Mechanical behaviour of wood compressed in radial direction-part I. New method of determining the yield stress of wood on the stress-strain curve

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ABSTRACT

A test equipment was developed, which allows for real time observation of the deformation behavior of wood cellular structure under a compression load applied in radial direction. Compression tests were performed on jack pine (Pinus banksiana) and balsam poplar (Populus balsamifera) specimens to explore the relationship between the yield stress and the first failure occurring in wood cell layers during radial compression. The microstructural changes for P. banksiana and P. balsamifera wood below and above the yield point were analyzed. The study results showed that for P. banksiana the first failure of wood cells occurred at the first earlywood layer, while for P. balsamifera it occurred at the layer with the largest vessels. The first failure of wood cell layer for each species tested was found to correspond to the yield point on the stress-strain curve. A new method of determining the yield stress for wood specimens under radial compression was developed.

1. Introduction

When wood is compressed in the transverse direction, structural changes in wood cells occur due to the deformation or failure of the cell walls, along with the decrease of void space in the cell lumen (Bodig, 1963; 1965; 1966; Wolcott et al., 1994; Ando and Onda, 1999; Tabarsa and Chui, 2000; 2001; Kutnar and Kamke, 2013; Aimeine and Nairn, 2015). The wood cellular structural changes are highly related to the mechanical behavior of wood during compression, which can be characterized by the stress-strain curve, as shown in Fig. 1 (Youngs, 1957; Schniewind, 1959; Kennedy, 1968; Kunesh, 1968; Easterling et al., 1982; Gibson and Ashby, 1988; Dai and Steiner, 1993; Wolcott et al., 1994; Ellis and Steiner, 2002; Zhou et al., 2009; Kutnar and Kamke, 2013; Zhong et al., 2014; Aimeine and Nairn, 2015; Polocoșer et al., 2017). To elucidate the impact of wood microstructural changes on its mechanical behavior, some researchers have proposed an important definition: the yield point, indicating when the wood cellular structure failure appears (Bodig, 1963; 1965; 1966; Ando and Onda, 1999; Tabarsa and Chui, 2000; 2001). The mechanical behavior of wood is defined as elastic before failure of wood cellular structure, which can be illustrated by a linear-elastic region below the yield point on the stress-strain curve (Fig. 1). The mechanical behavior of wood is, however, considered to be inelastic after wood cell walls start to fail. This inelastic behavior can be described by the region above the yield point on the stress-strain curve, including a plastic or plateau stage, and a densification stage (Fig. 1). Knowing the yield point of wood is helpful to design the hot-pressing operation that will lead to the favorable densification of wood which is desirable for the improvement of the mechanical properties of the wood-based composites

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or densified wood products. Moreover, as indicated in Fig. 1, locating yield point on the stress-strain curve provides a measure of another important mechanical property: modulus of elasticity (MOE), for wood specimens under compression.

Traditional method of determining the MOE for a test specimen under compression is to collect all load and deformation data during a compression test, and then to plot the stress-strain curve using the stress and strain data respectively. The linear part of the stress-strain curve below the yield point is used to compute the value of the MOE, as is illustrated in Fig. 1. Accuracy of locating the yield point on the stress-strain curve is, therefore, a prerequisite to determine the value of the MOE. The yield stress in wood is, however, difficult to be determined accurately. Currently, the technical method of determining the yield stress is to locate a “morphological turning point”, on the transition zone between the elastic and plateau region of the stress-strain curve by a visual and manual evaluation. The morphological turning point is considered to be the target yield point for a given wood specimen (Bodig, 1965; Tabarsa and Chui, 2001). This approach is mainly dependent on whether morphological turning point could be found efficiently and accurately under a visual observation. Therefore, the clearer the morphological turning point appears on the stress-strain curve, the more readily and accurately the value of the yield stress can be obtained. This case can be illustrated by the stress-strain curve shown in Fig. 2, for a jack pine specimen. However, when there is no pronounced morphological turning point between elastic and plastic regions of the stress-strain curve, such as in Fig. 3, for a balsam poplar specimen, in this case it is difficult to locate the yield stress.

