WOOD AS A BIMODULAR MATERIAL

Terrance E. Conners

Associate Professor
Mississippi Forest Products Laboratory
P.O. Drawer FP
Mississippi State, MS 39762

and

Patrick J. Medvecz

Research Associate
Appleton Papers Research Center
P.O. Box 359
Appleton, WI 54911

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ABSTRACT

Wood is usually considered to be a material with equal stiffness in tension and compression, but this supposition is not uniformly supported by experimental evidence. On the basis of data in the literature, the authors believe that there is sufficient evidence to conclude that some woods, particularly hardwoods, exhibit bimodular behavior. For the hardwood data analyzed here, the ratio of Young's modulus in tension to Young's modulus in compression (E_t/E_c) averaged 1.08 and ranged as high as 1.28. Comparisons with composite materials with known bimodular behavior suggest that fiber displacement around rays (and the resulting fiber curvature) might be one cause of this behavior. Some data also indicate that the equality of the tension and compression moduli may be affected by the moisture content. There are similarities with synthetic fibers which suggest that wood fibers might also be bimodular, but the question of whether bimodular behavior can be ascribed to both undelignified fibers and solid wood remains unanswered.

Keywords: Young's modulus, moisture content, bimodular, mechanical properties, failure mechanisms, modulus of elasticity, tension, compression, fibers.

INTRODUCTION

Different strengths observed for wood in uniaxial tension and compression alert us to the different failure mechanisms for wood in uniaxial stress. Many consider it to be obvious that tensile properties are derived from the nearly longitudinal alignment of cellulose microfibrils in the cell wall; compression behavior, however, must be inherently more complex due to the potential for buckling of the lamellae towards the cell lumens. This may perhaps explain the different strength capacities in tension and compression; might the uniaxial Young's moduli (E) be affected as well?

One purpose of this paper is to review available data on uniaxial wood moduli. In practice it is commonly assumed that the tensile and compressive moduli are equal, but there is insufficient evidence in the literature to unequivocally support this belief. Materials with known bimodular behavior will be described in an attempt to discern whether there are common structural characteristics that might make bimodular behavior likely in wood. Whether the (in-) equality of this relationship could be moisture-dependent will also be examined. Finally, the authors briefly discuss whether wood fibers themselves could be bimodular, or whether only wood (as a fibrous composite) is a bimodular material.

TABLE 1. *Summary of comparable Young's moduli found in the literature.*

Author	MC%	Common name	Species	E_t/E_c
Dietz	9	Douglas-fir	*Pseudotsuga menziesii*	1.035
Dietz	24	Douglas-fir	*Pseudotsuga menziesii*	1.028
Sawada	15	Sugi	*Cryptomeria japonica*	1.049
Sawada	16	Sugi	*Cryptomeria japonica*	0.884
Sawada	16	Obi-sugi	*Cryptomeria japonica*	1.107
Sawada	14	Yezo-matsu	*Picea jezoensis*	1.030
Sawada	13	Akamatsu	*Pinus densiflora*	1.056
Sawada	14	Buna	*Fagus crenata*	1.015
Sawada	14	Mizu-nara	*Quercus crispula*	0.991
Sawada	13	Keyaki	*Zelkowa serrata*	0.990
Sawada	14	Ichii-gashi	*Quercus gilva*	0.991
Sawada	14	Apitong	*Dipterocarpus* spp.	1.187
Sawada	15	Apitong	*Dipterocarpus* spp.	1.073
Sliker	11	Red oak	*Quercus rubra*	0.999
Sliker	13	Douglas-fir	*Pseudotsuga menziesii*	0.976
Sliker	13	Western hemlock	*Tsuga heterophylla*	0.996
Stern	9	Yellow poplar	*Liriodendron tulipifera*	1.154 S
Stern	9	Yellow poplar	*Liriodendron tulipifera*	1.101 H
Walker	6	Yellow poplar	*Liriodendron tulipifera*	1.279*
Walker	6	Yellow poplar	*Liriodendron tulipifera*	1.037**
Mazur	12	Eastern spruce	*Picea* spp.	0.848
Zakic	12	Poplar	*Populus euroamericana*	1.930
Conners	6	Yellow poplar	*Liriodendron tulipifera*	0.955 S
Conners	12	Yellow poplar	*Liriodendron tulipifera*	0.840 S
Conners	18	Yellow poplar	*Liriodendron tulipifera*	0.989 S
Conners	Green	Yellow poplar	*Liriodendron tulipifera*	1.171 S
Schneider	0	Sugar maple	*Acer saccharum*	1.244
Schneider	12	Sugar maple	*Acer saccharum*	1.278

