Influence of the Number of Layers on the Strength of Beech Laminated Elements in the Three-Point Flexural Test

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A chair is a piece of furniture whose elements are loaded with relatively high forces. The strength of these elements is vital for the safety of using this type of furniture. The research aims to test the chair material system made of beech wood. The authors analyzed laminated elements with 9, 11, and 13 layers of veneers. The veneers were 1.23 mm thick, with perpendicular fiber directions in adjacent layers, and bonded with 220 g/m^2 of PVAc adhesive. The moisture content of the elements was 6 ± 1%. A three-point bending flexural test was performed to determine the stress-strain response of the tested three variants. A complementary numerical analysis allowed a more precise comparison of the three analyzed laminated elements variants. It was confirmed that all variants exceed the desired minimal values in chair support design. Moreover, the average strength values for tested laminated elements, differing in the number of veneers, were sufficient even with a reduced number of veneer layers. The experiments and numerical analysis results confirmed the usability of the three tested types of beech laminated elements to be used as highly loaded chair elements.

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INTRODUCTION

For functional furniture as chairs, the strength quality is important because the chair must support the users weight. The sizes and shapes of parts creating the furniture frames should be rationally designed, as they should carry the required loads imposed upon them in service. In strength furniture designing, analyzing the forces and moments acting to the ends of each part can be used to calculate the internal stresses, and by comparing their values with the allowable design stresses for the material used, it can be seen whether each of the parts has been appropriately designed (Bekhta *et al.* 2009). In this way, furniture is designed that meets specific requirements and is not oversized (Ceylan *et al.* 2021).

When designing the chair construction, the fact that the load investigated is more static than dynamic must be considered. Static and cyclic loading are common types of loading during furniture strength testing. Static loading could be performed relatively fast, it does not precisely represent the service loads for seating furniture (Likos *et al.* 2013). Load-bearing capacity is one of the best ways to assess chair quality. The load-bearing capacity is the maximum force or weight allowed for a specific object without an unacceptable risk of failure. In terms of furniture or chair, it refers to the maximum weight that the chair can support without inflicting damage on the chair or causing harm to the user.

Molded chair laminated elements made from glued European beech veneers are composite wood materials and represent a standard design solution for modern chairs worldwide. They provide a pleasant slim appearance and comfort for chairs, and they are always ergonomically molded, creating favorable seating conditions. They are molded plywood materials whose production has continuously increased with the growth of seating furniture manufacturing (Irle *et al.* 2013). Laminates are made from laminated veneers, similar to plywood. Different from plywood, the fiber direction of veneers is in the same direction (Thoemen *et al.* 2010). Therefore, the lamellas are very flexible, and they do not break when stressed. Their top veneers must be free from cracks and other defects (Ritschel *et al.* 2013; Gumowska *et al.* 2018). Lamellas are used for particular purposes: for seats, load-bearing constructions of seating furniture, flexible bed slats, and other. An example of the use in the construction of a chair is shown in Fig. 1. Such elements are bent and can be loaded with relatively high forces.

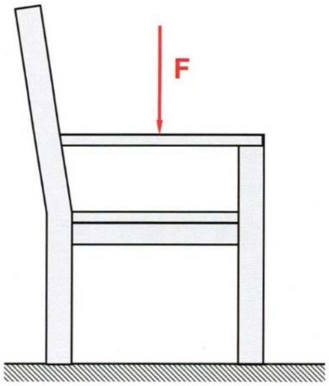


Fig. 1. Structure of the chair with the lumbar support made from molded laminated elements

Through veneer layer application on the element base, there arise the conditions to form a variety of molds replaced by other technologies only with difficulties. Laminated products made of veneers allow efficient use of wood resources with a relatively low percentage of waste and, thus, a high yield. The adjacent layers of veneers, with wood grains, rotated up to 90° to one another, and wood adhesives make the lamellae have different properties compared with the natural wood. Their machining is more complex (Sydor *et al.* 2020), and their load-bearing capacity is greater (Branowski *et al.* 2018).

The paper aims to investigate the effect of the sheer tensile strength of molded beech lamellas on the stability of the material used to manufacture chairs.

EXPERIMENTAL

Materials

Testing the tensile strength of the laminated elements outer layers loaded in the three-point bending flexural test is based on determining the maximum force applied perpendicular to the longitudinal plane of the laminated element. The tensile stress in the lower layer limits the material strength. Destruction of the sample is manifested by cracking of the lower stretched layer.

Laminated elements with various structures used in this research were purpose-manufactured in standard industrial operation. After typical hydrothermal processing, the beechwood (*Fagus sylvatica* L.) logs were rotary peeled with KSB peeling machine. The 600 × 500 mm veneer sheets were made with rotary peeling with a 4-ft lathe KSB (Královopolská Strojírna, Brno, Czech Republic) at the Technical University in Zvolen, Slovakia. The selected veneer, free of knots and cracks with an average thickness of 1.23 mm were dried and conditioned to 6 ± 1% moisture content and used for plywood assembling. The fiber direction in the adjacent veneers during plywood assembling was parallel. The PVAc adhesive Rakoll ® E WB 0301, with a viscosity of 5500 mPas and pH of 3.5 with good water resistance, was used to bond veneers into the laminated elements (H.B. Fuller Deutschland GmbH, Nienburg/Weser, Germany). Two-roller adhesive spreader was used, and the adhesive was deposited on both sides of every second veneer (the adhesive deposit was 220 g/m^2). Plywood was pressed in a hydraulic press in a compression mold corresponding to the respective laminated elements shape. The pressure was 0.8 N/mm^2, and the pressing time was 30 min at 20 °C. After their stabilization, the plywood was cut into the furniture elements with desired sizes with a saw blade mounted on the lower vertical axis shaft. Their stabilization time was 120 h. Subsequently, the lamellas were sanded using a belt sander with P-80 paper (primary sanding) and then with P-120 and P-150 papers (over-sanding).

