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RESEARCH ON THE ANISOTROPIC PROPERTIES OF WOOD AT HIGH-RATE LOADING

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ABSTRACT

Wood is widely used as a shock absorbing material. For the design of various protective structures and modelling their behaviour under dynamic load conditions, models equipped with authentic parameters are required. Since wood is a highly anisotropic material, this effect should be taken into account in modelling. The behaviour of the three structural types of wood is studied: pine, birch and sequoia. The stress-strain curves of pine and birch were obtained when the specimens are loaded along and across the fibers. To achieve a greater degree of deformation, the mode of multicyclic loading of the sample was used. For sequoia, an analysis of the effect of the stress-strain state on the strength and deformation properties was carried out. In the condition of uniaxial deformation, the nonuniformity of the radial expansion of samples with a different cutting direction relative to the grain was evaluated. It was found that the lateral confinement strongly affects the stress-strain behavior of the sequoia, suppressing cracks along the fibers and thereby slowing down the fracture.

Keywords: wood, anisotropy, confining test, multicyclic loading.

INTRODUCTION

Annually in the world a huge number of containers are transported with dangerous, including radioactive, substances of various types, spent nuclear fuel, ammunition components, etc. Ensuring the safety of transportation of such substances and products by air, road, sea and rail transport is of great importance due to the potential risk of harming to people, the environment and property during transport. The design of the container must withstand, without damage to the contents, significant dynamic loads that can occur when a container falls from an airplane, as well as a result of an accident or a terrorist attack. As one of the damping materials that can soften the results of such intense dynamic impacts on containers and their contents, wood of different wood species can be used. In order to reliably calculate the behavior of containers with similar damping materials, data on their properties under shock actions, in particular dynamic stress-strain curves, are needed (Manual for LS-DYNA, 2007). If for quasi-static effects there are still a few data on the mechanical properties of individual types of wood, then the data on the dynamic properties are rather scarce (Buchar, 2001, Reid, 1997; Wouts, 2016).

As is known, wood is an anisotropic material. To date, it is customary to consider wood to be a material whose properties possess orthogonal anisotropy. When calculating wooden structures, the design of a cross-isotropic material is usually used, the properties of which differ along and across the fibers.

The purpose of this study is to determine the influence of the "texture" configure of the sample on the strength and deformation properties of wood, the study of property degradation under cyclic loads, as well as the conditions of lateral confinement on the dynamic mechanical behavior of the sequoia.

To assess the degree of anisotropy, detailed studies of pine and birch (the most common representatives of coniferous and deciduous trees) as well as sequoia, which can be used as damping materials in layered protective structures, were carried out.

EXPERIMENTAL METHOD

The dynamic properties of wood under compression were investigated with the help of an installation (Bragov, 1995), which implements the Kolsky method with a slit Hopkinson pressure bar. The installation consists of a pneumatic loading device (gas gun) with a control system, a set of measuring and recording equipment and measuring bars 20 mm in diameter made of D16T alloy equipped with low-base strain gauges. The amplitude of the loading pulse, proportional to the speed of the impactor, ranged from 30 MPa to 235 MPa, and the strain rate was from 300 s^{-1} to 3000 s^{-1}, respectively.

Due to the large difference in the acoustic impedances ρC of measuring bars and the wood specimen, the amplitude of the reflected pulse can reach 90% of the amplitude of the loading wave. In this case, the sample is subjected to several loading cycles. To reliably record of repeated loads during one experiment, it is necessary to exclude the effect onto the loading process in the second and subsequent cycles of a pulse passing through the sample and reflected later from the back end of the support bar in the form of a tensile wave. For this, the length of the support bar should be increased in comparison with the length of the loading bar by as many times as the load cycles need to be registered (Bragov, 2001). In this series of experiments the loading bar had a length of 1.5 m, a supporting bar was 4.5 m, which allowed recording the main and two additional loading cycles (Figure 1). The markers on the rays indicate the origin and the ends of the pulses (incident, reflected and transmitted) recorded during the three-cycle loading of the specimen.

