 10 percent-based on OD mass of flakes plus wax and resin solids. Nonaligned, moderately aligned, and highly aligned panels were made at each of four target SGs for each of the two species. Target SGs were: 0.48, 0.64, 0.80, and 0.96 based on OD mass and on volume as removed from the press. Aligned panels were made with the equipment described by Geimer (4). Aligner fin spacing was 0.375 inch (9.53 mm) for all aligned panels. Flake fall distance was 4 inches (10.2 cm) for moderately aligned panels and 1 inch (2.54 cm) for highly aligned panels. There were three replications of each board type for a total of 72 boards. Panels were conditioned to equilibrium at 74°F (23°C) and 65 percent relative humidity. Specific gravity values stated hereafter in this report are based on mass and volume at conditioned MC.

Axial tension and compression tests were performed on specimens from each panel. Tension tests were performed on surface-layer specimens, core-layer specimens, and full-thickness specimens. Tension specimens were obtained from 2- by 14-inch (51- by 356-mm) billets cut from the panels. Surface-layer and core-layer specimens were obtained by resawing these billets with a bandsaw and smoothing the sawn surface with a planer. Allowing for sawkerf and planing, a 2- by 14-inch billet would yield one 1/4-inch- (6.4-mm.) thick core-layer specimen or two 1/8-inch- (3.2-mm.) thick surface-layer specimens. Surface-layer specimens were marked such that each specimen was identified as being from either the top surface or bottom surface of the board (as formed and pressed). Neck-down of tension specimens was performed by routing following a template, after any sawing, resawing, planing, or (where performed) nondestructive SG distribution measurements.

Tension test specimens were longer than specified in ASTM D 1037-78 (1). The necked-down section of the test specimen was 6.5 inches (16.5 cm) long, and elongation under loading was measured over a 6-inch (15.2 cm) distance in the necked-down portion of the specimens. McNatt and Superfesky (12) found that variability in tensile MOE is reduced when elongation is measured over a 6-inch distance, particularly for flakeboards with large flakes. Furthermore, lengthening the test specimen reduces the potential for nonuniform tensile deformation to occur during testing.

Compression test specimens were also longer than prescribed in ASTM D 1037, so that compressive deformation could be measured over a 6-inch gauge distance. To avoid buckling of these longer-than-standard test specimens, the specimens had to be double thickness. Compression tests on (laminated) double-thickness specimens performed by McNatt and Superfesky (12) showed that lamination and lengthening of gauge distance reduced variability in compression MOE data more than lengthening of gauge distance reduced variability in tensile MOE data. This suggests that lamination as well as specimen length influences variability of test data.

As indicated earlier, an objective of this study was to obtain multiple regression equations of axial stiffness versus specimen SG and flake alignment, for each species. The SG of each laminated compression test
specimen was measured, and an SG measurement was made of a specimen retrieved from the necked-down section of each tension specimen after testing. Hence, for each axial stiffness value there was a unique corresponding SG value. We did not, however, obtain a unique flake alignment measurement for each individual test specimen. Alignment was measured indirectly with ultrasonic wave speed equipment (resonant frequency of the wave source was a nominal 50 kHz). The device used to measure wave speed was the same as that used by Geimer (5) and by Gerhards and Floeter (8). Measurements were made on trimmed (22-by-26-in.) panels prior to their being cut into specimens. Therefore, all specimens from each panel were assumed to have the same extent of alignment. Because test specimens were much longer than they were wide and because Gerhards and Floeter had shown that wave speed as measured with this equipment was influenced by transit distance, we had reason to believe that along-specimen and across-specimen wave speed measurements would not be comparable. Hence, we did not make these measurements.

Specific gravity distribution through the thickness of each board was measured by gamma radiation attenuation with the device developed by Laufenberg (10). This device was also used in an attempt to measure SG distribution within surface layers. Unfortunately, this device, as we had it set up, could not accurately measure SG within the outer 0.020 inch (0.51 mm) of a specimen and thus was of questionable value for measuring SG distribution within 1/8-inch-thick surface layers.

