CHARACTERIZING MICROSCOPIC BEHAVIOR OF WOOD UNDER TRANSVERSE COMPRESSION. PART II. EFFECT OF SPECIES AND LOADING DIRECTION

Taghi Tabarsa

Assistant Professor
Faculty of Wood and Paper Engineering
Agricultural and Natural Resources University
Gorgan/Iran

and

Ying Hei Chui

Professor and Director, Wood Science and Technology Centre
Faculty of Forestry and Environmental Management
University of New Brunswick
Fredericton, N.B., Canada E3B 6C2

(Received February 2000)

ABSTRACT

Specimens of four species with different cellular structures (white spruce, jack pine, white ash, and aspen) were tested in radial compression. Deformation characteristics were observed and measured using a microscope at different magnifications. The magnified images were recorded with a video recorder, which were then played back for deformation measurements. Stress-strain responses of these specimens were determined from the measured load and deformation. As expected, the softwood and hardwood responses to radial compression were influenced by the anatomical features. Tangential compression tests were also conducted on white spruce and jack pine specimens. It was found that the mechanisms of deformation in radial and in tangential compression were distinctly different for these softwood species. In radial compression, cell-wall deformation dominated elastic behavior, and collapse of the weakest cells in earlywood coincided with the onset of yielding observed in the stress-strain curve. Cell collapse developed only in earlywood, while latewood cells mainly underwent elastic deformation. In tangential compression, elastic deformation was dominated by the bending of the latewood layers. For the two hardwood species, the measured elastic strain under radial compression was dominated by deformations in the vessels. Yield point on stress-strain curves was related to the collapse of these vessels.

Keywords: Radial compression, tangential compression, cellular structure, cell-wall collapse, stress-strain response.

INTRODUCTION

Response of wood to transverse compression is an important property during processing of wood composites (Schniewind 1959; Kunesh 1968; Mataki 1972; Welonse et al. 1983). A number of scientists have discovered that wood behavior in transverse compression is dependent on its anatomical features (Bodig 1965; Easterling et al. 1982; Stefansson 1995; Tabarsa and Chui 1999). Some reported that wood responds differently to radial and tangential compression because of its anisotropic nature (Dinwoodie 1965; Kennedy 1968; Bodig and Jayne 1982).

In spite of a number of investigations on wood behavior under transverse compressive stress, this behavior, especially at elevated temperature which is of interest to the wood composite industry, is still not fully understood (Tabarsa and Chui 2000). Interaction of test parameters and lack of proper test equipment for observing behavior in real time are two of the major factors hindering progress in

Wood and Fiber Science, 33(2), 2001, pp. 223–232

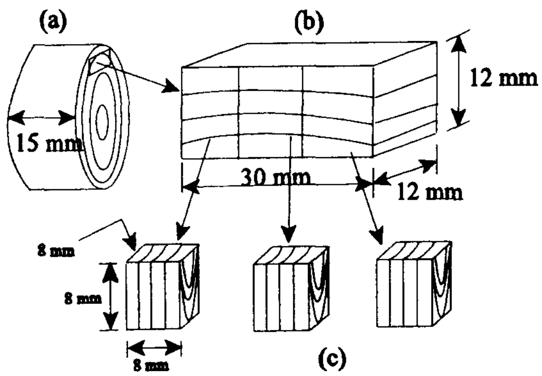

FIG. 1. Preparation of test specimens.

this area. The development of a new test procedure by Tabarsa and Chui (2000) was an attempt to address the second factor. The test procedure can be used to provide more advanced information on the relationship between stress-strain response and structural deformation of the cellular network. Such information is considered important for the development of mathematical models for predicting behavior of wood under transverse compression, which will be discussed in future papers by the authors.

In this study, a test procedure developed by Tabarsa and Chui (2000) was used to investigate the stress-strain relationships of two softwoods and two hardwoods with different cellular structures. Tangential compression tests were also conducted on the softwood specimens. The objective was to study the relationship between anatomical features, the fracture mechanism, and the stress-strain responses of the four selected species, and the influence of loading direction on softwood stress-strain response.

