

## Research Article

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# Determination of shear stresses in the measurement area of a modified wood sample

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**Abstract:** The purpose of the experiment was to determine the distribution of shear stresses in the measurement area of a natural and modified wood sample. Previous wood shear tests conducted on a typical Iosipescu specimen have shown that a complex stress state exists at the bottom of the notch. With transverse loading of the samples, flexure occurs and normal stresses arise from the bending moment and thus fibers are deformed. For the investigations oriented on shear, shear with stretching, and shear with compression, a special specimen was prepared which differed by notch geometry from a typical Iosipescu specimen. A new test machine is described in the article, which is equipped with special specimen holders to perform investigations in complex stress conditions. Crack patterns recorded for natural and modified wood are presented. For all tests, numerical finite element model simulations were performed to obtain stress distributions inside the specimens. The calculated stress distributions were visualized as contour line projections for natural and modified wood. Transverse shear strength values for the modified Iosipescu sample were found to exceed the magnitude of previously published ASTM D1037-87 test results. The test results proved that the strength properties of anisotropic materials in a complex state of stress can be assessed with great accuracy. This is very important in engineering applications.

**Keywords:** modified wood, shear test, mechanical properties, modified Iosipescu sample, flat stress loading device

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## 1 Introduction

There are many reports on the results of shear strength tests of polymer composites and natural wood available in the literature whereas only few studies have covered the shear strength of modified wood.

El-Hajjar and Haj-Ali [1] applied a modified Arcan fixture with butterfly specimen geometry to measure the in-plane shear response of thick-section pultruded fiber-reinforced polymer (FRP) composites.

The objective of the proposed testing method is to determine both material shear stiffness and its nonlinear stress–strain response up to ultimate stress. Finite element models (FEMs) for the butterfly specimen are generated to examine the effects of the notch radius and material orthotropy on the uniformity and distribution of stresses in the gage area. Butterfly geometry with a blunted notch and roving orientation parallel to the applied load is found to have a uniform shear stress in the gage section. The axial shear response is measured under different biaxial stress states by varying the angle of the applied load. The tested nonlinear shear stress–strain responses compare favorably to results previously obtained from off-axis compression tests used to calibrate a multiaxial constitutive model for this material.

Bank [2] noted the nonlinear shear response in pultruded composites using the Iosipescu fixture to test specimens cut from pultruded beams. Several methods have been proposed for the measurement of the in-plane shear properties in pultruded composites. These include off-axis test methods, such as the  $\pm 45^\circ$  tension/compression test, the cylinder–torsion method, and variations to the Iosipescu specimen.

However, Haj-Ali and Kilic [3] proposed the use of the  $\pm 45^\circ$  compression test for thick pultruded composites. Its application to laminated composite systems has been limited due to its inability to preclude buckling before a shear-induced failure. In the cylinder torsion method, a torque is applied to a thin cylindrical specimen at the ends to induce a state of shear. A major disadvantage is the likelihood of failure at the ends (grips).

Barbero et al. [4] used torsion tests on pultruded rods made of only roving layers to determine the shear stiffness and strength.

Davalos et al. [5] used torsion tests on rectangular bars to determine the shear moduli in E-glass/vinylester pultruded composites.

Zureick et al. [6] proposed the use of a modified Iosipescu specimen for shear property measurement in pultruded composites. A major advantage of this method compared with the off-axis test was the low levels of the longitudinal strain and the large gage section.

Arcan et al. [7] proposed a biaxial fixture, commonly known as the Arcan fixture, to produce biaxial states of stress. The compact nature of the Arcan fixture enables obtaining the shear properties in all in-plane directions in a relatively simple manner. The Arcan fixture can be used to apply both shear and axial forces to the test specimen.

Voloshin and Arcan [8] used this method to determine the longitudinal and through-thickness shear modulus in a unidirectional laminated FRP composite. Their results compared favorably with those obtained from cylinder torsion tests.

Hung and Liechti [9] used Moiré's interferometry to examine the strain fields and their uniformity in unidirectional laminated specimens of AS4/PEEK tested in an Arcan fixture. They found that aligning the fibers with the loading direction and using a 90° notch produced a uniform "pure shear" state in the gage section.

Xie et al. [10] have presented the composite sandwich matting comprising paulownia woods as core material and glass FRP as face skins and lattice webs. Compressive tests and shear tests were carried out to characterize the mechanical properties of the paulownia wood and poplar wood core according to ASTM C365 and ASTM C273, respectively. Core shear failure occurred when the shear stress exceeded the shear strength of paulownia wood core.

Taghiyari et al. [11] investigated the shear strength of heat-treated solid wood of three species (beech, poplar, and fir) bonded with polyvinyl acetate adhesive reinforced by nanowollastonite. After the heat treatments, the samples were prepared for the determination of their shear strength. Dimensions of the specimens and testing method used were according to the ASTM D143-14 (2014) standard. Determination of shear strength was carried out using an Instron 4486 universal testing machine. The results demonstrated that shear strength was significantly dependent upon the density of the specimens.

In turn, Janowiak and Pellerin [12] evaluated the shear strength properties of three wood composite materials.

A modified Iosipescu test apparatus was used to determine shear strength. In-plane shear was also characterized using ASTM D1037-87 test standards.

This study specifically utilized the University of Wyoming version of the original shear test device. Transverse shear strength values were found to exceed the magnitude of previously published ASTM test results.

When Yoshihara et al. [13] examined the applicability of the Iosipescu shear test for measuring the shear properties of wood, sitka spruce and Japanese ash were used for the specimens. The test results showed that the Iosipescu shear test is effective in measuring the shear modulus and the yield shear stress. To measure the shear strength properly by the Iosipescu shear test, the configuration of the specimen and the supporting conditions should be examined in more in detail.

Shear strength has been determined based on uniaxial tension tests of off-axis specimens and the examination of the proper off-axis angles. Three tree species were used for the studies by Yoshimura and Oto [14]. Uniaxial tension tests of the specimens with various off-axis angles were conducted, and the shear stress at failure was obtained. The authors thought that the shear strength predicted by uniaxial tension tests should be treated as an approximate value despite the simplicity of the tension test. Other test methods should be adopted to obtain the precise shear strength of wood.

