STRESS-STRAIN RESPONSE OF WOOD UNDER RADIAL COMPRESSION. PART I. TEST METHOD AND INFLUENCES OF CELLULAR PROPERTIES

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ABSTRACT

A new test system was developed for real-time microscopic observation of wood cell-wall deformation and stress-strain relationship under transverse compression. The system consists of a small compression device, a stereo-microscope, a video microscaler, a videocassette recorder and a computer-based data logger. The significance of this system is that it allows the influence of cellular structure of wood on its stress-strain behavior and the cell-wall collapse mechanism to be studied. This test system was used in a research program aimed at generating some basic understanding of microstructural behavior of wood under transverse compression. Tests were conducted on white spruce specimens to evaluate the proposed test procedure and system, and the influences of some microscopic and macroscopic features such as wood density, cell-wall thickness, and earlywood/latewood ratio. End-matched specimens were tested using the test system at three levels of magnification. Gross and individual ring behaviors were observed and measured by testing at a low magnification (12×). Earlywood and latewood behaviors were measured separately using a medium level of magnification (32×). Finally the mechanism of cell-wall collapse was observed using the highest magnification (160×). Test results show that earlywood and latewood have varying degrees of influence on the various segments of the gross stress-strain curve in radial compression. First collapse of cellular structure occurs at a location with minimum cell-wall thickness and density. Initiation of cell-wall collapse and its gradual progression are clearly visible using the apparatus, thereby verifying the capability of the proposed method.

Keywords: Wood, transverse compression, stress, strain, cell-wall collapse, cell-wall thickness, density profile.

INTRODUCTION

In the manufacture of composite wood products, the various processes employed subject the wood material to compressive stresses perpendicular-to-the-grain, sometimes at elevated temperatures. The performance of these products in service depends on how wood responds to such stresses (Kunesh 1961). For example, dimensional stability is related to the springback characteristics, which are in turn dependent upon the amount of compressive strain and mechanism of failure in wood structure during hot-pressing (Tabarsa and Chui 1997). Compressing wood at room temperature and low compression strain (in the elastic region) causes high springback. Conversely, compressing wood at high temperatures, well past its softening temperature, and high compression strain (in the plastic region) leads to a

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denser product. In order to achieve a certain degree of densification, wood material is often compressed beyond its elastic limit during processing of wood composites. Therefore, characterizing wood behavior in transverse compression beyond the elastic limit is critical in understanding how the manufacturing processes affect physical and mechanical properties of wood composites.

The anisotropic nature of wood means that the response of wood to an applied stress depends on the direction of loading. A number of researchers have observed the differences in stress-strain responses of wood under radial and tangential loading (Youngs 1957; Schniewind 1959; Bodig 1965; Kennedy 1968; Kunesh 1968). They attributed the differences in behavior to ray alignment in these two directions, which is particularly profound in species with broad rays such as oak (Schniewind 1959; Kunesh 1961). Those researchers used light microscopy to observe the microstructural deformation behavior after compression. Easterling et al. (1982) used scanning electron microscopy (SEM) in an attempt to observe the progressive failure of the cellular structure of balsa. They observed that cell walls bent uniformly at the beginning of loading, then plastic collapse developed first at the surface of the loading platen. Thus their observation was not truly a material failure.

As discussed above, the motivation of the current work is to better understand the wood-adhesive system (mat) behavior during processing of wood composites. Modeling such behavior has attracted the attention of scientists in the last few decades. A number of theoretical models were developed to predict the consolidation of the mat system during hot-pressing (Dai and Steiner 1993; Wolcott et al. 1994). These models require proper material property input that should ideally reflect the actual characteristics, such as earlywood percentage, of wood. Conventional transverse compression tests such as ASTM D143 method (ASTM 1997) that measure gross wood response are inadequate in this regard. The usefulness of these models will be enhanced if more appropriate test methods and data on material properties are available.

