Stress–Strain Relationships for Spruce Wood: Influence of Strain Rate, Moisture Content and Loading Direction

by Svante Widehammar

ABSTRACT—The influence of strain rate, moisture content and loading direction on the stress–strain relationships for spruce wood has been investigated. The strain rates were approximately 8×10^{-3} s^{-1}, 17 s^{-1} and 1000 s^{-1}, and the states of moisture content were those corresponding to oven dry, fiber saturated and fully saturated. Compressive loads were applied along the principal directions of the stem of the tree, i.e., radially, tangentially and axially. The low and medium strain-rate tests were performed with the aid of a servohydraulic testing machine, while the high strain-rate tests were carried out using the split Hopkinson pressure bar (SHPB) technique. Magnesium or steel bars were used in the different SHPB tests in order to reduce impedance mismatch for the different directions of the wood specimens. The strain rate was found to have large influence on the behavior of the wood, especially under the condition of full saturation, where water transport in the deforming specimen is of major importance.

KEY WORDS—Spruce wood, strain rate, moisture content, split Hopkinson, thermomechanical pulping

Introduction

The thermomechanical pulping (TMP) process produces pulp for paper making out of wood chips. The central part of the process takes place in a refiner, which consists of two concentric circular discs with a diameter well above 1 m. Either one disc rotates and one is fixed, or both rotate in opposite directions. The distance between the discs is of the order of 1 mm. Pre-heated wood chips and water are fed into the center of the refiner and are transported radially outwards between the discs due to inertia. Through contact with radial bars on the discs, the chips are defibrated into fibers. The initial breaking of the wood chips is performed at high temperature (about 125°C), very high strain rate (about 10^3 s^{-1}), and a moisture content above fiber saturation. Experiments aimed at quantifying the behavior of wood under such conditions have been carried out, e.g., by Uhmeier and Salmén[1] and by Renaud et al.[2,3] Uhmeier and Salmén used servohydraulic testing equipment and reached 25 s^{-1} at 98°C for spruce wood, while Renaud et al. used the split Hopkinson pressure bar (SHPB) technique in order to achieve high strain rate at room temperature. The latter authors used three different types of hardwood which are all of minor importance for the Swedish pulping industry. Other tests of wood at high strain rates have been carried out, e.g., by Bragov and Lomunov[4] and by Reid and Peng.[5] The latter investigators performed their experiments on dry wood. There is an evident lack of published test data on wet spruce wood at strain rates similar to those which occur in a refiner.

This work is a first step aimed at testing the mechanical properties of spruce wood under conditions similar to those which prevail in a refiner. In this step, the strain rate and the moisture content were kept at realistic levels while the tests were performed at room temperature. Other values of strain rate and moisture content were also used for comparison. Low (8×10^{-3} s^{-1}) and medium (17 s^{-1}) strain-rate tests were performed with a servohydraulic testing machine (MTS), while the SHPB technique was used to attain a strain rate of approximately 10^3 s^{-1}. The tests were performed at three different states of moisture content, namely, corresponding to oven dry, fiber saturation and full saturation, and the loading directions were in the principal directions of the stem of the tree, i.e., radially, tangentially and axially.

Experiments

Experiments were performed at three strain rates (low, medium and high), at three states of moisture content (oven dry, fiber saturated and fully saturated), and in three loading directions (radial, tangential and axial). This makes 27 combinations of testing conditions. For each combination, five experiments were performed, all at room temperature (about 20°C).

The strain, strain rate and stress in the specimens were evaluated for the specimen dimensions at the actual moisture content, i.e., after shrinkage or swelling.

Specimens

Sapwood from a single tree of spruce was used in all experiments. The tree was approximately 115 years old, grown in the middle of Sweden, and the specimens were taken at a height of 7–8 m. In the specimens, there were approximately 0.8 annual rings per millimeter, and the density was 486 kg m^{-3} (dry weight per wet volume).

Conditioning was carried out on specimens of the size $12 \times 12 \times 12$ mm^3. The oven-dry condition, at which no water is present in the wood, was reached in a ventilated oven at 103°C when the weight of the specimens was stabilized. This occurred after about 5 h. Fiber saturation is defined as the condition when the fiber walls carry as much water as possible without free water in the cavities in the center of the cells, the lumen. This condition was approximately reached

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by inserting fresh specimens into a climate chamber, first with 50°C temperature and 80% relative humidity for 3 h and then 20°C temperature and 98% relative humidity for 45 h. Finally, the condition of full saturation, at which the wood carries as much water as possible, was reached by boiling the specimens for 20 min and then impregnating them in cold water for 20 min. This procedure was repeated twice.

