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FINITE ELEMENT SIMULATION THE MECHANICAL BEHAVIOUR OF PRESTRESSED GLULAM BEAMS

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For many years, prestressed glued beams have been successfully used, for example, in construction as supporting structures. Based on the analysis of recent studies of prestressed wooden beams, the aim of the research was to develop a design with a reduced consumption of materials. The technical result is achieved in that the method of manufacturing a prestressed straight wooden beam consists in gluing thin pre-curved lamellas to the required height, after which the glued lamella block is cut in height along the longitudinal axis and then the cut parts are glued together with each other by their curved sides (surfaces) . The purpose of the experiment was to investigate the bending stiffness of a rectilinear beam glued from curved lamellae in the case when there are no preliminary stresses in the lamellae, with the case of the presence of such stresses. The first load option was to create a pre-stressed state of the beam and determine the maximum normal stresses. The prestressed state of the lamellae in the bent and fixed (glued) position was simulated by stretching the upper layers of each of the lamellae during their global contact. When bent, it was found that each of the lamellae has stretched areas in the upper part with tensile stress from SX = +25 MPa to SX = +35 MPa and compressed regions in the lower part with compression stress from SX = -30 MPa to SX = -60 MPa. The second variant of the load was to create a workload on the top plane of the beam in the absence of prestressing. The maximum deflection in the middle of the beam was URES = 1,535 mm. The values of internal stresses in this case are in the range from SX = - 57 MPa in the compressed zone to SX = + 82 MPa in the tension one. The third variant of the load consisted in the presence of both prestressing and working load. The maximum deflection in the middle of the beam was URES = 0,466 mm. The values of the internal pressure with the range from SX = - 10 MPa to SX = - 100 MPa in the compressed area to SX = + 20 MPa to SX = + 60 MPa in tension one. The results of computational experiments show that by applying prestressed, in the direction opposite to the bending of the workload, we can compensate for the influence of the workload. It has been established that the application of the prestressing phenomenon makes it possible to create structures of rectilinear glued wooden beams of reduced material consumption, while the effect of increasing the carrying capacity of a wooden beam will be limited by the compressive strength of the material from which it is made. In order to obtain more accurate values of the increase in the coefficient of increasing the bearing capacity of the proposed construction of a wooden beams, it is planned to conduct in-vito experiments on a special software and hardware complex of the laboratory of mechanical tests of the Department of Forest Resources exploitation of the ZhNAU.

Key words: *preliminary tension, wooden glued beams, reinforced wooden beams, pre-stressed wooden beams.*

ДОСЛІДЖЕННЯ МЕХАНІЧНОЇ ПОВЕДІНКИ ПОПЕРЕДНЬО НАПРУЖЕНИХ ДЕРЕВ'ЯНИХ КЛЕЄНИХ БАЛОК МЕТОДОМ КІНЦЕВИХ ЕЛЕМЕНТІВ

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Протягом багатьох років попередньо напружені клеєні балки успішно застосовуються, наприклад, в будівництві в якості несучих конструкцій. Метою дослідження ставилося розробка *конструкції із зменшеною витратою матеріалів. Спосіб виготовлення полягає в склеюванні тонких попередньо зігнутих ламелей до необхідної висоти, після чого склеєний ламельний блок розрізають по висоті уздовж поздовжньої осі, а потім розрізані частини склеюють між собою своїми вигнутими сторонами (поверхнями). Основне завдання – дослідити згинальну жорсткість прямолінійної балки склеєної з вигнутих ламелей в разі, коли попередні напруження в ламелях відсутні, з випадком наявності таких напружень. Перший варіант навантаження полягав у створенні попередньо напруженого стану балки і визначенні максимальних нормальних напружень. З'ясовано, що кожна з ламелей має при її вигині розтягнуті області у верхній частині з напругою розтягнення від SX = +25 МПа до SX = +35 МПа і стислі області в нижній частині з напругою стиснення від SX = -30 МПа до SX = -60 МПа. Другий варіант навантаження полягав у створенні робочого навантаження на верхню площину балки за відсутності попереднього напруження. Максимальний прогин склав URES = 1,535 мм. Величини внутрішніх напружень, при цьому, знаходяться в межах від SX =- 57 МПа в стислій зоні до SX = + 32,47 МПа в розтягнутій. Третій варіант навантаження складався в наявності як попереднього напруження, так і робочого навантаження. Максимальний прогин склав URES = 27,49 мм. Величини внутрішніх напружень, при цьому, знаходяться в межах від SX = - 10 МПа до SX = - 100 МПа в стислій зоні до SX = + 20 МПа до SX = + 60 МПа в розтягнутій. Результати обчислювальних експериментів показують, що, застосовуючи попередньо напружений стан, у напрямку, протилежному вигину від робочого навантаження, можна компенсувати вплив робочого навантаження. Встановлено, що застосування явища попереднього напруження дозволяє створювати конструкції прямолінійних склеєних дерев'яних балок зменшеної матеріаломісткості, а ефект збільшення несучої здатності дерев'яної балки обмежується міцністю на стиск матеріалу, з якого вона зроблена. У перспективі для отримання більш точних значень коефіцієнта збільшення несучої здатності запропонованої конструкції дерев'яних балок планується провести експерименти in vitro на спеціальному програмно-технічному комплексі лабораторії механічних випробувань Департаменту експлуатації лісових ресурсів ЖНАЕУ.*