S = sapwood, H = heartwood.
* = uniaxial test data, ** = bending test data.

REVIEW OF THE LITERATURE

Previous determination of uniaxial wood moduli

The equality of Young's modulus in longitudinal tension and compression is often assumed (Ethington 1961; Mark 1961; Moe 1961; Nwokoye 1972; Bazan 1980; Anderson 1981), but the assumption of moduli equality seems to be more firmly rooted in tradition than in factual evidence. Relatively few researchers have conducted tests to compare these values, and then usually with a limited number of tests at only one or two moisture contents. Data gathered by some have led them to believe that negligible or only slight differences exist (Lamarle 1845, 1846; Dietz 1942; Sawada 1958; Sliker 1973; Bazan 1980). Others, however, have concluded that there are significant differences between the moduli (Stern 1944; Walker 1961; Mazur 1965; Zakic 1976; Conners 1985). Where available, data from these sources are presented in the following text and in Table 1; for convenience, all data have been converted to ratios of the Young's modulus in tension (E_t) to the Young's modulus in compression (E_c). The degree of departure from unity indicates the degree of bimodularity. Except where noted, all tests were conducted on small clear uniaxial specimens.

Reports of the equality of Young's moduli

Todhunter and Pearson's book (1886) contains references to tests of wood specimens at least as far back as the 17th century. Many of these early studies were conducted to understand elementary mechanics better, and wood was used because it was readily available. At some point, it appears to have been assumed that the Young's moduli in tension and compression (the "stretch and squeeze moduli") were equal for wood (ex., Hagen 1842). The first-mentioned comparison of these moduli in wood, however, was conducted by Lamarle (1845, 1846). He originally hypothesized that the moduli were unequal, but experimentation persuaded him that they were essentially the same. No details of his experiments are provided.

Lamarle may have been the only investigator until the 20th century to test whether wood was bimodular. Dietz (1942) refers to diagrams depicting different slopes for tension and compression stress-strain curves, but it is not clear if these curves were hypothetical constructs or if they were based upon tests by Bach and Baumann (1924). Regardless, Dietz collected his own data to make this comparison. He conditioned and tested Douglas-fir samples at two moisture contents (MC), 9% and 24%, and also corrected each sample for small differences in density in an attempt to eliminate errors resulting from using unmatched specimens. Four or five tension specimens and about the same number of compression specimens were tested at each of the two moisture contents; Dietz found only minimal differences between the moduli. Using his reported data, values for E_t/E_c have been calculated to be 1.035 and 1.028 at 9% and 24% MC, respectively.

Sawada (1956, 1958) collected tension and compression data from twelve species with moisture contents between 13 and 20%. Nine species were tested at comparable MCs in tension and compression, and about 12 specimens were usually divided between compression and tension tests. E_t/E_c ratios ranged from 0.884 to 1.187. The tensile moduli were generally higher than the compressive moduli, but Sawada concluded that the differences were small and perhaps within experimental error.

Sliker (1973) worked with three species, but at essentially a single moisture content. His tests were conducted using the identical pieces of wood for several tests (bending followed by tension, then by compression). Five red oak specimens were maintained at 11% MC, and five western hemlock and three Douglas-fir specimens were maintained at 13% MC. Sliker's data were not corrected for specific gravity differences among samples, and he reported that there were insignificant differences between the tensile and compressive longitudinal Young's moduli. Ratios of E_t/E_c calculated from his averaged data for each species range from 0.976 to 0.999.

