

## MODEL OF THE WOOD RESPONSE TO THE HIGH VELOCITY OF LOADING

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Paper deals with the experimental and numerical study of the wood beam response to the explosive loading. The beams made from the Oak, Beech, Pine, Spruce and Birch have been tested. The mechanical properties of these woods at dynamic loading have been determined. Two methods, Hopkinson Split Pressure Bar Test and Charpy Impact test have been used. The minimum detonation pressures at which no damage occurs has been evaluated. These thicknesses are in a reasonable agreement with the mechanical properties determined by the tests mentioned above. The numerical simulation of these experiments has been performed using of LS DYNA 3D finite element code. Results of the numerical simulation s are in reasonable agreement with the experimental ones,

## INTRODUCTION

Wood is an anisotropic cellular material such as honeycombs, metal ring systems, polymeric foams and some others. These materials are very convenient for the design of impact energy absorbers and as core materials in lightweight structures. Their behavior under static loading is well summarized in the book [1]. Wood in particular has also been used as a protective material for high velocity impact events for many centuries [2,3] and is very often used as an impact energy absorbing material at the design of the transportation flasks for nuclear fuel etc. There have been only a few systematic studies of the behavior of wood under high rates of loading following from some impact events [2]. Recently the extensive impact test data have been obtained for some wood species [4,5]. These data have been used for the development of the models of the macro-deformation and micro-deformation modes resulting from the dynamic uniaxial compression at the specimen impact.

The present paper focuses on the other kind of the dynamic loading which is the effect of the detonating explosive. In order to have a chance to explain the observed experimental results, the data on the wood behavior under dynamic loading have been obtained.

## MATERIAL AND EXPERIMENTAL PROCEDURE

For the experiments the following wood species have been selected: Oak, Beech, Pine and Spruce. The following material properties of these woods have been determined:

1. The wood strength properties at static loading in tension, pressure and in bending.
2. The mechanical properties under dynamic three point bending using Charpy test.
3. The mechanical properties at high strain rates using of the Hopkinson Split Pressure Bar Test (HSPBT)

The free supported beams (100 x 100 x 1500 mm) made from the woods mentioned above have been loaded by the explosive charge. The layer of PMMA has been inserted between the charge and the beam in order to reduce the amplitude of the loading pressure pulse. The time dependence of the loading pressure has been recorded using of the managanin gauges. At this study the minimum amplitude of the pressure pulse at which no beam damage occurs has been found. The possibility of a numerical simulation of given experiments has been also studied. The finite element code LS DYNA 3D has been used. This code enables to simulate the course of the shaped charge detonation and the interaction of the detonation products with the wood elements (plates and beams). The numerical simulation is long – term work which is still in progress. In the given paper the preliminary results for the plates and beams made from the spruce and birch wood.

## EXPERIMENTAL RESULTS

### *Mechanical properties at the static loading.*

The testing of wood under static loading in tension, pressure and in bending represents a standard procedure. Owing to this fact, no description of these experiments is presented. The results of this testing are given in Table 1.

Table 1. Strengths of the tested woods. (ME – modulus of elasticity in MPa, MR – modulus of rupture in MPa)

WOOD	Density (kg/m <sup>3</sup> )	Strength in tension    (MPa)	Strength in tension ⊥ (MPa)	Strength in pressure    (MPa)	Strength in pressure ⊥ (MPa)	MR	ME	Tough ness J/cm <sup>2</sup>
Spruce	440	84	1.5	30	4.1	60	9 100	4.9
Pine	530	102	2.9	54	7.5	98	11 750	6.9
Oak	700	108	3.3	42	11.5	116	11 600	7.4
Beech	720	130	3.5	46	7.9	104	13 100	7.8
Birch	730	134	6.9	50	10.8	134	16 100	6.6

*Charpy test.*

The specimens of dimensions 10 x 10 x 55 mm have been used – see Fig. 1. The specimens were loaded across the growth rings. The impact energy of the hammer was 101.8 J and corresponding impact velocity 2.738 m/s. The record of the loading force  $F$  as the function of the specimen displacement  $s$  has been obtained for each specimen. From this record it is possible to evaluate many quantities describing the mechanical properties [6]. In the given paper we evaluated only the maximum of the load Force  $F - F_m$  and the energy absorbed by the specimen during the loading –  $W$ . Between 30 and 50 specimens were tested for each wood. The results of the loading are given in Table 2.

Table 2. The main properties of the specimens tested using of the Charpy hammer. ( $v_x$  is the variation coefficient, P0.95 denotes the interval where the data lie with the probability 95%.)