To solve the technical issue, it is necessary to fundamentally understand the mechanism of the development of the yield stress for wood under transverse compression. Bodig (1965), in an investigation of the anatomy of wood impacting on the initial stress-strain relationship for wood compressed perpendicular to the grain, found that the first failure of wood cells occurred in the weakest earlywood layer of the specimens for western red cedar (*Thuja plicata Donn*) and Douglas fir (*Pseudotsuga menziesii*). He pointed out
that the maximum stress could only be determined by the weakest earlywood layer, and the strength of the latewood and other earlywood layers add nothing to this value. Based on these findings, Bodig further proposed the “weak layer theory” to explain the mechanism of failure for wood under transverse compression. Bodig, however, could not confirm whether the weakest cells of earlywood layer were responsible for the onset of yield point, because all photographs on the failed wood cells were taken after the compression test due to the limitation of image processing technology. Ando and Onda (1999), afterwards, incorporated coniferous wood specimens: hinoki (Chamaecyparis obtusa), sugi (Cryptomeria japonica) and kuromatsu (Pinus thunbergii), into a Scanning Electron Microscopy (SEM) chamber to observe continuously the deformation process of wood cellular units during the compressive stage. Their findings showed that the first fracture occurred in one row of earlywood tracheids just after the load-displacement curve exceeded the proportional limit on the stress-strain curve. Tabarsa and Chui (2000) applied a real-time observation technology to examine the effect of microscopic changes of a wood specimen under compression on the stress-strain relationship. They reported that for softwoods: white spruce (Picea glauca) and jack pine (Pinus banksiana), the first collapse of cell layer occurred in cell row with the thinnest cell wall in earlywood section, while for hardwoods: aspen (Populus tremuloides) and white ash (Fraxinus americana), the first failure occurred at the largest vessel elements. The findings from Ando and Onda (1999) and Tabarsa and Chui (2000), therefore, confirmed that the weak layer theory proposed by Bodig (1965) could be applied to explain the mechanism of the failure for wood under transverse compression.

In view of above studies, a new approach to determining the yield point for wood under compression could be proposed by matching the morphological change on the stress-strain response to the first failure in wood cellular structure.

This study is intended to verify the proposed approach, and to explore the influences of the changes in wood cellular structure on the stress-strain curve for wood compressed in radial direction. This paper is the first report in a series of mechanical behavior of wood compressed in radial direction. The second paper (Part II) covers influence of temperature and moisture content.

2. Materials and methods

Jack pine (P. banksiana) and balsam poplar (P. balsamifera) were chosen because jack pine is a commercially important softwood species for dimensional lumber production, while balsam poplar is another commercially important species used in the production of oriented strand board and laminated veneer lumber. These two wood species have distinctly different anatomical features. As the softwoods, jack pine has an abrupt earlywood to latewood transition within one annual ring, while as the diffuse porous hardwood, balsam poplar has a uniform texture within one annual ring (Panshin and de Zeeuw 1980).

Five logs with approximately 50 cm in length were cut at breast height from jack pine and balsam poplar trees respectively. Each log was then cut into 15 mm thick disks. From each disk, wood blocks with nominal dimensions 18 mm (tangential) × 10 mm (longitudinal) × one complete annual ring including one more latewood section (radial) were cut from the clear sapwood sections. The reason for selecting specimens with the thickness including only one complete annual ring instead of multiple annual rings was because the fast heat transfer from the surface layer into core of a specimen with about one to two annual-ring thickness could be achieved during a testing process to meet the requirement of this study. The determination was based on preliminary experimental results. All the blocks were cut from the same annual growth ring along the tangential direction to minimize variations in the cellular structure. Only those wood blocks, whose density fell within a range of 0.41–0.42 g/cm³ for jack pine wood, and 0.39–0.40 g/cm³ for balsam poplar wood, were used. This small density range was selected to minimize any influence that the variation of density might have on the results. Compression test specimens of nominal dimensions: 14 mm (tangential) × 7 mm (longitudinal) × one complete annual ring with one more latewood section (radial) under the same density-range for each testing species, were cut from the conditioned wood blocks. Thickness of each specimen varied since it was cut to ensure there was at least one full growth ring. Subsequent measurement of compression deformation would be confined to one growth ring.

Fig. 3. The elastic-plastic transition zone of stress-strain curve for a balsam poplar wood in radial compression at moisture content = 12% and T = 90 °C.
To allow high quality images of the microscopic deformation to be visually examined and recorded by using a digital camera during compression test, one end surface of each specimen was cut and finished with a microtome. This surface was the one exposed to a light microscope to be observed. All test specimens were preconditioned in a conditioning chamber at a temperature of (20 ± 1 °C) and relative humidity (RH) of (65% ± 1%) for two months to achieve the equilibrium moisture content (EMC) of approximately 12%. Then, these samples were kept in a humidity chamber, which was modified using a desiccator containing saturated NaNO₃, to maintain their moisture content (MC) at 12%.