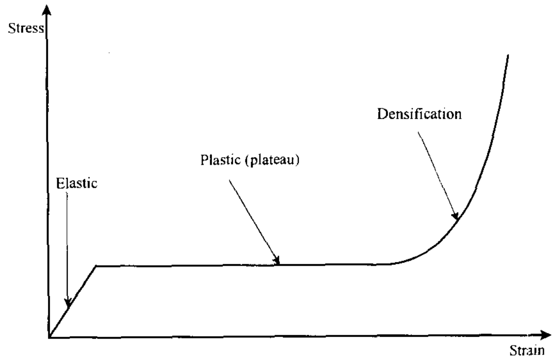

FIG. 1. An idealized stress-strain relationship of wood under transverse compression.

The gross behavior of wood with different cell arrangements in its three principal planes is much more complex than that of isotropic materials. During transverse compressive loading, a typical stress-strain curve of wood has three distinct regions (Fig. 1; Bodig 1965; Easterling et al. 1982). The initial part is a linear elastic region in which the stress is directly proportional to strain. The second part, sometimes known as the plateau, is a plastic region in which strain increases rapidly with a small or no change in stress. After the plastic region, stress increases sharply with strain. This rapid increase in stress was thought to be a result of the elimination of air voids and compression of the solid wood structure; hence this region is termed the densification region. All these regions are known to be affected by cell morphology, but that influence has not yet been fully understood.

In conventional transverse compression tests, wood is assumed to be a homogenous material, and usually average gross strain is measured. In reality, deformations are not uniformly distributed throughout a specimen. For instance, cell-wall collapse, which is believed to coincide with the start of the plastic region, initiates from the weakest layers of earlywood and develops toward latewood (Bodig 1965). The studies reviewed above suggested that macroscopic failures occurring during mechanical tests can be better understood by microscopic observations. One of the common limitations of the above studies was that observation of microstructural deformations was made on microtomed specimens, which were prepared after the test. Therefore, the mechanism of failure and some of the influences of anatomical features were not observed. The work described here forms part of a research study aimed at achieving a better understanding of the microscopic wood behavior during transverse compression at various temperatures. In order to achieve this objective, it was necessary that a new test procedure and apparatus be developed that would enable the influence of wood anatomy on the compression stress-strain behavior of wood to be studied. This paper discusses the proposed test procedure, development of the apparatus, and some test observations and results using the apparatus.

TEST SYSTEM FOR CHARACTERIZING WOOD BEHAVIOR UNDER TRANSVERSE COMPRESSION

To satisfy the needs of this project, the compression test apparatus had to be capable of measuring the small compression deformation of the cell structure accurately and allowing the cellular deformation to be observed in real time. It was found that these two objectives could be met by recording the magnified image of the cellular structure during a compression test, from which the small compression deformation could be quantified using a video microscaler. A video microscaler is an electronic device that superimposes two adjustable parallel reference lines on an image. The video microscaler can be properly calibrated to provide the actual distance between any two points on the image.

To apply the load to the test specimen, a miniature compression device was designed and fabricated (Fig. 2). The design of the compression test device allows for the insertion of heating elements, enabling the test specimen to be tested at temperatures ranging from room temperature to 160°C. The compression force is applied by a small screw-jack mechanism with the rate of compression controlled by an electric motor. For the tests reported here, the deformation rate was held constant at 0.3 mm/min. The compression force was measured by a 22 kN load cell, which was placed between the specimen and the screw in the compression device.

The compression device was fixed to the stage of a light microscope equipped with a vertical illuminator. The cellular structure was made visible by the light reflection technique. The microscope stage was attached to a movable platform that was specially designed to allow translation movement in three orthogonal directions. The recorded image was maintained in-focus during a test by manually adjusting the position of the stage. A video camera was mounted on top of the microscope so that the image of a specimen surface was magnified and recorded by a videocassette recorder (VCR) and displayed on a television monitor. The recorded image was played back and the microstructural deformation measured using the video microscaler. This test system therefore served the dual functions of allowing the surface deformation characteristics of a specimen to be observed during the compression test and for the measurement of the deformation. The load cell readings were recorded using a computer-based data logging system. Synchronization of the clocks of the computer and video camera before a test enabled the recorded load readings to be matched to the deformation measurements from the video microscaler.