Ключові слова: *попереднє напруження, дерев'яні клеєні балки, армовані дерев'яні балки, попередньо напружені дерев'яні балки.*

Introduction

Lightweight constructions are one of the indicators of a developed civilization. All buildings, including vehicles, buildings, goods, etc., are becoming easier every year, and demand for them is increasing. Lightweight designs have attracted the attention of engineers over the years. However, frivolity can lead to the destruction of the structure (loss of structural stability), as it can lead to a decrease in the stiffness of the structure. Thus, the study of structural problems associated with stability becomes more important than ever. Pre-stressed structures have been successfully used for many years, for example, in construction as bearing beams. The wooden structure uses pre-stressed rectilinear beams, as well as dome wooden structures, glued along the radius of lamellae.

Patent for bent, glued bearing beams of two or more slats Hetzer received in 1906 (*Hetzer*, 1906). Novelty was not in the very gluing of wood, but in the addition of spatial forms of construction details by the method of bending. Bending of the glued beam creates in each of its slats a pre-stressed state. In this case, the upper half of each lamella is in the pre-stretched, and the bottom in the pre-compressed state. Gluing lamellae allows one to fix these lamellas. Such beams are widely used in the construction of bridges and dome buildings. However, the curved shape of the beam limits its technological capabilities when creating flat surfaces.

A known method for increasing the flexural stiffness of wooden beams by creating a pre-stressed state (pre-stressed glulam beams). For example, a pre-stressed wooden beam includes a glued panel of boards, cabinets mounted at the ends of the beam, and pre-stressed fittings fixed to the ends of the cassette, the difference is that in order to enhance the bearing capacity by providing a long-lasting effect of the previous tension, provided derelexation knots, each of which is connected to the end of the armature, and the rack is provided with ribs, while the grooves are formed in the beam with the formation of a degree on its ends, which are located between the edges of the circulations of the dereleasing knots (*Nakashidze*, 1986).

Many attempts have been made at improving the load carrying capacity of glulam beams by the addition of reinforcement. The earliest of these utilised steel with either thin plates glued onto the outer laminates of beams, or bars bonded into pre-cut slots between laminates (*Clarke et al.*, 1993; *Leijten*, 1988). More recently, with the availability of materials such as pultruded glass fibre reinforced plastic (GRP) and carbon fibre reinforced plastic (CFRP), similar ideas have again been tried (*Gentile, Svecova & Rizkalla*, 2002). Indeed, there are companies that manufacture and supply stock rangesof reinforced beams. The principle aim of the reinforcement is to enhance further the strength of beams made from good quality timber rather than as a means of enhancing beams made from lower quality material.

Attempts have also been made at pre-stressing glulam by the use of high tensile steel tendons. Both post tensioning, with the tendons passing through pre-cut longitudinal grooves in the glulam and anchored off at end plates, and pre-tensioning with bonded tendons have been tried (*Peterson*, 1965). With the high modulus of elasticity of steel compared to that of timber, pre-stress losses due to elastic shortening of the timber at the transfer stage and to creep in the timber over the longer term were perceived as major problems. It is not surprising, therefore, that no commercially successful method of pre-stressing via the use of steel tendons is in existence.