In order to meet the requirement of this study, a testing technique was developed to allow simultaneously recording of applied compression load and images of microscopic deformation of the cellular structure behavior of the specimen. Microtest in-situ tensile/compression and bending stages (Deben research, 2003), originally designed for performing mechanical test on small specimen within the confined space of a SEM chamber, was modified and adopted as a compression module. The modified testing apparatus contains heat blocks that allow the specimen to be heated to an elevated temperature up to 140 °C. The apparatus with a load capacity of 5 kN, along with a computer-based data acquisition system, was used to record load data and to control the compression module. The light microscope stage was fixed to a movable platform that could be moved in three orthogonal directions. The recorded image was manually focused based on the specimen’s position on the stage. A digital camera, mounted on top of the stage, was used to take an image of the specimen surface at 5-second intervals. VirtualDub software (VirtualDub 2007) was used to play back one image at a time.

Fig. 4 shows the developed test apparatus with the real-time observation system and a testing specimen. The testing system with the VirtualDub software was calibrated at first. The initial width of the growth ring in the test specimen was then measured before compression using the VirtualDub software. The deformed ring width was measured one frame at a time using the software as compression load increased, thereby allowing the strain to be calculated. The load corresponding to each picture frame was displayed on the monitor, which was used to calculate the stress corresponding to the measured strain from the picture frame. Using this procedure, the complete stress-strain curve of each specimen can be generated, and that the microstructural deformation characteristics of the specimen at regular close intervals on the stress-strain curve are known. According to preliminary experiments, it was found that the light microscope with a magnification level of 80× could be used to observe and analyze the response of one growth ring in a specimen. Under this magnification, the location of the onset and progressive collapse of cell wall structure can be observed clearly.

In this study, five conditioned specimens from each species were used for compression test. To preserve the MC of specimens during test, all surfaces except for the surface under observation of the light microscope were sealed with wax. During the test, each specimen was compressed in the radial direction under the pressing temperature of 90 °C and a loading speed of 1.5 mm/min. Data of load versus elapsed time and deformation were recorded.

3. Results and discussion

Since the primary focus of this paper is on the identification of the yield point on the stress-strain curve influenced by a significant change in microstructural behavior, only the linear-elastic and plateau region on the stress-strain curve for wood under compression are of interest here.

3.1. Initial compression stage on stress-strain curve

The typical enlarged stress-strain curves with up to 20% compressive strain, including the full linear-elastic region and beginning of inelastic-plateau region for the jack pine and balsam poplar specimens at a certain condition are shown in Figs. 2 and 3.

As indicated with points A and B in Figs. 2 and 3 respectively, there is an initial low stiffness region at the beginning of each stress-strain curve. This low stiffness region can be attributed to the initial seating of the specimen in the test apparatus due to the
unavoidable micro-surface irregularity on the specimen surface that is in contact with the loading platens (Erickson, 1955). When a specimen was placed in the compression module, there were only a few contact spots between the surface of a specimen and the loading platens initially. Therefore, the deformation of the specimen increased rapidly with even a small increase in applied load. As compression load increased further, a larger area of the specimen surface came to contact with the loading platens leading to a stiffer response, until the total surface of a specimen came to contact with the loading platens. At this point, the stress-strain response started to follow a linear trend, until the yield point. Since the initial low stiffness region is related to the surface roughness of the specimen, rather than a true mechanical response of the material, this region is generally ignored in the determination of the values of MOE for wood specimens under compression.

3.2. Effects of wood cellular structural changes on stress-strain curve

Typical stress-strain curves for jack pine and balsam poplar wood specimens compressed at a certain condition are shown in Figs. 5 and 6, respectively. To better explain the phenomena observed, Figs. 7, 8, 9 and 10 present photographs indicating the cellular-structural changes at different compressive stages for the two species tested. In these figures, the letter on the right lower corner of the photograph (O, P, Q, R, S, T, U, or V) refers to the deformation or failure of cell walls that corresponds to its compressive stage represented by the same letter on the stress-strain curve in Figs. 5 and 6.

3.2.1. Jack pine

First failure of wood cells. Fig. 7-O shows the image indicating the shape and position of a row of seven wood cells (A, B, C, D, E, F, and G) in the earlywood near the boundary with the latewood of the previous year before failure, while Fig. 7-P presents another one showing the onset of the failure of the same row of seven wood cells (a, b, c, d, e, f, and g) due to cell wall collapse. After reviewing
the recorded images, the major deformation of wood cells in the linear-elastic region was found to occur in the thin-walled earlywood cells. With an increase in applied load, the radial cell walls were bent into their cell lumens. The magnitude of deformation on these radial cell walls was not uniform in the earlywood section. The most deformed cells were found to occur in the first cell row at earlywood cell, which is located in the new annual ring. However, this earlywood cell row is connected directly to the last row of the latewood layer in another old annual ring. It was observed that the first earlywood layer generally has the larger cell lumens and the thinnest cell wall thickness, which can be considered as the weakest location in the earlywood section during compression test, as shown in Fig. 7-O. In contrast, the thick-walled latewood cells did not appear to deform during the elastic compression stage. With an increase in compressive load, the most deformed wood cells in this earlywood layer started to fail first, as shown in Fig. 7-P. Most importantly, the occurrence on the first failure of these wood cells was observed to coincide with the turning point (yield point) in the transition zone between linear-elastic and non-elastic region, as indicated as the point P on the stress-strain curve in Fig. 5.