WOOD	Moisture content (%)	$F_m$ (kN)	P 0.95	$V_x$ (%)	W (Nmm)	P 0.95	$V_x$ (%)
Spruce	8	1350	1315-1401	10.7	4029	3519-4539	42.9
Pine	9	1791	1767-1827	5.3	6708	6286-7130	19.7
Beech	9	1845	1763-1953	8.3	3562	3120-3678	20.1
Oak	8	1996	1883-2109	16.5	3037	2705-3369	32.0
Birch	7	2311	2198-2424	13.5	7146	6791-7501	13.7

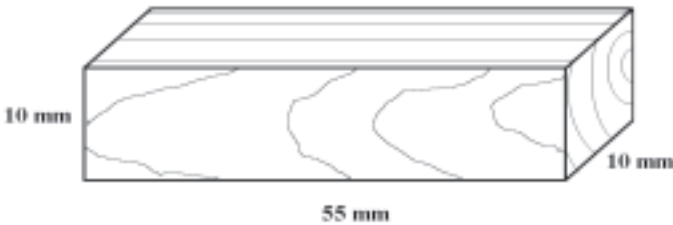


Fig.1. Specimen for the testing of wood under dynamic three point bending.

*Hopkinson Split Bar Tests.*

From these tests, see [7] for details, the dependence of the dynamic crushing stress on the strain rate has been evaluated. The results are displayed in Fig. 2. The experimental data can be fitted by the linear function:

$$\dot{\sigma} = \sigma_B + \alpha \cdot \dot{\epsilon} \tag{1}$$

where  $\dot{\sigma}$  is the dynamic crushing strength and  $\dot{\epsilon}$  is the strain. The dot above the symbol denotes its derivation with the respect to the time. The parameters of this relation are given in Table 3.

Table 3. The parameters of the Eq. (1).

WOOD	$\sigma_B$ (MPa)	$\alpha$ (MPas)	Minimum of the strain rate	Maximum of the strain rate
Spruce	74.34	0.0271	400	1100
Pine	78.37	0.0406	485	1150
Beech	86.72	0.0464	490	1140
Oak	78.00	0.0657	532	1180
Birch	113.00	0.0321	560	1300

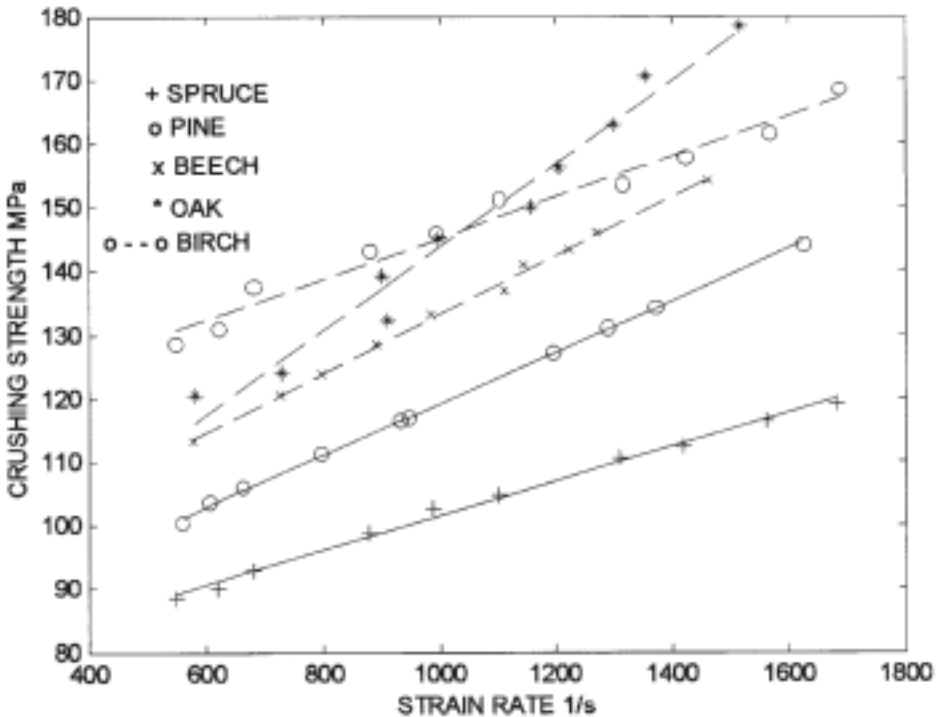


Fig. 2. The dependence of the crushing strength on the strain rate.

In the experiments described in the previous section the evaluation of the loading stress pulse parameters at which no fracture of the beam occurred has been performed.

The reduction of the stress pulse amplitude, maximum of pressure  $p_m$ , has been performed by the inserting of the PMMA layer between explosive charge and the beam surface. The determination of the minimum values of  $p_m$  represents 8–10 experiments. The values of the stress pulse amplitudes at which no beam fracture occurs are given in Table 4.

