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TENSION STRESS SIMULATIONS OF LAYERED WOOD USING A FINITE ELEMENT METHOD

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ABSTRACT

This article investigates the material thickness of the individual layer composition influence on the stresses under tension loading. The SolidWorks application was used for tension stress simulations. This simulated course of tensions was carried out for soft and hard materials as a function of their thicknesses. Hard material was represented by beech wood and soft material by aspen wood. Subsequently, the tensile stress and deformation of various two- and three-layered compositions of these materials were analyzed. Based on our results, the soft material was the weakest link; therefore, the ultimate tensile strength of the entire layered material is directly dependent on it. Hard material can withstand greater tensile stress and deformation without breaking, as soft material does.

KEYWORDS: Layered material, finite-element method, stress simulation, tension, deformation

INTRODUCTION

Wood has many specific characteristics which are sought after; on the other hand, it also has characteristics which need to be limited. The physical properties (shrinkage, swelling, and durability) of wood can be changed by means of impregnation or thermal treatment (Kvietková et al. 2015), whereas the mechanical properties (flexural strength, tensile strength, and pressure) are altered by laminating and densification, etc. Currently, the materials used in the woodworking industry are going through some changes. These changes relate mainly to improving the properties of the most widely used materials or the creation of new materials with specific properties. Layered (laminated) wood materials can be changed using a combination of non-wood materials or just by changing the individual layers.

Lamination is the technique of manufacturing a material from multiple layers, so that the final laminated material achieves improved strength, stability, appearance, or other properties from the use of differing materials. A laminated material is usually permanently created by heat, pressure, welding, and adhesives or their combinations, respectively. The laminating process is very important in industrial practice, both in civil engineering and the wood processing industry (Glos et al. 2004, Frese and Blaß 2006).

Prior to lamination, we need to know the properties of the individual layers or materials which will be used; this knowledge serves to ensure that the properties of the material which results from their being joined can be predicted, or a combination, respectively. There are many methods for modelling and simulation which allow deeper scientific knowledge, since they provide complex information about the materials. These methods provide a realistic behavior of the materials under various loading types (Fekiač et al. 2015, Gaff et al. 2015).

Solidworks is a 3D CAD design system intended for the widest range of industrial applications. It provides tools for modeling parts and assemblies and creates two-dimensional drawings (Vláčilová et al. 2007). SolidWorks is understandable enough for casual designers, but its computational power is appreciated the professionals thanks to simulations that can be done at the design stage to greatly reduce the number of prototypes needed while avoiding costly rework proposals. Simulations allow the model to analyze strength characteristics, durability, and cost; compare its variants; provide a prediction of failure and collapse; thermal and heat transfer analysis; effect of repeated loads; and more.

The finite-element method (FEM) is a method often used only in connection with the simulations, helping to evaluate the effects of various load forces and material properties. The FEM belongs to the most universal, most suitable, and most used numeric methods for the solution of engineering or field tasks. In this context, FEM is used for stress analysis using design tools (computer-aided design, or CAD) and simulation of mechanical systems (Benča 2006).

The main goal here was to determine the influence of various compositions of layered materials and of the thickness of the individual layers on the stress-strain course during tensile loading. The simulation of the course of stresses was accomplished by means of FEM.

MATERIAL AND METHODS

Materials

Beech and aspen wood species were selected to have the properties of their wood identified. Beech wood represented hard materials (H) while the properties of aspen were needed to represent soft material (S). European beech trees (*Fagus sylvatica* L.) as well as Eurasian aspen trees (*Populus tremula* L.) were harvested from the Javorie region, near the city of Zvolen, in the center of Slovakia. Beech and aspen wood was cut out to make specimens with the dimensions of 20 x 20 x 350 mm according to ISO 13061-6 (2014) (Fig. 1). Thirty specimens of each wood species were prepared for investigation.

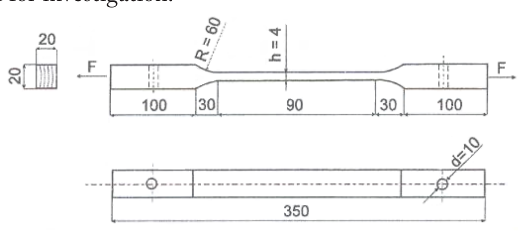

Fig. 1. Tensile strength specimen.