Frame structure of the chair members is shown in Fig. 1. The structure of the chair members was the same in all cases.

Fig. 2. The frame structure of the chair members

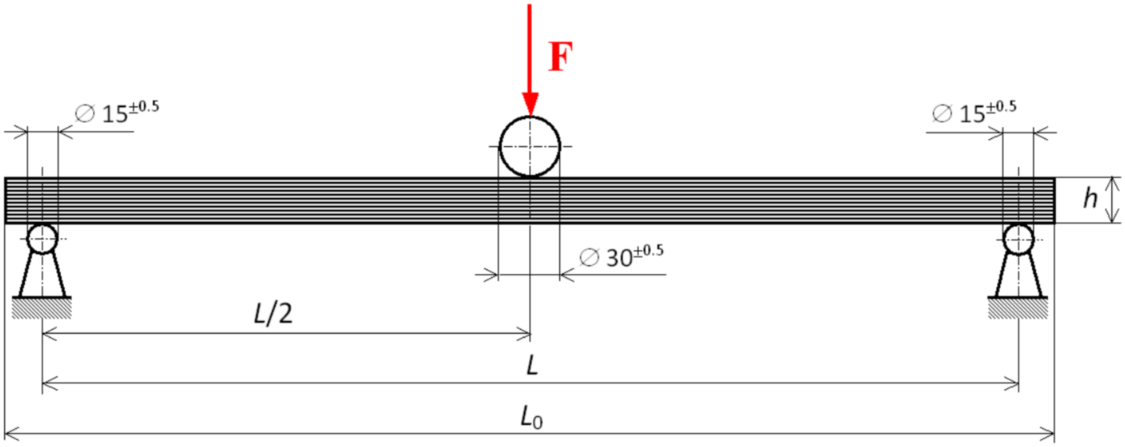
The following series of lamellas were manufactured:

1. Series A, 6 pieces of laminated elements made of 9 glued beech veneers, each with an average size 600 × 50 ×11.03 mm^3 (length × width × thickness),

2. Series B, 6 pieces of laminated elements made of 11 glued beech veneers (600 × 50 ×13.53 mm^3),
3. Series C, 6 pieces of laminated elements made of 13 glued beech veneers (600 × 50 ×15.99 mm^3).

The conditioning of the laminated elements was completed at a temperature of T = 20 ± 2 °C and a relative air humidity of φ = 65 ± 5%. The average moisture content of the samples from the laminated elements after conditioning was 10.4% (A series), 10.6% (B series), and 11.7% (C series).

The test samples were extracted from the flat lamella zones. A total of 12 rectangular samples with 50 × 50 mm^2 dimensions were made from each lamella series. The samples were bonded between two metal clamping fixatives. The surfaces of the samples were machined to ensure the perfect bonding and a mutual perpendicularity of the sample layers with tensile strength. All steps in the experiment were completed under laboratory conditions at the Technical University in Zvolen. The flatwise bending and bending strength test was performed according to EN 310 (1993). The universal testing machine had a jig that consisted of two parallel supports of a cylindrical shape that could be moved in a horizontal plane. In the center of the supports it had a load mandrel moving in a vertical plane. The test machine has a measuring device that recorded the measured values. For all testing samples, mechanical tests were conducted using a TIRA 2200 Heckert Testing Machine (Schalkau, Germany). The scheme of bending in three-point bending flexural test is shoved in Fig. 2.



$$L = L_0 - 50 \text{ mm};\ 150 \text{ mm} \le L_0 \le 1050 \text{ mm};\ 100 \text{ mm} \le 20h = L \le 1000 \text{ mm}$$

Fig. 3. Indicative scheme of bending according to EN 310 (1993)

RESULTS AND DISCUSSION

The mechanical properties calculated based on the experiment results are presented in Table 1.

Table 1. Mechanical Properties of Lamella Structure – Beech (Moisture Content 12%)

Parameter	Value		
Modulus of Elasticity (GPa)	$E_x \approx E_L = 16.67$	$E_y \approx E_R = 1.13$	$E_z \approx E_T = 0.63$
Shear Modulus (GPa)	$G_{xy} \approx G_{LR} = 1.2$	$G_{yz} \approx G_{RT} = 0.19$	$G_{xz} \approx G_{LT} = 0.93$
Poisson Ratio (-)	$\mu_{xy} \approx \mu_{LR} = 0.044$	$\mu_r \approx \mu_{RT} = 0.33$	$\mu_{xz} \approx \mu_{LT} = 0.027$
Bending Strength (MPa)	$n_v = 9$	$f_{b,0,k} = 102.76$	$f_{b,0,d} = 90.43$
	$n_v = 11$	$f_{b,0,k} = 93.37$	$f_{b,0,d} = 82.17$
	n_v 13	$f_{b,0,k} = 84.41$	$f_{b,0,d} = 74.28$

(Langová *et al.* 2013)

Proposed values of the bending strength related to the beech veneer structure mentioned in Table 1 are presented using Eq. 1,

$$f_{b,0,d} = k_{\mathrm{mod}} \frac{f_{b,0,k}}{\gamma_M} \tag{1}$$

where $f_{b,0,k}$ is a characteristic value of the bending strength of lamella structure, γ_M is the partial safety coefficient (for lamella structure $\gamma_M = 1.25$ (Manual IStructE 2007; Harris *et al.* 2007), k_{mod} is the modification factor (for bonded lamella structure $k_{\mathrm{mod}} = 1.1$).