In their paper, Warguła et al. [15] have presented the results concerning tensile, compression, and shear of pine wood samples in all significant directions. The static shear test was performed using instrumentation. Its geometry allowed the stress conditions as close to technical shearing as possible.

The Iosipescu sample has gained more recognition in composite testing due to its shape [16–18]. The geometry of the Iosipescu sample according to ASTM D5379M:93 is shown in Figure 1.

Destruction of the Iosipescu sample can be achieved in a uniform stress condition although the presence of unwanted transverse stress complicates the interpretation of shear strength [16,19]. The definition of shear strength is not unambiguous [19,20]. For instance, for the same material, Broughton refers to "destructive stress" of 58 MPa [19], Morton et al. [21] specify "shear strength" of 68 MPa, but Adams and Lewis [8] refers to "shear strength" of 115 MPa [22].

When testing a flat sample, it should be noted that obtaining the criterion of destruction necessitates the production of shear forces. The homogeneity of stress in the sample area under examination is an important feature of the sample. According to the authors, the correct

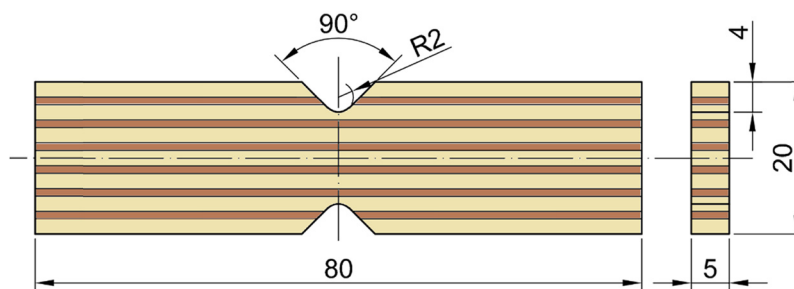


Figure 1: Geometry of the Iosipescu sample.

determination of the modulus of elasticity (MOE) of wood, has not been fully resolved yet [17,23] whereas the determination of tangential stress is far from being resolved [20,24].

## 2 Materials and methods

### 2.1 Materials

A series of samples of the sapwood of Scots pine (*Pinus sylvestris*), part of them in natural state and part subjected to polymerization with methyl methacrylate (MMA), were tested for tensile/compressive and shear strength.

The purpose of the experiment was to test the strength of natural and modified wood on a prototype device under simultaneous tensile/compressive conditions and shear, applying the Iosipescu method. The results of the tests were used to determine the shear strength and stress distribution in the notch of the sample made of the tested materials. A number of methods have been developed with the purpose of increasing the durability of wood as structural material. One of them is impregnation with a monomer and subsequent polymerization *in situ*. The resulting material is termed wood-polymer composite (WPC). There are two types of composites obtained in this way: cell lumen type and cell wall type [25]. Cell lumen impregnation of wood creates a material in which the polymer fills the wood cell cavities, which increases the stability of the internal structure of the wood. Such modification results in a material with higher resistance to crushing and higher overall stiffness and hardness [25–30]. The subject matter of this work is the toughness of sapwood obtained from Scots pine (*P. sylvestris*) and the WPCs manufactured by its polymerization with the use of MMA. Scots pine is ubiquitous throughout northern Europe and is commonly used as a relatively cheap and easily available construction material.

This work was motivated by the possible application of WPC in a broadly understood marine industry, where materials are exposed to unfavorable environmental conditions. Assuming that shear strength provides valuable macroscopic index of usefulness of the material, an experiment was designed to assess the necessary level of impregnation with polymer from the point of view of specific needs and to investigate of the shear strength. The goal was to obtain a quantitative material suitable for further analysis and planning the development of research. The exact procedure and the results have been described in detail.

All samples of the shear test were cut along the grain from the sapwood of Scots pine. Prior to the shear test, all samples and the material were cut from preprocessed wood to ensure the intended moisture content and polymer loading. A supply of timber approximately 3 m long and 350 mm in diameter was first inspected for knots and insect or fungal injuries to select defect-free pieces. Then, 500 mm × 50 mm × 30 mm lumber was cut from the sapwood along the grain. This lumber was naturally dried under laboratory conditions at 22°C (±2°C) to reach a moisture content of 12 ± 2%, and seasoned for 2 years. Humidity was determined using an electric resistance hygrometer (electrometric method) in accordance with the PN-EN 13183-2: 2004 standard. Next, the samples were fabricated. After the material had been cut, it was machined on a planer, which defined the final finish of the lateral faces of the samples. All samples were measured and weighed, and their mass was recorded numerically with an accuracy of 10<sup>−4</sup> g. Two types of samples were produced of 40 each. One set was left in the natural state, and the second one was saturated with a polymer to 35% mass content.

Natural wood was marked as K0 and modified was marked as K35. The modified wood with contents of methyl polymethacrylate was marked as K35, where the number represented the number of kilograms of methyl polymethacrylate with respect to 100 kg of dry wood. This process was

carried out in an autoclave according to a fixed and strictly observed procedure.

1. While placing a batch of samples in the autoclave, care was taken to fix them in such a way that the monomer had unobstructed contact with each face of each sample.
2. To remove moisture from the wood cell lumens, a negative pressure of 0.1 MPa was created and maintained for 30 min. The rationale was to open the way for deep penetration of the monomer, which could otherwise be obstructed by water trapped in the lumens.
3. At this point the monomer, the MMA, was fed into the autoclave. The level of saturation of the batch was controlled by timing the bath.

The saturation process being completed, the samples were measured and weighed again. It was found that their dimensions did not deviate from the presaturation ones by more than 1–2%. The next batch underwent polymerization in a tank filled with a 30% water solution of sodium nitrate. The content of the tank was warmed up to 75°C, and this temperature was maintained for 2 h. Then, to ensure full polymerization to poly(methyl methacrylate), this temperature was gradually raised to 120°C for 1 h. The content of the polymer in each sample (polymer loading) was confirmed on the increase of its weight in comparison with the presaturation weight and determined according to formula (1):

$$\text{PMA load} = l = \frac{m - m_0}{m_0} \times 100 \%, \quad (1)$$

where  $m_0$  is the mass of the untreated sample and  $m$  is the mass after saturation.