Bazan (1980) tested 169 different-sized clear eastern spruce and Douglas-fir beams with center and third-point loading conditions; most of his tests were conducted at 12% MC, with a few spruce beams tested at MCs between 15% and 20%. Based on measurements of the extreme fiber deformation, he concluded that the modulus of elasticity in tension was usually about 6% greater than it was in compression. Bazan noted that the differences between the moduli were slightly greater for beams at the higher moisture contents, but he believed that they were not significant.

Reports of the inequality of Young's moduli

Stern (1944) also examined the equality of the uniaxial moduli. He worked with yellow poplar at 9% MC and found that the Young's moduli were significantly different; the average ratio of E_t to E_c was 1.154 for sapwood and 1.101 for heartwood. Stern tested a relatively large number of specimens: 15 compression and 27 tension specimens from sapwood, and 29 compression and 68 tension specimens cut from the heartwood. Walker (1961) also worked with yellow poplar, and concluded that the longitudinal modulus was greater in tension than in compression ($E_t/E_c = 1.279$) when the moduli were determined from uniaxial tests; the differences appeared to be substantially smaller when the moduli were determined from beam tests ($E_t/E_c = 1.037$). Walker did not differentiate between heartwood and sapwood in his testing program, and his specimens were unusually large; he used the same

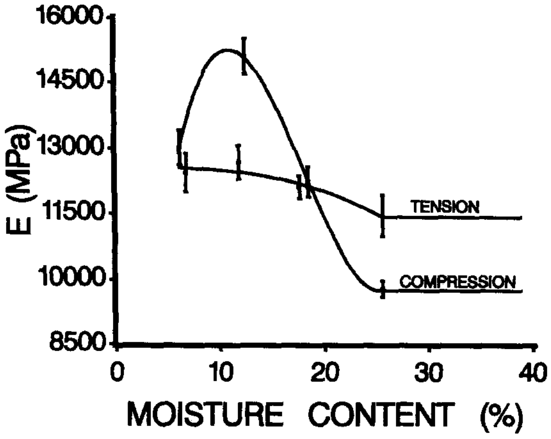

FIG. 1. Conners' data (1985) for uniaxial moduli (E) of yellow poplar. Green moisture content was defined to be 25.6%. Bars indicate means and +/− one standard error of the mean; lines shown are predictive models for data.

three 2-in. × 10-in. × 60-in. pieces of clear wood for tension and bending tests, and cut a 2-in. × 10-in. × 10-in. piece from each board to provide compression test specimens. Later, Mazur (1965) used eastern spruce to determine the Young's moduli in uniaxially loaded specimens at 12% MC. His data, based on 37 tension and 37 compression tests, indicate a value for E_t/E_c of 0.848. Mazur and Walker both thought that the unequal moduli resulted from localized differences in density within individual wood specimens (e.g., growth rings).

More recently, Zakic (1976) tested clear European poplar specimens in tension and compression at 12% MC. He tested a total of twenty specimens, half in tension and half in compression. Zakic did not indicate whether he corrected his moduli data for specific gravity variation among samples, but he found that the average Young's modulus in tension was nearly twice as high as the corresponding compression modulus (E_t/E_c = 1.930). This difference is far greater than others have reported.

Conners (1985, 1988) collected tension and compression data from yellow poplar specimens at four MC conditions: 6%, 12%, 18%, and green, defined by Conners as 25.6% based upon compression data trends. Approximately thirty sapwood specimens were divided between tension and compression tests for each moisture content. At 6% and 18% MC, the tensile and compressive moduli could not be differentiated by statistical tests (E_t/E_c = 0.955 and 0.989, respectively), while at 12% MC the compressive modulus was greater (E_t/E_c = 0.840), and for green specimens the tensile modulus was greater (E_t/E_c = 1.171) (See Fig. 1). Statistical tests at each moisture content did not indicate significant relationships between specific gravity and the longitudinal moduli.

The final data of which we are aware were collected by Schneider et al. (1990). Tension and compression specimens of sugar maple were tested at two moisture contents, oven-dry and 12%. About 20 specimens were tested in each moisture content/test type category. Based on the authors' reported data, calculated E_t/E_c ratios are 1.244 for the oven-dry wood and 1.278 for the wood at 12% MC.