After the specimens had been conditioned to the right moisture content, they were reduced to the size 12 × 12 × 6 mm^3 with a sliding microtome. The shortest length of the specimens was oriented in the loading direction and the surfaces normal to this direction were made accurately flat and parallel by the microtome. For oven-dry wood, the surfaces normal to the axial direction were subjected to this treatment in fresh condition since these surfaces were too hard to treat with the microtome in dry condition.

Servohydraulic Tests

A servohydraulic testing machine (MTS) was used. The specimens were placed between two flat steel disks and a displacement ramp was applied. Two strain rates were used: low (8×10^{-3} s^{-1}) and medium (17 s^{-1}).

SHPB Tests

The SHPB technique is commonly used to determine stress–strain relationships for materials at high strain rates. A general presentation of the technique has been made by Al-Mousawi et al.[6] A specimen of the material to be tested is placed between the ends of two bars with colinear axes. A projectile is fired on the free end of one of the bars, the sender bar. This generates an elastic pulse, the incident pulse, which propagates towards the specimen. When this pulse arrives at the specimen, it is partially reflected and partially transmitted into the second bar, the receiver bar. By measuring and analyzing the incident, reflected and transmitted pulses, the mechanical behavior of the material of the specimen can be estimated.

In SHPB experiments, the characteristic impedance of the bars, $Z = S\sqrt{E\rho}$, where S is the area of the bar cross-section, E is Young's modulus and ρ is mass density, should correspond to the characteristic impedance of the specimen. Most of the incident pulse will be reflected if $Z_{\text{specimen}} \ll Z_{\text{bar}}$ or transmitted if $Z_{\text{specimen}} = Z_{\text{bar}}$. Both cases will give bad accuracy of the results as the transmitted or reflected pulse will be very weak. In the cross-fiber directions of the wood, i.e., the radial and tangential directions, the characteristic impedance is low. Magnesium alloy (AZ61-F) bars were used to match this condition, as both E and ρ are relatively low. For the same reason, the cross-sectional area of the specimens was made the same as for the bars rather than smaller.

The characteristic impedance in the axial direction of the wood specimen is much higher than in the cross-fiber directions. A much higher stress is needed to compress the wood axially, and therefore much more energy is needed to produce large strains. As the yield strength of the magnesium bars was too low, steel bars (alloy St37-2K) were used for the axial tests.

The experimental setup is shown in Fig. 1. Bars with square cross-section 12 × 12 mm^2 were used. Projectiles with diameter 12 mm and length 500 mm were manufactured from the same materials as the SHPBs.

The method used for data analysis here includes correction for dispersion in the SHPBs and uses the technique of redundant measurements to increase the accuracy of the results. All three pulses, i.e., incident, reflected and transmitted, are used in the evaluation procedure. The method is similar to that described and evaluated in Widehammar,[7] but no correction for warping of the bar cross-section is made here.

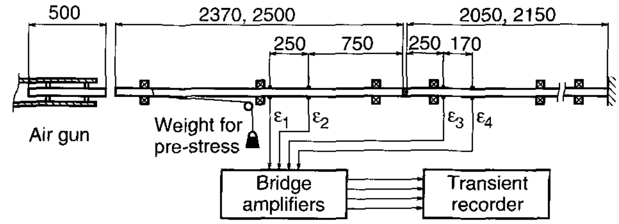

Fig. 1—Experimental setup for SHPB tests with dimensions in millimeters; the shorter bars are for magnesium and the longer bars for steel

No special lubrication was used, see the Discussion section.

The strains were measured at two sections of each bar in order to obtain redundant measurements. Both measurement sections of the sender bar were far enough from the specimen so that the incident and reflected pulses were separated in time. Strain gages with resistance 350 Ω and length 3.2 mm were used. The signals were amplified (Measurements Group Amplifier Model 2210) and recorded (Nicolet Transient Recorder Integra 20) at 1 MHz sampling rate and transferred to a PC and analyzed using Matlab.

