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Strength properties of raw wood after a wildfire

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Abstract. Using fire-damaged wood is one of the efficient and resource-saving approaches to forest conservation. The object of the study is raw wood exposed to fire. The aim of the study is to analyze the mechanical properties of fire-damaged pinewood, the height of the trunk, and determine the possibility of its use as a structural material. Tests were carried out for static bending, compression along the fibers, and tension along the fibers. We performed the tests on samples taken from the lower, middle, and upper parts of the fired wood and compared them with wood that was not exposed to fire. It was established that during a ground and medium fire, the strength properties of wood are most reduced in the apical part of the trunk by 41.80 % compared to wood undamaged by fire. The smallest decrease in strength occurred in the lower part of the tree. It was determined that with sufficiently small damage to wood by fire, i.e., a decrease in the cross-sectional area to 15 %, it can be partially used as a structural material.

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1. Introduction

Wood is characterized by the presence of various defects (knots, shrinkage cracks, oblique, etc.). Therefore, at the stage of designing wooden structures, there are increased requirements for knowledge of the strength characteristics of wood, features of load resistance [1–5]. Using wooden structures is inseparably associated with trends in energy and resource-saving of wood, increasing the strength and rigidity of elements while reducing their assembly weight and increasing operational reliability [6, 7].

Thus, in works [8–10], a method was proposed and scientifically substantiated to restore destructed wooden structures by impregnating them with a polymer composition. In [11] authors propose a method for estimating the residual resource of wooden structures by changing their geometric parameters. A general formula is given for calculating the service life of wooden structures. The authors of [12] studied samples of wood building materials (plywood, oriented strand board, and chipboard) in laboratory conditions because of exposure to heat flow from a natural flame. Experimentally confirmed that particle size plays a significant role in the ignition of the building structure. The works also describe and substantiated the issues of resource-saving of wood and the reduction of material consumption for building structures [13, 14].

Forest fires cause great damage to the state of natural forest ecosystems around the world. Many countries are facing this scourge. For example, in December 2010, in Israel (near Haifa), 5000 hectares of forest were engulfed in fire. The fire lasted over three days and was extinguished with the help of 24 countries [15]. A forest fire in the state of California (USA) covered 45000 hectares; in October 2017, 44000 hectares of forest burned down in Portugal because of fire [15]. Turkey's forest fires in 2021 brought significant damage to the economy [16].

Over three million hectares of forests in Siberia (Russia) covered by fire in 2019 clearly show what danger fires in the forest pose to the life and health of people and what damage they cause to property and wildlife [17–20]. Almost two-thirds of Russia's territory is covered with forest. According to the Federal Forestry Agency of the Russian Federation, the total area of forest fund lands is 1 billion 146 million hectares. From 9000 to 35000 forest fires are registered annually in Russia, covering areas from 0.5 to 3.5 million hectares [21]. Over 8.7 million hectares of natural territory burned down in 2021 in Yakutia, Russia [22].

Now there is a shortage of coniferous wood [23, 24]. The maximum use of natural resources should be increased through the wider use of wood with reduced technical characteristics. Thus, one of the main issues of forest research is the question of the technical quality of fire-damaged wood and the possibility of using it as a structural material.

In the works [25–27], studies of the residual mechanical properties of wood after a fire were carried out: static bending, estimation of Young's modulus, impact strength coefficient. The question of the strength properties of damaged wood under typical stress states, such as tension and compression along the fibers, has remained unexplored.

Using wood exposed to fire is one of the effective and resource-saving approaches to conserving forests. Works [28–31] show that partially charred wood keeps sufficiently high physical properties, making it possible to use it as a structural material. However, the amount of results obtained, including international studies, is insufficient to form a clear legal framework governing the use of raw wood exposed to fire in building structures [32–34]. Therefore, the research direction related to studying the physical and mechanical properties of raw wood exposed to fire is an urgent task. The research aimed to analyze the mechanical properties of fire-damaged pinewood, the height of the trunk, and determine the possibility of its use as a structural material.

2. Materials and Methods

Wood exposed to fire (high temperatures) is of considerable scientific interest. We are talking about wood, which is partially charred, and the rest has a visually healthy appearance (Fig. 1). The question arises: what are its residual strength properties? Whether such wood can be used as a structural material. To study the suitability of wood exposed to fire for use as a structural material, it is planned to analyze the mechanical properties of wood by comparing its characteristics with reference samples, i.e. unaffected by fire. As a "reference" wood was taken the 2nd grade pine (Pinus sylvestris), not exposed to fire, growing in the same area (Namsky Appany, Namsky Edeytsy, and Namtsy-1 Khomustakh).