Analysis

There appears to be little agreement among these data regarding equality or inequality of the tensile or compressive moduli, even when the same species are studied. Stern and Conners, for example, both tested yellow poplar, but Stern's data indicate that Young's modulus in tension should be higher at 9% MC; the trend indicated by Conners' data implies the opposite. Most of the data identified for comparison here were collected from uniaxial tests, but some authors (Walker and Bazan, for example) have collected E_t and E_c data from strain measurements at the extreme fiber region of beams. Because of the difficulty in machining tension specimens and in obtaining well-matched specimen pairs for uniaxial testing, we wondered if beam tests could provide equally valid data for moduli comparisons. Because of the number of beams tested, we chose to examine Bazan's data.

Analysis of Bazan's data by the authors appears to demonstrate that there are effects due to the beam size and loading configuration as well as a confounding effect due to the species tested. No statistically significant differences were detected between E_t and E_c for the (2 in. × 6 in. and smaller) Douglas-fir beams at 12% MC, but the spruce data appeared to be different. Examination of the tensile and compressive moduli for different beam test categories (load configuration, beam depth and moisture content) showed that greater differences were usually observed between the moduli under center loading conditions than under third-point loading conditions. Also, there were indications that beams with greater depth exhibited more significant differences; this might be due to volume effects or small defects that were not detected by the investigator. The smallest beams (1.50 in. × 1.65 in.) did not show any greatly significant differences between the moduli. Bazan's data also indicated that greater differences were observed at higher moisture contents, but these observations were recorded with his largest beams and may not be indicative of actual material characteristics. Since size and load configuration appear to have significantly affected Bazan's observations, we decided to discount his data for purposes of this paper. Beam size probably affected Walker's beam observations as well. We believe that beam tests with smaller specimens might provide useful data for future comparisons, especially if the tests are conducted with third-point or similar loading (Yokoyama 1988).

The remainder of the data presented above represent only averages with unknown variability in most cases. Most investigators chose to test at only one or two moisture contents, and in most cases fewer than twelve specimens were tested in tension and compression at the same MC. With this in mind, the authors examined the available data to determine whether the average E_t/E_c ratio departed significantly from unity (see Fig. 2). Walker's beam data were removed from the data set due to potential inaccuracies; also, Sawada had reported two sets of data for both sugi and apitong, and

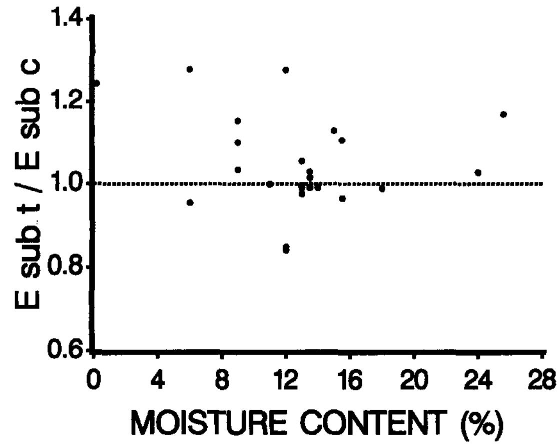

FIG. 2. E_t/E_c data from Table 1 plotted as a function of moisture content. Dotted line represents equality of tension and compression moduli.

each pair of values was averaged for this analysis. Zakic's point for poplar was removed as an apparent outlier. While it is not a good practice to use statistics on averaged data, a t-test of the remaining data showed that the average E_t/E_c value, 1.05, was significantly different from unity at the 90% confidence level. Although this analysis by itself could not be considered to be strong evidence of bimodular behavior, the variability in the E_t/E_c ratios is rather striking. Hardwoods and softwoods were therefore analyzed separately to determine whether their mechanical responses were different. Hardwoods generally have an E_t/E_c ratio greater than or equal to unity and softwood ratios are more equally dispersed about 1.0. The average E_t/E_c ratio for these hardwood data was 1.075, with a range from 0.840 to 1.279 (Fig. 3). This ratio was determined to be greater than 1.0 with 95% confidence using a one-tailed t-test. Softwoods did not show any statistical evidence of bimodular behavior, but this statement must be viewed with caution in light of the paucity of softwood data analyzed. Overall, hardwoods as a class seemed to be more variable than softwoods; this variability may be more important than the observed modulus ratio.