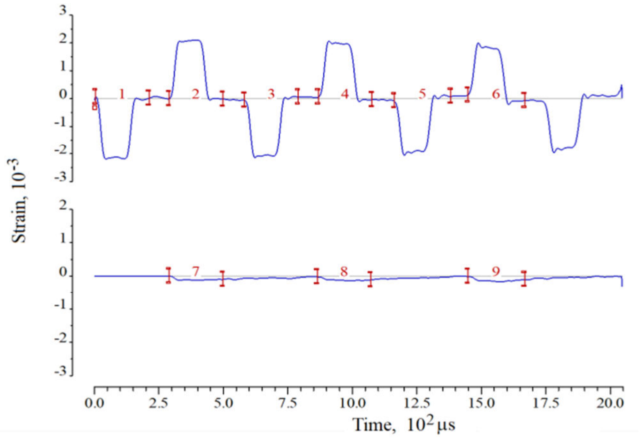


Fig. 1 - A typical oscillogram for testing wood

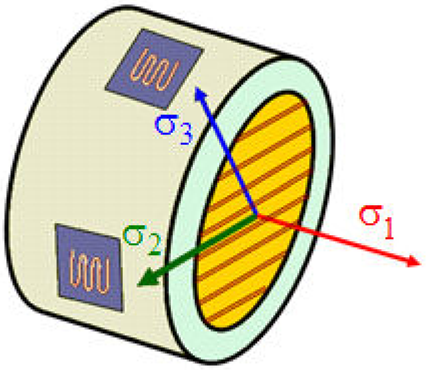


Fig. 2 - Separate registration of circumferential deformation of jacket

Due to the substantial anisotropy of the properties of wood, the uniform (axisymmetric) expansion of the specimen during compression is possible only when the specimens are loaded along the fibers, whereas when the specimen is loaded at different angles to the direction of the fibers the expansion occurs unevenly. This effect is especially strong when loaded at an angle of 90°. The circular cross-section of the specimen in that case becomes elliptical with a long axis parallel to the direction of the fibers.

To study the influence of the type of stress-strain state on the behavior of the sequoia, in addition to tests under a uniaxial stress state, some of the experiments were performed under conditions of uniaxial deformation. The specimen was placed in a rigid jacket limiting its radial expansion. Additional strain gauges glued on the side surface of the jacket made it possible to measure the radial stress component in the specimen that allowed, in combination with traditional measurements of longitudinal stress component by using the Kolsky method, to determine the stress tensor in the specimen (Bragov, 1994).

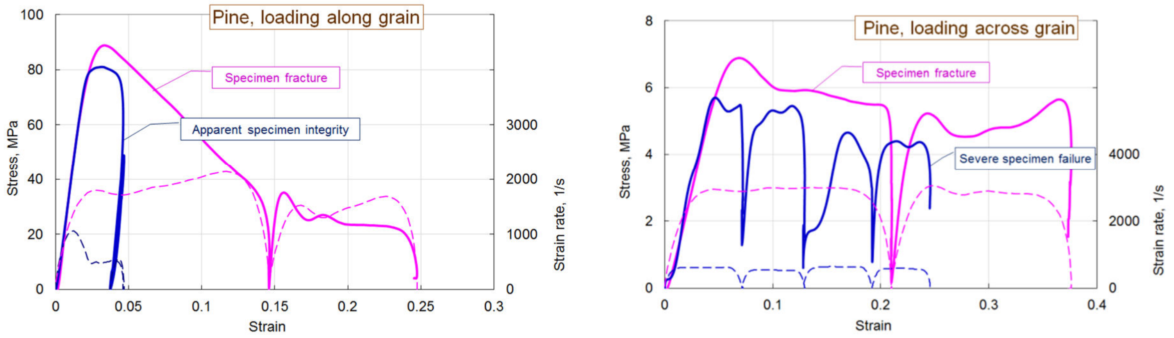
In experiments with uniaxial deformation, the degree of anisotropy of the sequoia was estimated by separately measuring two orthogonal components of the radial stress in the sample. For this purpose two independent strain gauges were glued on the lateral surface of the confining jacket allowing two orthogonal radial stress components to be registered separately and to estimate the degree of anisotropy of the wood (Figure 2). To study the properties of pine and birch, specimens were made in the form of tablets with a diameter of ~20 mm and a height of ~10 mm with different cutting directions relative to the axis of the tree trunk. The angles between the direction of application of the load and the direction of the arrangement of the fibers were 0° and 90°. The moisture content in the specimens was ~10%. In addition, samples of sequoia with a diameter of ~20 mm and a height of ~10 mm with cutoff angles of 0°, 30° and 90° were tested. Humidity of these specimens was 7%.