The condition for the lamellar structure not to suffer damage in the form of a loss of integrity in the veneer structure is that the tensile stress $\sigma_{b,0}$ in the lower veneer arising from the bending of the lamella structure does not exceed the proposed values $f_{b,0,d}$, *i.e.*, it must follow $\sigma_{b,0} \leq f_{b,0,d}$.

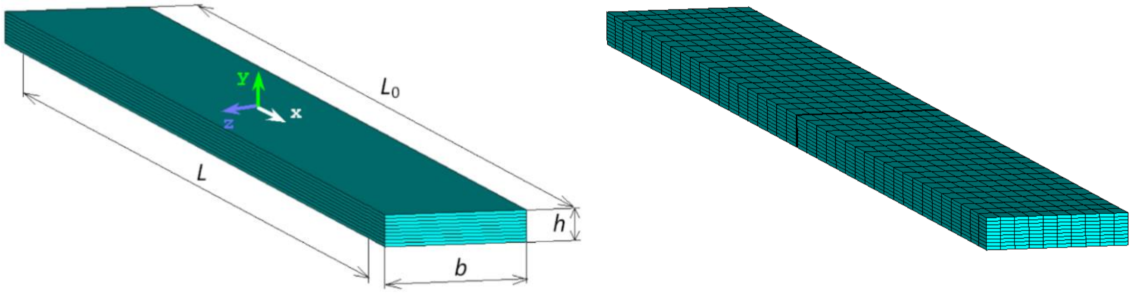
Simulation of the lamella structure loading with various numbers of lamellas was completed using the finite-element method by the Ansys software (Ansys Inc., Release 18.2, Canonsburg, PA, USA). The computational model meets the standard EN 310 (1993) (Fig. 2). Dimensional parameters and sample structure used for computational simulation are summarised in Table 2.

In the FE analysis, the beech veneer's mechanical properties comply with the fiber direction of the beech veneer used. The values of modulus of elasticity, shear modulus, and Poisson ratio were established according to the coordinate axes of the model and with the corresponding fiber directions of the laminated element structure, specified in Table 2.

Table 2. Sizes and Structure of the Model Used in Numerical Simulations

Sample Length	Sample Width	Distance of Supports	Thickness of Veneer	Number of Veneers	Thickness of Lamella
L_0	b	$L = L_0 - 50$ mm	h_i	n_v	$h_{n_v} = \sum_{i=1}^{n_v} h_i$
(mm)	(mm)	(mm)	(mm)	(-)	(mm)
600	50	550	1.23	9	11.07
				11	13.53
				13	15.99

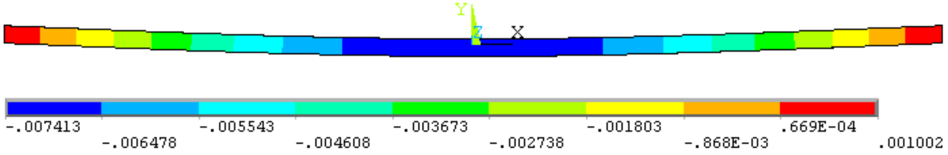
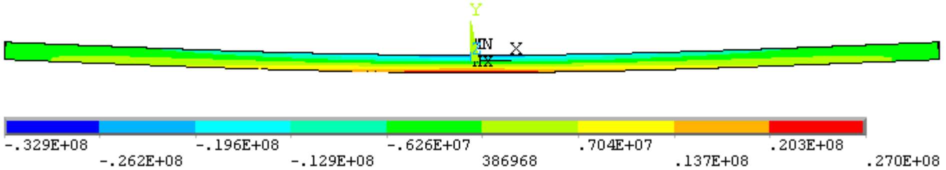
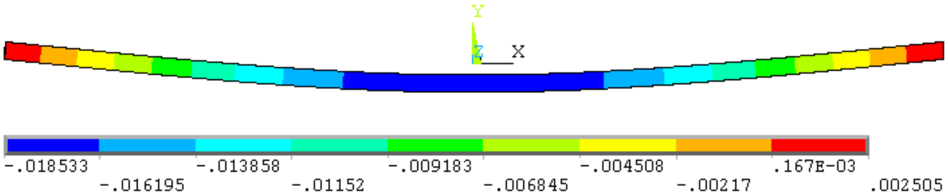
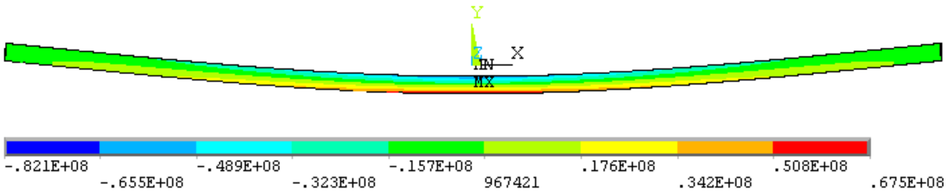
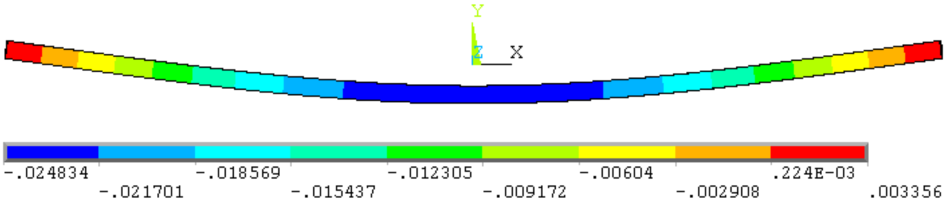
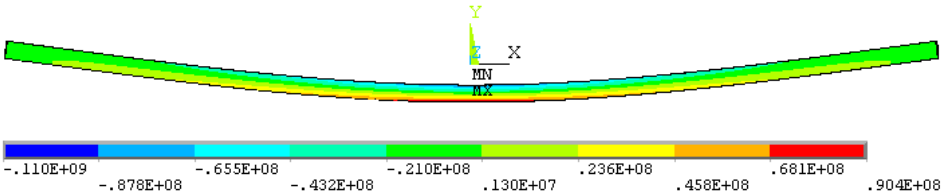
The size of the lamella model and finite-element model are illustrated in Fig. 4.