Wooden building structures are mainly made of coniferous species (pine, spruce, larch), so we will limit ourselves to considering the residual strength of pine samples. For testing, samples were taken from wood (pine) exposed to fire. Forest growth areas are the Namsky Appany, Namsky Edeytsy, and Namtsy-1 Khomustakh (Yakutia, Russia). The type of intended purpose of the forest is operational. The type of fire is grassroots, stable, and medium. Samples were taken from trees in which the area of damage by fire along the trunk section was 10–15 % (Fig. 1). According to the nature of fire damage to trees and analysis of data from forest fire reports, we can conclude that the temperature of the fire was approximately 400 °C.

We selected from the bottom, middle and top parts. Samples were made from each cut along the radius: in the center, by 0.5 radii (middle), and on the periphery. Trees for testing (models) were selected as follows. Model trees are cut into ridges. The charred part of the tree was removed. The ridge is sawn into boards, and the boards into bars (blanks), and samples are made from the blanks (Fig. 1b).

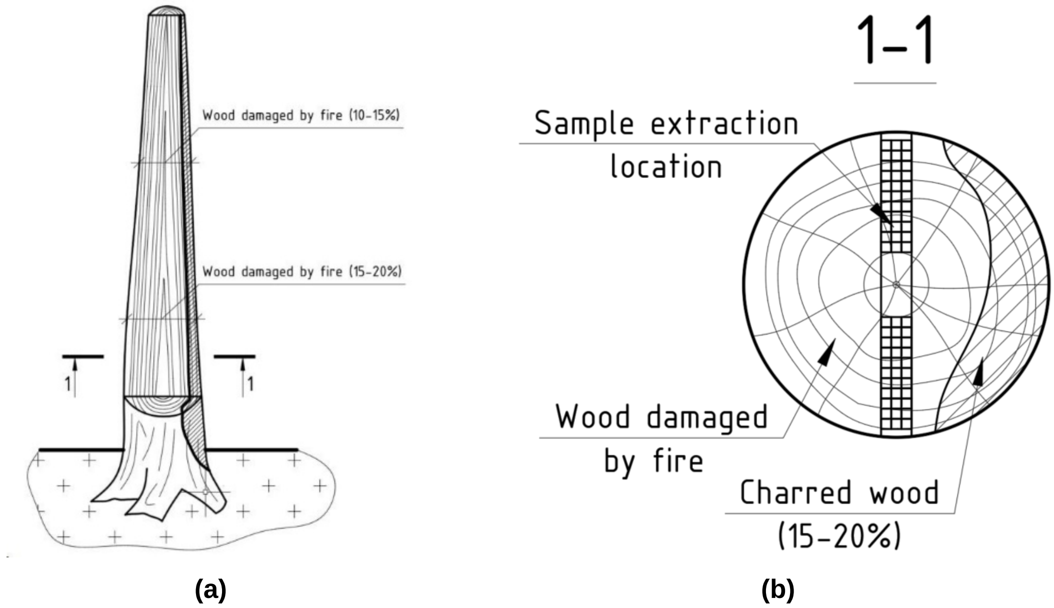


Figure 1. Growing tree exposed to fire: (a) general view; (b) section.

To characterize the properties of wood as a homogeneous material, without defects, samples of a small section are selected for testing in order to avoid the influence of the curvature of the annual layers. At the same time, the samples must include a sufficient number of anatomical elements characteristic of the tested breed (at least 4 or 5 annual layers). Therefore, tests are carried out on samples with a cross section of 20×20 mm. The dimensions of the samples were determined with a sliding caliper with a measurement error of no more than 0.1 mm. The selection of units for testing was carried out according to the “Wood. General requirements for physical and mechanical tests". The least stressed places in the wooden beams are located in the middle part of the section (closer to the neutral axis), since the normal stresses in these areas have minimum values.

Sampling from the general population was carried out in one stage using systematic sampling. The minimum number of samples to be tested (nmin) was determined by the formula:

$$n_{\min} = \frac{V^2 \cdot t_\gamma^2}{P_\gamma^2}, \tag{1}$$

where, V is coefficient of variation of wood properties, %. The coefficient of variation was taken for testing: compression along the fibers – 13 % stretching along the fibers 20 %, for static bending – 15 %; γ is required confidence level; t_γ is quantile of Student's distribution; P_γ is relative accuracy of determining the sample mean with a confidence level.

The relative accuracy of determining the sample mean was taken as 5 % at a confidence level of 0.95. In case of partial replacement or damage of samples, the number of samples was increased by 20 % relative to the calculated number in each type of test.

The wood was stored at natural humidity after sampling. Before mechanical testing, the moisture content of the samples was adjusted to 12 %. The studies were carried out according to the methods described below.