RESULTS AND CONCLUSIONS

As a result of a series of experiments on the study of pine and birch, when loading along and across the fibers, stress-strain curves were obtained as well as strain rate change curves. To assess the degradation of strength properties, additional loading cycles were recorded in the experiments. When loaded along the fibers, the specimens have a significantly higher strength than when loaded across the fibers, so the magnitude of the reflected wave and, respectively, the amplitude of the repeated loading wave in the first case will be less than in the second one. This causes a different degree of deformation of the specimens when loading along and across the fibers. In addition, some samples with an insignificant degree of damage were re-loaded, which made it possible to evaluate the process of deformation up to high degrees of deformation.

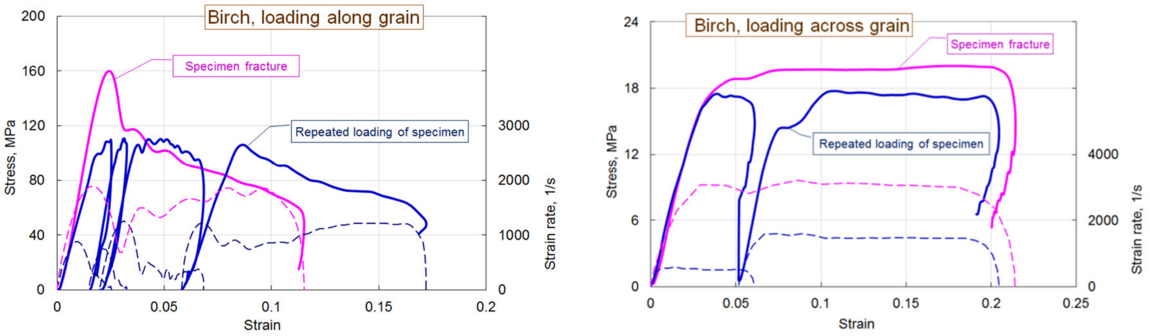
Further, the obtained diagrams of deformation of pine and birch are shown for loading along and across the fibers. Figures 3 and 4 show diagrams for two regimes with respect to the amplitude of the loading wave and the corresponding strain rate. At a low strain rate the damage to the specimen is negligible, while at a high strain rate, the integrity of the specimen is significantly impaired. The solid lines show stress-strain curves, while the dotted curves in the lower part of the figures show the corresponding strain rate changes.

A well-known tendency to decrease the strength properties of wood with an increase in the cutting angle is well traced: the largest value of the load-branch modules and breaking stress is inherent in specimens of both types of wood with a cut-out angle of 0°, and the smallest values for specimens with a cut-out angle of 90°. For small angles of cutting after reaching the ultimate stress, a considerable relaxation of the stress is observed, i.e. decrease in load-bearing capacity with an increase in the degree of deformation, possibly caused by micro-destruction of bonds between fibers and loss of their stability. The recession of the stress-strain curve and the nonlinear nature of the unloading are evidence of the destruction of the specimens, which is confirmed by their inspection after the test. For the cutting angle 90°, the bearing capacity for a considerable degree of deformation does not only decrease, but on the contrary the material exhibits a property of some hardening.



(a) (b)

Fig. 3 - Typical stress-strain curves of the pine when loaded along (a) and across (b) the fibers



(a) (b)

Fig. 4 - Typical stress-strain curves of the birch when loaded along (a) and across (b) the fibers

The nature of the deformation and fracture of the samples strongly depends on the cutting angle of the materials. Specimens after loading across the fibers are characterized by uneven (oval) expansion with extrusion of the material in the direction across the fibers. In addition the axial deformation of these specimens is very uneven: the shape recovery coefficient is much higher at the edges of the specimens in the zone of extrusion of the material, so that the central part of the specimen in the direction of the minor axis of the ellipse (into which the specimen cross section is transformed) is significantly larger than the peripheral zones in the direction of the large axis of the ellipse. The residual deformation of the specimens has the character of being pierced by the lateral surface of the cylinder.