The concept of pre-stressing glulam with GRP tendons is new and has been recommended as a realistic method of upgrading low grade glulam (*Rodd & Pope*, 2003). With GRP tendons it is considered that the problems of pressurising losses and of potential tendon debonding in pre-tensioned systems are less of a problem than with steel tendons. This is because GRP has a modulus of elasticity of only about 25% that of steel. This means that it has to be strained to a much higher level than steel in order to reach its limiting strength. Therefore, losses due to elastic and time dependent shortening of the timber after release the pre-tension force are relatively smaller than those with steel tendons. Also, the flat strip form in which GRP is readily available means that there is a relatively larger surface area than with the traditional round or square cross-section of steel tendons and, therefore, that bond stresses are lower, which would reduce risk of de-lamination.

In addition, the preliminary compression strength of the stretched beam zone (lower plane) can be created by fixing in the compressed wood area in this zone, while in the compression zone of the beam under the action of the work load (upper plane), insert with a guaranteed tension is installed. Thus, in the upper zone of the beam, a preliminary tensile stress is created, while in the lower zone the previous compression stress (*Anshari et al.*, 2017). However, the disadvantage of such a design is its complexity, hence increasing labor costs for its manufacturing.

In this paper, 3-D finite element models have been developed by using commercial code *SolidWorks Simulation* to simulate the prestressing behaviour of reinforced glulam beams using prestressed wood lamelles. Glulam timber is modelled as orthotropic linear elastic materials in tension, and in compression in the embedding areas. Contact conditions between the prestressed wood lamelles are modelled.

Materials and methods

The purpose of this study is to continue to study the properties of prestressed wooden structures by simulating their mechanical behavior under load using the finite element method and verification of the calculated models obtained.

3-D finite element models were developed to simulate the pre-camber deflection and the pre-stress state of the glulam beams reinforced. In the modelling, the size of the glulam timber beam was 300 mm in length, 20 mm in depth, 20 mm in width. To simplify the model, some parameters were neglected, such as distortion in the grain, knots, temperature and density variation. Although there are strain rates and strain ratios in 3 directions of the L, R and T, the swelling ratio in the L direction was neglected.

Interaction between the glulam lamellas is modelled by defining both the tangential and the normal contact behaviour. Friction formulation is ‘rough’ in tangential behavior and ‘Hard contact’ for pressure-overclosure in normal behaviour.

Material properties of glulam used in the modelling were obtained from experiment results through shear and compression tests. Orthotropic elastic material properties for glulam are listed as follows.

Results of the research and discussion

The technical problem, the solution of which is aimed at the proposed method, is to increase the bearing capacity of the beam at a given height by creating its pre-stressed state, as well as simplifying the construction of the beam, and expanding its technological capabilities.

The technical result is achieved by the fact that the method of manufacturing a pre-stressed straight beam is to glued thin pre-bent lamellae to the required height, after which the glued lamellar unit is cut in height along the longitudinal axis, and then the cut pieces are glued together by their curved sides (surfaces).

The manufacturing method is given in Fig. 1 – glued block of pre-folded lamellae. On Fig. 2 – a straight wooden beam is pre-stressed, after gluing the cut pieces between them with their curved sides.

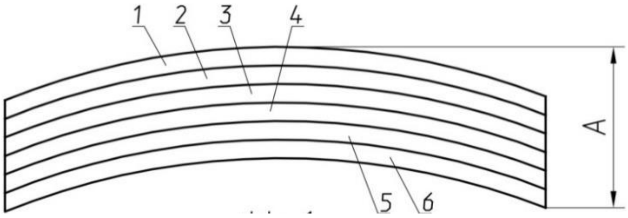


Fig. 1. **Glued block of pre-folded lamellae**

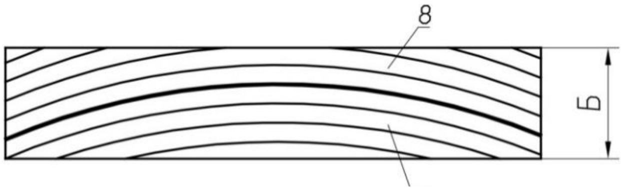
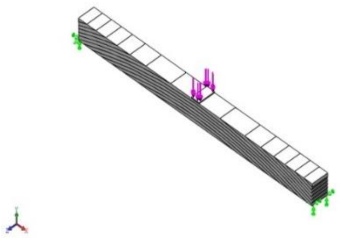


Fig. 2. **Straight wooden beam that is pre-stressed**

As a research object in the computing experiment, a beam size of 300 x 20 x 20 mm, glued from lamellae of a straight form of 300x20x3 mm in size from a material, the mechanical properties of which are presented in Table 1. The conditions of consolidation are the same for different variants of the load is adopted. In the *SolidWorks Simulation* terminology, the geometry of the lower transverse edges is fixed. They are shown on the link to the model in Table 1. Here is shown the workload in the form of force P = 1000 N on the upper plane of the beam in the middle of its passage. Design models were studied for four types of beams of the same size: solid from the array beam; beam glued from straight lamellas; curved beam slats with a radius of 1000 mm; beam of curved slats with a radius of 500 mm.