Subsequently, the specimens had to be conditioned to a prescribed equlibrium moisture content (EMC) of 12%. Conditioning was carried out using a conditioning chamber APT Line II (Binder, Germany), under the following conditions: relative air humidity (ϕ) = 65 ± 3% and temperature (t) = 20 ±2°C. Determination of moisture content was carried out according to ISO 13061-1 (2014).

The methodology for determining essential properties were identical to the previous work Gaff et al. (2015).

Methods

Tension

Tensile testing was carried out using a FPZ 100/1 machine (Heckert, Germany), according to ISO 13061-6 (2014). The test specimens were placed between the vises (loading force acted in a parallel direction with respect to the length of the specimen) and loaded until breaking occurred. An ALMEMO 2690-8 datalogger (Ahlborn, Germany), connected directly to a laptop, recorded all values of loading tensile force.

Measurements

The tensile strength and modulus of elasticity were calculated from values of loading force obtained by the datalogger. Shear strength values were calculated according to ISO 3347 (1976) in preliminary tests.

For the calculation of density and moisture content, a digital caliper 500/150/20 determined dimensions and weight of specimens (Mitutoyo, Japan).

Calculations and evaluation

The tensile strength parallel to the grain was calculated according to ISO 13061-6 (2014) and Eq. 1,

$$\sigma_t = \frac{F_{\max}}{bh} \tag{1}$$

σ_t - ultimate tensile strength of wood (MPa), F_{max} - maximum force (N), b - width of the specimen in narrowed part (mm), h - thickness of the specimen in narrowed part (mm).

The ultimate shearing strength parallel to the grain was calculated according to ISO 3347 (1976) and Eq. 2,

$$\tau_s = \frac{F_{\max}}{bh} \tag{2}$$

τ_t - the ultimate shearing strength of wood (MPa), F_{max} - the maximum force (N), b - the width of the specimen (mm), h - the thickness of the specimen (mm).

Density was calculated according to ISO 13061-2 (2014) and Eq. 3,

$$\rho = \frac{m}{hbl} = \frac{m}{V} \tag{3}$$

ρ - density of the specimen (kg·m^{-3}), m - mass (weight) of the specimen (kg), h, b, l -the height, width and length (m), V - the volume of the specimen (m^3).

The moisture content was calculated according to ISO 13061-1 (2014) and Eq. 4,

$$w = \frac{m_w - m_0}{m_0} * 100 \tag{4}$$

w - moisture content of the specimens (%), m_w - mass (weight) of the specimen at certain moisture w (kg), m_0 - mass (weight) of the oven-dry test specimen (kg).

An oven-dry state was determined according to the ISO 13061-1 (2014) standard.

Simulation

Based on the identified properties of beech and aspen wood, we have defined the input density and mechanical properties of hard and soft materials by means of software SolidWorks®. All necessary characteristics, such as moduli of elasticity, Poisson's ratio in a transverse plane, and tensile strengths as well as shear strengths, were recalculated to 12 % moisture (Tab. 1).

Tab. 1. Properties of materials.

Properties of wood	Beech	Aspen
Density (kg·m^{-3})	700	460
Modulus of Elasticity (MPa)	16,750	10,700
Poisson's Ratio TR	0.394	0.496
Tensile Strength Parallel to Grain (MPa)	135.0	108.0
Shear Strength Parallel to Grain (MPa)	14.5	7.7

The first step involved a simulation of hard and soft material with different thicknesses 2, 4, 6, 8, 10, 12, 14, 16, 18, and 20 mm (Fig. 2).

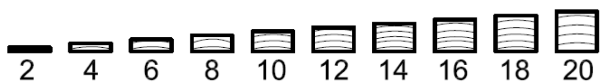

Fig. 2. The model material creation with the thickness increase by 2 mm.

In the next step, different combinations of these materials were created. The rule was - constant thickness of the first material and thickness increasing in 2 mm for the the second material. This way, combinations were created according to Fig. 3, Fig. 4 and Fig. 5.

In this way, the following combinations were created:

1. Two-layer combination of **hard (H) and soft (S)** materials with the **constant thickness of hard material** (Fig. 3).

Fig. 3. Hard material with constant thickness placed on the upper side of layered material.

2. Three-layer combinations of hard and soft material; in first case, **the hard material (H) had constant thickness** (1st alternative) (Fig. 4) and in second case, **the soft material (S) had constant thickness** (2nd alternative) (Fig. 5).