Table 4. Values of  $p_m$  of the stress pulses at which no fracture occurs.

WOOD	Minimum values of $p_m$ (MPa)
Spruce	560
Pine	680
Beech	760
Oak	840
Birch	1060

The values of the given pressure are much more higher in comparison with the values of the strength at the static and dynamic loading.

### NUMERICAL SIMULATION

The numerical simulation of the problem shown in Fig.1 has been performed using finite element code LS DYNA 3D. The wood has been considered as the orthotropic elastic solid with a failure. The failure is achieved if a very simple criterion is yield:

$$\epsilon_1 \geq \epsilon_{max}$$

where  $\epsilon_1$  is the maximum principal strain, and  $\epsilon_{max}$  is the principal strain at the failure. The elastic constants have been determined from the ultrasound measurements [8].

The failure strain has been chosen as 5%. For higher values of this strain no complete fracture of the beam occurred.

The behavior of the TNT detonation gas products, the Jones-Wilkins-Lee (JWL) equation of state has been used, together with the programmed burn model – the detonation velocity has been assumed to be 6930 m/s [9]. The JWL equation has the form:

$$p = A \left[ 1 - \frac{\omega}{R_1 V} \right] \exp(-R_1 V) + B \left[ 1 - \frac{\omega}{R_2 V} \right] \exp(-R_2 V) + \frac{\omega E}{V}$$

Where  $p$  is the detonation pressure,  $V$  is the relative volume and  $E$  is the internal energy density. The parameters has been taken from [10]:

$$A=272.7 \text{ GPa}, B= 3.231 \text{ GPa}, R_1 = 4.15, R_2 = 0.95, \omega = 0.3$$

Initial density of the explosive was 1630 kg/m<sup>3</sup>.

The finite element model of the charge and the beam is introduced in Fig. 3.



Fig. 3. Finite element model of the experiment .

With the respect to the real geometry the 1/4 geometry has been used.

In the first step the maximum of the strain at which the beam failure occurs has been determined. In our previous paper [11] we have found that the failure of the spruce wood occurs at the strain 11%. If we use this value we can see that no damage of the beam occurs – see Fig. 4.



Fig. 4. The final shape of the spruce beam (time  $t = 8$  ms).

The experiments showed that all beams were broken into two parts. By the gradually decreasing of this strain we achieved the value of 5%. Just above this strain no failure occurs. In Figs. 5–6 the development of the beam failure is shown.

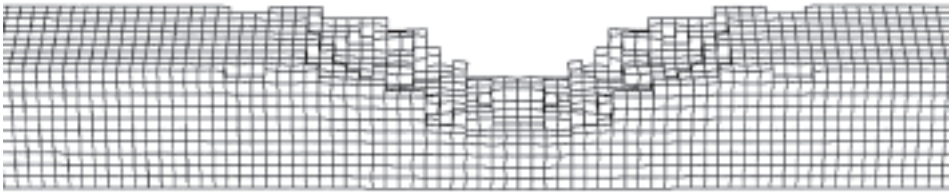


Fig. 5. Damage of the spruce beam at the time  $50 \mu\text{s}$ .

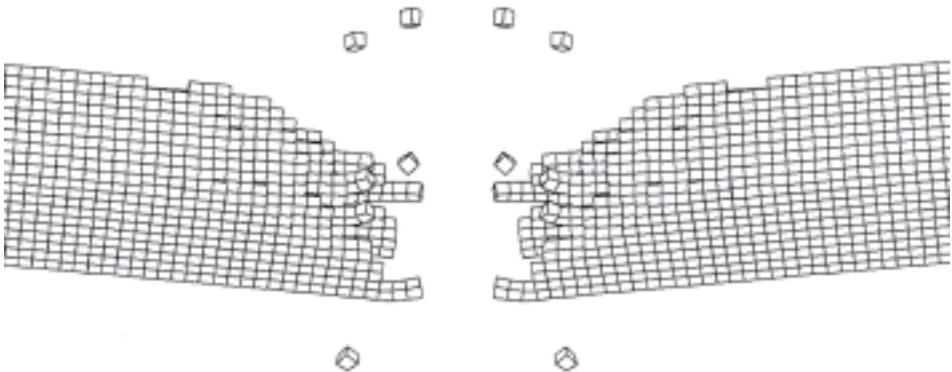


Fig. 6. Damage of the Spruce beam at the time 3 ms.

Even if the model of the wood behavior is very simple the resultant beam damage is very similar to the experimentally observed beam fracture. If we used the Tsai-Wu model [12] of the wood damage as in our previous paper [13] the numerical analysis led to the results that the complete fragmentation of the beam should occur. It means this model is inconvenient for the analysis of the given experiment.

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