Apart from the thinner tracheid cell wall in the earlywood cell row, the first failure location in jack pine can also be explained by the “boundary effect” caused during compression. The transition between earlywood and latewood is abrupt meaning that there is a sudden change in material mechanical properties going from earlywood (lower-density section) to latewood (higher- density section). From the viewpoint of the material science, when two types of materials with distinctly different mechanical properties are bonded together, high stress concentration occurs at the boundary where the composite is under stress, resulting in the first failure occurring to the material with lower density.

The appearance of the first failure of wood cells on the weakest row of earlywood tracheids was also observed by others (Bodig, 1965; Ando and Onda, 1999; Tabarsa and Chui, 2000), despite in different location (cell row) from the beginning of the growth ring due to a variety of softwood resources selected from different studies. In addition, Kunesh (1961) reported that the main cause of failure of the compressed specimens from softwoods was due to buckling of the rays, by investigating the mechanical behavior of Douglas fir (Pseudotsuga menziesii) and western hemlock (Tsuga heterophylla) in radial compression. However, it was observed from this study that the uniseriate rays in test jack pine specimens began to deform and then fail simultaneously with the weakest tracheid cell walls in the earlywood cell row. These very fine rays did not act as spaced columns in support of compressive load. This finding is different from the observation results reported by Kunesh (1961). It should be noted that Kunesh’s conclusion was not based on real-time observation of micro-structural deformation during compression test. Rather it was based on microscopic examination of failed specimens after the test. Because of this, it was not possible for him to identify the first failure of the cellular structure that preceded the buckling of ray cells.

**Progressive failure of wood cells.** After failure of the first earlywood layer, the earlywood cell-layer next to the first failed layer started to fail one after another gradually along the direction to latewood section, as shown in Fig. 8-Q.
This progressive failure of earlywood cell rows continued until all the earlywood cells collapsed, as indicated in Fig. 8-R. The region between points Q and R on the stress-strain curve corresponds to the plateau region (Fig. 5). It follows that the length of the plateau region is directly proportional to the ratio of the earlywood width to growth ring width. However, Ando and Onda (1999), who studied the microscopic deformation behavior for three softwoods: hinoki, sugi and kuromatsu, under radial compression, reported that failures could start to occur in cell-layers to both sides of the first failed cell-layer, and subsequent failures continued to earlywood cell-layers along two opposite directions to earlywood and latewood section until all the earlywood cells failed. The softwoods with different cellular structure used by Ando and Onda (1999), which caused the first failed cell-layer occurring in different location on earlywood layer, was thought to be the reason for different phenomena on progressive failure of wood cells in earlywood section. Because the collapse of the cell wall is related to an instability problem in material mechanics, which explains the flat plateau region whereby there was only a slight increase in stress over a large deformation region. After all the radial walls of earlywood tracheid are buckled and collapsed, resulting in the removal of the cell lumens and likely wall cavities, the cell wall substance was densified. This signifies the start of the densification region on the stress-strain curve, in which the stress increases rapidly with increasing strain.

3.2.2. Balsam poplar

First failure of wood cells. Fig. 9-S presents an image indicating the cellular structure and position of six vessels (A, B, C, D, E, and F) before failure, while Fig. 9-T shows another one that corresponds to the onset of failure of the same six vessels (a, b, c, d, e, and f). The examination of the recorded images during compression test, the deformation during the elastic region was found to occur primarily in the vessels (Fig. 9-S). With increasing compression, deformation in these vessels increased eventually leading to collapse of the vessels. However, deformation was hardly observed in the fibres which have small lumen and thick walls. For the balsam poplar specimens, first failure occurred generally at vessels with large diameter, and could be located anywhere within a growth ring. Similar to the jack pine specimens, the occurrence of the first failure of vessels in Fig. 9-T was found to correspond to a transition point T between elastic and plateau regions on the stress-strain curve in Fig. 6. The first failure occurred in a balsam poplar specimen could be attributed to its inherent anatomical features and structure. As a diffuse-porous hardwood species, balsam poplar wood contains vessels evenly distributed over the structure of balsam poplar. The diameter of a vessel is approximately 7–8 times larger than that of a fiber. This explains the location of first failure at large diameter vessels in balsam poplar. In addition, it was found that uniseriate rays in the earlywood layer deformed and failed together with the vessels during radial compression.