a) **b)**

Fig. 4. Model of analyzed lamella (a – sizes; b – finite-element model)

Table 3. Stress and Strain of the 9 Veneers Laminated Element

F (N)	Number of Veneers $n_v = 9$	
200	u_y (m)	
	σ_x (Pa)	
500	u_y (m)	
	σ_x (Pa)	
670	u_y (m)	
	σ_x (Pa)	

The FE model of the laminated element structure was gradually loaded with force (Fig. 2b) to meet the condition of the experimental testing (Fig. 1). For each force value, the strain u_y and tensile stress $\sigma_{b,0,max}$ in the lower veneers were computed (Tables 3, 4, and 5). Maximum bending of specific laminated element structure arising during loading is determined in the case when the value of the tensile stress of the lower lamella structure is $\sigma_{b,0,\max} = f_{b,0,d}$.

Table 4. Stress and Strain of the 11 Veneers Laminated Element

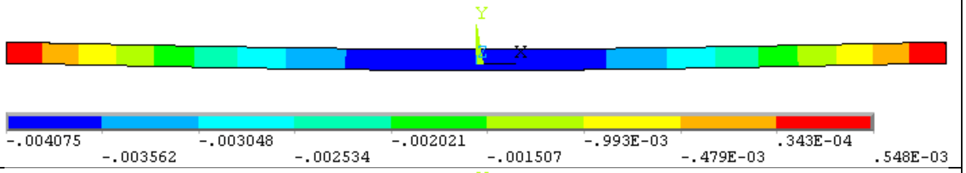
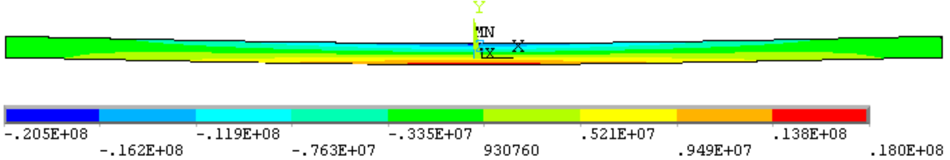
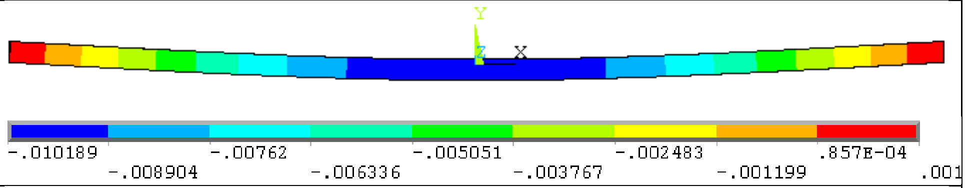
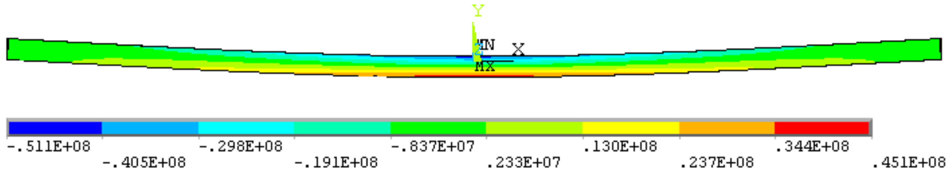
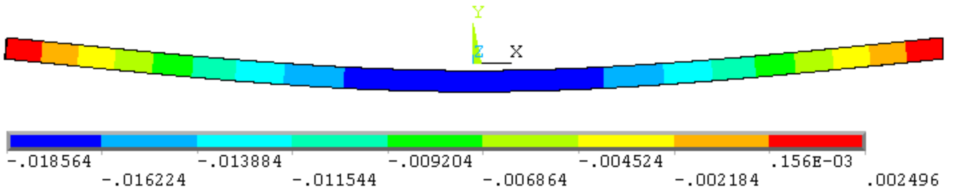
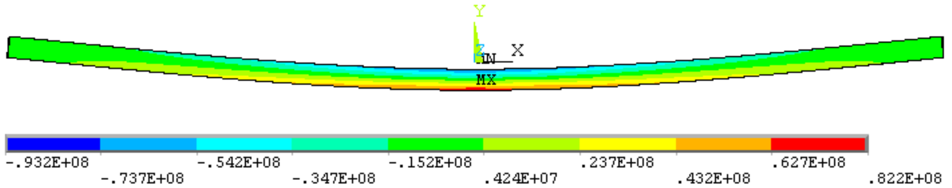
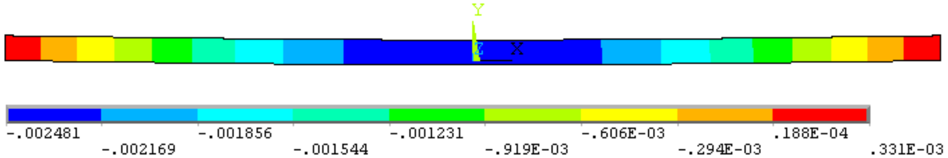
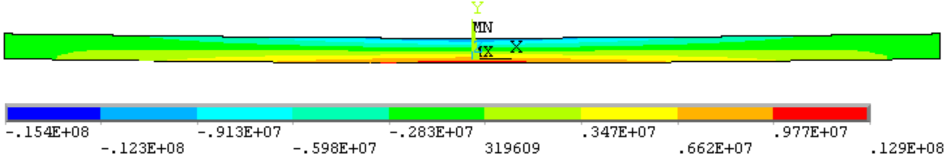