The studies were carried out on a REM-100-A-1 testing machine (Russia, Tomsk, Rusenergo LLC). The universal testing machine REM-100-A-1 is designed for mechanical testing in tension, compression, and bending of specimens and products made of materials whose breaking load does not exceed 100 kN. Mechanical testing of samples on the machine is carried out by deforming the sample to failure with controlled movement of the traverse.

Multichannel measuring complex TDS-530 was used to register relative deformations with a high degree of accuracy. The complex performs simultaneous hardware-synchronized reception, digitization, processing of signals through all measuring channels and transmission of measured values via digital interfaces during single and multiple measurements in real time. The use of the complex makes it possible to register edge deformations of materials through the use of strain gauges with a base of 20 mm. The latter are glued to the previously cleaned and prepared surface of wooden elements using an adhesive composition based on cyanoacrylate. The deformations measurement accuracy was 0.001 mm.

2.1. Determination of the tensile strength of wood weakened by fire during static bending

The samples were made in the form of a rectangular prism (bar) with a cross-section of 20×20 mm and a length along the fibers of 300 mm. The sample was loaded uniformly at a constant loading rate (Fig. 2a,b). The sample is placed in the machine so that the bending force is directed tangentially to the annual layers (tangential bending) and loaded according to the scheme shown in Fig. 2c.

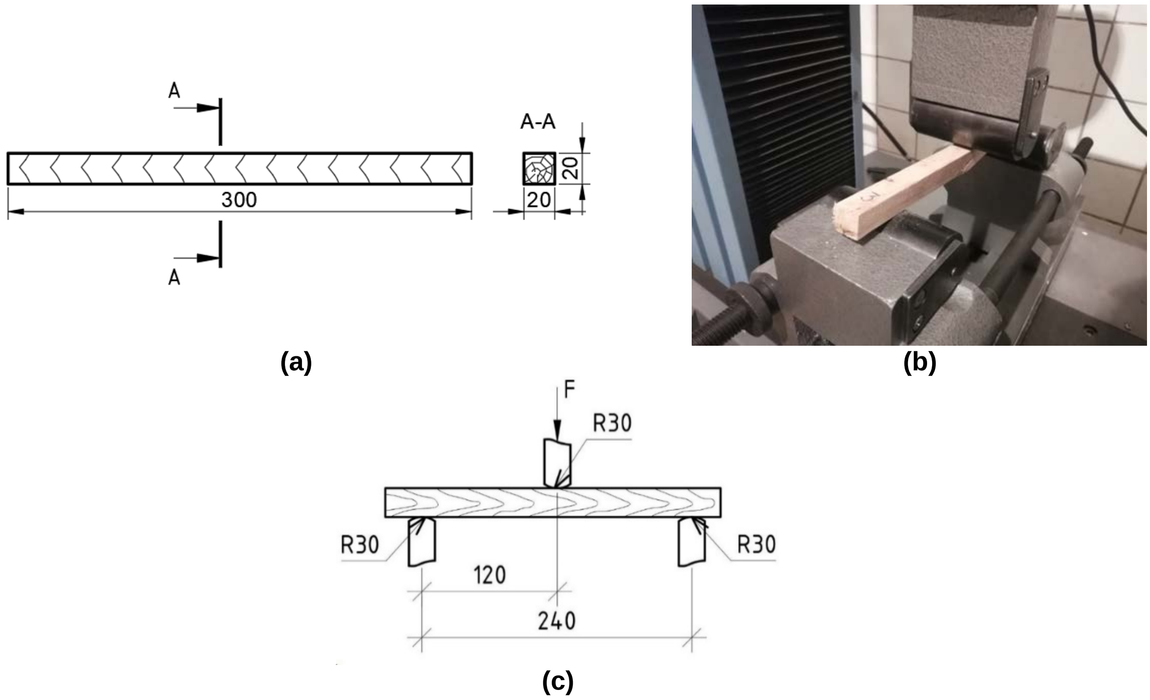


Figure 2. Testing wood weakened by fire for static bending: (a) the shape of the test piece, mm; (b) sample testing; (c) sample loading scheme.

The sample was loaded evenly at a speed of 4 mm/min for the loading head of the testing machine. The destruction occurred 1.5 min after the start of loading. Five series (repetitions) of tests were carried out. The number of tested samples was taken equal to 36. In all cases, the specified number of tested specimens refers to one series of tests for each type (compression, tension, shearing and bending). Each series of tests included specimens from different parts by trunk height (butt, middle and top) and tree growing region (3 regions).

2.2. Determination of the tensile strength of wood weakened by fire in compression along the fibers

The samples were made in the form of a rectangular prism with a base of 20×20 mm and a length along the fibers of 30 mm (Fig. 3). The sample was loaded uniformly at a constant loading rate.