EVALUATION OF TEST APPARATUS AND INFLUENCES OF MICROSCOPIC AND MACROSCOPIC FEATURES ON STRESS-STRAIN RESPONSE

One of the goals of this research is to study how the engineering stress-strain behavior of wood under transverse compression is influenced by its anatomical features. This implies a need to observe both localized and gross behaviors. It was found that in order to achieve this goal, tests need to be conducted at differ-

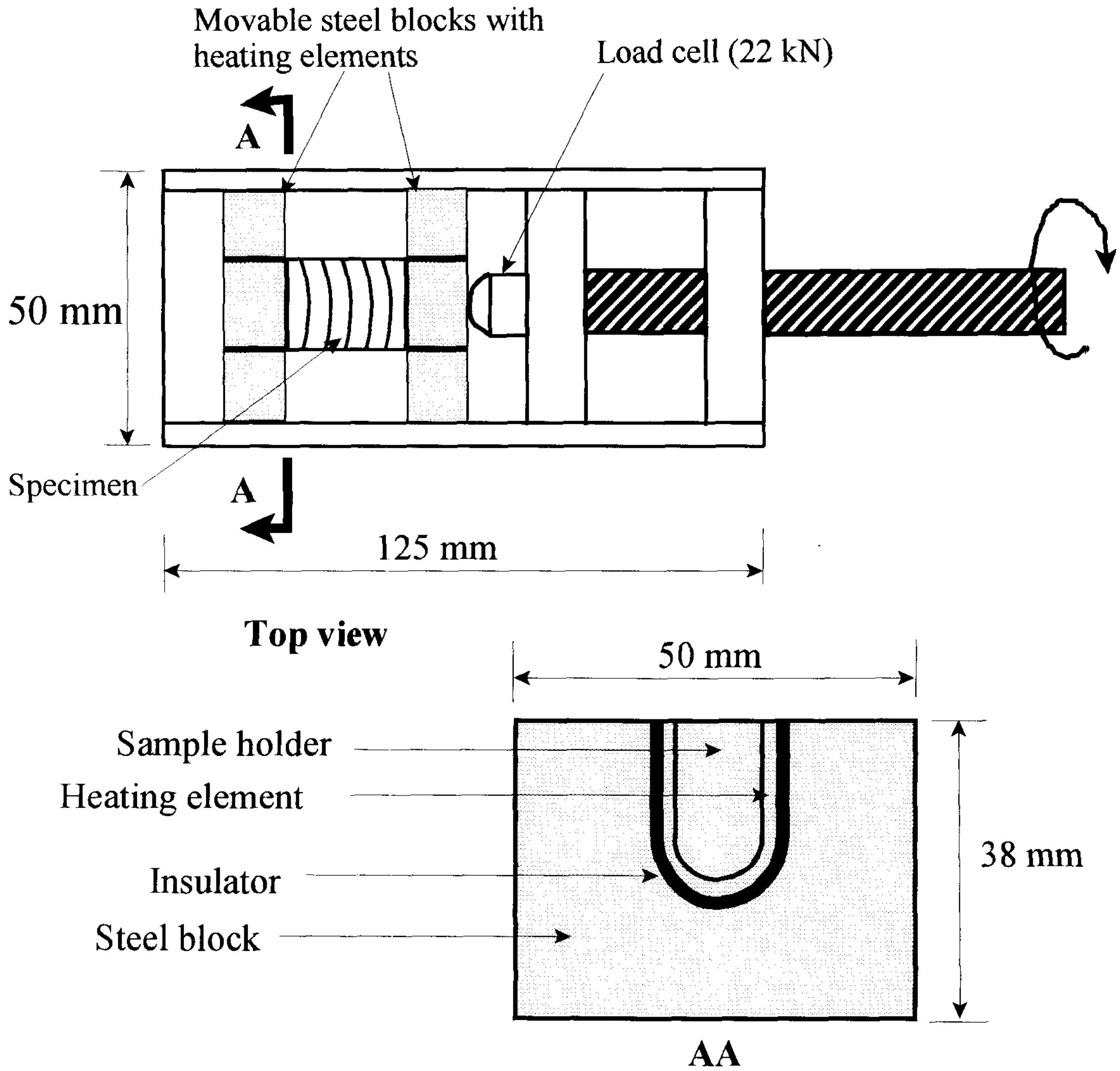

FIG. 2. Miniature compression device.

ent levels of magnification using matched specimens. Initial work showed that three levels of magnification were desirable: low (12×), medium (32×), and high (160×). A compression test at low magnification provides gross stress-strain behavior of wood specimens containing a few growth rings. At this magnification, stress-strain behavior of individual growth rings can also be measured separately from the same specimen. The medium magnification is required for analyzing the response of one growth ring in a specimen. At this magnification, the stress-strain behavior of earlywood and latewood can be measured separately and their contribution to the gross behavior quantified. Also at this level, the location of the onset and progressive collapse of cell-wall structure within a growth ring can be observed. The high magnification is required for a qualitative assessment of the cell-wall failure mechanism and for measurement of the dimensions of cell-wall structure using the video microscaler.

To examine the feasibility of the proposed compression test procedure and test system, a series of tests was conducted. The species used was white spruce (*Picea glauca*). These tests also provided some basic information on the influence of microscopic and macroscopic features on stress-strain response of softwood to radial compression. Three matched specimens with dimensions 8 × 8 × 8 mm were prepared. The specimens were conditioned at 65% relative humidity and 21°C prior to testing. The radial-tangential plane of each specimen was microtomed to provide a smooth surface for microscopic observation during the compression tests. Actual dimensions of the specimen were measured before the test. For the measurement of microstructural deformation, it was required that reference points be attached to the surface of the specimen. After some exploratory work, fine metallic wires with a diameter of 0.025 mm were chosen for this purpose.