However, owing to the previous research by the first author ([27], p. 250), it was known beforehand that the time of saturation needed to obtain the intended sequence 0.35 of polymer loading in a sample was 15 min.

## 2.2 Methods

In this work, the measurement of the shear resistance of the composite Iosipescu specimens in the test are according to the V method (ASTM D5379M:93).

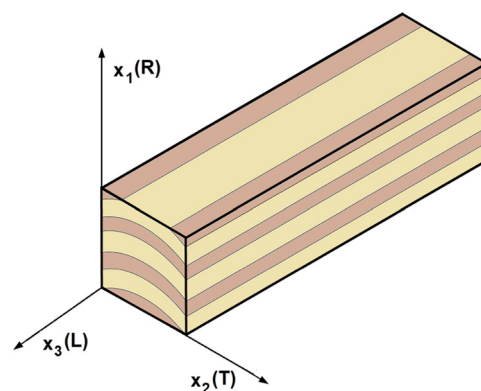
A new method for testing material properties has been applied to determine the shear strengths of specimens of *P. sylvestris*. The method permits the realization of pure shear in the critical section of the specimen. The large strength ranges of wood fibers and the vast differences in strength between earlywood and latewood fibers can still cause significant scatter in the test data, but the effect of combined stresses can be effectively controlled.

Owing to the special properties of wood, failure always follows the slope of the grain. The new method can only yield shear strength parallel to grain, which is required for engineering design purposes. The determination of shear strength of solid wood has been hampered by the difficulty in devising specimens and loading devices to produce a state of uniform shear stress. Many investigators have studied this problem and developed different methods for shear testing, but the presence of complex stress conditions at the site of failure remains unresolved [23].

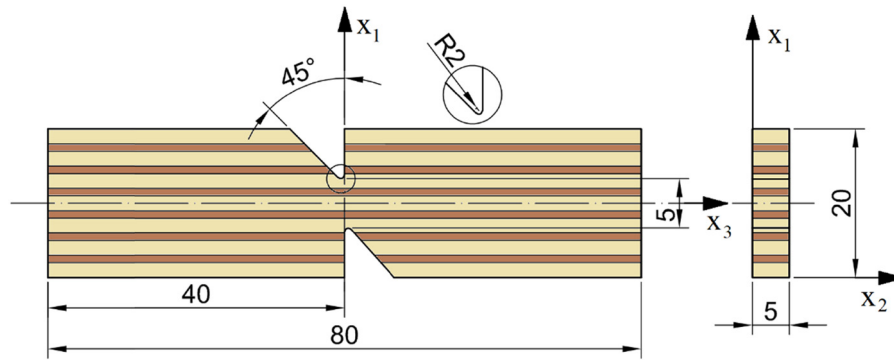
The following assumptions were made for measuring the shear strength of wood composite samples. The essence of the tests is to maintain a uniform stress state, in the examined sample area, so a number of tests have been carried out and the literature has been analyzed in detail, ultimately taking the appropriate shape and dimensions [26,27,31–33]. The shear strength and load distribution were studied in complex load conditions (shear/tensile and shear/compression) in the measurement section of the sample.

In the literature, the following letters are used to denote the anatomical directions of the wood: R – radial direction, T – tangent, and L – longitudinal with respect to the surface of individual layers of fibers. On the other hand, in the theory of elasticity, the index notation 1, 2, 3 is used, in particular:  $x_1$  – radial direction,  $x_2$  – tangent, and  $x_3$  – longitudinal as shown in Figure 2.

Finally, the shape and dimensions of the wooden test sample are shown in Figure 3. The angle of the notch,  $\beta$ , is 45° and the depth of the notch is  $p = 7.5$  mm. Samples of different layers of early- and latewood have been tested. On average, the sample contained nine layers of earlywood and eight layers of latewood or vice versa. The thickness ratio of late-to-earlywood layers was 0.5.



**Figure 2:** Indicators and letter notation of the anatomical directions of wood.



**Figure 3:** Shape and dimensions of the sample for determining shear strength: clear layers – earlywood and – dashed layers – latewood.

The depth of the notch was considered in relation to the thickness of the layers so that the beginning of notch does not occur halfway through the thickness of the layer, but at its edge. It has been assumed that the layers are arranged in parallel and have a constant thickness over their entire length. In the measurement section, the outer layer may be a layer of early- or latewood (Figure 3).

The determination of strength on the wall of the tested materials required the use of appropriate instrumentation. The device used in the tests was designed according to a proprietary concept [26,27,31,33,34].

Figure 4 shows a prototype device producing a flat stress state in the test sample. In this instrument, the position of the axis of the sample relative to the direction of load,  $F$ , may be variable. Therefore, depending on the angle of alignment of the sample in relation to the load direction, in addition to shear, compressive and torsional

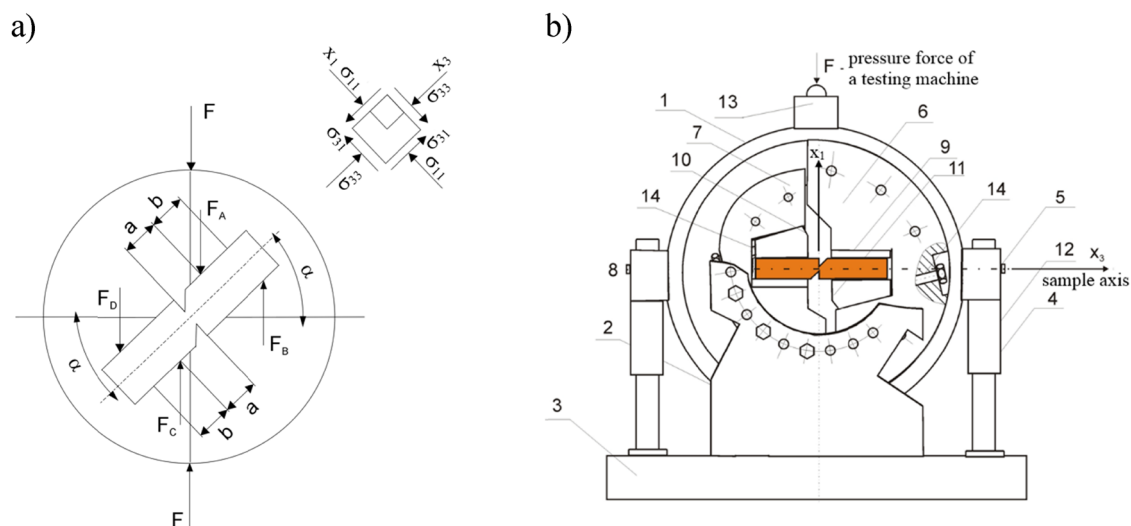
forces are also applied. The purpose of the study was therefore to determine the shear strength and load distribution in complex load conditions (shear/tensile and shear/compression) in the measurement section of natural and modified wood samples.