As noted earlier, Conners' data indicate that

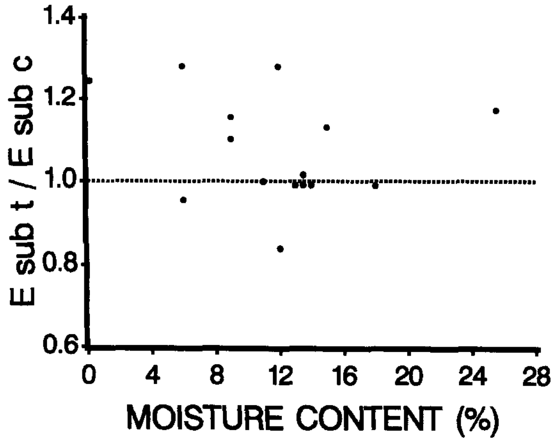

FIG. 3. E_t/E_c data from Table 1 plotted as a function of moisture content. Hardwood data only.

TABLE 2. *Tension and compression moduli data for several different materials.*

Material	E_t/E_c
Aramid/polyester	1.15
Glass/epoxy	1.25
Boron/epoxy	0.8
Graphite/epoxy	1.4
Carbon/carbon	2–5
ZTA Graphite	0.8
ATJ-S Graphite	1.2
Fabric/rubber	2.6
Sintered, porous stainless steel	10.0
Various fabrics/rubber	2–14
Polyester cord/rubber	59
Aramid cord/rubber	294
Rayon cord/rubber	278

very different trends can be recorded for Young's modulus in tension and compression at varying MCs, but not enough studies have been conducted to suggest whether similar observations might be expected with other species. More comprehensive testing of single species at differing moisture contents might be useful. Additional data may also result in the contradiction of the conclusions from the statistical analysis presented in the preceding paragraph.

Although we may speculate at this point whether the reported differences between compression and tension moduli are reproducible, other materials are known to exhibit bimodular behavior. Consequently, we must concede the possibility (if not the likelihood) of wood behaving in a similar fashion. In the following sections, we review some of the published information about bimodular materials and attempt to extend this knowledge to wood.

BIMODULARITY OF FIBROUS MATERIALS

The bimodularity of fibrous materials is considered in the following subsections. Reports of bimodularity in synthetic fibers and composites are first summarized here. The mechanisms contributing to bimodular behavior in these systems are then examined. Finally, wood is compared to the model composite systems in the last subsection.

The bimodularity of synthetic fibers and composites

The bimodular behavior of various materials has been thoroughly documented in the past. As early as 1963, Clark showed that several composites consisting of rubber and either rayon, braided steel, or nylon cord exhibited significantly different moduli in compression and tension. Similarly, Patel et al. (1976) found that composites of rubber and either polyester or aramid fibers displayed significant bimodular behavior ($E_t/E_c = 59$ for a polyester cord/rubber composite and $E_t/E_c = 294$ for an aramid cord/rubber composite). Other materials have likewise been shown to be bimodular, including other aramid composites (Zweben 1978; Piggott and Harris 1980), graphite composites (Jones and Nelson 1976), porous stainless steel (Ducheyne et al. 1978), glass fibers in an epoxy matrix (Davis and Zurkowski n.d.), boron fibers in an epoxy matrix (Air Force Materials Lab 1971), carbon fibers in a carbon matrix (Kratsch et al. 1972), granular ZTA graphite (Seldin 1966) and granular ATJ-S graphite (Starrett and Pears 1973). The E_t/E_c ratios for these and some other materials range from 1.2 to nearly 300, as documented in Table 2 (data from Zweben (1978), Jones (1977) and Bert (1979)). It is evident that a single explanation for bimodular behavior is not likely to accommodate the range of composition and structure displayed by the materials in this table.