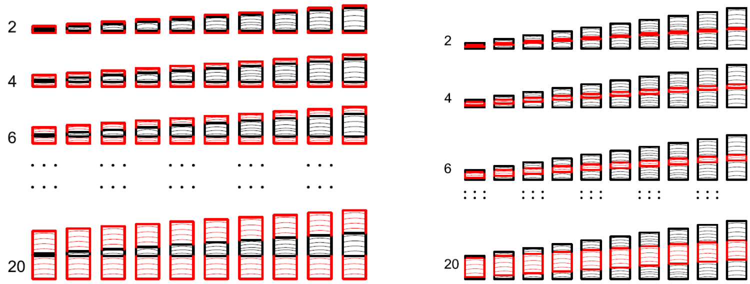

Fig. 4: Principle of combination of hard and soft materials with constant thickness of hard material.

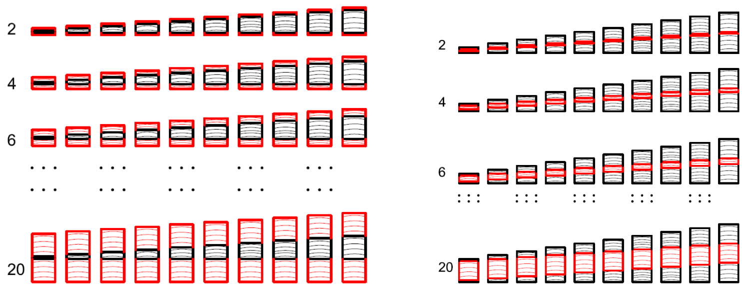

Fig. 5: Principle of combination of hard and soft materials with constant thickness of soft material.

Simulation of tensile stresses and the deformations was divided into the following steps, in accordance with the earlier work of Gaff et al. (2015):

1. The creation of 3-D models in SolidWorks 2009 software.
2. Identifying and calculating of material properties.
3. The creation of finite element mesh and determination of loading forces.
4. Simulation of tensile stresses using the CosmosWorks 2009 application.
5. Final evaluation of results.

A stress-strain curve was created from the average values. We subsequently used this curve for model simulation in SolidWorks® application. In this way, the model curves for both hard and soft wood species were created.

SolidWorks use X, Y, and Z axes of the global Cartesian system. For our analyses, the mesh of volume tetraedric elements was used (Fig. 6) (Gaff et al. 2015).

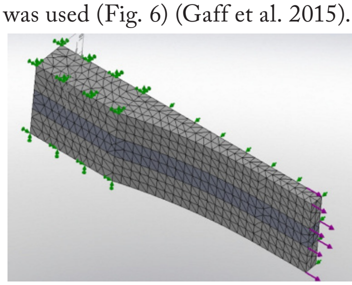

Fig. 6. Finite element mesh on model

A comparison of the reference (real) curves generated from the measurements and the model curve from the simulation is shown in Fig. 7.

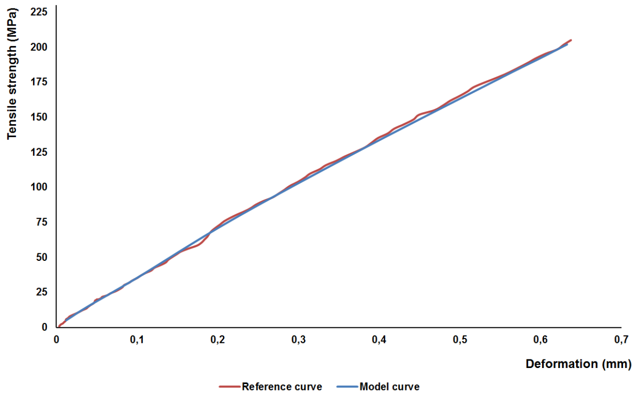

Fig. 7: Comparison of reference and model curves for hard material (H).

The difference between these two curves is small. This fact confirms the correctness of the simulation. The values of model and the real specimens are shown in Tab. 2.

Tab. 2: Comparison of reference and model specimen.