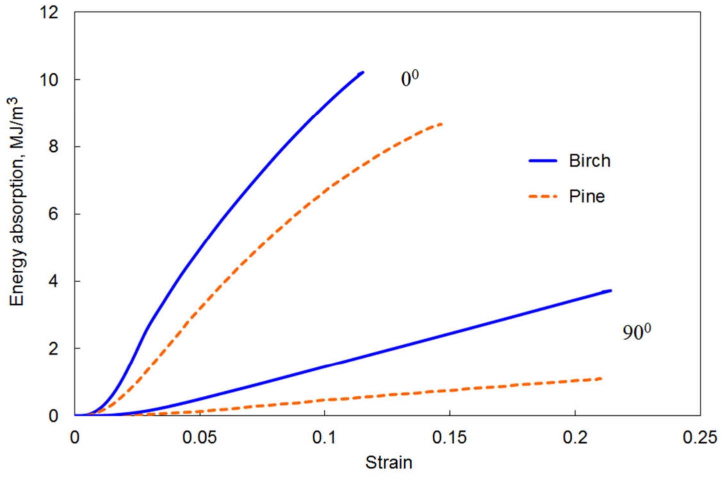


Fig. 5 - Energy absorption of pine and birch

The obtained strength properties and energy absorption characteristics are given in Table 1. The average modulus of the birch load branch with an angle of 00 has largest value. The fracture stress is also maximized for this wood.

Table 1 - Strength and damping characteristics of pine and birch

Cutting angle (°)	Fracture stress (MPa)	Load branch modulus (MPa)	Energy absorption (MJ/m^3)
Pine			
0	84	3500	8.59
90	5.9	116	1.05
Birch			
0	160.7	8312	9.99
90	16.1	447	3.36

In addition to pine and birch, specimens of sequoia were studied under conditions of uniaxial stress as well as uniaxial deformation (a sample in a rigid confining jacket). The specimens were cutting out at 0°, 30° and 90° angles to the direction of the fibers.

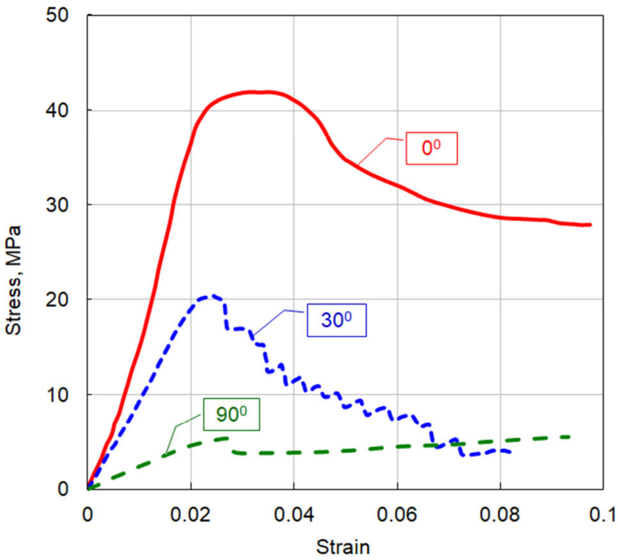


Fig. 6 - Quasi-static properties of sequoia

The results of static testing of the sequoia under conditions of a uniaxial stress state are shown in Figure 6. It can be clearly seen that the samples with a cutting out at 0° have the greatest strength and the largest modulus of the loading branch, while the samples with a cutting angle of 90° have the smallest indexes.

A set of dynamic stress-strain curves with allowance for the multi-cycle loading was obtained for different types of stressed-deformed state of sequoia specimens at different angles between the load direction and the direction of the wood fibers (Figure 7). Under the conditions of a uniaxial stress state the strength properties of the sequoia are higher, while the deformative properties are lower than under conditions of uniaxial deformation. The results show a strong anisotropy of the sequoia properties. These results can be used to parametrically identify the tree model as an anisotropic material.