Three matched specimens were tested at magnification levels of 12×, 32×, and 160×, respectively. Direction of loading was radial, and the tests were conducted at room temperature. The first specimen that contained two growth rings was tested at a 12× magnification. The metallic wires were glued to the microtomed surface of the specimen. Data of load versus time was recorded using a computer-based data-logging system. The magnified images of the specimen surface were recorded continuously in real time using a videocassette recorder via a video camera and a light microscope. The time was superimposed on the recorded images. The clocks of the video camera and the computer data logging system were synchronized prior to the test. The recorded image was then played back. The deformations were measured at regular time intervals. Strain was calculated as the change in distance between two reference points over the original distance between these points. Compressive strains for individual rings and for the complete specimen can be measured separately using this technique. Matching the time shown on the television monitor to that stored in the load versus time data file enabled the corresponding load causing the compressive strain to be identified. The compressive stress was then calculated as the compressive force divided by the load area.

The second specimen was similarly tested in compression and its deformation characteristics recorded using a magnification of 32×. Fine metallic wires were not used since distinctive features, which can be used as reference points, were clearly visible. Under this magnification, only one ring could be observed. Load and deformation for the growth ring and its earlywood and latewood regions were obtained separately. In addition, structural changes in earlywood and latewood were recorded in real time. The procedures for measuring and calculating stress and strain were as described above for the specimen tested using a 12× magnification.

The deformation characteristics of the third specimen were observed and measured using a magnification of 160×. Metallic wires were not required at this magnification level. The purpose of doing this test was to qualitatively assess the mechanism of deformation and collapse of cell walls. Load versus time data were, however, recorded as in the other two specimens. Another reason for conducting tests at this level of magnification was to measure the cross-sectional dimensions of the wood cell such as cell-wall length and thickness. These dimension measurements will be required for a subsequent phase of the project whereby the feasibility of applying the cellular theory in predicting stress-strain response of wood will be assessed. These measurements would also help to explain the various features of the stress-strain curve and the collapse mechanism of the cellular structure.