Resultant reactions, to which pressures at four points of the sample are reduced, shall be determined using the following equations:

$$F_A = F_C = F \left( 1 + \frac{a}{b} \right), \quad F_B = F_D = F \frac{a}{b}, \quad (2)$$

where  $F_A > F_B$ ,  $F_C > F_D$ ,  $a > b$ ,  $F$  is the force applied by the strength testing machine and  $a$  and  $b$  are distances describing the location of the resultant reactions.

The geometry and kinematic load pattern of the sample are shown in Figure 5. The device (Figure 4) consists of mobile blocks which move along an inclination of



**Figure 4:** Device for producing a plain stress state in the samples: (a) load pattern, (b) equipment diagram, 1, housing; 2, bracket; 3, base; 4, guide; 5, guide bushing; 6, right-hand holder; 7, left-hand holder; 8, jaw insert of the left-hand holder; 9, jaw insert of the right-hand holder; 10, left-hand retaining block; 11, right-hand retaining block; 12, guide bushing; 13, spheres and sphere mount  $\phi 12$ ; and 14, M6 bolt [26,27,31].



$\alpha$  relative to the axis of the sample. The measured value shall be the force dependent on the movement of the sample.

Depending on the angle  $\alpha$  between the direction of the effective load and the longitudinal axis of the sample, it is possible to determine the load distribution in the test sample for shear, shear/tensile, shear/compressive, and compressive and tensile forces. For the load sample, the stress distribution was primarily analyzed in the 7.5 mm length measurement section with a notch. If the angle  $\alpha = 0^\circ$ , the stress state is closest to the pure shear. The apparatus allows for an angle change from  $-45^\circ$  to  $+45^\circ$ . Tensile and compressive forces were applied in the direction of axis  $x_3$ , with the sample mounted directly in the jaws of the strength testing machine. The values of tensile strength ( $\alpha = +90^\circ$ ) and compressive strength ( $\alpha = -90^\circ$ ) were determined by stretching and compressing the samples on the MTS 810.12 machine at temperature  $23^\circ\text{C}$  and air humidity of 42%, with the use of a 50 kN load cell. Moving and stationary blocks are preclamped so that the  $F$  force component of  $F_{x_3}$  is less than the friction force between the blocks and the sample. However, this clamping introduces a preliminary stress condition. Therefore, the clamp value was determined experimentally to be sufficient while not significantly affecting the strength of the sample.

Figure 5 shows some displacement of the upper blocks relative to the lower ones. This offset has been experimentally established. It is sufficiently large to produce common displacements on the interfaces of the blocks with the sample. This is particularly relevant in view of the calculation model used for FEM stress analysis.

The tests have been carried out on the apparatus shown in Figure 3. For angle  $\alpha = 0^\circ$ , the sample is sheared under the influence of a vertical displacement applied

along the axis  $x_1$  (Figures 4 and 5). The sample weighing apparatus records the force to which the movement  $\Delta l$  corresponds. During the shear of the sample, the displacement along the axis  $x_1$  (right part of the instrument) corresponding to the force  $F = F_t$  is directed along the  $x_1$  axis. For negative angles of rotation of the sample in the instrument (counterclockwise) (Figure 4), force  $F$  induces shear ( $F_t$ ) and compression ( $F_c$ ) in the sample whereas for positive angles of rotation (clockwise), force  $F$  induces shear ( $F_t$ ) and stretch ( $F_m$ ) in the sample.

### 3 Results

Table 1 shows the strength values of the wood samples K0 and K35 depending on the angle  $\alpha$  until the first crack.

Figure 6 shows the relation between the load of the natural wood sample K0 and the modified K35 and the displacement of the holder for  $\alpha = 0^\circ$ . The digits 1 to 4 mark subsequent cracks in the natural wood sample.

The characteristics in Figure 6 illustrate the change in the sample load with time for woods K0 and K35. Differences can be observed in the transfer of wood load at K0 and K35. In a sample made of natural wood K0, when loaded, the layers of early- and latewood are destroyed alternately, hence the large number of distinctive “peaks,” both ascending and descending. The K35 material, in which the mechanical properties of the early- and latewood layers are similar, displays an entirely different behavior.

Figure 7 shows images of cracks in natural wood K0 versus modified wood K35. The nature of cracks in natural and modified wood samples varies significantly. The beginning