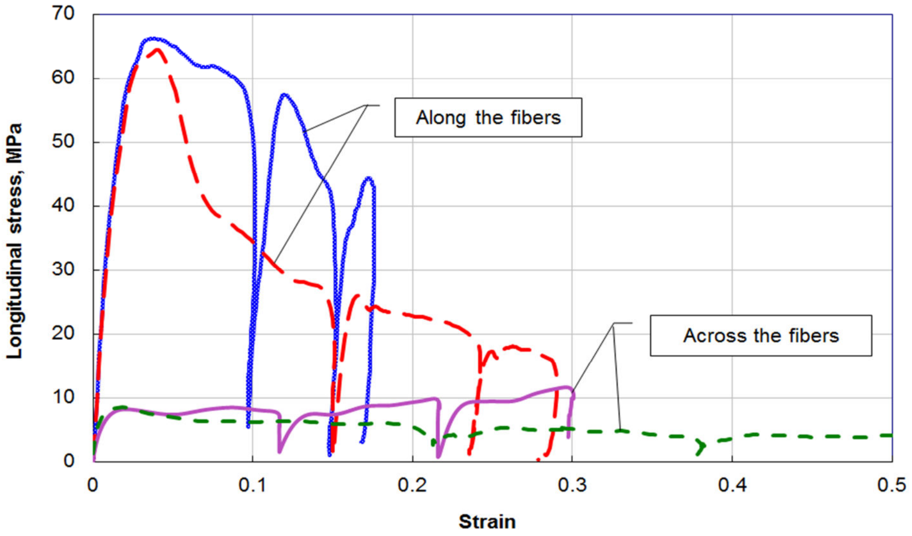


Fig. 7 - Behavior of sequoia under uniaxial strain condition (solid lines) and under uniaxial stress condition (dashed lines)

It is of interest to compare the dynamic properties of the sequoia with the results of similar tests obtained by other authors. In Figure 8 shows stress-strain curves for the 0°, 30° and 90° cut-out angles kindly provided by R. Gray (LANL). Unfortunately, in his experiments, due to the usual single loading of the specimen, a significant degree of its deformation was not achieved. When loaded along the fibers, the amplitude of the loading wave was not sufficient to destroy the sample, so it is impossible to estimate the strength of the sequoia in this case.

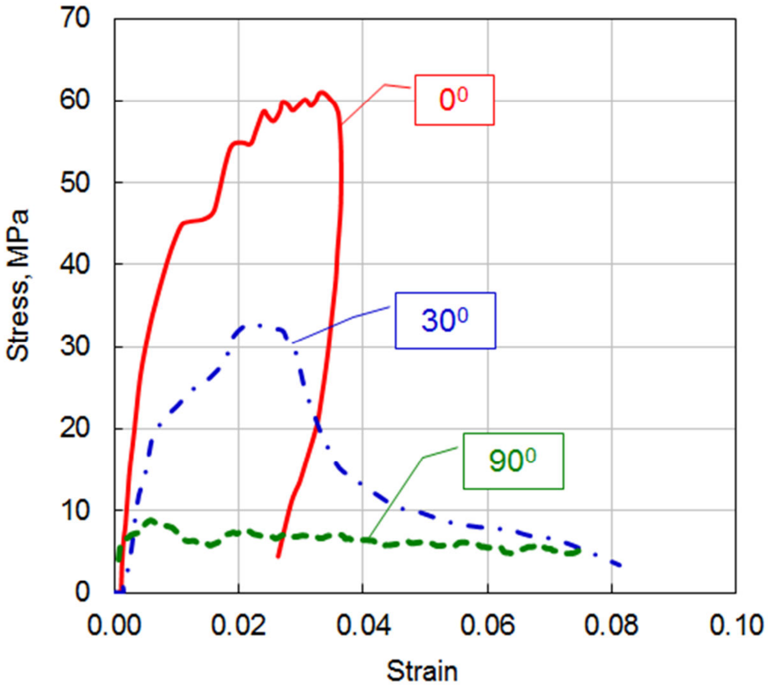


Fig. 8 - Sequoia properties for different angles of specimen cutting out (LANL)

In Figure 9 for three cut-out angles, static stress-strain curves are shown as well as dynamic curves obtained at RIM-LSU and LANL. It can be seen that the results are in good agreement. The undoubted merit of the results obtained at the RIM-LSU can be considered a high degree of deformation achieved due to the use of a multi-cycle loading system.