Static bending tests were performed on two specimens from each board using quarterpoint loading. Bending span was parallel to the boards' longer dimension (parallel to alignment in aligned panels). Span, specimen width, and rate of loading were as specified in ASTM D 1037 (1).

Results and discussion

Wave speed and wave speed ratio

As previously found by Geimer (5), wave speed parallel and perpendicular to the panels' longer dimension (parallel and perpendicular to alignment in aligned panels) was positively correlated with the SG of boards made to the same target alignment, with the best correlation obtained on nonaligned panels. The increase of wave speed with increasing SG is small, however, when compared with both the increase (or decrease) of wave speed parallel (or perpendicular) to the direction of alignment with increasing alignment (Fig. 1). Figure 1 also shows that the rate of increase in wave speed with increasing SG is greater across the alignment direction than along it. As a result, wave speed ratio (WSR)—i.e., the ratio of wave speed parallel to alignment to that perpendicular to alignment—is negatively correlated with SG (Fig. 2). However, the correlation of SG with wave speed or WSR does not preclude the use of SG and wave speed or SG and WSR as independent variables in the same multiple regression equation.

Wave speed and hence WSR are not direct measures of alignment. Geimer (5) found the relationship between WSR and percent alignment (measured by hand) depended to some extent on flake type and wood species (Fig. 9 of Geimer's 1979 report). Despite the imperfect relationship between WSR and percent alignment, there is strong impetus not to measure percent alignment by
hand but instead to measure wave speed. Hand measurement of percent alignment is very tedious, and of course the value obtained is influenced only by alignment of the surface layer. On the other hand, wave speed as a measure of alignment is quick, repeatable, and influenced by all layers through the thickness.

Regression equations to model MOE as a function of SG and alignment are based on Equation [2] (elementary wave theory (2)):

\[ E = \text{density (wave speed parallel to test direction)} \]

Therefore, within the same board, the ratio of stiffness parallel (to flake alignment) to stiffness perpendicular (to flake alignment) should be equal to the square of the WSR. Figure 6 in Geimer’s 1979 report shows that his data roughly conform to this relationship. Figure 3, which shows E ratio plotted against WSR for full-thickness tension data, indicates that our data also roughly conform to this relationship. The following model was fit to the data:

\[ \ln(E \text{ ratio}) = a + b \ln(\text{WSR}) \]

Several points should be made about this logarithmic transformation:
1. It preserves the shape of the underlying relationship (i.e., exponential on the original E ratio/WSR scale);
2. The error term is now multiplicative on the original scale (additive on the logarithmic scale).

In addition, the logarithmic transformation is sometimes used for other reasons:
3. It reduces the influence of outliers (in our data, high values of E ratio);
4. The model is now linear in the parameters, so a linear regression package can be used. Prior to the availability of nonlinear regression packages, this was an important practical consideration;
5. The variability of the dependent variable (here E ratio) tends to increase as the average of this variable increases. The logarithmic transformation suppresses this effect, which is desirable since statistical tests are based on the assumption of homogeneity of error variances.

By themselves, however, 3, 4, and 5 are not acceptable reasons for using the logarithmic transformation. Nonlinear regression packages are readily available (e.g., the SAS procedure NLIN (13)), and heterogeneity of variances can be dealt with (to allow valid statistical tests) by using weighted least squares. Only the first reason, by itself, justifies the choice of the logarithmic transformation. Since the shape of the relationship between E ratio and WSR was expected by theory to be exponential, and since Geimer’s data and our data appear to confirm this, we had ample justification for choosing a logarithmic model.

For empirical data to concur with Equation [2], the estimates of a and b in Equation [3] should be 0 and 2, respectively. For pooled aspen and Douglas-fir full-thickness tension data, the least squares estimate of a is 0.044 and of b is 2.378. A 95 percent confidence interval for a would include 0, but a 95-percent confidence interval for b does not include 2. The estimated equation is plotted with the data in Figure 3. In summary, Equation [2] approximates the relation of E ratio and WSR. Wave speed ratio is an adequate indicator of alignment, but it is related to panel density (a factor independent of alignment) and hence, is not synonymous with alignment.