Table 1. **Fixing conditions and material properties**

Link to the model	Properties	
		
	Type of model:	Linear Elastic Isotropic
	Flow limit:	1.12e+008 N/m^2
	Bulk density:	600 kg/m^3
	Modulus of elasticity:	1.4e+010 N/m^2
	Poisson coefficient:	0.394

Grid of finite elements of the model is presented in Fig. 3. The purpose of the experiment was to investigate the flexural stiffness of the rectilinear beam glued from the curved lamellae in the absence of previous stresses in the lamellae, in the presence of such stresses. Methodological grid of computational experiments includes four variants of load conditions shown in Table 2.

In each of the options, the following values (symbols according to the *SolidWorks Simulation* program) were calculated: *Von Mises* – equivalent stress over Mises, MPa; *SX* – normal stress at bending cross section, MPa; *URES* – movement in the direction of the resultant load, mm.

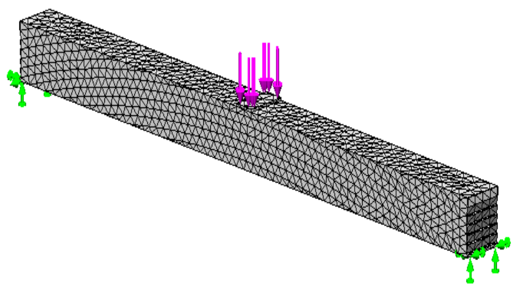


Fig. 3. **Grid of finite elements of a straight-line beam patterned from pre-deformed lamellae**

Results and discussion

The research results in *SolidWorks Simulation* are presented in Table 2.

The first version of the load was to create a pre-stressed beam and determine the maximum equivalent and normal stresses.

Pre-camber model. Figure 4 shows the simulated upward deflection, i.e. pre-camber, for a beam reinforced by gluing prestressed lamelles.

The pre-stressed state of the lamellae in a bent and fixed (glued) position was imitated by stretching the upper layers of each of the lamellae with their global contact. The diagram of normal stresses of the fourth type of glued beam under the action of the previous stress is shown in Fig. 9.

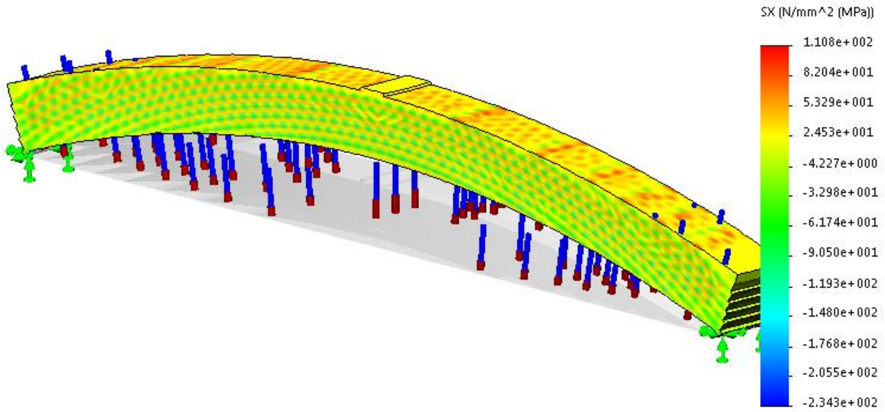
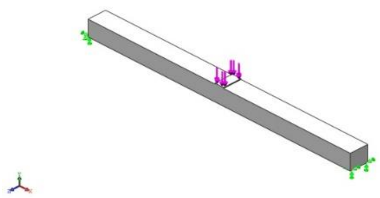
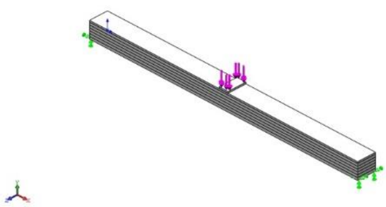