The loading occurred evenly at a speed of movement of the loading head of the testing machine of 4 mm/min. The destruction of the sample occurred 1 min after the start of loading. Five series (repetitions) of tests were carried out. The number of tested samples was taken equal to 29.

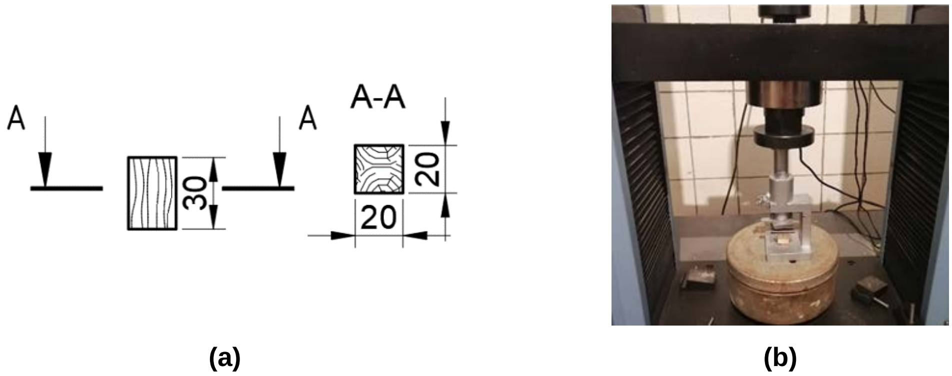


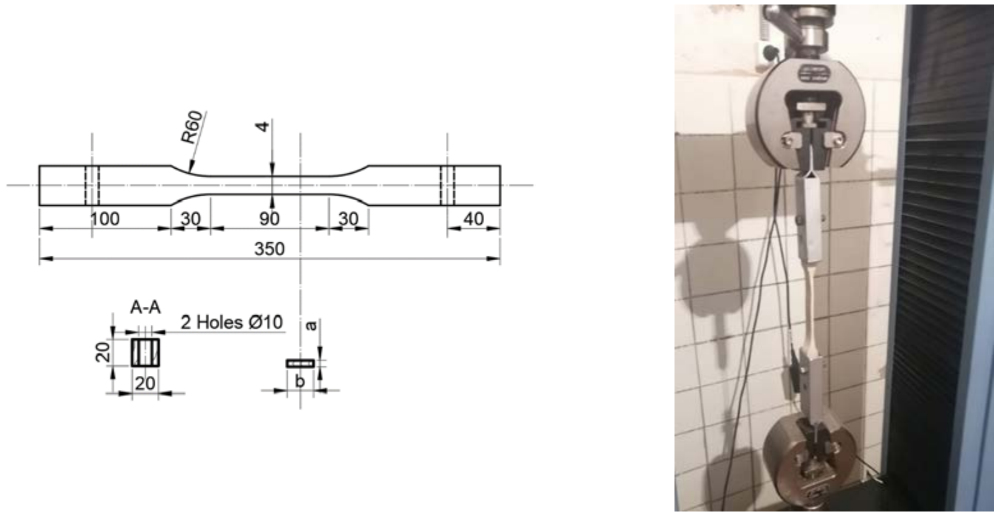
Figure 3. Testing wood weakened by fire for compression along the fibers: (a) the shape of the test specimen, mm; (b) sample testing.

The strength of the rod in compression and the loss of stability depends on the area and shape of its section, the length l and the type of fastening of its ends, which is taken into account by the stability coefficient φ. In relative short elements, the length of which does not exceed seven times the height of the section, they work in compression without loss of stability. Therefore, in the calculations, when determining the compressive stresses σ, the stability coefficient was not introduced.

2.3. Determination of the tensile strength of wood weakened by fire in compression along the fibers

Sample blanks were gouged out. The samples were made according to the shape shown in Fig. 4.

The sample was placed in the grips so that the part of each head adjacent to the rounding remained free for 20–25 mm. The tensile load coincided with the longitudinal geometric axis of the sample.



(a) **(b)**

Figure 4. Tensile testing of wood weakened by fire along the fibers: (a) the shape of the test specimen, mm; (b) sample testing.

Loading occurred evenly at a speed of movement of the loading head of the testing machine of 10 mm/min. The destruction of the sample occurred on average 98 seconds after the start of loading. Five series (repetitions) of tests were carried out. The number of tested samples was taken equal to 33.

The strength of wood is related to its density. Therefore, density indicators were determined for the studied parts of the tree. The essence of the method is to determine the mass and volume of the sample at the appropriate moisture content of the wood and calculate the density indicators. The results of laboratory tests are presented in Table 1.

