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Abstract. The report presents the dynamic test results for wood. Compression tests were done according to Kolsky method, using a 20-mm dia split Hopkinson pressure bar (SHPB). The samples were loaded both along and across the fibers. Obtained are dynamic deformation diagrams for pine, birch and lime. Direction of cutting is noted to affect the mechanical properties of the woods tested. The obtained deformation diagrams are nonlinear and differ in their loading and unloading brunches. For the wood species tested, the stress values resulting in different forms of fracture, such as cracking and spallation, were obtained. Alongside with the SHPB tests, plane-wave experiments were conducted and shock adiabates for the wood samples were obtained.

Résumé. Cette communication représente les résultats des épreuves dynamiques sur la lignine. Les épreuves sur la compression sont exécutés á la méthode de Kolsky en utilisant le tige de coupe a 20 mm de Hopkinson. La charge des modeles est exécutée de long en large des fibres. Des diagrammes dynamiques sur la deformation de pin, de bouleau, de tilleul sont obtenues grâce aux épreuves. On a marqué l'influence de la direction de la découpure d'un modele sur les proprietés mécaniques des varietes de lignine épreuvées. Les diagrammes obtenues sur la déformation sont non-lineaires et se different par la chargement et la déchargement. Pour les varietés de lignine épreuvées on a obtenu des significations des tensions qui detruient la lignine p.ex. fendille, casse. On a executé des experiences sur des ondes plats et on a obtenu des adiabates de choc de la lignine.

INTRODUCTION

In the recent years the ever growing concern in safely transporting nuclear energetic waste and toxic matters have been drawing special attention to the design of the stressed state and strength of containers for transporting such materials. Such containers may experience rather intensive dynamic loading in the event of collapse, acts of terrorism or other emergencies. Wood can be used for alleviating the outcomes of such effects. To adequately analyze the damping properties of wood under impact loading data on its dynamic properties are needed, which are practically very scant.

The present paper describes the laboratory methods for studying the dynamic compressibility of wood and presents experimental data on the dynamic properties of pine, lime and birch in the pressure range from several MPa to ~500 MPa and strain rates over 10^3 s^{-1}.

For the moderate pressure range (up to 20 MPa), a well-known Split Hopkinson Pressure Bar (SHPB) method [1,2] is used. For the pressures of over 30 MPa and strain rates in excess of 10^4 s^{-1}, the response of wood is investigated using the plane-wave impact experiment [3].

1. EXPERIMENTAL APPARATUS

Two complementary methods were developed for studying the dynamic compression of wood in a wide range of pressure: the SHPB method and the plane-wave impact experiments. Dynamic deformation diagrams and shock adiabates for three wood species were obtained in the tests.

1.1 The Split Hopkinson bar technique

Kolsky method using the Split Hopkinson Pressure Bar (SHPB) [1] is one of the most elaborated and popular dynamic test methods of materials for strain rates of 10^3 s^{-1}. The main scope of the method is dynamically testing metals and their alloys; sometimes it is used for analyzing the mechanical properties of polymers and composites. There exist but few studies where the SHPB method is used for dynamically testing soils [4], rocks and concretes [5,6]. At Research Institute of Mechanics, State University of Nizhny Novgorod, the experimental apparatus is used for dynamically testing structural materials, polymers, ceramics, concretes, soils and wood [7,8]. Its main components are then following: a pneumatic loading device (gas gun), a split-Hopkinson pressure bar, and recording equipment with a personal computer for the automated processing of experimental results.

The split-Hopkinson pressure bar system consists of two bars, each 20 mm in diameter and 1 m in length. The bars are made of high-strength steel with a yield strength of 1800 MPa. The incident bar was loaded by a striker (100-400 mm long) which was allowed to vary the duration of the generated pulses from 40 to 200mcs. The striker velocities could vary from 5 to 30 m/s. Such loading parameters made it possible to obtain the strain rates of $5 \cdot 10^2$ to $5 \cdot 10^3$ s^{-1} and the maximum stresses in wood specimens of up to 150MPa in the experiments.

Elastic strain pulses are measured by small foil strain gauges cemented in the middle of the pressure bars and they are recorded by digital storage oscilloscope. Next the experimental data are transmitted to a PC for processing and analysis. The original data-processing software package allows one to synchronize the selected pulses and to plot true deformation curves. When needed, operator-controlled smoothing of the registered pulses can be provided, using integral splines. Statistic processing and regressive analysis of the data can also be carried out.