MATERIALS AND METHODS

Figure 1 depicts the process of preparing test specimens having the final dimensions of a 8 × 8 × 8 mm. At the start of the process, a one-meter long log was cut at breast height from each tree of four species: white spruce (*Picea glauca*), jack pine (*Pinus banksiana*), aspen (*Populus tremuloides*), and white ash (*Fraximus americana*). The logs were cut into 15-mm-thick disks, (Fig. 1 a). Wood blocks with nominal dimensions of 12 × 12 × 30 mm (longitudinal × radial × tangential) were cut from defect-free sapwood of these disks (Fig. lb). All wood blocks were cut from the same annual rings and along the tangential direction because variation of cell dimensions in this direction is insignificant compared to the radial direction (Panshin and de Zeeuw 1980). The blocks were conditioned in a chamber maintained at 21°C and 65% relative humidity (RH) until equilibrium. Some control specimens were placed in the chamber to monitor weight loss of woods during conditioning. After one month, the control specimens reached a steady weight indicating that the blocks achieved the target equilibrium moisture content. The moisture content of control specimens was measured to be 12 ± 1%. Test specimens with nominal dimensions of 8 × 8 × 8 mm were cut from the blocks. One cross-sectional surface of all specimens was microtomed before returning them to the conditioning chamber to maintain the moisture condition until testing.

TABLE 1. *Experimental design—number of replicates for each combination of species, loading direction and magnification.*

		Species			
Loading direction	Magnification	White spruce	Jack pine	White ash	Aspen
Radial	12×	5	5	5	5
	32×	5	5	5	5
	160×	5	5	5	5
Tangential	12×	3	3	—	—

Table 1 shows the experimental design of this study. For each species, three matched groups of five replicates were subjected to radial compressive stress. Compression tests were conducted following test set-up and procedure developed by Tabarsa and Chui (2000). Readers are referred to the paper by Tabarsa and Chui (2000) for details. In their test set-up, the load was recorded by a load cell inserted between the body of the compressing device and the test specimen and wired to a data logging system. The actual deformation of cellular structure was measured using an optical system. This system enabled the recording of the magnified image of the cellular structure of specimen in real time at different scale such as gross, single ring, earlywood/latewood segment, facilitating the matching of any point on the stress-strain curve to the cellular structural deformation behavior.

The three groups of matched specimens were tested at three levels of magnification, respectively, in radial compression. These magnification levels were: 12×, 32×, and 160×. Gross (entire specimen size with multiple growth rings) load-deformation data were obtained at the 12× magnification level. Single growth ring data were recorded at a magnification of 32×. Mechanism of cellular structural deformation was studied qualitatively at a magnification of 160×. Since at the lowest magnification of 12×, border of growth rings was not clearly visible, fine metallic wires (0.025-mm diameter) were glued to the border of growth rings and used as reference lines for measuring growth ring deformation for specimens tested at this magnification.

In addition to the radial compression tests on four species, three specimens each of white spruce and jack pine were subjected to tangential compression using the same apparatus to compare the differences in behaviors between radial and tangential compression. These were tested at one magnification level of 12× only (Table 1).

Although the test set-up recorded magnified images from tests, quality of prints produced from these images proved too poor for publication purposes. To circumvent this problem, a special compression device was fabricated for use inside a Scanning Electron Microscope (SEM). Matched specimens of each test group were tested using this device to produce images for illustration and publication purposes. All micrographs presented in this paper were taken using SEM. Specimens were end-matched to those tested in the test program, so that characteristics were similar. Surface to be viewed was sputter-coated with gold, and a vacuum was applied prior to testing. Loading was stopped at the appropriate stages of deformation to allow pictures to be taken with a still camera.

TABLE 2. *Summary statistics for modulus of elasticity and yield stress of four species in radial compression.*

Species	Modulus of elasticity		Yield stress	
	Mean (MPa)	COV (%)*	Mean (MPa)	COV (%)*
White spruce	139	18	2.9	9
Jack pine	83	24	1.7	28
Aspen	95	17	2.6	14
White ash	425	14	10.9	3

* Coefficient of variation.

All load and deformation data collected during compression tests were converted to stress and strain, respectively, using standard equations. Stress-strain curves were plotted and compared. Modulus of elasticity (MOE) was determined using linear regression method on the initial, linear part of the stress-strain response. The yield point was taken to be the end of this linear region, although the exact location of the 'end' was usually difficult to pinpoint from a transverse compression stress-strain curve as the deviation from a linear response was gradual. The occurrence of the yield point generally signifies a sudden change in the cellular structure. As will be explained later, the nature of this change differs, depending on species and direction of loading. The yield stress reported in this paper for each species was determined based on an occurrence of a significant change in the cellular structure, which was usually related to collapse of certain cell types.