For an adequate analysis of mechanical tests, the rheological properties of wood should be taken into account. Currently, a complete rheological model of wood consists of the following components [35]:

– elastic deformation ε^{el};

– non-regenerating plastic deformation ε^{pl};

– deformation shrinkage or swelling deformation caused by a change in wood moisture ε^{ω};

– viscoelastic creep deformation ε^{ve};

– mechanical sorption deformation ε^{ms}.

As a result, the total relative strain tensor of the wood comprises five components [35]:

$$\varepsilon = \varepsilon^{el} + \varepsilon^{pl} + \varepsilon^{\omega} + \sum_{i=1}^{n} \varepsilon_i^{ve} + \sum_{j=1}^{m} \varepsilon_j^{ms}. \quad (2)$$

The proposed rheological model reflects the deformations that occur most fully under real deformation conditions.

3. Results and Discussion

The experimental data of wood samples weakened by fire were compared with reference samples. Pine samples from undamaged wood by fire were taken as samples undamaged by the fire. Based on the test results, statistical processing of experimental data was carried out. The accuracy rate P (%) was determined by the formula:

$$P = \pm \frac{m}{V} \cdot 100\%, \tag{3}$$

where m is the average error of the arithmetic mean; V is the coefficient of variation.

Fig. 5 shows the results of testing samples for the static bend.

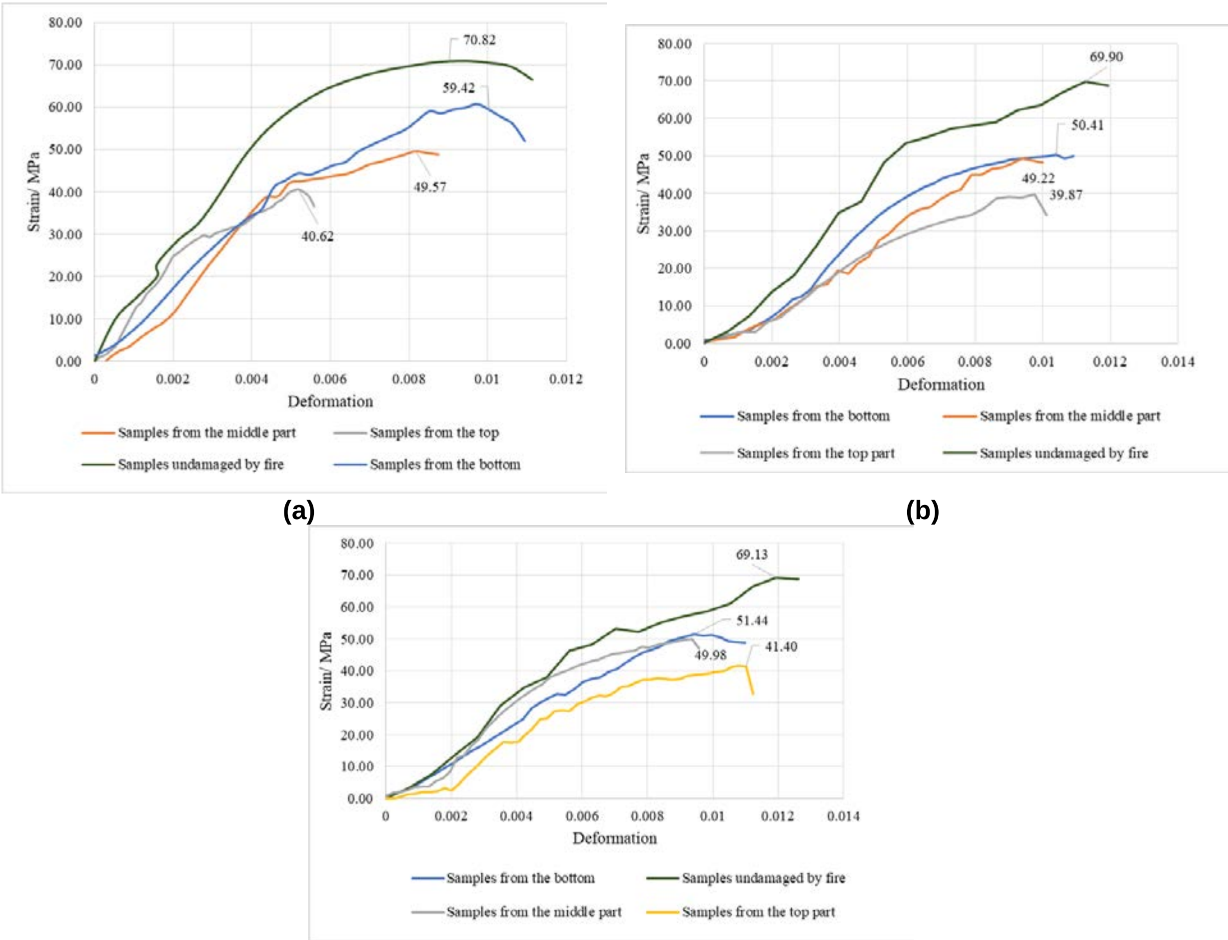
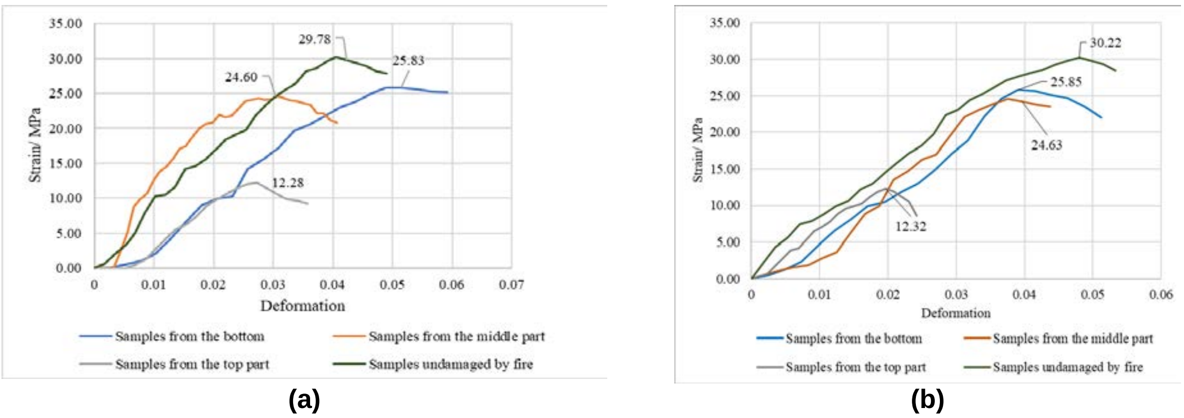
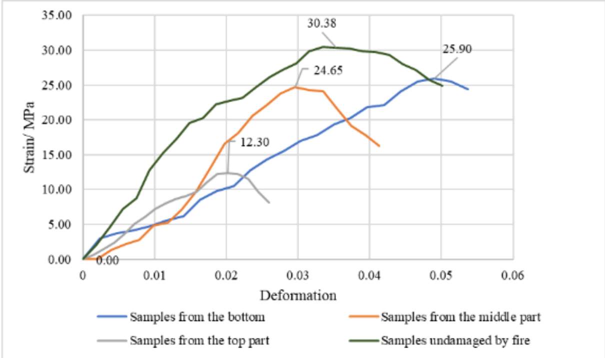