1.2 A plane-wave impact setup

The reflection method [3] (also named «impedance matching» method) was used in the experiments to determine the shock compressibility. A 8-mm layer of wood is placed between two plates (screening plate and supporting one) of an aluminum alloy. Compression waves in the 5-mm thick screening plate were generated by striking it with the plate-striker accelerated in a 57-mm gas gun. As a result, a plane compression wave was formed in the screening plate and in the wood specimen. The impact velocity was varied from 100 to 500 m/s and measured using a set of electric contact gauges. The propagation velocity of the compression wave in the specimen was measured by two dielectric pressure gauges located on the surfaces of the specimen. The thickness of the striker, the screening plate and the specimen were chosen such that the unloading waves from the free surfaces could not affect the picture of plane strain in the compression wave. Measurements of the impact velocity and the compression wave propagation velocity in the specimen together with the known adiabates of the striker and the screening plate make it possible to determine the shock adiabat of the medium studied [3].

1.3 Specimens

Wood being an anisotropic material, the specimens used were cut out and loaded both along and across the fibers. The SHPB dynamic tests were conducted for pine, birch and lime specimens. The specimens were made in the form of tablets 20 mm in diameter and 10 mm in height. The flat surfaces of the tablets were thoroughly ground. To study impact compressibility 70 mm dia, 8 mm thick plate specimens were used. Only the pine specimens were tested. All the tests were conducted in ambient temperature.

The densities of the wood species tested and some static properties of these materials are summarized in the Table 1.

Table 1

Material	Density, g/sm^3	Modulus along the fibers, MPa	Modulus across the fibers, MPa	Tensile strength along the fibers, MPa	Compressive strength along the fibers, MPa
Pine	0.45	16600	1126	100	41.4
Birch	0.56	16660	1124	-	46.7
Lime	0.51	-	-	115.8	39.8

2. TEST RESULTS AND DISCUSSIONS

Figs.1,2,3 show the dynamic deformation diagrams of the wood specimens tested, where 'a' indicates the tests along the fibers and 'b' across the fibers. True stresses in the specimens as a function of strain are depicted by the solid lines and the corresponding strain rate histories (in the bottom of the diagrams) by the dotted ones. Numerical indices on the diagrams are for matching the curves with one another. All the Figures (except for Fig.3b) show two characteristic diagrams, one for a low strain rate (marked '1') and the other for a high strain rate (marked '2'). In the first case the specimens retained apparent integrity, whereas in the second case they showed signs of failure in the form of cracks.

The presented data testify to the fact that, for all the materials tested, the loading branches of the diagrams are nonlinear, the highest nonlinearity of the diagrams being observed for the lower stress values and strains under 1%. It may be due to the fact that at the initial stages of loading the collapse of the pores and capillaries occurs in the wood. These processes do not require large loading values. After such 'compaction', deformation resistance of the material abruptly increased, leading to a steeper loading branch of the deformation diagram. It is to be noted that this portion is characterized by a practically linear stress-strain relation. The values of the corresponding 'modulus' for the specimens loaded both along and across the fibers are presented in Table 2.

Table 2

Material	Along the fibers		Across the fibers	
	Average modulus of loading branch, MPa	Average modulus of unloading branch, MPa	Average modulus of loading branch, MPa	Average modulus of unloading branch, MPa
Pine	3900...4900	8800...9300	700...750	-
Birch	4100...4700	10800...11900	700...810	1100...1200
Lime	4100...4300	9700...10000	400...410	460...500

It is evident that for the birch and lime specimens the paths of the loading branches are practically strain-rate independent, for loading both along and across the fibers. Loading the specimens along the fibers with pulses of higher amplitudes leads to higher stresses as compared to the earlier observed ones.

The test results for the three materials for high strain rates (curves '2' in Figs. 1a, 2a and 3a) testify to the fact that upon reaching the maximum the stresses decrease with the strains. This occurs as a result of breaking the bonds between the annual layers and individual fibers and their buckling. In this case the maximum strain values may be taken as a compressive strength parameter of the material. The corresponding strains amount to 4-5%.