**Between- and within-board variability**

Several specimens were tested from each board in compression, surface-layer tension, core-layer tension, and full-thickness tension. In general, there was more variability of MOE values between boards than within a given board. Therefore, the board-to-board variation must be used in statistical tests. The proper variance can be incorporated into the statistical procedures by 1) averaging the values for a given board for a particular test and then using these values in the subsequent analysis; or 2) carrying along the board-to-board variation error term. The first procedure was used.

When averaged MOE values were plotted against SG, it was evident that between-board variability was greater for some test types than for others. Compression test values were the least variable and surface-layer values were the most variable. This no doubt reflects decreasing variability with increasing specimen thickness.

**Regression equations**

The following regression equation was used to fit the data parallel to board alignment from the tests of compression, full-thickness tension, top-surface-layer tension, bottom-surface-layer tension, and core-layer tension:

\[ \ln(E) = a + b \ln(\text{specific gravity}) + c \ln(\text{wave speed parallel}) \]

This model, chosen because it is of the same form as

**Figure 3.** - E ratio versus wave speed ratio, with regression equation. A = aspen, F = Douglas-fir.
Equation [2], assumes that the response surface is a plane when plotted on logarithmic axes, but a curved surface when plotted on the original axes.

Alternatively, a linear model of the following form might be used

$$E = a + b(SG) + c(\text{wave speed parallel})$$

According to such a model, the response surface is a plane on the original axes. This would mean that the effect of the independent variables is additive—for example, that a given increase in SG yields a given increase in MOE, regardless of the alignment. As can be seen in Figure 4, given increases in SG have a greater absolute effect on MOE of highly aligned panels than they do on MOE of moderately aligned or nonaligned panels. Hence, a plain linear model is inappropriate. A logarithmic model reflects the multiplicative effect of SG and alignment on the response variable.

Another alternative model might substitute WSR for wave speed parallel to test direction in Equation [4]. Wave speed ratio is intuitively easier to relate to alignment than wave speed parallel, but models using WSR did not fit the data as well as a model using wave speed parallel to test, and such models would not concur with the fundamental Equation [2].

To estimate regression coefficients, we first fit a separate regression equation to each type of axial stiffness data (compression, full-thickness tension, core-layer tension, and surface-layer tension) for each species. Upon doing so, we found that slopes of the regression equations (i.e., the coefficients of ln(SG) and ln(wave speed)) were not statistically different between test types. Therefore, we pooled data from test types and calculated common slope values from the pooled data. We then checked for significant differences in elevation of regression equations. Because we found some differences, we calculated separate elevation values for each test type. Regression coefficients are listed in Table 1.

Relative elevations of regression equations (indicated by a-values in Table 1) are believed to reflect the effect of wood structure fracture in core layers. Wood in core layers was cold and brittle compared with that in surface layers at the instant of maximum pressure exertion on the mat. The a-values in Table 1 indicate that the regressions for surface-layer tension and for full-thickness tension have greater elevation than the corresponding regressions for core-layer tension. Note also that the elevations of regressions for top surface layers exceed those of corresponding regressions for bottom surface layers. We believe this is caused by settling of fine furnish to the bottom surfaces of the flakeboard mats. The fines increase SG of the bottom layer faster than they increase its MOE.

It is also evident from Table 1 that the regressions for full-thickness tension have greater elevation than the corresponding regressions for laminated compression specimens. We hypothesize that the flakes bend or buckle under compressive load, thereby lowering compression MOE values. With deformation measured over the standard (2-in.) gauge length, McNatt (11) and McNatt and Superfesky (12) also found that tensile MOE of waferboard and aligned flakeboard usually exceeded the corresponding compressive MOE (the opposite was true for fine-furnish particleboards). In fine-furnish particleboards, the particles more approximate cubes than do flakes and hence are less likely to bend under compressive load. The interparticle voids on the other hand may gape under tensile load, thereby lowering tensile MOE values. On pages 41 to 46 of his book, Gordon (9) discusses the inequality of MOE in tension and compression within a given material.