RESULTS AND DISCUSSION

Stress-strain curves for the entire specimen and for two of the growth rings are presented in Fig. 3. These curves were obtained from the specimen tested at 12× magnification. As can be seen, the three curves are similar to each other. This is because both rings were similar

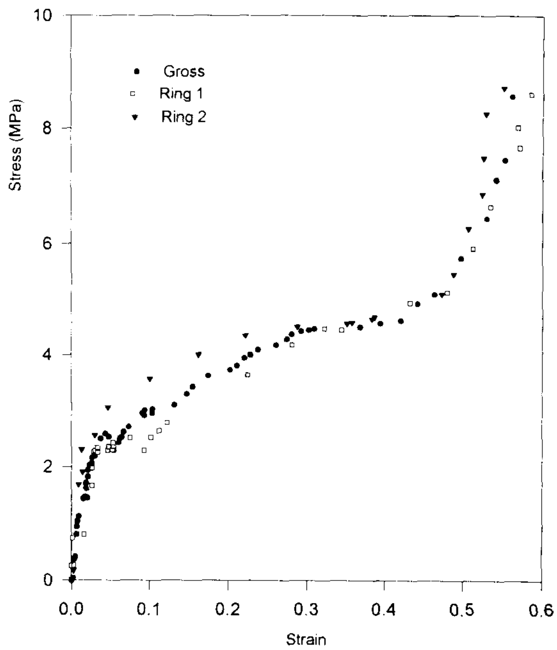

FIG. 3. Stress-strain relationships of gross behavior and individual annual rings under radial compression.

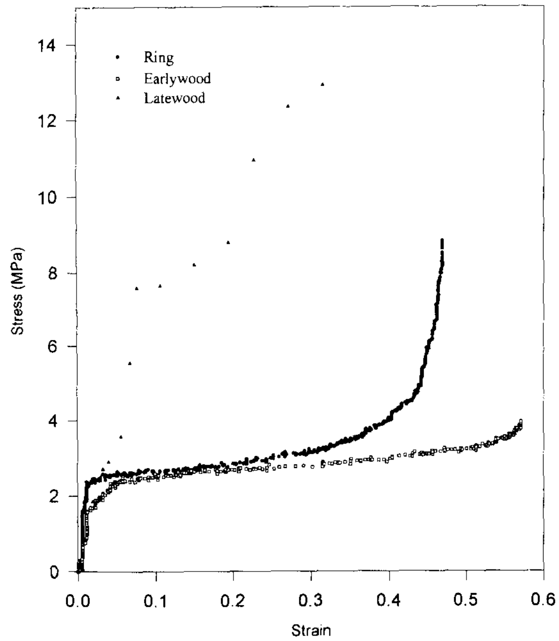

FIG. 4. Stress-strain relationships of one annual ring and of its earlywood and latewood under radial compression.

in terms of width and earlywood/latewood percentage. The specimen exhibited linear-elastic behavior up to a stress of about 2 MPa and a compression strain of 2%. Stress increased to 2.5 MPa, then dropped down to 2.3 MPa. After that, stress increased at a considerably lower rate up to a compressive strain of about 45%. Beyond this point, stress increased sharply with little change in strain. The resulting stress-strain curves have the familiar regions illustrated schematically in Fig. 1.

Using the magnification of 32×, the behavior of one growth ring in a specimen under transverse compression was studied in greater detail. Stress-strain data for the entire ring, earlywood and latewood are presented separately in Fig. 4. As can be seen in Fig. 4, earlywood behaves differently from latewood. Although the responses are similar in the elastic region, the curves differ significantly in the plastic region. The earlywood response has a clear and long plateau region. The plateau region is, by comparison, very short in the latewood.