RESULTS AND DISCUSSION

Stress-strain responses in radial compression

The average MOE and yield stress determined from radial compression tests on the four species (white spruce, jack pine, aspen, and white ash) are presented in Table 2. The results shown in Table 2 were obtained by analyzing the gross specimen measurements. Typical experimental stress-strain responses (gross and two individual rings) of these spe-

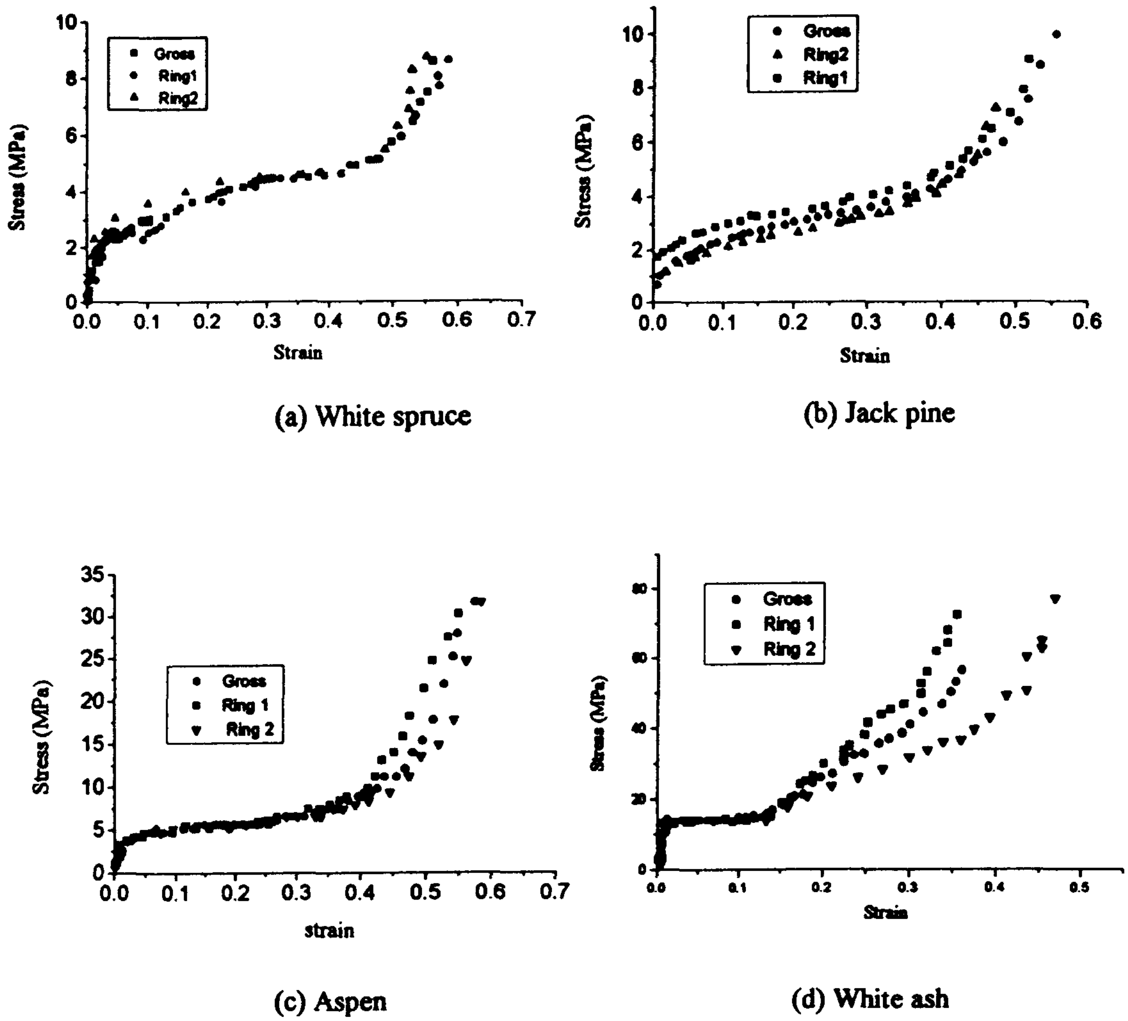

FIG. 2. Stress-strain curves of four species under radial compression.

cies are shown in Fig. 2. Other curves from the same species were similar to the presented curve. This is not surprising as the specimens were prepared from the same growth rings. As can be seen, stress-strain curves of these species follow a common pattern and are similar to those found by others (Bodig 1965; Kunesh 1968; Stefansson 1995).