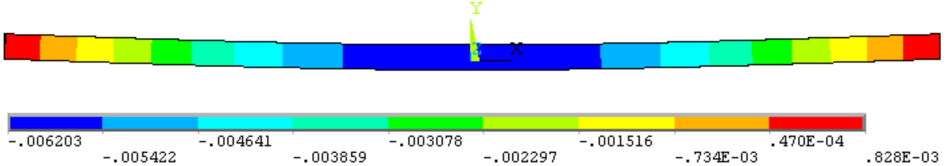
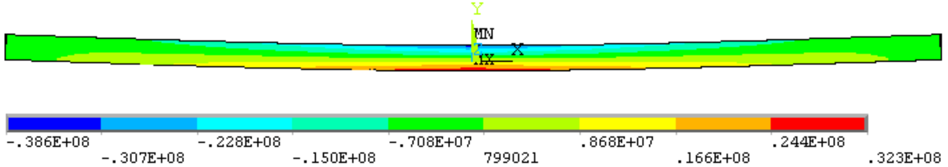
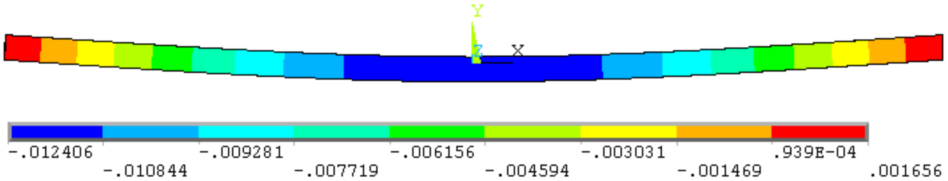
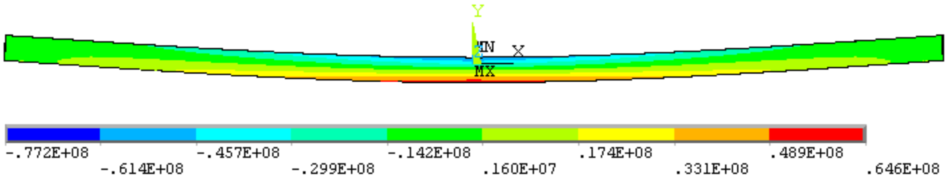
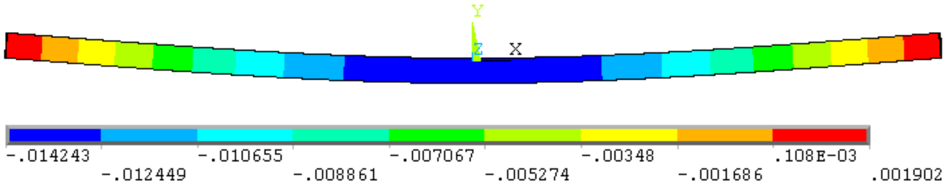
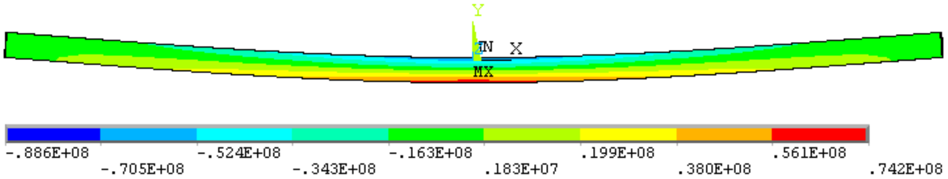
F (N)	Number of Veneers n_v = 11	
200	u_y (m)	
	σ_x (Pa)	
500	u_y (m)	
	σ_x (Pa)	
911	u_y (m)	
	σ_x (Pa)	

Figure 4 shows a mutual comparison of bent laminated element variants (with 9, 11, and 13 veneers), concerning the maximum tensile stress value in the lower veneer. The distribution of tensile stress across the thickness of designed laminated elements structures at the point of maximum tensile stress resulting from their bending is given in Figs. 5, 6, and 7. Maximum ultimate tensile stress ($\sigma_{b,0,max} = f_{b,0,d}$) in the lower veneers caused by the bending of individual structures were designed following Langová *et al.* (2013) and their values are mentioned in Table 2 (strength characteristics). Since the bending quality also depends on the density of the laminated element samples, it is important to note that the laminated elements produced were on average density 780 to 810 kg/m^3.