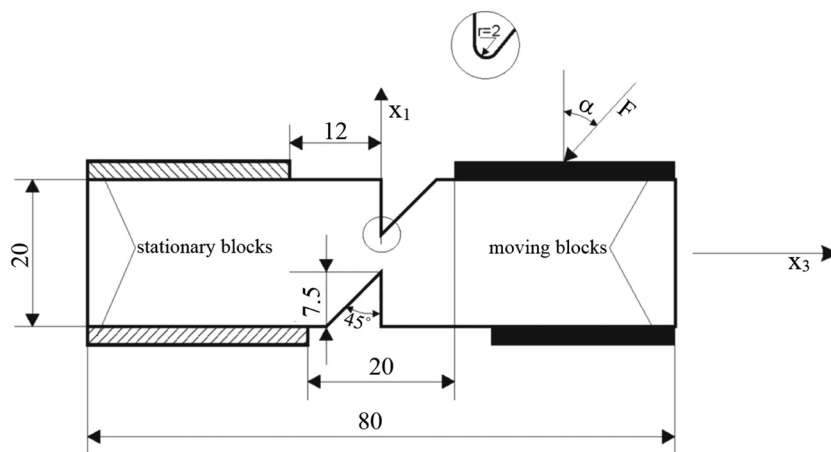
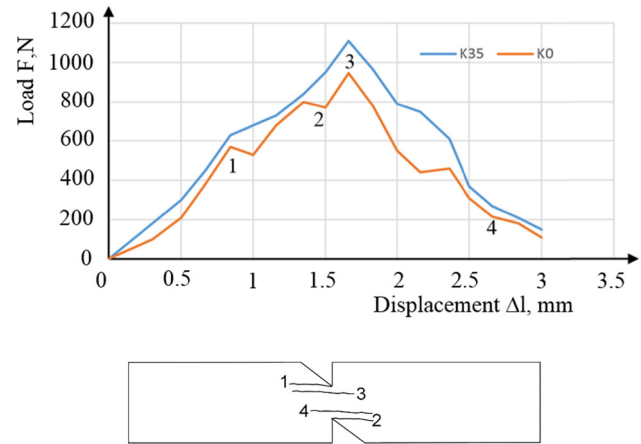


Figure 5: Sample kinematic load diagram.

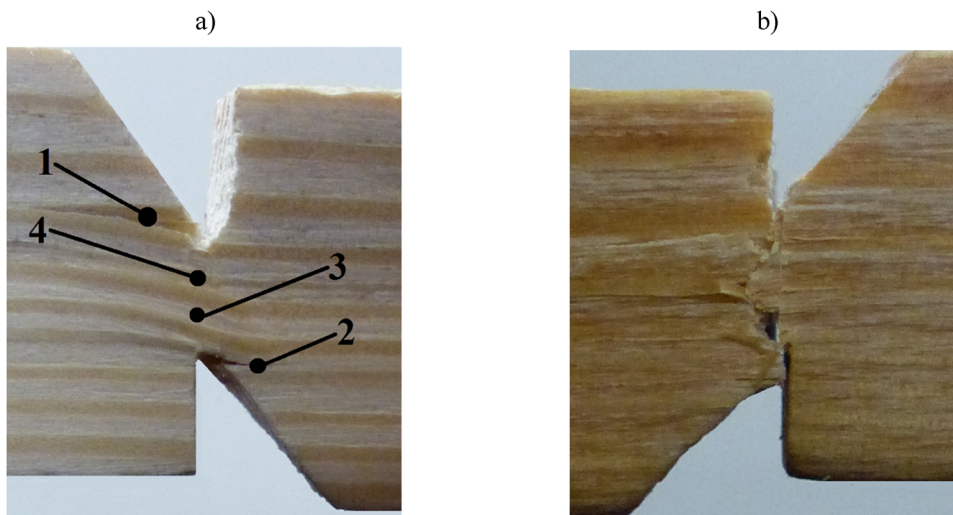
**Table 1:** Mechanical properties of wood K0 and K35

K0		K35	
Sample designation	Stress (MPa)	Sample designation	Stress (MPa)
$\alpha = 0^{\circ} - \text{shear}$			
N12	23.00	K31	25.00
N13	21.50	K32	23.70
N14	22.10	K33	25.60
N15	22.70	K34	27.90
N16	21.20	K35	26.20
Average value 22.10		Average value 25.68	
$\alpha = +15^{\circ} - \text{tensile shear}$			
N17	24.57	K36	33.45
N18	26.04	K37	29.85
N19	27.00	K38	31.45
N20	24.34	K39	27.45
N21	27.40	K310	30.40
Average value 25.87		Average value 30.52	
$\alpha = +30^{\circ} - \text{tensile shear}$			
N22	31.90	K311	41.16
N23	32.18	K312	34.95
N24	30.22	K313	37.05
N25	32.50	K314	39.15
N26	30.36	K315	32.44
Average value 31.43		Average value 36.95	
$\alpha = +45^{\circ} - \text{tensile shear}$			
N27	38.39	K316	50.23
N28	42.00	K317	48.54
N29	40.20	K318	47.78
N30	38.20	K319	51.16
N31	42.20	K320	48.04
Average value 40.20		Average value 49.15	
$\alpha = -15^{\circ} - \text{compressive shear}$			
N32	21.84	K321	25.30
N33	22.95	K322	22.30
N34	22.53	K323	27.30
N35	24.28	K324	20.30
N36	20.60	K325	23.80
Average value 22.44		Average value 23.80	
$\alpha = -30^{\circ} - \text{compressive shear}$			
N37	22.42	K326	27.08
N38	23.15	K327	25.90
N39	23.50	K328	26.54
N40	22.90	K329	27.18
N41	23.14	K330	26.00
Average value 23.02		Average value 26.54	
$\alpha = -45^{\circ} - \text{compressive shear}$			
N42	26.10	K331	28.10
N43	27.30	K332	26.20
N44	26.22	K533	30.05
N45	27.56	K334	33.90
N46	26.63	K335	32.00
Average value 26.76		Average value 30.05	

**Figure 6:** Displacement curve–load, with characteristic points of the beginning of the crack (1, 2, 3, 4 – subsequent stages of the cracking of the wood sample), course of force  $F$  versus displacement  $\Delta l$  with marked points 1–4 illustrating the successive stages of wood sample cracking.

of cracks 1 and 2 in sample K0 starts at low loads, close to the base of the notch (Figure 7a and b) during the test period (points 1 and 2, Figure 6). These cracks develop very quickly and only stop in the area of high compressive stresses, below the laden surface. The load values at which cracks 1 and 2 occur are very sensitive to the flexure applied by the instrument in the plane. Cracks 3 and 4 also develop from the notch, but closer to the incision slope, as can be seen in Figure 7. Their development is much slower and cannot always be linked to declining load. Further cracks indicate the end of the duration of the sample. They are related to a very abrupt load decline and appear very quickly, one after the other, developing immediately, similarly to cracks 1 and 2 (Figure 6). Some authors suggest that the final crack occurred in a state of homogeneous shear stress, but no attempt was made to clarify this issue [19,22,35]. Other authors even proposed to interpret the shear stress after the end cracks have appeared, as is done for shear strength.