Mechanisms for bimodular behavior

Although the phenomenon of bimodularity has been observed for a number of materials (mostly fibrous), there have been few explanations for this behavior. It appears that the mechanisms responsible for bimodularity are not well understood. Bert (1979) states that all of the mechanistic models for bimodular fibrous composites can be grouped into two classes, the "mean fiber angle" model and the "tie-bar/column on elastic foundation" model. These models account for bimodularity by assuming that there is some initial curvature in the fibrous reinforcement of some materials; the curvature disappears in tension, but it increases under compressive stress. Composites with curved fibers have actually been observed to have greater tensile moduli, and it has been shown that small degrees of fiber curvature will result in significant differences between the tension and compression moduli (Herrmann et al. 1967). The models appear to implicitly assume that the matrix material is relatively flexible compared to the fiber. They fail to account for transverse shear deformations of the fibers and composites, however, and cannot account for bimodularity of porous stainless steels or other nonfibrous materials.

Some fibrous materials may be inherently bimodular because of the fiber chemical structure (molecular conformation). Greenwood and Rose (1974) found differences in the ultimate compressive and tensile strength of aramid (Kevlar) composites and concluded that these differences resulted from unlike modes of aramid fiber deformation in tension and compression. They believed that tensile deformation resulted from elastically extending the polymer backbone, and compression deformation was attributed to molecular delamination between the weakly hydrogen-bonded polymer chains. Photomicrographs appear in the literature depicting this phenomenon, which in a compressively stressed fiber appears as a series of kinked bands (Greenwood and Rose 1974; Lafitte and Bunsell 1982; Davidovitz et al. 1984; De Teresa et al. 1985). The mode of compressive strain or micro-buckling seen in aramid has also been shown for other systems including polyethylene (Holland and Black 1979; Kolbeck and Uhlmann 1976) and graphite (Jones and Johnson 1971). Data are unavailable for the compressive stiffness of aramid fibers, but Greenwood and Rose stated that they did not believe that Kevlar 49 fibers were elastic in compression. It seems reasonable that different polymer deformation mechanisms in tension and compression should lead to differences in the fiber moduli.

Bimodularity has also been observed in fibrous composites made from fibers with little inherent compressive stiffness except that obtained from the restraint of the surrounding matrix (Tabbador 1979). Tabbador, writing about cord-reinforced rubber composites, stated that the "reinforcing elements are one-dimensional structural members with high tensile stiffness but low compressive resistance when not laterally restrained. These cords, however, attain appreciable stiffness when embedded in a matrix that provides lateral support. The apparent compressive stiffness of such composites is therefore less than that of tensile stiffness, as a consequence of micro-buckling response of the cords to compressive forces. This concept has been applied to explain the smaller elastic modulus in longitudinal compression than in tension in the same direction."

Potential mechanisms for bimodular behavior of wood

There are two separate aspects to bimodular behavior that require examination: 1) bimodularity appears to be more commonly observed in hardwoods; 2) bimodularity may be moisture-dependent. Each of these will be discussed in turn.

Moisture-independent bimodularity.—On a gross level, fibers must often have some initial curvature because of displacement by wood rays, etc. Therefore, the "mean fiber angle" or the "tie-bar/column on elastic foundation" models might be useful in understanding why wood sometimes appears to be bimodular. Perhaps hardwoods are affected more because their fibers are shorter and consequently perturbed along a greater proportion of their length, or perhaps hardwoods are affected more because they generally have a greater proportion of rays compared to softwoods (Panshin and deZeeuw 1980). Kink bands similar to those seen in aramid fibers also occur in compressed wood fibers, predominantly around ray cells (and especially at the outer rays) (Keith and Côté 1968; Dinwoodie 1968). Ray size and shape, and the degree to which fiber displacement is affected, could be important. Tabbador's explanation of bimodular behavior might also be appropriately applied, as wood fibers are essentially limp when removed from the encrusting lignin/hemicellulose matrix by chemical maceration.