After the strains reach their peak, failure of the material begins. However, even for the strains higher than the breaking strain and corresponding to the strain peak, the material retains its fairly high strength characteristics and deformational stability, to which testifies the unloading path of the specimen after the pulse is no longer applied. The unloading branches of the diagrams are generally steeper than the loading ones. The paths of the unloading branches could not be followed up to the end as the stress relaxation process in the specimens is rather lengthy (especially for the orientation across the fibers); thus, for the length of the pressure bars used, a spurious pulse reflected from the rear end of the supporting bar is superimposed on the final part of the transmitted pulse. It should be kept in mind that due to the pronounced nonlinearity of the deformation diagrams the values of the loading and unloading modulus obtained from the diagrams and summarised in Table 2 for each of the wood species are, to a considerable degree, tentative. The unloading modulus for all the materials (except the pine with the direction across the fibers) are positive, i.e., despite the considerable deformation achieved (due to the breakage of the bonds between the fibers) the material fibers retain substantial elasticity. The comparison of the processed residual strain pulses for the majority of the specimens with their actual residual strain testifies to a high degree of the recovery of shape after loading.

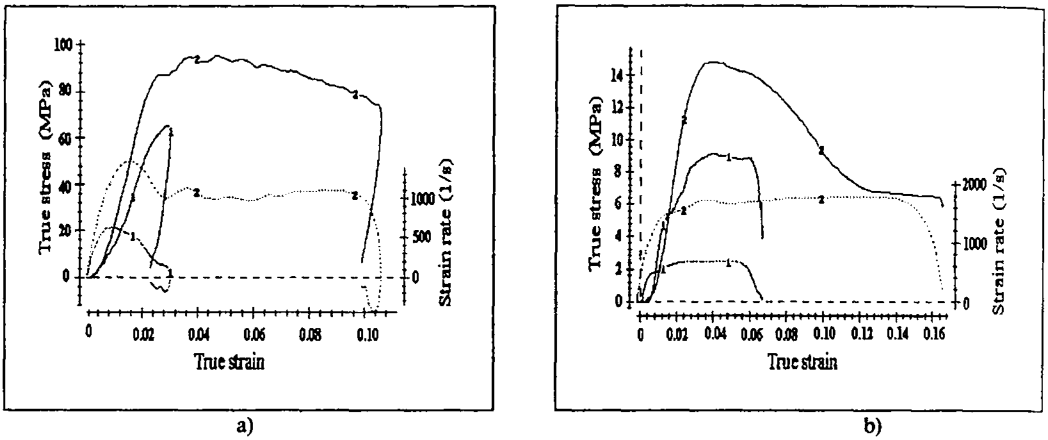


Figure 1: Dynamic diagrams for the pine specimens both along the fibers (a) and across the fibers (b)

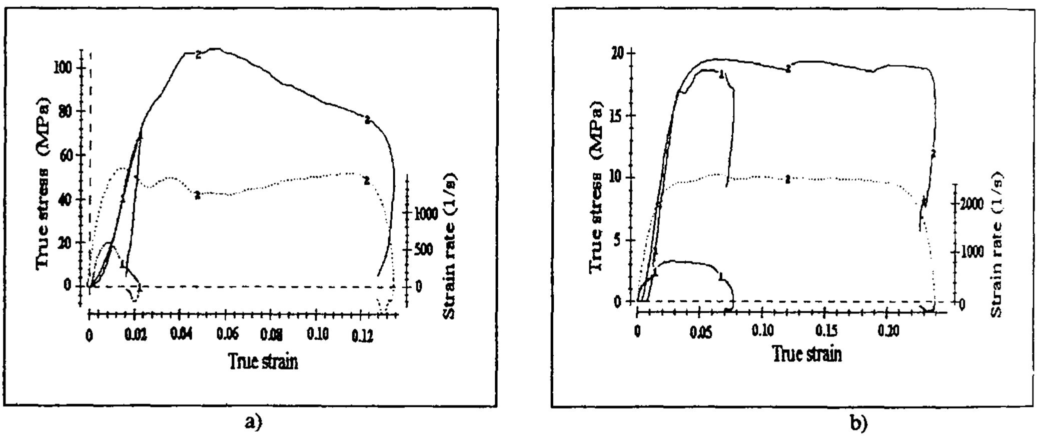


Figure 2: Dynamic diagrams for the birch specimens both along the fibers (a) and across the fibers (b)