At the start of the loading, all species exhibited elastic behavior where stress was directly proportional to strain. White ash showed the highest MOE (425 MPa) and jack pine the lowest (83 MPa). MOE of white spruce and aspen was 139 MPa and 95 MPa, respectively. There have been a limited number of studies that determined the MOE in compression perpendicular to grain. Focus of most previous studies was on strength properties. Youngs (1957) reported an MOE value of 700 MPa (100,000 psi) for red oak, which had a similar density and anatomical features to white ash. Kunesh (1968) reported MOE values of 140 MPa (20,000 psi) to 700 MPa (100,000 psi) for hemlock and Douglas-fir compressed in the radial direction. Using a conventional compression apparatus, Kunesh found that

MOE was dependent on stress area and specimen thickness. Generally MOE increased with increasing thickness but decreased with increasing stress area. It seems that the MOE values measured using the proposed technique are considerably lower than those determined using the conventional method. This discrepancy may reflect the differences in deformation measurement techniques and wood characteristics between this and previous studies.

As has been discussed by Tabarsa and Chui (1999), at the initial stage of loading in the radial direction all cells deformed elastically, but the distribution of deformation was not uniform in a growth ring. Earlywood cells with thin walls exhibited larger deformation than latewood cells with thick walls. Therefore, cell-wall thickness and the proportion of thick-walled cells are major factors in determining the MOE of wood in radial compression. This explains why the jack pine MOE was lower than white spruce MOE despite its higher mean density because jack pine has a higher earlywood to latewood ratio. The higher MOE of white ash is related to its thick-walled fibers, which dominate the growth ring volume.

The slope of the stress-strain curve changes after reaching a relatively small strain at the yield stress. The part of the curve below the yield point is referred to as the elastic region. The last part of the stress-strain response of all curves with a steep slope is generally known as the densification region. The relatively flat part of the response curve is called the plateau. Such a three-part curve was also observed by others (Youngs 1957; Bodig 1965; Kennedy 1968; Wolcott et al. 1994; Stefansson 1995).

As shown in Table 2 and Fig. 2, the yield stresses of the studied species were different. Jack pine showed the lowest yield stress (1.7 MPa) and white ash the highest (10.9 MPa). Aspen and white spruce yield stresses were similar at 2.6 and 2.9 MPa, respectively. The white ash value was similar to that reported by Bodig (1965) for Oregon ash, which yielded at 10 MPa in radial compression. The yield stress found for white spruce was similar to that reported by Stefansson (1995) for Norway spruce in Europe. Wolcott et al. (1994) found the yield stress of yellow poplar to be about 2.5 MPa, which was close to the value obtained here for aspen.

The plateau regions of stress-strain curves of these species in radial compression were also different. For both softwoods, stress increased slightly after yielding (up to 4–6 MPa). In white ash, stress after yield point did not increase. The slopes of the stress-strain curves for all species increased steeply after reaching the plateau region. Figure 2 also compares individual ring and gross measurements. As can be seen in the figure, individual ring and gross behaviors of each species are similar, except in the densification region, which shows some deviation. This could be due to the fact that at the high stress levels, localized failure may occur in one ring but not in the others.

Microscopic observations in radial compression

Although stress-strain curves of the four species followed a similar pattern, yield stress and plateau region of stress-strain curves were different. Correlating the recorded images with measured stress and strain readings provides information to explain the differences in responses. The results of these image examinations are discussed separately for each species.

White spruce.—White spruce is a softwood with a gradual earlywood-to-latewood transition. Cell dimensions and cell-wall thickness in one growth ring change gradually from earlywood to latewood. As explained by Tabarsa and Chui (1999), in the elastic region radial walls of cells bent towards the cell lumen. The magnitude of deformation was not uniform in all cells. The largest deformation occurred in the thin-walled cells in earlywood and the smallest deformation in thick-walled cells in latewood. The first collapse occurred in the weakest region of earlywood, which was lo-

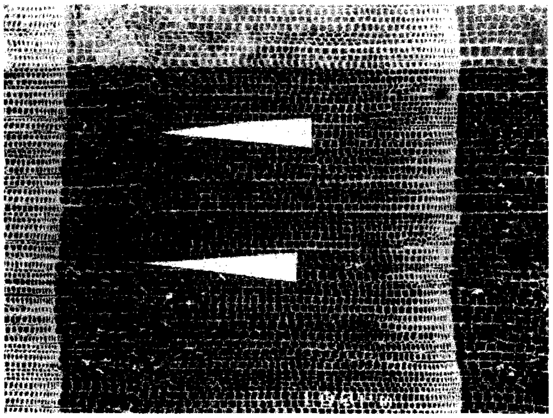

FIG. 3. Micrograph showing first collapse of earlywood cells in white spruce—direction of loading is up-down. (55×)

cated a few cell rows (about the tenth) from the beginning of a growth ring (Fig. 3). Cell-wall thickness of the test specimens was measured, and these measurements were reported in an earlier paper by the authors (Tabarsa and Chui 1999). A review of these cell-wall thickness measurements revealed that first cell collapse occurred at the cells with the thinnest walls. Cell collapse then developed further until all cells in earlywood region collapsed. After the collapse of all cells in earlywood, stress increased rapidly. During this region, elastic deformation of latewood cells dominated as the latewood became the more flexible part of the growth ring. At this point the stress-strain curve entered the densification region in which the slope increased steeply.