Reference specimen			Model specimen		
Tensile strength (MPa)	Limit of proportionality (MPa)	Deformation (mm)	Tensile strength (MPa)	Limit of proportionality (MPa)	Deformation (mm)
205.125	130	0.6375	202.06	130	0.63

RESULTS AND DISCUSSION

Fig. 8 shows the tensil stress-deformation curve as a function of the soft material **(S)** thickness. After evaluation of the results it was found that the material has always been broken in the same place, namely at approximately 101 MPa and 0.53 mm deformation. The proportionality limit was found at 70 MPa. From this comparison, it can be concluded that the resulting curves, which characterize material property, not depend on the thickness. Basically, when we define soft material so that the ultimate strength should be occur upon reaching 100 MPa and deformations of 0.5 mm, so when reaching these boundary conditions the rupture occurs.

In Fig. 9, the course of the curves for the individual single-layer hard materials can be seen. The graph shows a certain difference from the other thicknesses. It is assumed that the curve of the weakest or the strongest ones can be varied. In this case it did not happen, because the variation from the other curves occurred in the case of thicknesses 6 and 8 mm. For other thicknesses (2, 4, 10, 12, 14, 16, 18, and 20) the ultimate tensile strength of was found between 205 MPa at a deformation of 1 mm and the proportionality limit of 120 MPa. At thicknesses 6 and 8, the ultimate tensile strength was 205 MPa at 0.9 mm deformations and proportionality limit of 130 MPa.

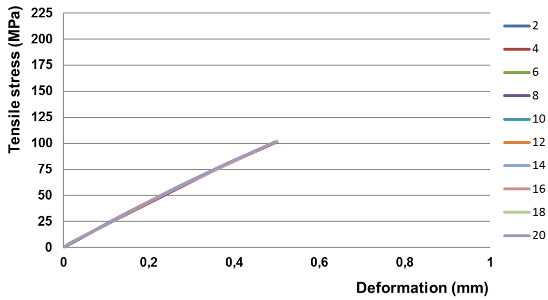

Fig. 8: Tension vs. deformation curve at various thicknesses of soft material.

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The ultimate tensile strength of 205 MPa is a relatively high value, far in excess of average values of strength in the beech, which are around 120 MPa. According Kúdela (1999) beech wood can achieve such high tensile strength values but only in case if it is a tension wood (he found ultimate tensile strength parallel to the fibers at 190 MPa for the tension beech wood) or if wood has been cut from a tree with a high density.

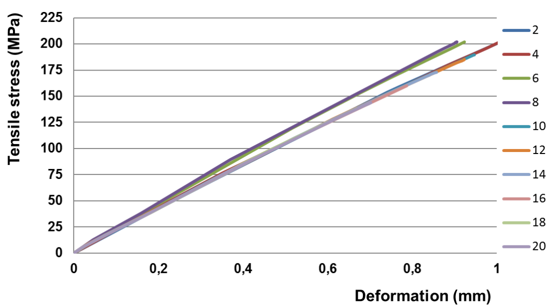

Fig. 9: Tension vs. deformation curve at various thicknesses of hard material.

The two- and three-layer compositions of soft and hard materials were evaluated in a similar way. In these samples, the hard material had constant thickness. With the gradual increase in the thickness of 2 mm, it can be assumed that the samples acquired new properties, but it is not so. During the evaluation of the results it was found that deviations of deformations and stresses are very small. Therefore, the selection was carried out, wherein we have chosen specimens that characterize a particular group. Combinations 6-2, 6-8, 6-14 and 6-20 were selected for the two-layer material (Fig. 10).

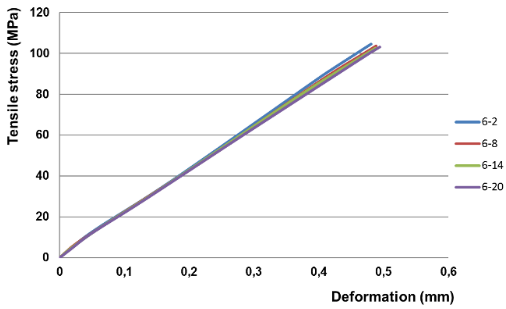

Fig. 10. Stress-deformation curve for two-layer composition with 6-mm constant thickness of hard material

Samples achieved little variability of properties. Basically, it confirms the case of single-layer materials, i.e., individual thicknesses had almost identical simulation results. Based on the results it can be concluded that ultimate strength is determined by the weakest link in composites, i.e., by soft material. Laminate also acquires properties as the weakest link in the system.