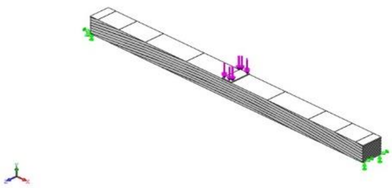
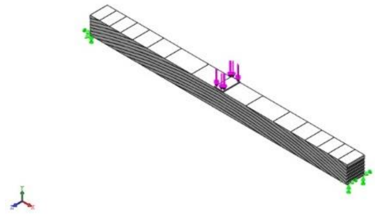
Fig. 4. **Sections of pre-created normal stresses in each of the slats of the beam, modelling of precamber for a beam reinforced**

As it follows from Fig. 4 each of the slats has stretched areas at the upper part with a stretching stress of *SX* = +25 MPa to *SX* = +30 MPa and a compressed area at the bottom with a compression stress of *SX* = -30 MPa to *SX* = -60 MPa.

Table 2. **Methodological network of experiments and results of simulation studies**

Beam type	**Test results**		
	MOR Von Mises, MPa	**MOR SX, MPa**	**URES, mm**
1	**2**	**3**	**4**
Solid from the array 	37,3	27,4	1,458
Glued straight lamellae 	38,1	31,1	1,466

End of table 2

1	2	3	4
Prestressed lamella radius 1000 	63,3	50,2	0,481
Prestressed lamella radius 500 	62,4	49,9	0,466

The second variant of the simulation was to create a working load on the upper plane of the beam in the absence of previous tension. The displacement diagram of this variant is shown in Fig. 5. As we see, the maximum deflection in the middle of the beam was *URES* = 1,535 mm.

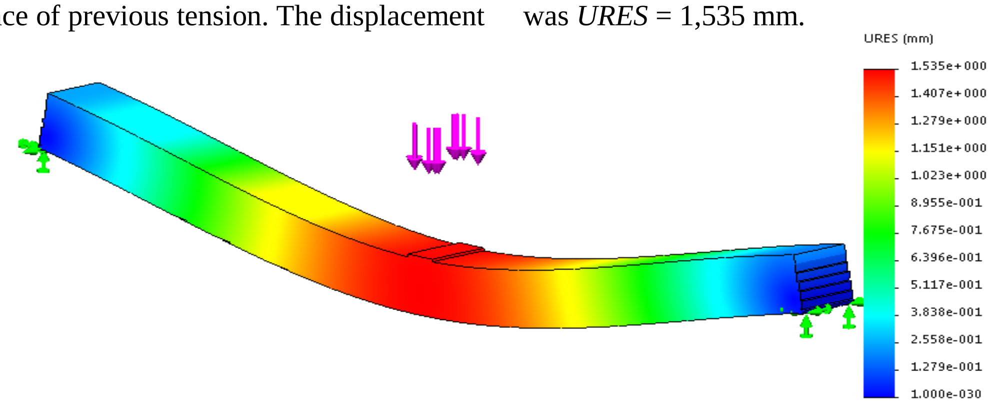


Fig. 5. **Sheet displacement of beam without previous tension in the direction of bending load**

The diagram of normal stresses when bending a beam is presented in Fig. 6. The values of internal stresses are in the range from *SX* = - 57 MPa in the compressed zone to *SX* = + 32.47 MPa in the stretched.