These observations differed from those reported by Kunesh (1968), who noted that the buckling of rays in Douglas-fir and western hemlock was the primary cause of failure during radial compression for these species. The initiation of cell collapse in earlywood was also observed by others (Bodig 1965; Easterling et al. 1982; Stefansson 1995). However, because of equipment limitations, they were unable to report the exact location of the first cell collapse.

Since cells in latewood region have thick cell walls, they do not collapse as easily as earlywood cells unless external load increases substantially. In reality, fracture of earlywood region likely occurs before collapse of latewood cellular structure. At the test conditions adopted in this study, cells in latewood region did not collapse.

Jack pine.—Jack pine is a softwood with an abrupt earlywood-to-latewood transition. Its cell dimensions and cell-wall thickness change abruptly from earlywood to latewood (Panshin and de Zeeuw 1980). As in the case of white spruce, radial walls of cells bent toward the cell lumen in the elastic region. The largest cells, which had thin walls and were located at about the 14th cell rows from the beginning of a growth ring, collapsed first. With increasing applied load, cellular structure collapse developed further in the earlywood region. For the specimens tested in this study, cells in earlywood of jack pine were larger in diameter and hence had larger radial wall lengths than those in white spruce (Tabarsa and Chui 1999). These cell-wall differences, which agree with those reported by Panshin and de Zeeuw (1980), are thought to be the reason for the lower yield stress and MOE in jack pine.

The plateau region for jack pine was observed to be shorter than that for white spruce. The narrower earlywood region of jack pine was the reason for its shorter plateau. As in the case of white spruce, after collapse of all cells in earlywood, deformation in latewood increased with applied stress until the test specimen fractured, but no latewood cellular structure collapse was observed.

The above findings for white spruce and jack pine provide some justification for the use of mechanics-based models such as the ones developed by Gibson and Ashby (1982) for predicting gross stress-strain relationship of wood based on cell-wall dimensions and mechanical properties. Work on assessing the suitability of such a predictive model has been conducted by the authors and will be reported in a future publication.

Aspen.—Aspen is a diffuse-porous hardwood with similar sized vessels distributed over its structure. Vessel diameter of aspen is about 6–8 times larger than fibers; therefore

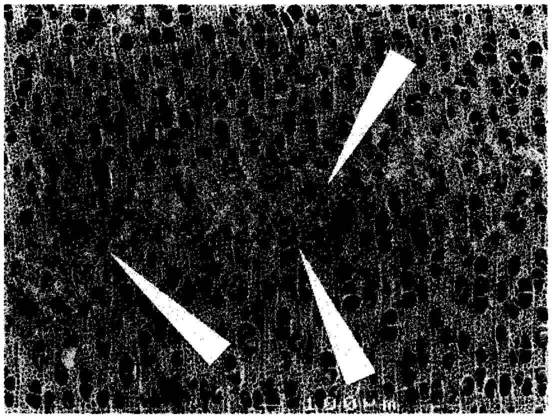

FIG. 4. Micrograph showing some locations of collapsed vessels in aspen—direction of loading is up-down. (30×)

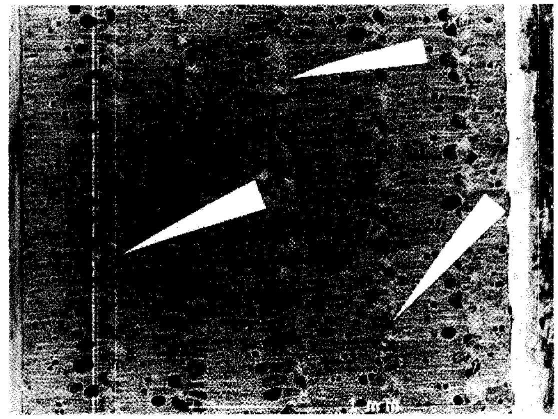

FIG. 5. Micrograph showing some locations of collapsed vessels in white ash—direction of loading is up-down. (20×)

vessels dominate its cellular structure. The vessels are surrounded by paratracheal parenchyma which are thin-walled elements. In addition they are conductive elements with numerous pits causing them to be weaker than fibers that have thick walls (Panshin and de Zeeuw 1980).