The cracks in samples K35 resemble the nature of cracks in homogeneous materials. Cracks 1 and 2 start to form slowly with a significant loading force close to the base of the notch (Figure 7b) during the test period. These cracks are slowly developed with significant loads passing through cracks 3 and 4 leading to the destruction of the sample (Figure 7b). Differences in the nature of cracks in samples of modified wood K35 and natural wood K0 can be observed with the naked eye. It is difficult



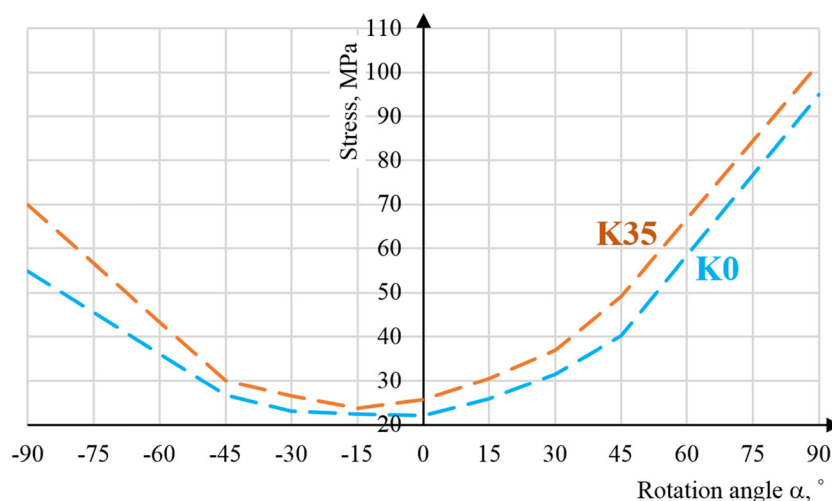
**Figure 7:** Images of shear cracks in samples: (a) natural wood K0, (b) modified wood K35, (1, 2, 3, 4 – subsequent cracking stages).

to capture the location and moment of initiation of cracks 3 and 4 which are formed below the notch in Figure 7b. Their development is rapid and only a computer record of the data allows the character of cracks to be restored. The cracking of the K35 material has not been thoroughly analyzed. For both natural wood and modified wood, we have assumed the limit strength for the samples – a load value corresponding to one crack (Figures 6 and 7). The analysis carried out with the FEM showed the presence of tensile and compressive stress in the measurement section of the sample for  $\alpha = 0^\circ$ , with prevalent shear stress at points 1 and 2. Harmful clockwise bending moment in the plane shall increase the transverse tensile stress at point 1 and apply transverse compressive stress at point 2. As a result, the total transverse tensile stress in

this point 1 is reduced. This causes a crack 1 to form earlier than crack 2. This was observed during the tests. The above course of sample cracking concerned applied to compression. Similarly, depending on the selected angle  $\alpha$  of axial alignment of the sample in relation to the direction of load, the values of force  $F$  were recorded, assuming that the strength of the sample corresponds to the first crack (point 1 in Figure 7).

By changing the angle of the sample, every  $15^\circ$  at  $-45$  to  $+45^\circ$ , a force  $F$  corresponding to the first rupture from angle  $\alpha$  was obtained. Figure 8 shows the relation between the loading of natural wood samples K0 and modified wood samples K35 and the angle  $\alpha$ .

Based on the graph shown in Figure 8, it can be noted that both natural wood K0 and modified wood K35 exhibit



**Figure 8:** Dependence of sample loading direction on the angle  $\alpha$  (an initial instance of a first crack appearing in the sample),  $\alpha$  – rotation angle of sample relative to its horizontal.



a higher tensile and tensile/shear strength (right part of the graph) than compression and compression/shear (left part of the graph).

A numerical simulation has been carried out to obtain the distribution of stresses inside the sample. The calculation model assumes a flat stress state whereas it was decided that each of the layers of soft and hard wood be described relative to their transverse direction by nine-node biquadratic elements. The physical characteristics of individual layers are described by means of the generalized Hooke law for orthotropic materials.

In the modified Iosipescu sample (Figure 3), the load distribution was mainly analyzed in the section marked with a bold line in Figure 9. When calculating the stress distribution in the section, the  $F$  force per sample was distributed to normal  $\bar{F}_{x_3}$  and shear  $\bar{F}_{x_1}$ . Stress values have been determined using the following dependence

$$\sigma_{33} = \frac{\bar{F}_{x_3}}{A}, \quad \sigma_{13} = \frac{\bar{F}_{x_1}}{A}, \quad (3)$$

where  $A$  is the transverse section of the sample.

The relationship between stress and deformation for the flat stress state was

$$\begin{Bmatrix} \varepsilon_{11} \\ \varepsilon_{33} \\ \varepsilon_{13} \end{Bmatrix} = \begin{bmatrix} \frac{1}{E_1} & -\frac{\nu_{31}}{E_3} & 0 \\ -\frac{\nu_{13}}{E_1} & \frac{1}{E_3} & 0 \\ 0 & 0 & \frac{1}{G_{13}} \end{bmatrix} \begin{Bmatrix} \sigma_{11} \\ \sigma_{33} \\ \sigma_{13} \end{Bmatrix}. \quad (4)$$

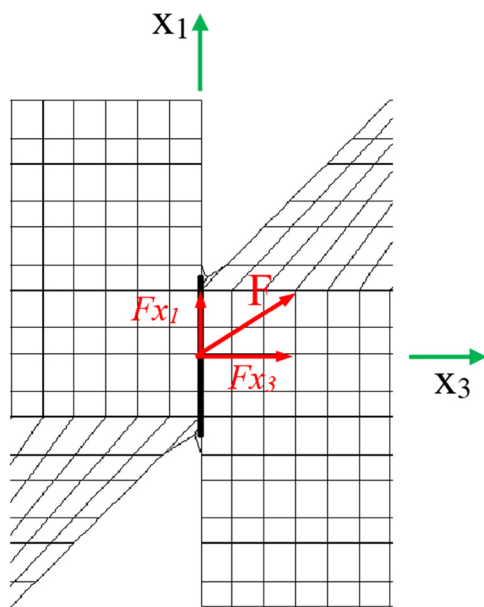


Figure 9: Sample section analyzed.