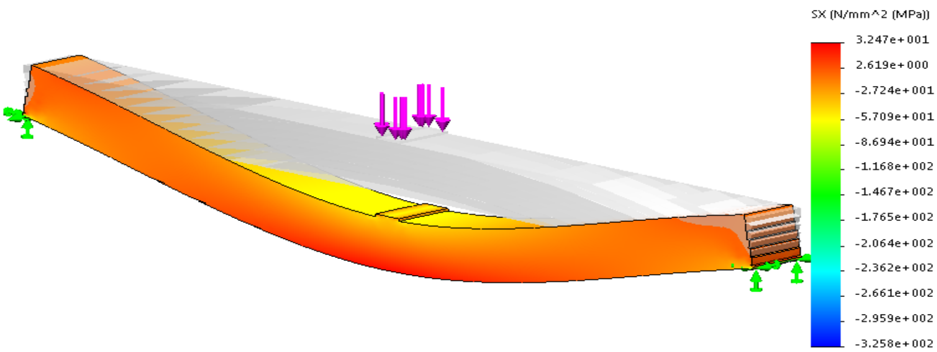
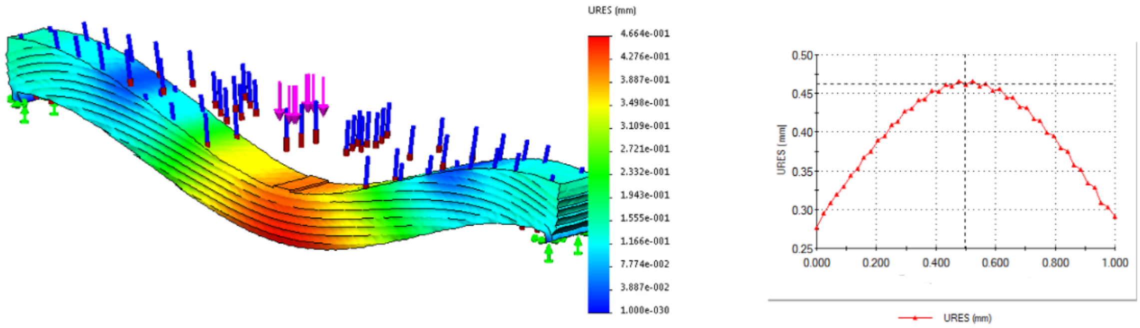


Fig. 6. **Circuit of normal stresses in the beam without previous tension**

The third version of the simulation was in the presence of both the previous tension and the workload. On Fig. 7. shows the diagram of displacements for this option. The maximum deflection in the middle of the beam was *URES* = 0.466 mm.



a) **b)**

Fig. 7. **The diagram of displacements of the pre-stressed beam in the direction of bending load (a); a parametric graph of the lower edge movement in the nodes (b)**

The diagram of normal stresses in the bending of the beam in the event of a previous tension is shown in Fig. 8. The values of internal stresses are in the range from SX = -10 MPa to SX = -100 MPa in the compressed zone to SX = + 20 MPa to SX = + 60 MPa in the stretched.

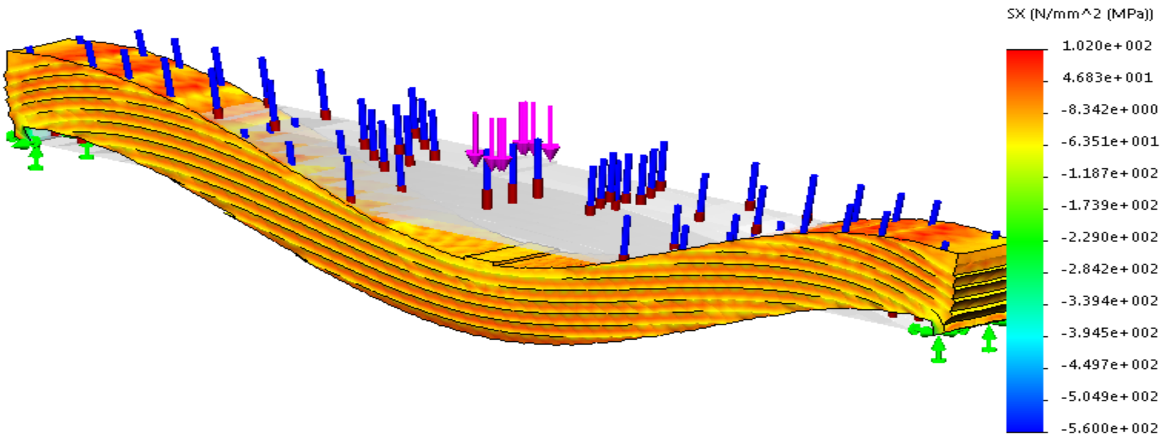


Fig. 8. **Circuit of normal stresses in the prestressed glulam beam**

In Fig. 9. Parameterized graphs of normal stresses are presented at design points of finite elements for various glued lamellae starting from the lowest one.