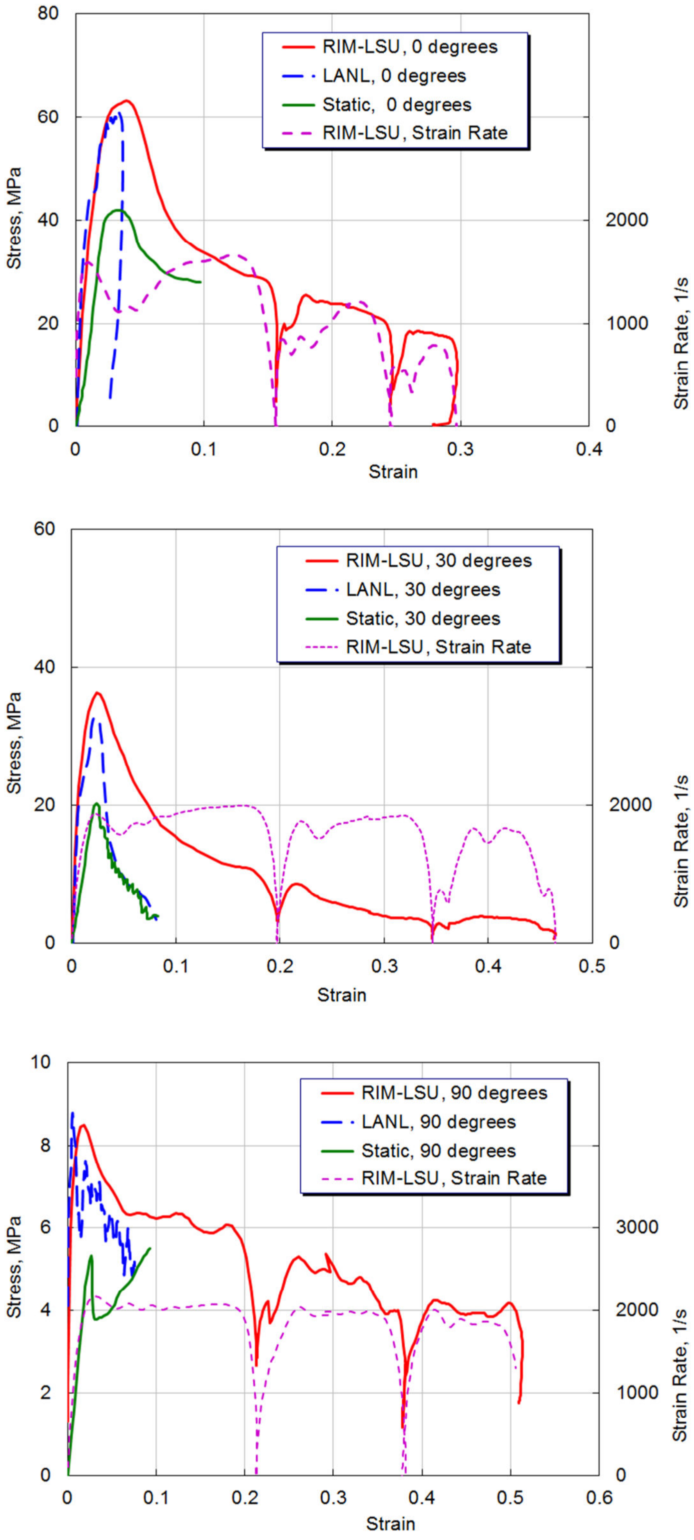


Fig. 9 - Static and dynamic properties of sequoia

Two independent strain gauges on the lateral surface of the confining jacket made it possible to estimate the nonuniformity of the radial expansion of the specimen: in one plane, the jacket lengthens, while in the other one it is shortening. Accordingly, in a sample, the components σ_2 and σ_3 of the radial stress may have different polarity (Figure10).