Figure 5. The strength of pinewood weakened by fire for static bending in different parts of the trunk: (a) Namsky Appany; (b) Namtsy-1 Khomustakh; (c) Namsky Edeytsy (Yakutia, Russia).

Fig. 6 shows the results of testing samples for compression along the fibers.

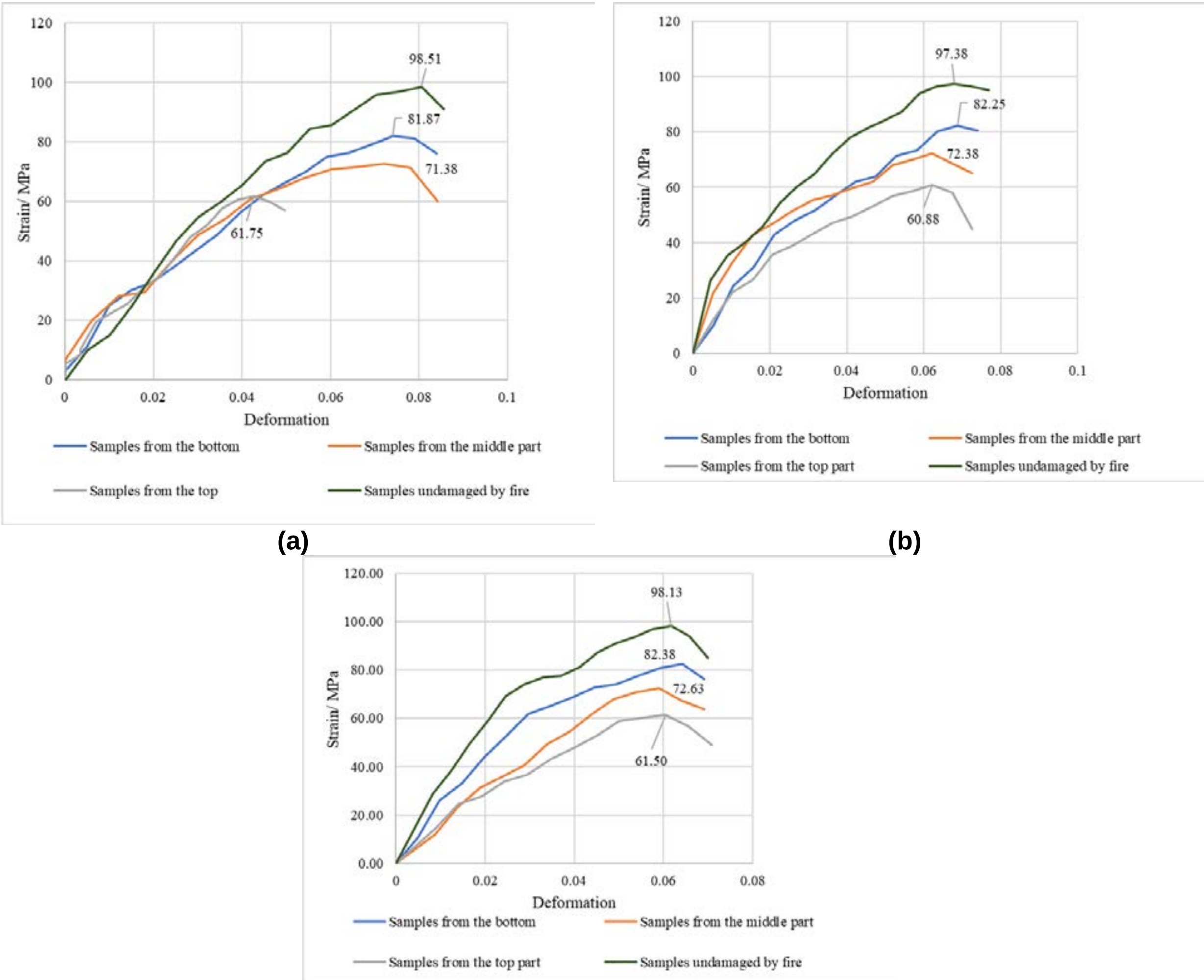




(c)

Figure 6. The strength of pinewood weakened by fire for compression along the fibers in different parts of the trunk: (a) Namsky Appany; (b) Namtsy-1 Khomustakh; (c) Namsky Edeytsy (Yakutia, Russia).

Fig. 7 shows the strength of pinewood weakened by fire in tension along the fibers in different parts of the trunk.



(a) **(b)**

(c)

Figure 7. The strength of pinewood weakened by fire in tension along the fibers in different parts of the trunk: (a) Namsky Appany; (b) Namtsy-1 Khomustakh; (c) Namsky Edeytsy (Yakutia, Russia).

Experimental data allow us to consider all materials up to certain loading limits as elastic and obey Hooke's law [36, 37]. The simplest form of the law of deformation in time describes the flow of an ideally viscous fluid in which strain is proportional to the rate of deformation ε:

$$\sigma = \kappa \cdot \varepsilon, \tag{4}$$

where σ is the strain, κ κ is the coefficient of proportionality, ε is the deformation.

The coefficient of proportionality κ is called the coefficient of viscosity or the coefficient of internal resistance.

Hooke's law is preserved to a greater extent in the diagram when the wood is stretched along the fibers to destruction (see Fig. 7). Wood works in tension almost like an elastic material and has high strength. The destruction of the stretched elements occurred brittle, in the form of an almost instantaneous rupture of the least strong fibers along a sawtooth surface.

The fracture mechanics of the sample under compression along the fibers is shown in Fig. 6. Up to about half of the tensile strength, the growth of deformations occurs according to a close to linear law, i.e., strain growth is directly proportional to the applied load [38, 39]. Thus, that wood working in real conditions almost elastically. In the section of a compressed element, the compressive force acting along its axis gives rise to almost equal normal compressive stresses σ. As the load increases, the increase in deformations increasingly outstrips the growth of stresses, indicating the elastic-plastic nature of the wood deformation. The destruction of the samples occurred plastically, as a result of the loss of local stability of the walls of a number of wood fibers. Therefore, compressed elements work more reliably than stretched ones, and are destroyed only after obvious deformations. Analysis of the dependence "strain-deformation" (Fig. 6) illustrates that viscoelastic deformations appear during failure. Defects in natural wood less reduce the strength of the compressed elements, since they perceive part of the compressed elements.

Fig. 5-7 illustrate that in the study areas after the fire (Namskie Appany, Namtsy-1 Khomustakh, Namsky Edeytsy, Yakutia, Russia), one common pattern is observed, namely the largest decrease in mechanical characteristics in the top part of the tree. The limiting normal strains σ at which the specimens failed in all types of tests was determined by the failure load indicators.