An analysis of the images showed that the cells located in earlywood accounted for virtually all the initial elastic deformation in a growth ring. In contrast to previous belief, first collapse of cellular structure occurred at a cell layer close to, but not next to, the previous latewood region. In fact, for white spruce, the first collapse occurred at approximately the fifth cell layer from the previous ring. Comparing this with other cell property measurements such as cell-wall thickness (Fig. 5) and density profile (Fig. 6) on the same specimen, this location corresponds to the cell layer with the smallest cell-wall thickness and gross wood density, which in turn is affected by cell-wall thickness. The cell-wall thicknesses were measured using the video microscaler, whereas the density profile was obtained using an X-ray densitometer.

This first collapse of cellular structure corresponds to the first drop in stress in Fig. 3 and the start of the plateau region. This collapse mechanism spread to other earlywood cell layers, first towards the previous growth

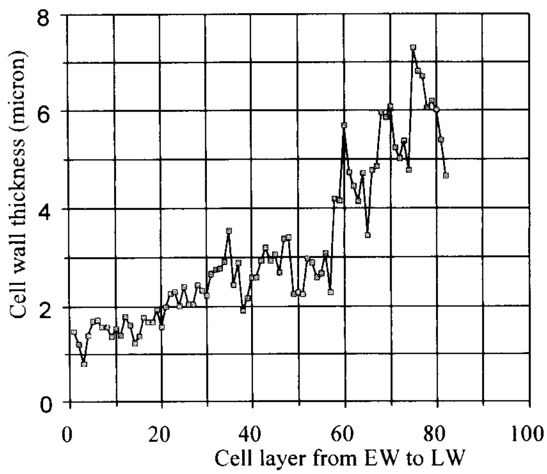

FIG. 5. Variation of cell-wall thickness within a growth ring.

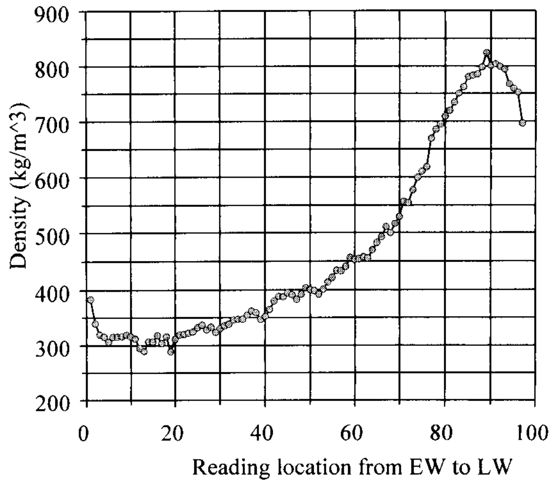

FIG. 6. Variation of gross wood density within a growth ring.

ring, then the latewood of the same ring. The gradual increase in cell-wall thickness from earlywood to latewood, as illustrated in Fig. 5, means that stress needs to be increased gradually in order to cause spreading of the collapse mechanism from earlywood to latewood. This explains the slow rise in stress with strain in the plateau region. For other species that exhibit a more uniform cell-wall thickness, it is expected that the plateau region will be close to a horizontal line.

The end of the plateau region and the start of the densification region corresponds to the collapse of the last cell layer in earlywood. This complete collapse of earlywood cell structure is illustrated in the SEM micrograph shown in Fig. 7. Therefore, the plateau region of the stress-strain curve of gross wood behavior is controlled primarily by the collapse behavior of the earlywood. Since at this point the latewood deformation was observed to be very small (Fig. 4), it can be concluded that the length of the plateau region on the stress-strain curve is approximately equal to the sum of the cell lumen dimension over the ring width in the radial direction. Such a finding is useful for the purpose of modeling the stress-strain response of softwood under radial compression.