Figs. 11 and 12 shows the distribution of stresses and the deformations in the components-layered material. Previous assertions that the hard material can withstand higher stresses at the same deformation as a soft material also applies in this case. Achieving a better synergistic effect in both materials would be necessary to design a soft material so that, at a lower stress, it is able to deform more. The combination of thus modified materials could achieve more interesting results (Fig. 11). Due to large amount of results, just a combinations with 6-mm constant thickness is shown

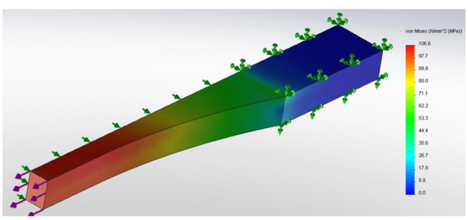

Fig. 11: The distribution of stresses in two-layer material, combination 6 - 8 (H – S)

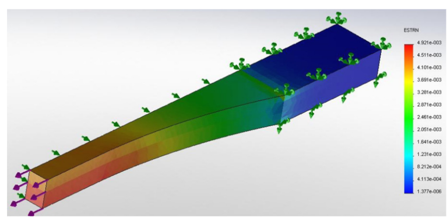

Fig. 12: The distribution of deformations in two-layer material, combination 6 - 8 (H – S)

Based on the previous arguments, three-layer materials can be considered as an analogy for two- and single-layer materials. Fig. 13 shows the behavior of the three-layer materials in terms of stress-deformation diagram. There was also an analogy and a some consensus with the previous characteristics of materials, but in contrast to the single and double-layer material, the three-layer material had significant increase in the ultimate tensile strength. Without the visual comparison, it may be presumed that the third layer affected the material properties, but not to an extent that it could be considered to significantly improve the mechanical properties.

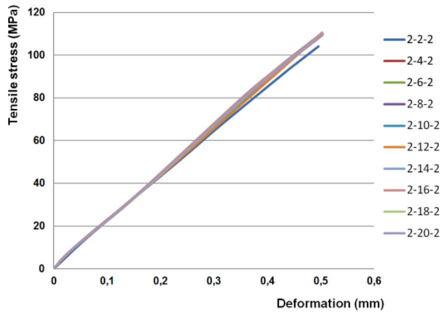

Fig. 13: Stress-deformation curve for three-layer composition with 2-mm constant thickness of hard material.

Fig. 14 shows that higher stress occurred in upper (hard) layers of material composition H-S-H. When compared to Figs. 14 and 15 it can be seen that the top layers are less deformed as central layers. It follows that material system is actually behaving according the weakest link, as stated in previous cases.

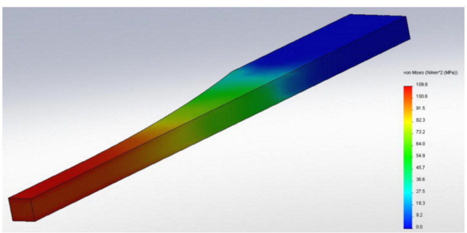

Fig. 14: The distribution of stresses in three-layer material, combination 2 - 4 - 2 (H - S - H).

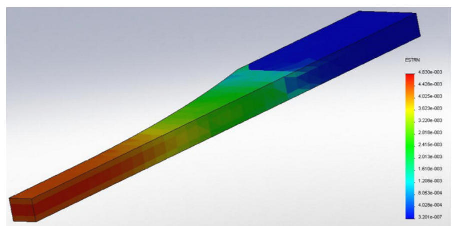

Fig. 15. The distribution of deformations in three-layer material, combination 2 - 4 - 2 (H - S - H).

When comparing the opposite combination of materials where the top layers are from soft material, combination (S-H-S) (Fig. 16), it was found that previous assertions are also applicable to this case. These assertions were confirmed by graphic and visual comparison. Breaking of the samples occurred around 105 MPa and at deformation of 0.5 mm.

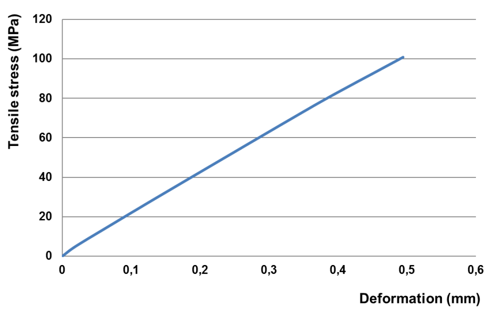

Fig. 16: Stress-deformation curve for three-layer composition with 4-mm constant thick top and bottom layers of hard material and 12-mm thick middle layer (S - H - S).