When aspen was subjected to radial compression, the weakest elements (vessels) exhibited the most deformation in the elastic regime. With increasing compressive load, deformation in the vessels increased until they collapsed. In contrast to earlywood failure in softwoods, vessel collapse did not appear consistently at one specific location in a growth ring (e.g., beginning of a growth ring). Often, all vessels were deformed and a crack appeared where a number of vessels were aligned close to each other. Thereafter collapse of vessels initiated, usually in the middle of the growth ring (Fig. 4). This point corresponded to the start of the plateau region of the stress-strain curve. Further compressing led to the removal of all vessel cavities, which corresponded to the onset of the densification region. During the densification region, the fibers around the vessels deformed elastically, but they did not collapse at the load levels used in this study.

White ash.—White ash is a ring-porous hardwood, with the larger vessels located in the earlywood (Panshin and de Zeeuw 1980). During radial compression, these large vessels exhibited the most deformation which led to the first collapse (Fig. 5) of the cellular structure. As can be seen in Fig. 5, first collapse occurred in large vessels located in earlywood of each growth ring. When most of the large vessel cavities were removed, the parenchyma cells around the vessels were crushed because of their thin cell walls. Fibers located around the vessels also started to undergo noticeable deformation. This coincided with the start of the densification region in the stress-strain curve.

Effect of loading direction on softwood stress-strain response in compression

Traditionally, for dimension lumber the differences in mechanical behavior of wood when stressed in radial and tangential direction were considered to be negligible. Bodig (1965) and Kennedy (1968) studied the behaviors of species with different structures in radial and tangential compression. They concluded that in tangential compression latewood layers behaved like columns spaced by the more flexible earlywood layers. Earlywood/latewood ratio was found to be an important parameter in explaining the differences in behavior of wood under radial and tangen-

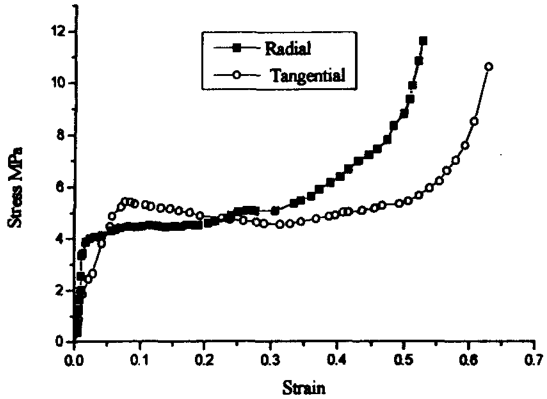

FIG. 6. Radial and tangential stress-strain curves of white spruce.

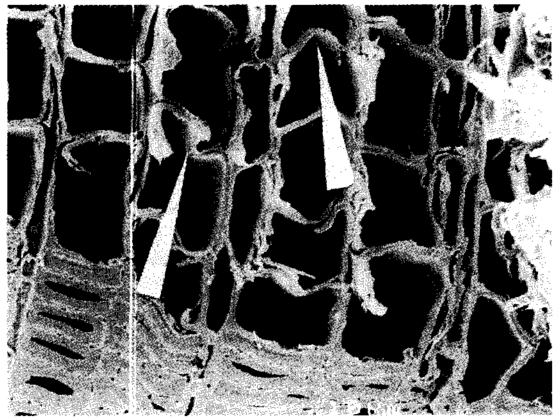

FIG. 7. Micrograph showing bending of tangential cell walls in white spruce under tangential compression—direction of loading is left-right. (400×)

tial compression. Kennedy (1968) indicated that species with low latewood percentage were stronger in radial direction, while species with high latewood percentage were stronger in tangential direction. The results from this study supported these findings as discussed below.

White spruce.— Three white spruce specimens were subjected to tangential compression tests. Mean MOE of white spruce in tangential compression was found to be 104 MPa, and mean yield stress was 4.96 MPa. MOE of white spruce in tangential compression was less than its MOE in radial compression, but yield stress was higher. Kennedy (1968) concluded in his study that species with a low latewood percentage may be expected to be stiffer under radial compression than tangential compression. This is because the latewood layers are the main source of resistance to the applied load as they are considerably stiffer than the earlywood layers when loaded in the tangential direction. Thus the thickness of latewood in relation to the earlywood thickness governs the deformation characteristics, and hence measured modulus, in tangential compression. Since white spruce is a species with a relatively low latewood percentage, the results here support Kennedy's conclusion.