On the basis of the tests, the parameters of elasticity of the layers of soft and hard wood were determined, which are given in the studies under [25–27,33]. Tables 2 and 3 provide the parameters of elasticity of the natural and modified wood layers.

The determination of stress distribution values in the analyzed measurement section of the samples was possible through the use of numerical methods. The stress distribution in orthotropic material subjected to uniaxial load can therefore be observed. The analysis showed that there are tangential stresses in addition to pure stretching (compression). Studies have shown that anisotropic materials do not have a homogeneous stress state when exposed to pure tensile, compressive, or shear forces as is the case with isotropic materials. In any case, there is a heterogeneous stress state with one or the other stresses prevailing. The stress values obtained in the measurement section are certain, approximate values. The data adopted in the calculation model were not always consistent with reality. For calculations, it was adopted that the sample contained 17 layers of wood. The ratio between the thickness of late and early wood fibers, 0.5, was different from reality. Although the face of the sample was in line with the assumptions, it may have been completely different at the rear of the sample. This is due to the structure of the wood. However, the calculated figures only roughly deviate from reality.

The stress  $\sigma_{31}$  (for  $\alpha = 0^\circ$ ) calculated with the FEM method is illustrated in the form of a contour map in Figure 9 for K0 wood and in Figure 10 for K35 wood. The tangential stress distribution in the measurement section of the K0 sample (Figure 10) indicates a much higher loading of latewood layers, compared to earlywood. In addition, throughout the measurement section under analysis, the material loading is more than twice as high as in the identical measured section of K35 wood (Figure 11). This is due to the “homogenization” of the material in the direction of latewood layers.

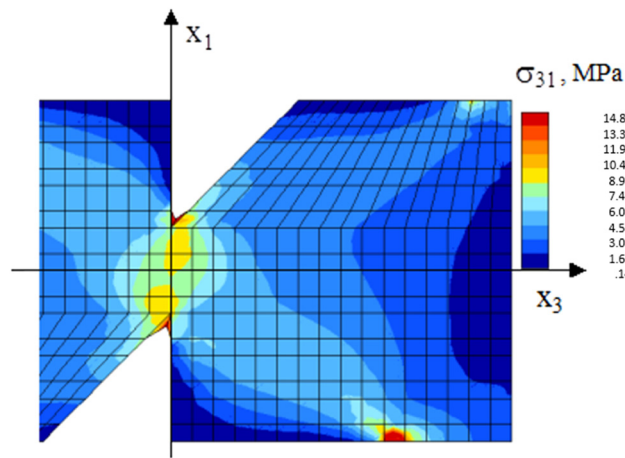
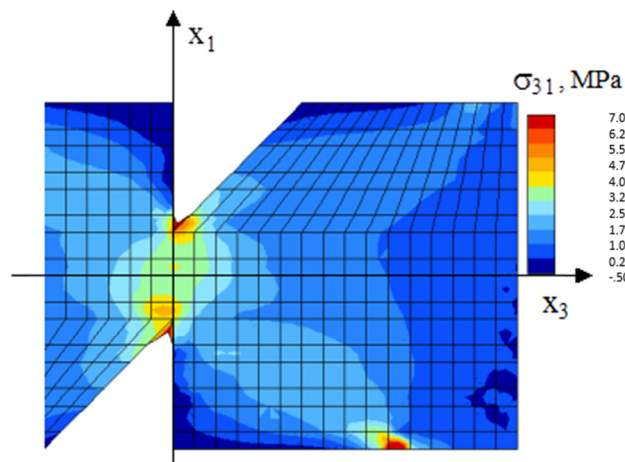
The loading of the sample was carried out by displacement of its edges in contact with the mobile blocks when inclined at  $\alpha$  relative to the axis of the sample. When the force in section  $x_3 = 0$ , calculated on the basis of the stresses, was equal to the value of the measured force, it was assumed that the resulting stress condition corresponded to the destruction of the sample. A comparison of the numerical values used in the calculation of the sample boundary displacement values and the measured values of these displacements pointed to degree of correctness of the calculation model applied. Figure 12a and b show the stress distribution in the analyzed section of the K0 and K35 wood samples, respectively (for  $\alpha = 0^\circ$ ). Stress distributions in the analyzed section of the sample for

**Table 2:** Parameters of elasticity of the layers of natural wood K0

Layers	$E_1 = E_2$ (GPa)	$E_3$ (GPa)	$G_{23} = G_{13}$ (GPa)	$G_{12}$ (GPa)	$\nu_{21} = \nu_{12}$	$\nu_{32} = \nu_{31}$	$\nu_{23} = \nu_{13}$
Soft	1.63	8.60	0.45	0.72	0.13	0.30	0.05
Hard	3.50	16.0	2.10	1.43	0.20	0.35	0.076