Comparing the graphs in Figs. 17 and 18 we can see that there is greater stress in a hard layer.

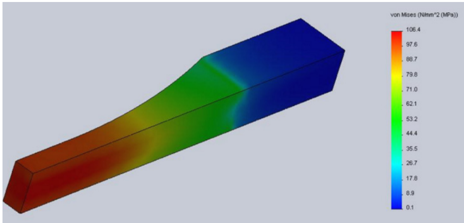

Fig. 17: The distribution of stresses in three-layer material, combination 4 - 12 - 4 (S - H - S).

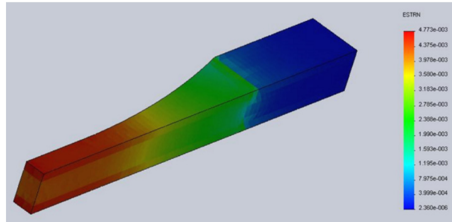

Fig. 18: The distribution of deformation in three-layer material, combination 4 - 12 - 4 (S - H - S)

Fig. 18 shows that a greater deformation was again achieved in soft materials in comparison with hard, i.e., there was a first infringement of samples in both soft layers. Despite the fact that we changed the order of layers as well as the thickness ratio, a change reaffirmed previous statement.

CONCLUSIONS

1. The soft material resisted lower tensions at the same deformation than the hard one; while for the hard material, the tension was greater for identical deformation as in the case of soft material.
2. The soft material achieved its deformation maximum value when the material was broken; while the hard material was able to bear even greater deformation, it was limited by weaker soft material.
3. The weakest layer of the composite defines the ultimate tensile strength of layered material.

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REFERENCES

1. Benča, Š., 2006: Výpočtové postupy MKP pri riešení lineárnych úloh mechaniky (FEM calculation procedures for solving linear mechanics problems), Monograph, Slovak Technical University, Bratislava, 150 pp.
2. Fekiač, J., Zemiar, J., Gaff, M., Gáborík, J., Gašparík, M., Marušák, R. 2015: 3D-moldability of veneers plasticized with water and ammonia, BioResources 10(1): 866-876.
3. Frese, M., Blaß, H. J., 2006: Characteristic bending strength of beech glulam, Materials and Structures 40(1): 3-13.
4. Gaff, M., Gašparík, M., Borůvka, V., Babiak, M., 2015: Simulating stresses associated with the bending of wood using a finite element method, BioResources 10(2): 2009-2019.

5. Glos, P., Denzler, J. K., Linsenmann, P., 2004: Strength and stiffness behaviour of beech laminations for high strength glulam, Proceedings of the Meeting 37 CIB Working Commission W18-Timber Structures, paper CIB-6.
6. ISO 13061-1 - 2014: Physical and mechanical properties of wood -- Test methods for small clear wood specimens -- Part 1: Determination of moisture content for physical and mechanical tests
7. ISO 13061-2 – 2014: Physical and mechanical properties of wood -- Test methods for small clear wood specimens - Part 2: Determination of density for physical and mechanical tests.
8. ISO 13061-6 – 2014: Physical and mechanical properties of wood - Test methods for small clear wood specimens - Part 6: Determination of ultimate tensile stress parallel to grain.
9. ISO 3347 – 1976: Wood-Determination of ultimate shearing stress parallel to grain.
10. Kvietková, M., Barcík, Š., Aláč, P., 2015: Impact of angle geometry of tool on granulometric composition of particles during the flat milling of thermally modified beech, Wood Research 60(1): 137-146.
11. Kúdela, J., 1999: Pevnosť reakčného bukového dreva pri rôznych spôsoboch zaťaženia (Strength of beech tension wood corresponding to various modes of loading), Proceedings of the Wood – Structure and Properties, Zvolen, Slovakia. Pp 53 – 60 (in Slovak).
12. Vláčilová, H., Vilímková, M., Hencl, L., 2007: Základy práce v CAD systému SolidWorks (The basics of working of CAD system SolidWorks), Computer Press a.s. Brno, Czech Republic, 319 pp.

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