<table>
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<th>Species</th>
<th>Compress. tests</th>
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$E$ in $10^6$ psi. SG based on mass and volume at conditioned moisture content. Wave speed in inches/microsecond. Standard errors (on log scale) for regression equations are 0.16 for Aspen and 0.13 for Douglas-fir.
gamma radiation attenuation equipment. The equipment measured attenuation for successive 0.005-inch-thick layers through the thickness, starting at the top surface. From this data, SG values were calculated for six successive layers through the panel thickness: the top 10 percent of the panel thickness, the subsequent 15, 25, 25, 15, and the bottom 10 percent. We then used Equation [4] and the coefficients listed in Table 1 to calculate the axial MOEs of these six layers (from their gamma-measured SGs and the board’s wave speed parallel to its longer dimension). Because we assumed that the board’s neutral axis in bending was approximately at its midthickness, and since bending specimens were tested top surface up, the coefficients we used from Table 1 were as follows: compression regression coefficients for the top three layers, core-layer tension regression coefficients for the fourth layer, and surface-layer tension regression coefficients for the bottom two layers. Using Equation [7] from Geimer et al. (7), a more exact location of the neutral axis was calculated. We then calculated predicted bending MOE with Equation [1].

Comparing predicted effective bending MOE to measured effective bending MOE, we found predicted values consistently exceeded measured values by 10 to 15 percent (Fig. 5). We feel that a 10 to 15 percent error is reasonable and that the data are useful. The consistency of overestimation is of concern. The contribution of interlaminar shear deformation to total bending deflection probably accounts in part for the overestimation of effective bending MOE by Equation [1], but it seems doubtful that it accounts for the 10 to 15 percent overestimation we found. McNatt and Superfesky (12) indicated that horizontal shear deformation will reduce measured effective bending MOE of quarterpoint-loaded flakeboard (on a span 24 times panel thickness) by only 3 or 4 percent.

Our concern with the consistent overestimation of predicted effective bending MOE led us to calculate regression equations for effective bending MOE with Equation [4] just as we had done for axial MOEs. We found that intercept values for bending stiffness regression equations were lower than for corresponding axial stiffness regression equations. This agrees with the observed disparity between measured and predicted effective bending stiffness, but it is contrary to what we would expect considering the panels’ usual vertical density distribution.

When coefficients for full-thickness tension regression equations were used to calculate axial MOE of all layers through the panel thickness, and these values were used in turn to calculate predicted effective axial MOE, the predicted values also exceeded measured effective bending stiffness and by a greater extent (approximately 20%).

Conclusions

1. Wave speed ratio of flakeboards appears to be an adequate indicator of alignment, but it is negatively correlated with panel density (a factor independent of alignment) and hence not synonymous with alignment;
2. A logarithmic model predicting axial MOE as a function of SG and wave propagation speed in the direction of testing provided best data fit. This concurs with previous work and with elementary wave theory;
3. For a given value of SG and wave speed parallel to test direction, full-thickness tension MOE values exceeded corresponding compression values. We believe this is caused by buckling of the flakes under compressive load. For more conclusive evidence we recommend future work in which stiffness tests in both compression and tension are performed on the same specimen;
4. Comparison of regressions for surface-layer tension MOE with core-layer tension MOE suggests that exertion of high pressure on unheated layers of flake mats reduces tensile MOE of the resulting board layers. Comparison of regressions for tension MOE of full-thickness specimens with those for the various layer specimens likewise suggests the detrimental effect of high pressures on unheated, and hence unplasticized, flakes;
5. Prediction of bending MOE from density distribution and axial stiffness regression equations for the gradient-density panels yielded values moderately close to, but consistently in excess of, measured values. Horizontal or interlaminar shear deformation is believed to be partially responsible.

Literature cited