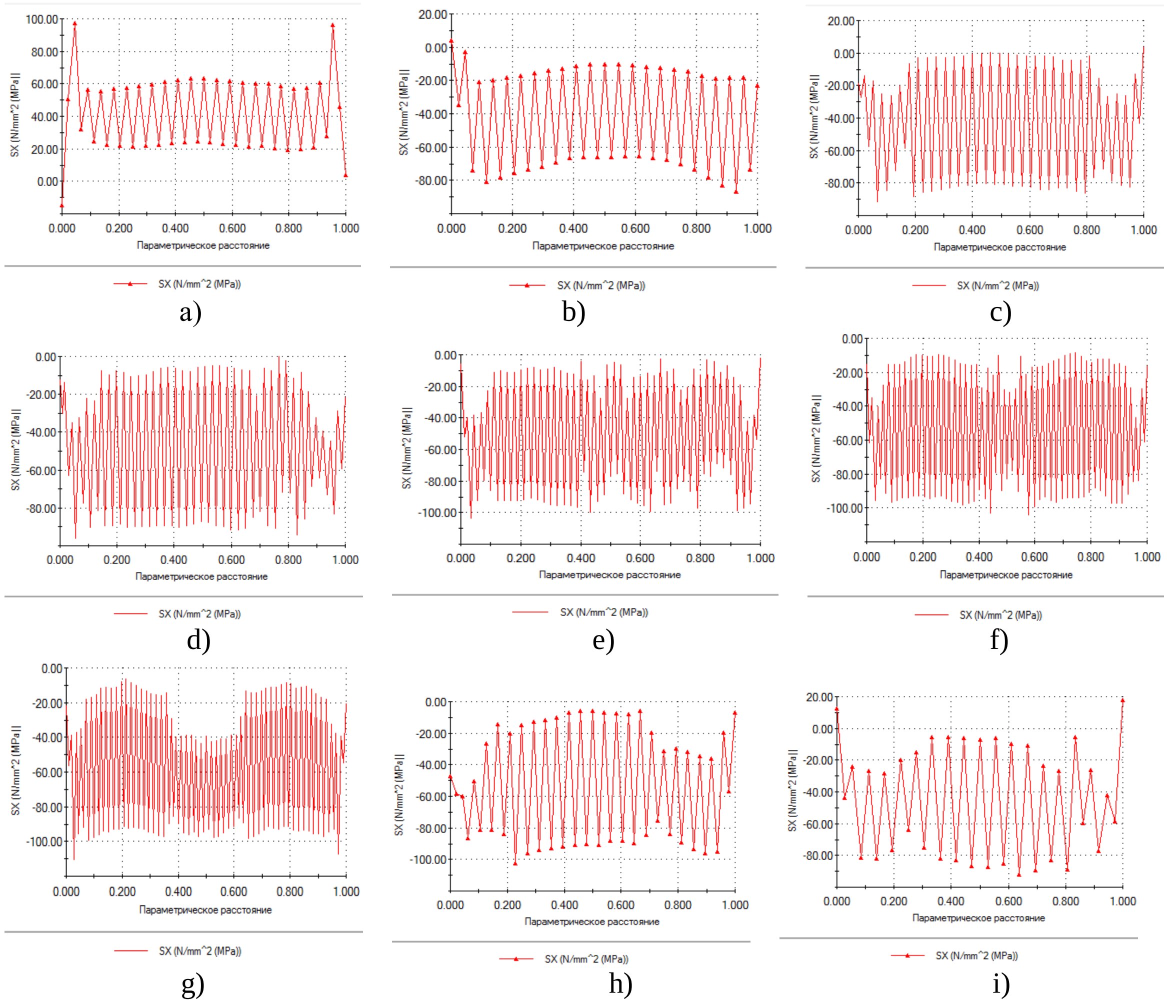


Fig. 9. **Parameterized graphs of normal stress at design points of finite elements: a – the lower edge of the first lamella; b – second lamella; c – the third lamella; d – fourth; e – fifth; f – is the sixth; g – the seventh; h – the eighth; i – the ninth.**

The results of the experiments presented in Table 2 indicate that for the initial and boundary conditions we adopted, the prestressing of the beam increases its carrying capacity by more than three times.

The use of the method provides for increasing the bearing capacity of the straight beam of rectangular cut at a given height, which will allow to expand technological possibilities and simplify the construction of the beam.

Conclusions

On the basis of the analysis of the obtained results of the simulation model, we can draw the following conclusions:

1. Application of the phenomenon of pre-stress allows to create structures of rectilinear glued wooden beams of reduced material content.

2. In this case, the effect of increasing the bearing capacity of a wooden beams will be limited to the strength of the compression of the material from which it is made.

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