One stress-strain curve of white spruce in tangential compression and one in radial compression are compared in Fig. 6. As can be seen in Fig. 6, in contrast to radial compression where stress increases slightly in the plateau region, in tangential compression stress drops gradually in the plateau region because of buckling of latewood layers. For the radial curve, stress decreases initially in the plateau region, then starts to increase as it enters the densification region.

Microscopic observations during test showed that under tangential compression, tangential walls of cells underwent noticeable deformation in the elastic range of the stress-strain curve (Fig. 7). The measured gross deformation appeared to be a combined contribution of this cell-wall bending and bending of the latewood as a single layer. Buckling of latewood layers, illustrated in Fig. 8, was observed, which coincided with the drop in its stress-strain curve in Fig. 6. This buckling behavior was also observed by Bodig (1965). At the start of buckling, compressive stress decreased with any further compression due to instability in the cellular structure. Readjustment of the position of the collapsed latewood and its interaction with the earlywood layers led to a stabilized structure (Fig. 8). This in turn caused the stress to increase again. So the densification region of the stress-strain curve of white spruce under tangential compression is related to the resistance of the collapsed latewood and earlywood layers against applied

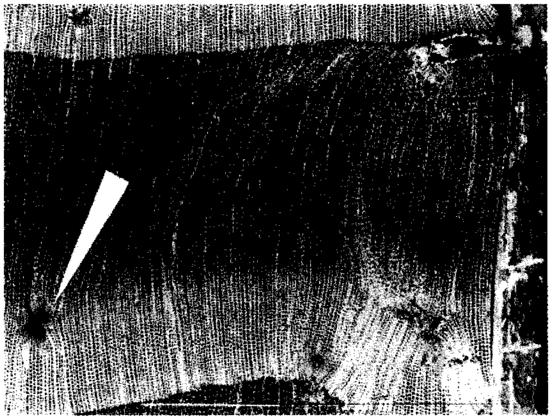

FIG. 8. Micrograph showing initiation of latewood buckling near resin canals in white spruce under tangential compression—direction of loading is left-right. (16×)

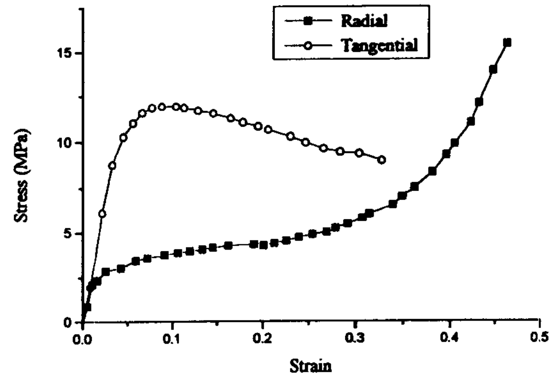

FIG. 9. Radial and tangential stress-strain curves of jack pine.

load. This is in contrast to the radial compression case where the densification region is governed by the elastic compression of the latewood cells.

Jack pine.—The average values of MOE and yield stress from the three tangential compression tests on jack pine specimens were 153 MPa and 10.9 MPa, respectively. A comparison of typical stress-strain relationships of jack pine in radial and tangential compression is illustrated in Fig. 9. In contrast to white spruce, MOE of jack pine in tangential compression was higher than its MOE in radial compression. This is thought to be related to the wider latewood layers of jack pine, as was suggested by Kennedy (1968).

As in the case of white spruce, the tangential stress-strain curve changes to a negative slope (i.e. stress drop with increasing strain) after reaching the yield stress. This behavior was also caused by the buckling of latewood layers. Prior to this buckling, microscopic observations revealed that the relatively large resin canals in jack pine played a major role in this behavior. As is shown in Fig. 10, large localized deformations can be seen near the resin canals. Buckling of latewood layer was observed soon after the resin canals collapsed, which coincided with the yield point. Unlike white spruce, the radial compression stress-strain curve does not have a densification region because of occurrence of premature cracking in the cellular structure. This behavior again is due to the presence of large resin canals which are sources of crack initiation.