Table 5. Stress and Strain of the 13 Veneers Laminated Element

F (N)	Number of Veneers n_v = 13	
200	u_y (m)	
	σ_x (Pa)	
500	u_y (m)	
	σ_x (Pa)	
1000	u_y (m)	
	σ_x (Pa)	
1148	u_y (m)	
	σ_x (Pa)	

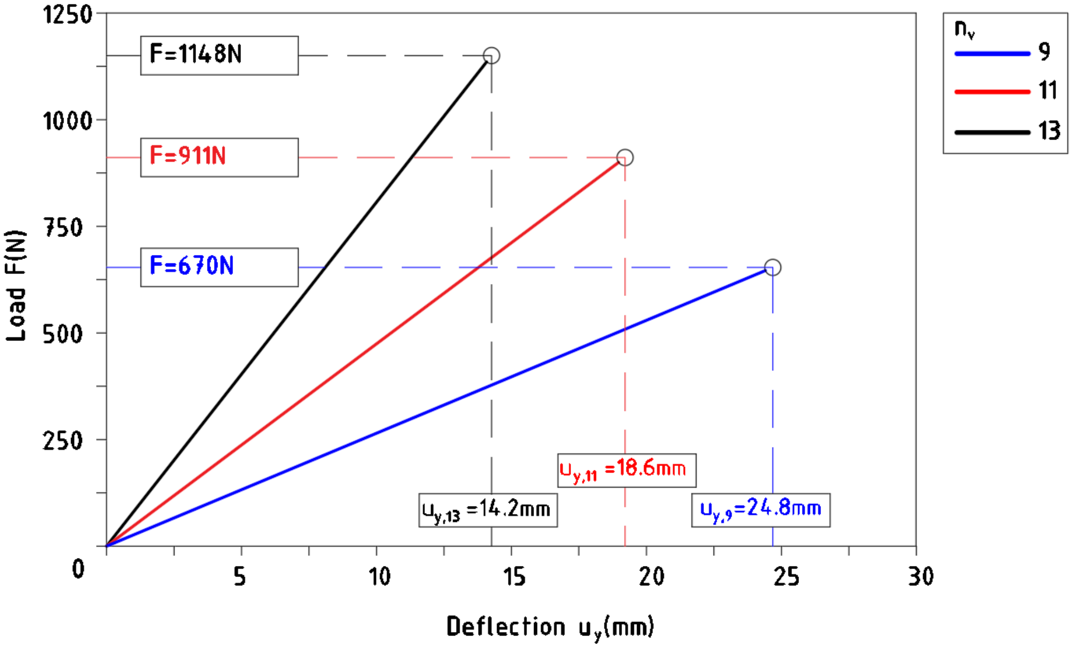


Fig. 5. Bending of three FE models

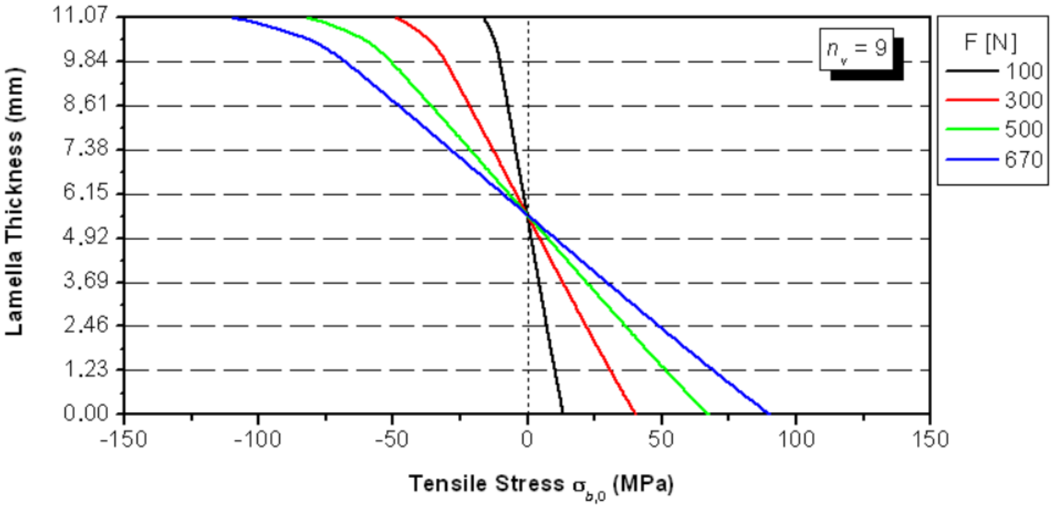


Fig. 6. Distribution of tensile stress (in the fiber direction) across the thickness of the FE model with n_v = 9

Perpendicular tensile strength is dependent on a large number of different factors, including physical factors such as moisture of veneers used, temperature, pressure, and pressing time (Klement *et al.* 2011; Demirkir *et al.* 2013; Wei *et al.* 2016; Sun *et al.* 2018; Klement *et al.* 2019). Other factors affecting the lamella sheer tensile strength include the adhesive properties, adhesive viscosity, amount of the adhesive deposit, and quality of the glue spread on the veneers (Bekhta *et al.* 2012; Murata *et al.* 2013; Kojima *et al.* 2014; Adhikari *et al.* 2016; Zhang *et al.* 2017). The type of veneers used, their quality, the wood species from which the veneers are made, the quality of the veneer machining, and the surface removal of small elements resulting from wood processing are also important (Erdil *et al.* 2003; Bal and Bektaş 2012; Wei *et al.* 2013).