On a finer scale, bimodularity might be attributed to the different modes of strain in compression and tension. There is evidence to suggest that wood fibers deform in both compression and tension in ways similar to aramid. Cellulose microfibrils and aramid fibers are both composed of polymeric chains, with strong covalent bonds between monomeric units along the chain axis and hydrogen bonding between the chains (Winandy and Rowell 1984; Northolt 1974). Mark has described wood as displaying elastic behavior in uniaxial tension (Mark 1972). Furthermore, he describes cellulose (as it exists in the microfibril) as also behaving elastically in tension. Page et al. (1971) showed that individual kraft pulp fibers displayed elastic behavior in tension up to about 40% strain and could afterwards collapse and twist. Extending the analogy of aramid fibers to wood, it seems possible that wood fibers deform in compression through delamination (kink bands) while they deform in tension by axial extension of the cellulosic polymer chains. The delamination would occur by the breaking of hydrogen bonds, either between individual cellulose chains or between assemblages of cellulose chains such as elementary fibrils.

Whether wood (as a fibrous composite) is the bimodular material, or whether the individual wood fibers have intrinsic bimodular characteristics is unknown. Possibly both conjectures are correct. Because wood fibers are so troublesome to test in compression, it is difficult to answer this question at the present time. Perhaps the observation that softwoods do not appear (based on limited data) to exhibit bimodular behavior could refute the bimodular fiber hypothesis; should not softwood fibers, with their higher percentage of cell wall occupied by pitting, show more bimodular behavior than hardwood fibers? On the other hand, perhaps fiber bimodularity would only be apparent in the absence of the encrusting matrix.

Moisture-dependent bimodularity.—None of the purely mechanical explanations for bimodular behavior noted in the previous section would seem to have relevance to discussions of moisture-related bimodular observations. We can only speculate about the reasons for Conners' observations; based upon data in the literature (Cousins 1976, 1978; Salmen 1982) it seems likely that the essentially unchanging tensile moduli are due to the crystalline cellulose component (shown to be relatively insensitive to moisture penetration according to Salmen). If compression stiffness is actually more sensitive to moisture, this might be due to moisture effects on hydrogen bonding, or to moisture-induced softening of amorphous cellulose, hemicelluloses, and (to a lesser extent) lignin.

It is interesting that Conners' data appear to demonstrate that bimodular behavior may be affected by the choice of moisture content for testing. It is possible that previous tests of some woods have not detected bimodularity for this reason. Conners' E_t/E_c ratios at 12% MC are lower than those calculated from Sawada's data near this MC, however; they are also lower than the ratios calculated from Schneider's data. We cannot as yet explain why different (hardwood) species appear to be affected in different ways. If experimental error is not the root cause, perhaps significant differences among species with respect to hemicellulose and lignin type, concentration and placement can affect mechanical property observations in this manner.

SUMMARY

There appears to be sufficient evidence to show that some woods may have different Young's moduli in tension and compression. On average, hardwoods are reported to have tension moduli that are about 1.08 times the compression moduli, but this is perhaps of less significance than the variability among the data reported in the literature. Hardwood tensile moduli have been reported to be as much as 1.28 times the compression moduli! Softwoods do not appear to have significantly different moduli, but this conclusion should be checked by further testing. Measurements collected from uniaxial testing may be more reliable than data from beam tests, but this probably depends on the size of the specimen and the loading configuration. Small clear specimens tested in third-point loading may be suitable for the simultaneous determination of the tension and compression moduli.

It is inferred from studies of engineered materials with known bimodular behavior that bimodular behavior in wood may be due to fiber curvature induced by ray contact. It seems likely that the study of analogous composites such as fiber-rubber composites would have relevant application. Wood fibers might be bimodular as well, as some bimodular polymers have structural similarities, but this hypothesis remains to be tested.

Moisture content possibly affects compression moduli more than tension moduli, and it seems likely that this is due to hydrogen bonding interactions or to varying hygroplasticization effects on the several wood components. Moisture content may affect experiments performed to detect bimodular behavior, but little consistency is apparent among the limited data available. Perhaps there are some species-specific effects due to differences in types and placement of hemicelluloses and lignins. Further study is warranted in this area.

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