CONCLUSIONS

From the above results and discussion, the following conclusions can be drawn for the four species tested in this study:

1. In radial compression, the deformations in both hardwoods and softwoods are not uniformly distributed throughout a growth ring. In the softwoods, deformation is inversely proportional to thickness of cell wall. First collapse of cell wall occurs in

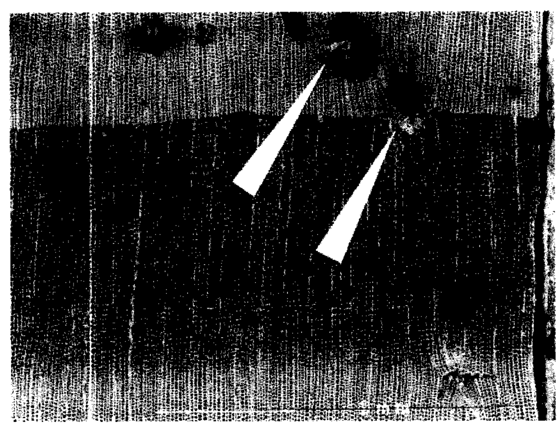

FIG. 10. Micrograph showing localized deformation near resin canals (dark region) in jack pine under tangential compression—direction of loading is left-right. (22×)

cells with the thinnest cell wall. In the hardwoods, the largest vessels surrounded by thin-walled paratracheal parenchyma cells deform more than fibers, and first failure initiates in these elements. In ring-porous white ash, first collapse of the cellular structure occurs in the large vessels in earlywood, while in diffuse-porous aspen, first failure appears as a crack running through neighboring vessels.

2. In the elastic range of the stress-strain curve, the mechanism of deformation in tangential direction is different from radial compression in the softwoods. In radial compression, the measured deformation is caused by the bending of the radial walls, while the tangential walls contribute little. In tangential compression, the total measured deformation contains both the bending deformation of the latewood layers and the cell-wall deformation.
3. For the softwoods, in tangential compression, yielding is initiated by buckling of latewood layers. Stress reduction with increasing strain is observed in the plateau region. For white spruce which has small resin canals, stress-strain response has the three characteristic regions: elastic, plateau, and densification. The densification region is not present in jack pine because of the initiation of premature cracking near the large resin canals.

ACKNOWLEDGMENTS

The authors would like to acknowledge the financial support of the Natural Sciences and Engineering Research Council (NSERC) of Canada and Ministry of Higher Education, Islamic Republic of Iran.

REFERENCES

BODIG, J. 1965. The effect of anatomy on the initial stress-strain relationship in transverse compression. Forest. Prod. J. 15(5):197–202.

———, AND B. A. JAYNE. 1982. The mechanics of wood and wood composites. Van Nostrand Reinhold Co. Inc., New York, NY.

DINWOODIE, J. M. 1965. The relationship between fibre morphology and paper properties. Tappi J. 48(8):440–447.

EASTERLING, K. E., R. HARRYSON, L. J. GIBSON, AND M. F. ASHBY. 1982. On the mechanics of balsa and other woods. Proc. R. Soc. Lond. A 383:31–41.

GIBSON, L. J., AND M. F. ASHBY. 1982. The mechanics of two-dimensional cellular materials. Proc. R. Soc. Lond. A 382:25–42.

KENNEDY, R. W. 1968. Wood in transverse compression. Forest. Prod. J. 18(3):36–40.

KUNESH, R. H. 1968. Properties of wood in transverse compression. Forest. Prod. J. 18(1):65–72.

MATAKI, Y. 1972. Internal structure of fiberboard and its relation to mechanical properties. *Cited in* A. J. Benjamin, 1972. Theory and design of wood and fibre composite material. University of Washington and Syracuse University Press. Pp. 219–253.

PANSHIN, A. J., AND C. DE ZEEUW. 1980. Textbook of wood technology. McGraw-Hill Inc., New York, NY.

SCHNIEWIND, A. P. 1959. Transverse anisotropy of wood: A function of gross anatomic structure. Forest. Prod. J. 9:350–359.

STEFANSSON, F. 1995. Mechanical properties of wood at microstructure level. Report TVSM-5057. Lund Institute of Technology, Lund, Sweden.

TABARSA, T., AND Y. H. CHUI. 1999. Microscopic observation of wood behaviour in radial compressing. Pages 463–470 *in* Proc. Fourth International Conference on the Development of Wood Science, Wood Technology and Forestry. Chilterns University College, Buckinghamshire, England.

———, AND ———. 2000. Characterizing microscopic behaviour of wood under transverse compression. Part 1: Method and preliminary test results. Wood Fiber Sci. 32(2):144–152.

WELONSE, J. D., R. L. KRAHMER, M. D. SANDOE, AND R. W. JOKERST. 1983. Thickness loss in hot-pressed plywood. Forest Prod. J. 33(1):227–234.

WOLCOTT, M. P., F. A. KAMKE, AND D. A. DILLARD. 1994. Fundamentals of flakeboard manufacture: Viscoelastic behaviour of the wood component. Wood Fiber Sci. 22(4):345–361.

YOUNGS, R. L. 1957. Mechanical properties of red oak related to drying. Forest. Prod. J. 9:315–324.