To decrease the possibility of an air gap between the bars and the specimen, the bars were slightly pre-stressed. The pre-stress was introduced by means of a weight of 2.5 kg hanging in a string, connected to the sender bar by a strangle snare close to a bar support before the strain gages (see Fig. 1). The pre-stress in the specimens caused by the weight was neglected in the evaluation.

The impact of the projectile onto the sender bar generated high-energy content at high frequencies. Due to dispersion, this resulted in a stress wave with superimposed oscillations further down in the bar. Therefore, four layers of copy paper were attached to the bar end in contact with the projectile in order to reduce the contribution from high frequencies. Furthermore, frequencies corresponding to wavelengths shorter than approximately twice the side length of the bar cross-section were filtered out in the analysis.

Results

Since the strain rate in the SHPB tests cannot be accurately prescribed, it varies between the combinations of experimental conditions. However, it is fairly stable for the five tests for each combination. The mean strain rates for all combinations are shown in Table 1.

The stress–strain curves in compression from all of the low, medium and high strain-rate tests are shown in Figs. 2–4, respectively. The scatter in the results for each combination of experimental conditions can be seen. One of the five curves from each experimental combination was taken as representative and is shown thicker. All representative curves are shown in Fig. 5, where the effects of the experimental conditions can be compared. Note the different scaling on the stress axis for the three rows in the figures.

TABLE 1—MEAN STRAIN RATES IN SHPB TESTS

Loading Direction	Mean strain rate (s^{-1}) Oven Dry	Fiber Saturated	Fully Saturated
Radial	985	1130	1041
Tangential	707	1044	945
Axial	973	1499	1653

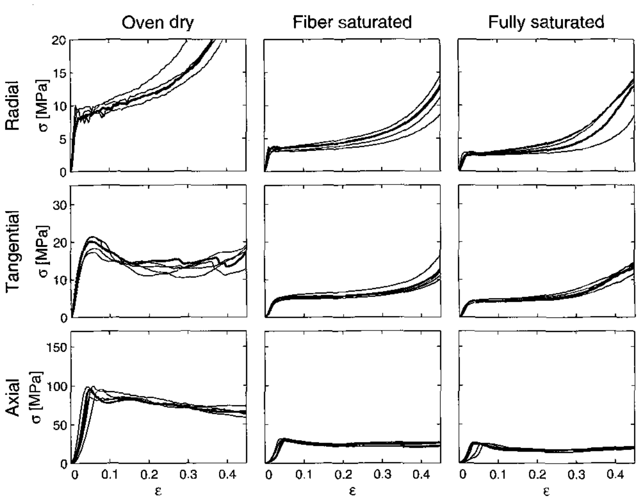

Fig. 2—Stress–strain curves in compression from low strain-rate experiments, with the thicker curve taken as representative

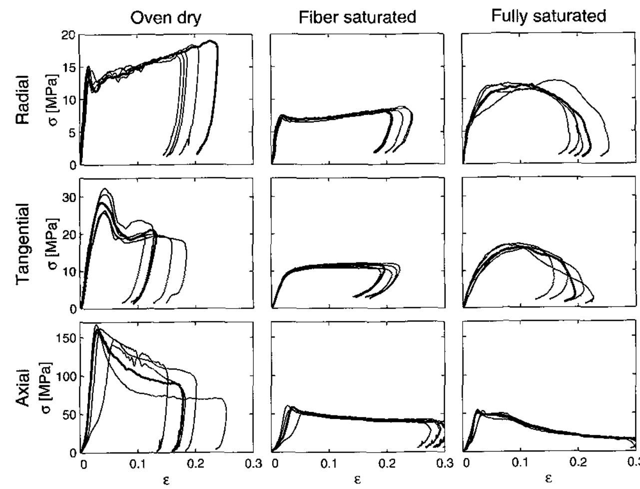

Fig. 4—Stress–strain curves in compression from high strain-rate experiments, with the thicker curve taken as representative