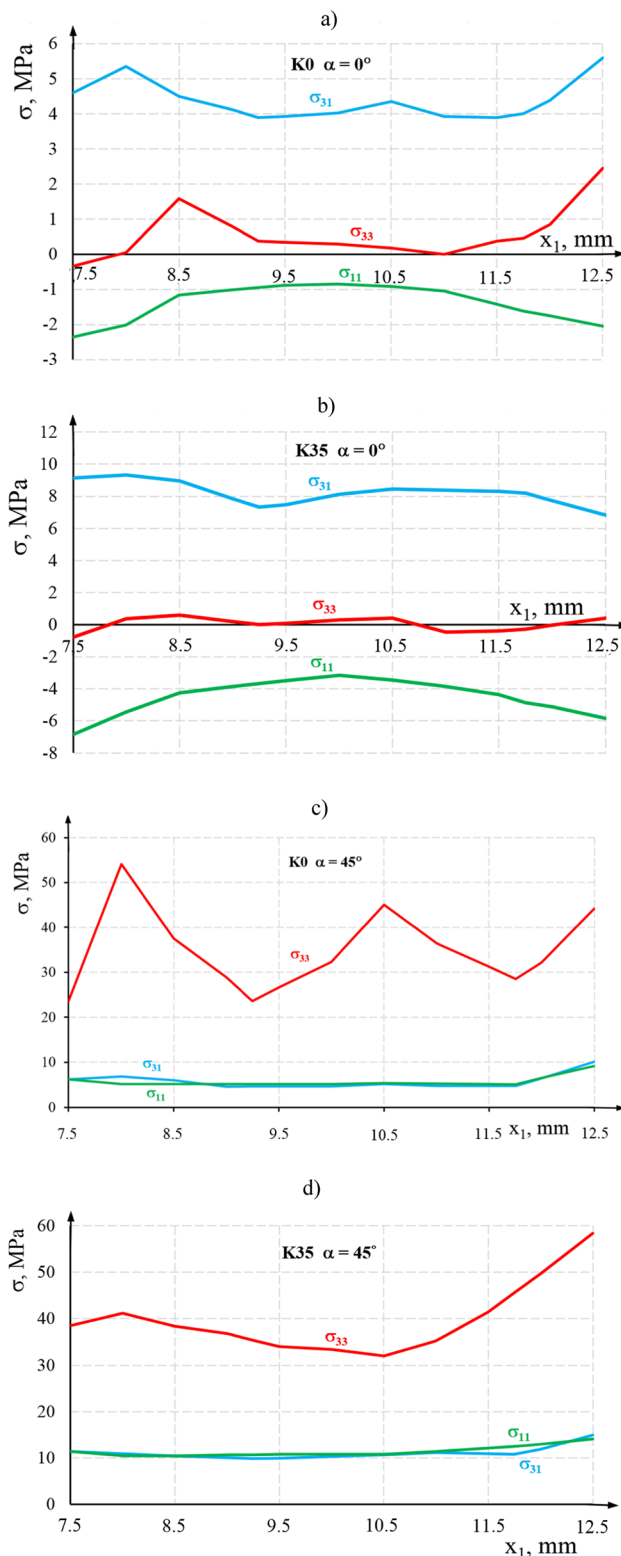
**Table 3:** Parameters of elasticity of the layers of modified wood K35

Layers	$E_1 = E_2$ (GPa)	$E_3$ (GPa)	$G_{23} = G_{13}$ (GPa)	$G_{12}$ (GPa)	$\nu_{21} = \nu_{12}$	$\nu_{32} = \nu_{31}$	$\nu_{23} = \nu_{13}$
Soft	2.61	15.04	1.19	0.78	0.08	0.31	0.05
Hard	3.68	16.04	2.12	1.57	0.11	0.32	0.078

**Figure 10:** Shear stress distribution  $\sigma_{31}$  in a selected area of the sample for K0 wood.**Figure 11:** Shear stress distribution  $\sigma_{31}$  in a selected area of the sample for K35 wood.

angle  $\alpha = 0^\circ$  corresponding to pure shear indicate that both natural and modified wood samples have a complex stress state. The highest values result in shear stresses  $\sigma_{31}$  at almost zero normal stresses, that is,  $\sigma_{33}$  and  $\sigma_{11}$ .

The nature of the stress distribution along the analyzed measurement section of the sample for natural and modified wood is different. The “sawtooth” nature of the stress distribution in the K0 sample section indicates a diverse load patterns of hardwood layers in relation to soft wood layers. In modified wood, the stress distribution is close to the state of equilibrium, as the values of the solid elasticity of the layers of soft and hard wood are similar. The modification of soft layers resulted in the “homogenization” of the material; therefore the curve indicates a more homogeneous distribution of stresses. On the other hand, Figure 12c and d for K0 and K35 shows the stress distribution in the analyzed section of the sample for an angle of  $\alpha = 45^\circ$  corresponding to the tensile/compressive instance. Different stress distribution occurs in the measurement section for both natural and modified wood. The highest stresses occur along the axis of the sample ( $\sigma_{33}$ ), the values of which significantly exceed the values of the shear stresses ( $\sigma_{31}$ ) and normal stress ( $\sigma_{11}$ ). In this case (tensile/compressive force), a very large variation of stresses is observed in the measuring section of the sample because tensile stresses predominate, and their strength along the fibers exceeds that observed for other directions. This is characteristic of anisotropic materials, for which the strength characteristics vary. The tangential stress distribution in the measurement section of a natural wood sample indicates a much higher loading of hardwood layers, compared with softwood. Numerical calculations have shown that, throughout the measurement section under analysis, the loading of natural wood is more than twice as high as in the identical measured section of modified wood. This result can be justified by the



**Figure 12:** Stress distribution in the measurement section of natural wood samples K0 and modified wood samples K35: (a and b)  $\alpha = 0^\circ$ ; c and d)  $\alpha = 45^\circ$ .

“homogeneity” of the material strain toward hard wood layers. In natural wood, the whole load is transmitted by hard layers whereas in modified wood both hard and soft layers have similar strength properties, resulting in an even distribution of stress in the tested section.

## 4 Conclusions

Studies have shown that natural wood exhibits very different layer strain compared to modified wood. Modified wood layers have similar strength properties. The adoption of the proposed geometry of the samples for shear testing on the tested materials showed that, throughout the measurement section under analysis, the strain of natural wood is significantly higher than in the identical analyzed measurement section of modified wood. The reinforcement of modified wood results from the “homogenization” of the material in the direction of latewood layers. The outer load shall be broken down into latewood layers and reinforced earlywood layers. The results of the study show that filling the wood structure with polymer causes homogenization of the material, resulting in similar average material values for early- and latewood.

A modified Iosipescu test apparatus was used to determine shear strength.

As a result, in its central part, apart from shear, tension/compression is also performed.

Transverse shear strength values were found to exceed the magnitude of previously published ASTM test results.

The authors think that the assumed geometry of the sample for testing on the wood wall allows obtaining shear strength values exceeding the values of previously published results.

The shear strength predicted by uniaxial tension tests should be treated as an approximate value despite the simplicity of the tension test.

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