When all earlywood cells have collapsed, the stress rises at a faster rate and the latewood cells begin to exhibit a larger deformation. On the stress-strain curve, this corresponds to the so-called densification region. Figure 4 indicates that the term 'densification' is probably inappropriate since the response in that region is purely the elastic response of the latewood to the applied stress and not the densification of the solid cell-wall material, as was previously assumed. Eventually the first cell-wall collapse occurs in latewood, which leads to the onset of a small plateau in the latewood curve in Fig. 4. This particular specimen frac-

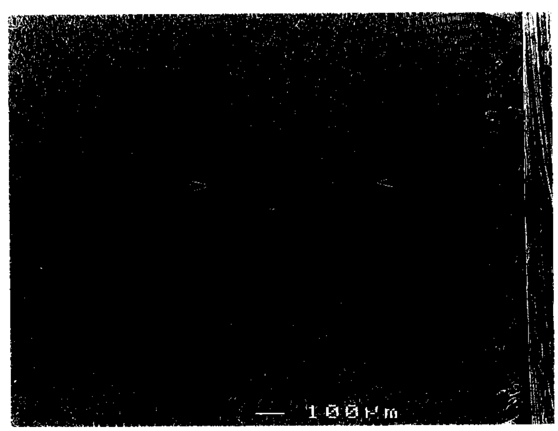

FIG. 7. Micrograph depicting collapse of layers of cells in earlywood under radial compression.

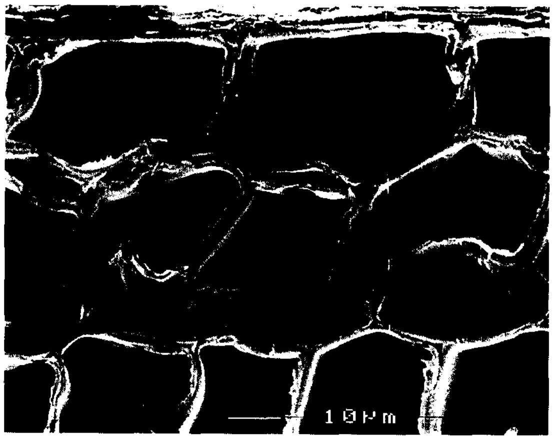

FIG. 8. Micrograph depicting elastic deformation of cell-wall structure.

tured prior to the complete collapse of latewood structure. Subsequent tests showed that collapse of latewood cell structure may not be achievable if the latewood consists of thick-walled cells.

To understand the mechanism of failure, another compression test was conducted on a matched specimen using a high magnification of 160×. At this magnification, cell walls are clearly visible. Since from the last test it was found that cell collapse initiated from early layers of earlywood, the microscope was therefore zoomed in on these earlywood layers before loading the specimen, and cell-wall deformation was recorded continuously. The position of the stage was adjusted continuously to ensure that progressive collapse of cell-wall structure was recorded. Examination of these images provided a valuable insight into cell-wall deformation during compressive loading. It was learned that during radial compressive loading the radial walls were bent elastically, (Fig. 8). When bending of radial walls reached a certain level, cell-wall collapse occurred. This finding indicates that, from a mechanics standpoint, the collapse of the softwood cellular structure is not a wall-buckling problem. Rather, it is the formation of plastic hinges that causes the collapse of the cell-wall structure. Such an observation will assist in identifying a theoretical approach for predicting collapse of cell-wall structure under radial compression. That theoretical study will be reported in a subsequent paper.

CONCLUSIONS

The following conclusions can be drawn from this study:

1. The test procedure and system developed for this study perform well and are capable of providing reliable gross stress-strain response of wood and the stress-strain responses of any components of the wood microstructure under transverse compression.
2. The elastic and plastic parts of the stress-strain response for white spruce under radial compression are primarily controlled by the earlywood. First collapse of cellular structure, which signifies the onset of the plastic region, occurs in the cell layer with the smallest cell-wall thickness and therefore smallest gross density in the earlywood. In the case of the white spruce specimen observed in this study, this layer is located at about the fifth layer from the previous growth ring.
3. The initial part of the densification region is largely an elastic response of the latewood to the compressive stress, and collapse of latewood cells may not occur due to their large wall thickness.
4. Cell-wall collapse is a result of formation of plastic hinges rather than buckling of the cell wall.

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