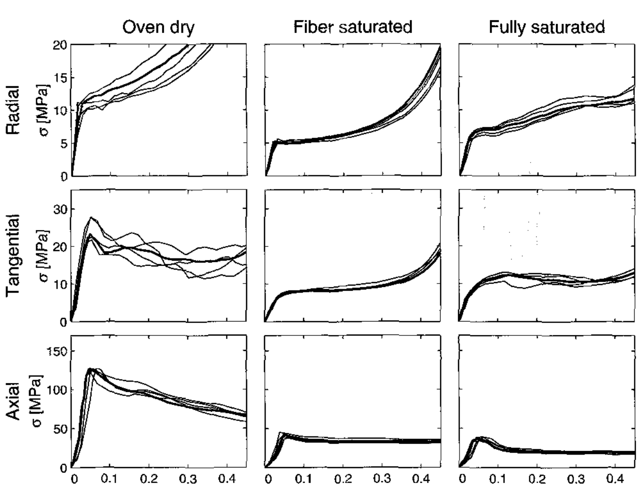

Fig. 3—Stress–strain curves in compression from medium strain-rate experiments, with the thicker curve taken as representative

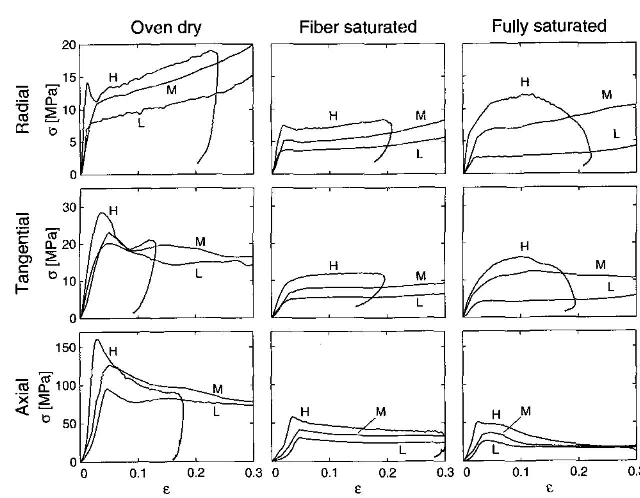

Fig. 5—Representative stress–strain curves in compression: L, low strain rate; M, medium strain rate; H, high strain rate

After the testing, some specimens were undamaged, except for some plastic deformation in the loading direction, while other specimens had broken into small pieces. In the low and medium strain-rate tests, the maximum strain was well controlled and set to 50%, but in the high strain-rate tests, i.e., the SHPB tests, the total strain could not be controlled before the tests or even calculated after. The stress–strain curves in Fig. 4 were obtained from the initial incident pulse. The reflected pulse, traveling backwards in the sender bar, was reflected at the free end of the bar and then hit the specimen again. Also, the transmitted pulse returned to the specimen after reflection. These reflection processes were repeated a number of times. As a consequence, it was almost impossible to know the maximum strain to which a specimen had been subjected after a test. In spite of this difficulty, the typical failure modes observed by visual inspections after the tests for all testing conditions will be described below and are illustrated in Fig. 6, where z is the loading direction in all cases.

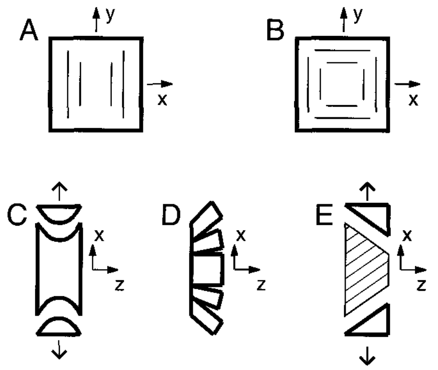

Fig. 6—Typical failure modes. Loading direction is z. Thin lines in A and B are cracks. The middle part in E broke into small pieces. See text for explanations

The oven-dry specimens were not damaged when they were compressed in the radial direction. When they were compressed in the tangential direction at low and medium strain rates, cracks occurred according to Fig. 6(a) where x is radial direction. At high strain rate, small pieces fell off the specimens in radial direction, i.e., x-direction in Fig. 6(c). When compressed in the axial direction at low and medium strain rates, the specimens were split into small pieces according to Fig. 6(d), where x is both radial and tangential direction, but the pieces were still kept together in the testing machine. In the high strain-rate tests, the specimens were totally split into small pieces.

No major damage could be seen on the fiber-saturated specimens for any testing condition.