Determining the limiting normal strains are convenient for a comparative assessment of the strength of various types of wood. The strength of wood under various types of stress states and with their various combinations (complex stress) must be known for a reasonable calculation of the elements of wooden structures.

Table 1 shows the averaged results of the tests. The tests show that the mechanical strength of wood decreases in different ways, depending on the type of load and the height of the trunk. The greatest decrease in strength for all types of tests is observed in samples taken from the upper part of the tree trunk. The smallest decrease in strength in all three tests was observed in samples taken from the bottom.

According to the test results, it can be seen that the ground fire was weak and did not fundamentally change the quality of the wood [40]. The properties of wood within the same trunk are not constant, and these changes are subject to the following generally accepted pattern: the best wood is in the bottom part of the trunk; as it rises along the trunk, strength decreases. The obtained data are consistent with the works [41, 42].

Table 1. Averaged results of the tests of wood samples.

Type of tests	$\frac{\textbf{Strain}, [\textbf{MPa}]}{\textbf{Accuracy index P}, \%}$			
	Bottom part	Medium part	Top part	Wood samples undamaged by fire
Static bend	$\frac{53.75}{\pm 0.36}$	$\frac{49.59}{\pm 0.33}$	$\frac{40.63}{\pm 0.32}$	$\frac{69.90}{\pm 0.38}$
Strength reduction, %	-23.10	-29.00	-41.80	-
Compression along the fibers	$\frac{25.86}{\pm 3.27}$	$\frac{24.63}{\pm 3.12}$	$\frac{12.13}{\pm 2.75}$	$\frac{30.13}{\pm 3.83}$
Strength reduction, %	-14.10	-18.20	-59.71	-
Stretch along the fibers	$\frac{82.17}{\pm 2.08}$	$\frac{72.13}{\pm 1.84}$	$\frac{61.34}{\pm 1.55}$	$\frac{98.01}{\pm 2.47}$
Strength reduction, %	-16.1	-26.40	-37.40	-
Wood density, kg/cm^3	476.61	427.46	439.55	495.65

Note. The numerator indicates the strain at the relevant tests; in the denominator – an indicator of accuracy (in percent) relative to wood samples undamaged by fire.

The decrease in the technical qualities of wood along the entire height of the trunk is explained by the destruction of wood, which occurred under the influence of high temperature. The structure of the wood changes, the water content in the wood decreases sharply, and its distribution along the tree trunk causes thermal destruction of the wood components [43]. Thus, high temperature during a fire has a devastating effect on the structure of wood. This type of destruction of cell walls can be explained by the fact that under the influence of high temperature free moisture boils off in the cavities of vessels, which in turn leads to an increase in excess pressure of the vapor-air mixture, which contributes to the destruction of cell walls in groups of vessels.

Wood with reduced technical qualities cannot be used for the load-bearing wooden structures in the shipbuilding and automotive industry and for wooden frames, roofs, and various supports. But it is suitable for the manufacture of non-load-bearing structures, rough finishes, the construction of temporary huts, sheds, etc., which, in conditions of an acute shortage of wood, solves many issues.

4. Conclusions

As a result of the study, the following conclusions can be drawn:

1. It has been established that the "strain-deformation" diagrams of tension, compression along the fibers and static bending of specimens exposed to fire are comparable to those of healthy wood specimens. A general characteristic trend is observed: the highest strength is shown for samples experiencing tensile forces. When stretched, the fracture was brittle. During compression, the samples were destroyed due to the loss of local stability. However, the compressed structural elements, as a rule, have a length much greater than the cross-sectional dimensions, and are not destroyed as small standard samples, but as a result of buckling, which occurs before the compressive stresses reach the tensile strength.

2. The destruction of samples during compression along the fibers had a viscous character of destruction; therefore, this wood can be used in compressible elements of wooden structures. Destruction is preceded by obvious signs in the form of significant deformations. Tensile specimens show higher strength, but fracture is brittle.

3. During the study, a decrease in strength was found in samples taken from the upper part of a tree trunk. Thus, with static bending relative to the wood samples undamaged by fire, the decrease is more than 20 %, with compression along the fibers, the decrease is 40 %, and with tension, the decrease is 30.61 %.

4. The smallest decrease in strength for all three types of tests was observed in samples taken from the buttom. Thus, with static bending relative to the wood sample undamaged by fire, the decrease is about 23 %, with compression along the fibers, the decrease is 15.0 %, and with tension, the decrease is 8.39 %.

5. It has been established that with sufficiently small damage to a tree by fire, i.e., reducing the cross-sectional area up to 15.0 %, its partial use as a structural material is possible.

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