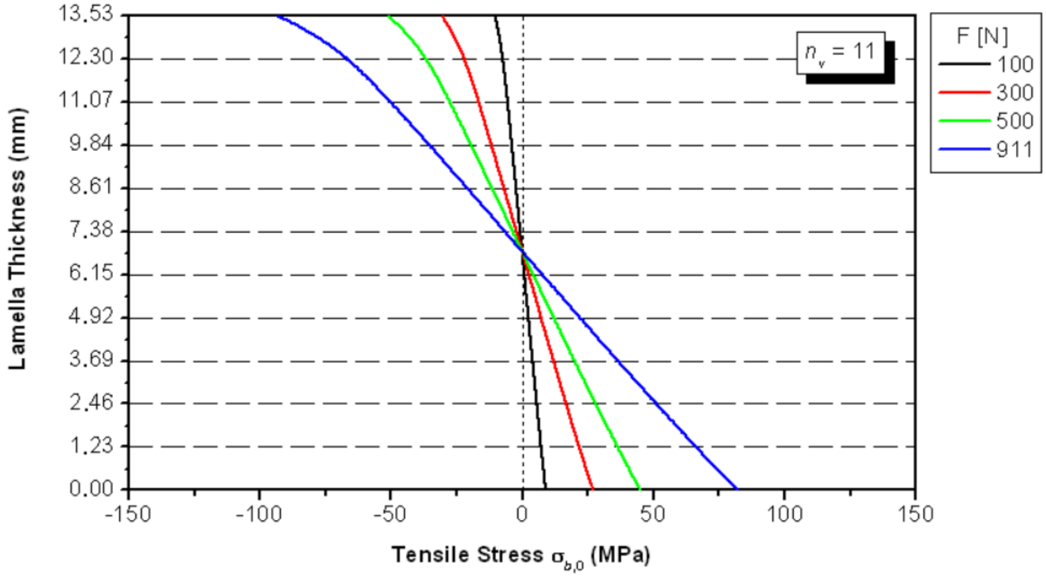


Fig. 7. Distribution of tensile stress (in the fiber direction) across the thickness of the FE model with n_v = 11

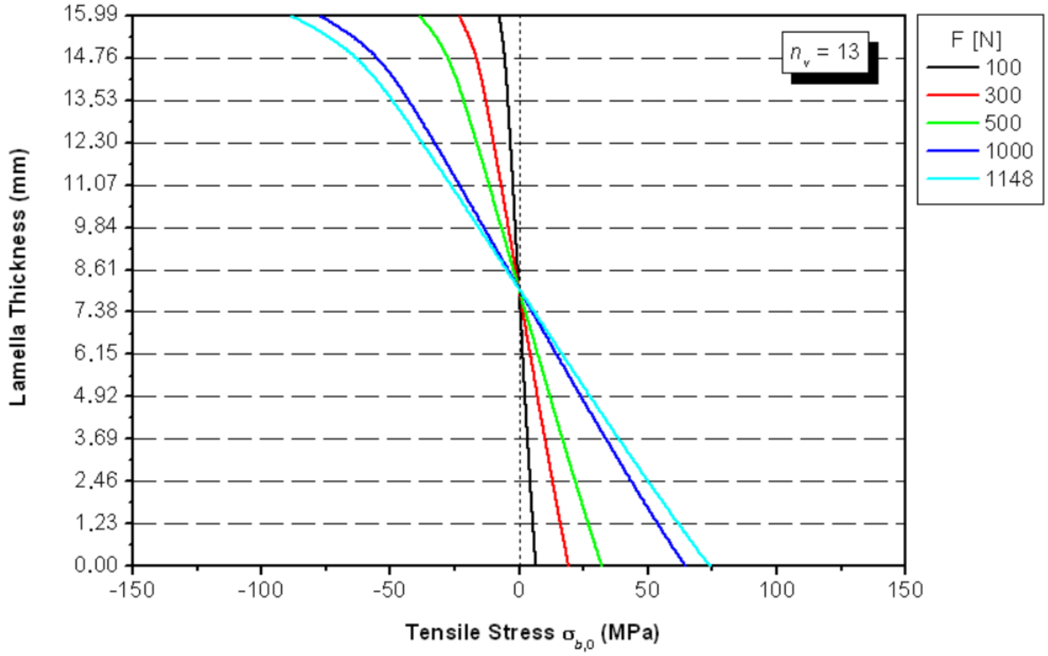


Fig. 8. Distribution of tensile stress (in the fiber direction) across the thickness of the FE model with n_v = 13

The effect of beech lamella perpendicular tensile stress on the quality of the final product is rarely mentioned in the scientific literature. The effect of cyclic stress on the attenuation rate of deflection of solid beech wood and laminated wood was examined by Sivák and Ruman (2017). They discovered that materials with higher thickness must be used to increase the attenuation rate of deflection. Popovska *et al*. (2017) investigated laminated wood modified with carbon polymer or carbon fabric. The tensile-shear strength values were compared to non-reinforced wood and polyurethane, and epoxide adhesives were used in their experiment. Bal and Bektaş (2014) examined the effect of selected factors (tree species, lamella combination, type of adhesive, number of loading cycles) on the impact bending strength (IBS) of laminated wood. Jivkov *et al.* (2013) studied the plywood tensile strength through a change of the layer position in the panel structure around the central axis, without changing the number and thickness of veneers. Buchelt and Wagenfuehr (2008) determined the flexural properties and tensile shear strength of five-ply plywood panels produced from eucalyptus (*Eucalyptus grandis*), beech (*Fagus orientalis*), and hybrid poplar (*Populus* × *euramericana*) using urea-formaldehyde (UF), melamine-urea-formaldehyde (MUF) and phenol-formaldehyde (PF) adhesives. Cristescu *et al.* (2015) presented the bending properties of laminated wood produced by the combination of beech veneer and plastic and described and evaluated the methodology of beech veneers for planar molding suitable to determine veneer formability in the plane.