The fully saturated specimens were not damaged in the low strain-rate tests. In the medium strain-rate tests, cracks were formed according to Fig. 6(a), where x is radial or tangential and y is axial, and Fig. 6(b), where x and y are radial and tangential directions, respectively. In the high strain-rate tests, the specimens were split into small pieces. When the specimens were compressed in the radial or tangential directions, triangular corners as in Fig. 6(e), where x is radial or tangential direction, could often be found, while in the axial tests, hardly any pieces could be found.

Discussion

Stefanson[8] and Tabarsa and Chui[9,10] have pointed out that the deformation in wood under compression is very local and that it varies largely within the annual rings. Therefore, the relevance of defining a global strain in wood may be questioned. As there were a number of annual rings within the specimen in this work, however, it seemed meaningful to define strain on a global basis.

In the evaluation of stress and strain in all experiments performed, the state of stress was assumed to be uniaxial. A necessary condition for this to be true is the absence of friction on the interfaces between the specimen and the bars or the disks of the servohydraulic testing machine. If this condition is not fulfilled, the friction will cause three-axial states of stress near the ends of the specimen in contact with the bars. As the specimens were relatively short, friction may have influenced the results. However, all specimens were of the same size, and the surface conditions were similar in all experiments. Therefore, the effect of friction is expected to be similar in the different tests. Since the material behavior of wood varies largely between different trees, and even within a tree, the stress–strain curves relative to each other are the most interesting results in these experiments. The assumption of uniaxial stress is then satisfying. Furthermore, large strains with small transverse strains dominate the curves, and small transverse strains make the friction effects relatively small.

As the SHPB tests in axial direction were made with steel bars and the others with magnesium bars, much more energy was used in the axial tests to produce approximately the same strain. This can be seen from the areas under the stress–strain curves, which represent the energies absorbed by the specimens.

The choice of the three states of moisture content was made in order to study the full possible range of moisture content. Oven dry and full saturation are extremes, and fiber saturation is a breaking point where different mechanisms of water absorption meet. Between oven dry and fiber saturation, added water is absorbed into the fiber walls. Therefore, in this regime, the resulting change in the mechanical behavior of spruce wood is connected with the behavior of the fiber walls at different moisture content. Above fiber saturation, added water is located in central cavities of the fibers, i.e., the lumen. Therefore, compression of the spruce wood is accompanied by transport of free water.

In Fig. 5, it can be seen that the influence of strain rate is clearly visible for all studied conditions. For oven-dry and fiber-saturated conditions, this result confirms that the fiber walls have a pronounced viscoelastic behavior for both dry and wet fiber walls as known from the literature; see, for example, Dinwoodie[11] and Sundholm.[12] In the cross-fiber directions, i.e., radially and tangentially, it can be seen that spruce wood is more strain-rate dependent under full saturation than under fiber saturation. The fiber walls are saturated in both cases and, by that, should have the same behavior. This indicates that the transport of free water in the deforming spruce wood is of major importance. Most probably, the size of the specimen is also significant since the distance to a free surface related to the fiber length determines the pressure gradient necessary for water transport out of the specimen; see, for example, Dinwoodie.[13]

In Fig. 5, it can also be seen that the stress level is lower under full saturation than under fiber saturation in the low strain-rate tests. Since the fiber walls are saturated in both cases and the dynamic effects should be negligible here, there should be no difference. The difference may be related to the findings by Uhmeier and Salmén,[1] who showed that boiling the specimens lowered the plateau stress by 13% at room temperature and 0.25 s^{-1} strain rate. They defined the plateau stress as the stress at 5% strain in radial direction.

In the axial direction, the difference is relatively small between fiber saturation and full saturation for the initial part of the curves. This indicates that the transport of free water is of minor importance or that no water transport takes place. Possible reasons for this behavior may be that cracks provide possibilities for water transport without large pressure gradients or that axial buckling of the fibers takes place without accompanying water transport. For larger strains, the fully saturated specimens seem to collapse while the fiber saturated specimens keep their rate dependence.

Overall, it can be seen that dry spruce wood has much higher strength than wet, and that compression in axial direction requires a much higher stress than in the cross-fiber directions.

Figures 2–4 show that the repeatability of the experiments is good. Therefore, the trends that can be seen in Fig. 5 are well grounded. The results obtained indicate that the SHPB technique is suitable for studying high strain-rate behavior of wood, and that the use of magnesium bars in the cross-fiber directions and steel bars along the fibers works well.

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