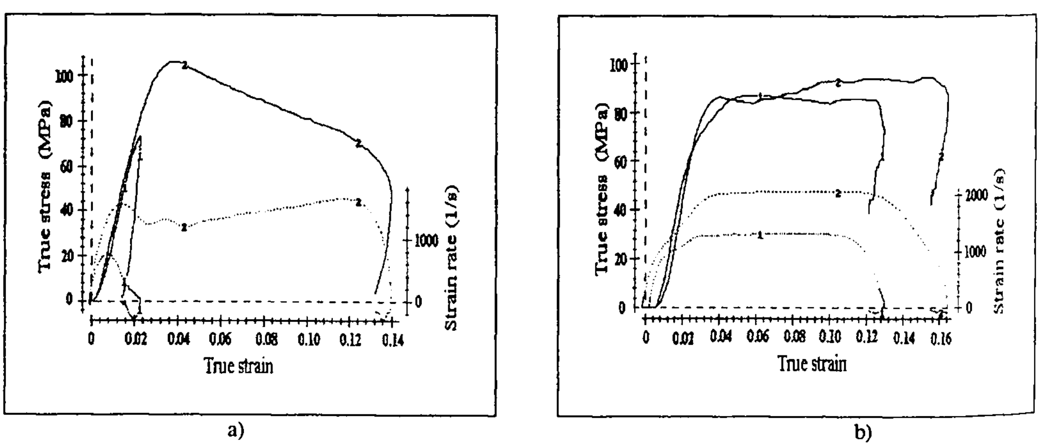
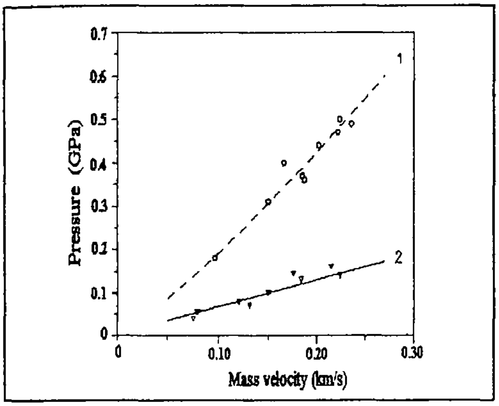


Figure 3: Dynamic diagrams for the lime specimens both along the fibers (a) and across the fibers (b)

In the tests with high strain-rate loading across the fibers the paths of the loading branches were rather peculiar: upon reaching the 3-4% strain level, the birch and lime specimens behaved as ideally plastic, whereas the pine specimens exhibited a substantial stress decrease. The difference in their behaviour may be due to a more homogeneous macrostructure of birch and lime as compared with pine.

The plane-wave experiments were conducted for the pine specimens cut out along and across the fibers. The obtained shock adiabates are shown in Figure 4a as a «pressure-mass velocity» relation (P~U) and in Figure 4b as a «wave propagation velocity-mass velocity» relation (D~U).



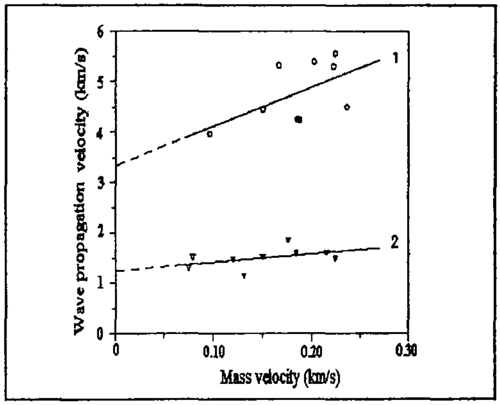


Figure 4. Shock adiabates for pine along (curves '1') and across (curves '2') the fibers.

In the P~U coordinates the data can be approximated by the equation of the form $P=X*U^Y$ and in the D~U coordinates by the linear relation $D=A+B*U$. The values of the parameters in the equations are given in Table 3.

Table 3

Materials	X	Y	A	B
Pine along the fibers	2.67	1.14	3.34	7.74
Pine across the fibers	0.58	0.93	1.25	1.71

CONCLUSIONS

The analysis of the test results for pine, birch and lime allows one to note the following common aspects in their behaviour. For the strain rates of about 1500 s^{-1} and higher, after reaching certain stress values which are rather close for all the materials tested (95-108 MPa for compression along the fibers) the decohesion of the material takes place, leading to the stress decrease with the increasing strain. After the loading is finished, unloading of the specimen takes place, with a considerable residual strain remaining in it. Visual examination of the specimens after the experiments testifies to their partial failure, allowing one to take the maximum stress values as a compressive strength characteristic. For low strain rates (500 s^{-1}) the loading and unloading branches of the deformation diagrams are nonlinear and close to one another. The highest nonlinearity of the diagrams is observed for low stress values. Moreover, there is a portion on the diagrams (under 0.2-0.3%) where the stresses are zero.

ACKNOWLEDGEMENT

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