The authors' analysis results, summarised in Figs. 5 through 7, follow the observations of Pizzi (2000). He used pressing synthetic thermosetting adhesives to manufacture plywood. Moreover, tensile stress results of beech plywood panels with a thickness of 12.7 mm, 5 plies, bonded with the addition of low amounts of melamine as melamine monoacetate, were mentioned. Jivkov *et al.* (2013) evaluated the effect of the beech veneer quality on the density, bending strength, and modulus of elasticity of 20 to 21-mm-thick plywood made of beech veneer. Their results showed a similar fact as in the current research that the stress and strain are remarkable affected by the load direction while bending. The results of their study provide an opportunity for the optimization of furniture construction made of beech plywood.

The perpendicular tensile strength test of lamellas determined that the resulting average values of the individual types of lamellas differing in the number of veneers is almost the same. This finding is not surprising. If all the technical conditions regarding the properties of veneers and adhesives are met, and the technological requirements for the pressing process are met, the number of veneers in the lamella in the three-point flexural test is not decisive. Generally, laminated veneer lumber with higher number of veneers tends to have higher mechanical strength due to the increment in material volume as well as the glue used (Schaffer *et al.* 1972). However, for the lamellar structure to not lose its integrity in the veneer structure, as has been mentioned earlier, is that the tensile stress ($\sigma_{b,0}$) in the lower veneer arising from the bending of the lamella structure does not exceed the proposed bending strength ($f_{b,0,d}$) as shown in Table 1, or in other words, $\sigma_{b,0} \leq f_{b,0,d}$. From Figs. 6 to 8, it was noted that all the laminated elements with different numbers of veneers complied with the rule indicating that the tensile stress did not exceed the proposed $f_{b,0,d}$ value. From the economic point of view, it would be beneficial if the lamellas with the least number of veneers were produced instead of those with a high number.

The lamellas are firmly bonded, and the glued joint broke down randomly at the weakest point in the cross-section of the sample. Buchelt and Wagenfuehr (2008) performed the tensile strength tests using beech veneers with a thickness ranging from 0.35 mm to 0.5 mm. The veneer was tested twice – in two test series, one with parallel fiber direction in adjacent veneers and the second with perpendicular fiber direction in adjacent veneers. The plywood strength properties do not depend on the veneer's thickness, but the wood material properties and technology are found to significantly influence mechanical strength (Klement *et al.* 2022).

Reduced perpendicular tensile strength values of molded elements would theoretically occur in cases where material would be exposed to water or excessive amounts of high air humidity. In this case, there is a presumption that the effect of high humidity would impair the bonding effect, resulting in a decrease in the perpendicular tensile strength of lamellas. The elements used in this test were stored, transported, and tested under the proper interior conditions and, prior to their testing, they were modified according to the requirements of the technical standards. The elements used in this test were consistently manufactured with all the relevant technological parameters to meet the requirements for high-quality products. Cristescu *et al.* (2015) consider the pressing temperature the most influential parameter for laminated beech board strength. Their results show that the choice of pressing parameters for laminated beech boards affects all the mechanical and physical properties.

Molded laminated elements used in manufacturing individual parts of chairs can be considered remarkable and modern elements, playing an essential role in chair construction because of their structure and subsequent properties. The quality requirements are relatively high, especially proper laminated element strength because the designed loading must be ensured. The strength of laminated elements was verified and tested using various methods.

CONCLUSIONS

1. Molded European beech laminated elements were studied in the form of chair construction. The basic idea of the research was to try to scientifically and meaningfully prove that oversized lamella armrests are not necessary and a lower number of lamellas in the chair construction may be sufficient. It was confirmed that tensile strength resulting from the three-point bending flexural test for all laminated structures is sufficient, and the desired minimal values are exceeded.
2. With a three-point bending flexural test, it was determined that there is an increase in the values of strength of the different types of laminated elements differing in the number of veneers. Beech laminated elements must be manufactured with correct technological parameters if consistent, high-quality products are required; laminated elements should be appropriately stored, transported, and used under proper interior conditions.
3. The stability and integrity of the chair structure made of beech laminated elements were verified and tested by various methods; the requirements for the quality of the beech laminated elements are relatively high, especially the general strength of the laminated elements in their assumed diverse load and stresses must be ensured. The load-bearing capacity of the three tested types of beech laminated elements was confirmed by the verification of the tensile strength of beech laminated elements in the three-point bending flexural test and FE analysis.
4. Reducing the number of lamellas in the construction of the chair without disturbing their stability and load-bearing capacity has several advantages: material savings in terms of wood veneers and glue, lower weight, lower production costs, less labour in production, more attractive slimmer design of the product, *etc.* All this was achieved while maintaining the strength and stability of the chairs so that they do not break and injure the user.

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