Progressive failure of wood cells. Following the failure of the weakest vessels, it was found that subsequent failure occurred in other vessels that were not necessarily close to the first failed vessels, as indicated by the arrows in Fig. 10-U. Further application of compressive load led to more vessel failure as shown in Fig. 10-V. This observed phenomenon can be explained by the unique anatomical feature of balsam poplar, with all vessels having similar diameter and uniformly distributed within a growth ring. With the progressive compression, some of vessel cavities were found to be removed gradually. When all of the vessel cavities were removed, this point corresponded to the start of densification region at the stress-strain curve, as shown in Fig. 6. Because of the limitations of the observation techniques used in this study, the deformation and failure occurred to fibres around vessels could not be observed after compression level reached the densification region of the stress-strain curve. This behavior is different from jack pine which is a softwood species with abrupt earlywood/latewood transition, and as a result collapse of cellular structure is progressive from first cell row in the earlywood towards the latwood of the same ring, as shown in Fig. 8.

3.3. Proposed method of determining yield point

As stated above, the identification of yield point on the compression stress-strain curve cannot be achieved solely from the examination of the stress-strain data. The finding from this study clearly shows that the yield point is related to the onset of first collapse of wood cell under compression. Therefore, with the use of on-line monitoring of micro-structural deformation behavior of the cellular
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Fig. 10. Deformation and failure of vessels for a balsam poplar wood (Loading direction is left-right; Magnification: 80×).

Fig. 11. Yield point at stress-strain curve for various jack pine specimens.

structure in conjunction with a mechanical test arrangement whereby the load and deformation are recorded, it is possible to accurately locate the yield point on the stress-strain curve. Once the yield point (including yield stress: $\sigma_y$ and yield strain: $\epsilon_y$) for a tested specimen is located on the compression stress-strain curve, its correspondent MOE value can be determined by computing the slope of the linear part of a line below the yield point on the stress-strain curve (MOE = tan $\alpha = \sigma_y/\epsilon_y$), which is illustrated and described in Fig. 1. By using the proposed technique, the yield point and MOE values of the five Jack pine and five balsam poplar specimens were tested and estimated. The determined results on the yield stress and MOE values for each of the jack pine and balsam poplar specimens are presented in Figs. 11 and 12.

From Fig. 12, it can be noticed that a sudden-drop (load inflection drop) right after the yield point was found on each of the stress-strain curves for balsam poplar specimens. The “load inflection drop” occurrence on the stress-strain curve for balsam poplar specimens could be explained as follows. After examination of the video made by recorded images, it was found that the first failure occurred generally at vessels with large diameter, resulting in the appearance of the yield point at stress-strain curve. After almost all of the large-diameter vessels failed, other medium-diameter vessels began to fail, thereby causing the “load- inflection drop” appearance on the stress-strain curve. Once all of the large- and medium- diameter vessels failed completely, the load-inflection drop stopped and the load-increase appeared on the stress-strain curve.
4. Conclusions

The microstructural changes of jack pine and balsam poplar specimens were examined using the developed test equipment to explore the relationship between the yield stress and the first failure occurring in wood cells. Although only limited numbers of specimens were investigated at a given condition, the following conclusions can be drawn from the experimental evidence:

Using the approach of matching the onset of first cell collapse to a specific location on the stress-strain curve for jack pine and balsam poplar wood compressed in radial direction, it is possible to accurately locate the yield point on the curve. The test system developed in this project, which consists of a mechanical compression module and a real time image-capturing system was found to be suitable for implementing the proposed approach. Further verifications are needed to test the developed equipment capable for use in a variety of wood species with various anatomical structures when compressed at different experimental conditions.

In jack pine, the first failure of wood cells occurs at the weakest row of earlywood section: the first earlywood layer in new annual ring next to the latewood layer in the old growth ring. Despite using the traditional “weakest theory” to explain this phenomenon, the “boundary effect” was first time to be applied to elucidate the cause of the failure occurrence to wood cells in the transition between earlywood and latewood in softwood species, where is a sudden change in material mechanical properties.
In balsam poplar, the largest vessels with large cell wall lumens are the point of first failure, and these vessels can be found anywhere in the cellular structure.

In jack pine, cell wall collapse progresses from the first failure point towards the latewood of the same growth ring. In contrast, for balsam poplar the progressive collapse of vessels follows a rather random pattern.

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