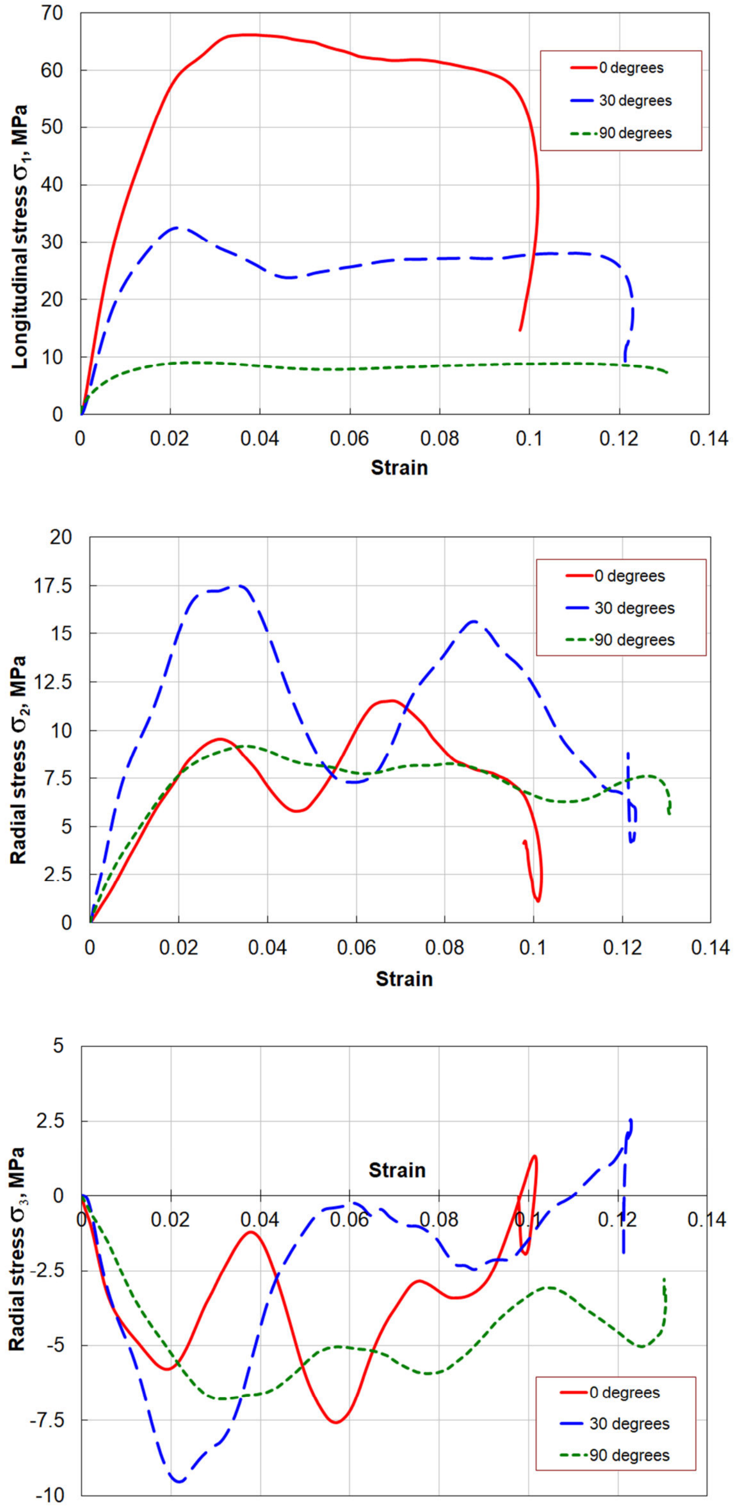


Fig. 10 - Anisotropy of sequoia properties under conditions of uniaxial deformation

These data should be used in a complex wood model, taking into account the different nature of the material's behavior, not only in compression and tension, but also with regard to the orientation of the fibers relative to the loading direction.

It was found that lateral confinement strongly influences the stress-strain behavior of the sequoia by suppressing cracks along the grain and thereby slowing down the fracture. A quantitative assessment of the dynamic properties of wood will be used to equip wood models that take into account its anisotropic properties. Such models are necessary for engineering numerical simulation and optimization of protective structures using wood as a damping material.

ACKNOWLEDGMENTS

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