STUDIES ON STRUCTURAL OPTIMIZATION OF LIGNOCELLULOSES COMPOSITE

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Abstract: The paper presents studies on structural optimization of lignocellulosic composite as sandwich structures by means of analytical method. The aim of research is to determine optimal thickness of core layer in terms of maximum stress in each stratum. The structural optimization was performed in case of three objective functions - maximizing stiffness, flexural maximizing in case of minimizing mass, minimizing material density. The results have applications in the design of composite materials for automotive interior due to design variables and input data used were taken into account and the application constraints.

Keywords: structural optimization, lignocellulosic composite, stiffness, strength,

1. INTRODUCTION

One of the current directions of development in the field of automotive interior components is to reduce manufacturing costs, both manufacturing technology and the type and amount of material used, while ensuring strength and stiffness performance characteristics. At the same time, providing a multifunctional character of structures is another important direction of research. A first optimization problem in automotive components, which occurs naturally, refers to maximize strength and rigidity and minimize weight. By balancing layer thickness of the cross section of the structure occurs minimize weight and maximize its resistance to bending. Mathematical algorithm optimization process is usually a strategy to find the best solution from the set of possible. Lately optimization techniques and procedures are included in complex information systems for computer-aided design. From the point of view of engineering applications, optimizing structures can be divided in several classes, as follows [1, 2]:

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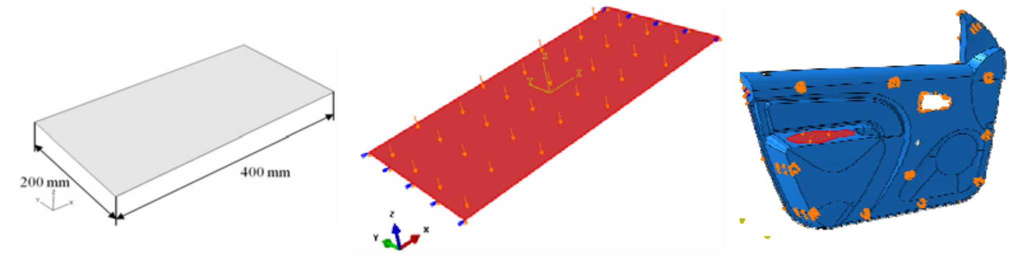
optimizing cross-sectional dimension, optimizing the shape and / or structure, topology optimization.

2. CASE STUDY ON STRUCTURAL OPTIMIZATION OF LAYERED LIGNOCELLULOSIC COMPOSITE

To optimize lignocellulosic stratification a plate with two sides simple supported with 200 mm length and two free sides with 400 mm length were considered. Plate was loaded with a force uniformly distributed on its surface (Fig. 1.) which produced cylindrical bending – a specific load of automotive component as can be seen in Fig. 1. c.



a) b) c)

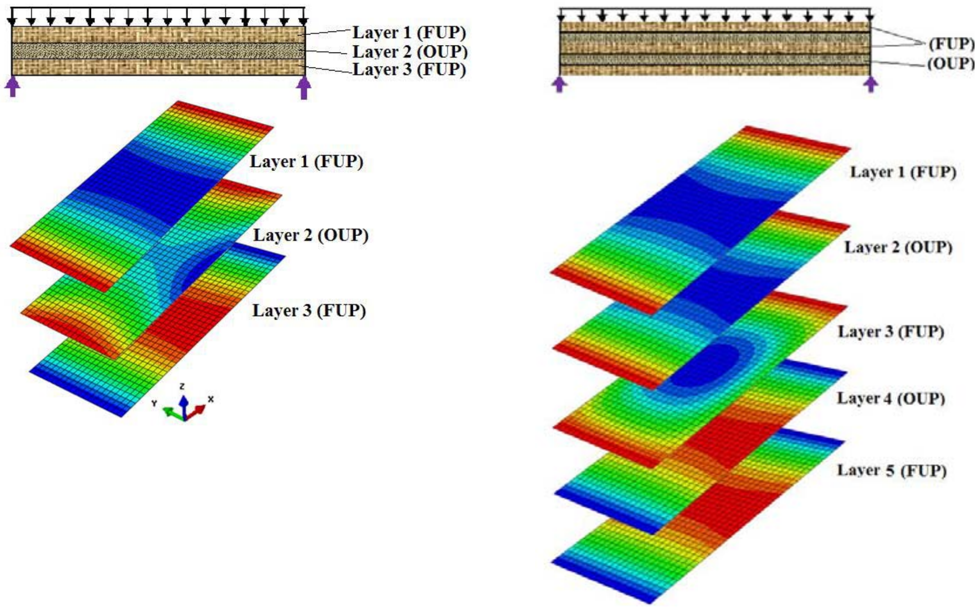
Fig. 1. a) Plate geometry; b) Loads and boundary conditions; c) automotive door

In the first stage of optimization, composite plate was modelled as two types of structure – with three layers and five layers (Fig. 2). Analyzing the normal stresses distribution of each layer of lignocellulosic composite, it has been found that in case of five layers, using a middle layer reinforced with natural fibres (FUP) is not justified. Thus, it was found that lignocellulosic composite with three layers is optimal in terms of its strength and weight. Further this type of layered was studied.

In Fig. 3 it can be seen that unlike the homogeneous materials where stresses σ_x distribution on the thickness varies linearly, in case of laminate composite the normal stresses is linearly on each layer, showing jumps at the interface between layers. It is worth mentioning that the material does not have adhesive layer between the lamina, their connection was carried out in the manufacturing process by using the same polymer matrix for the two types of reinforcing elements (natural fibres fabrics – layers 1 and 3 and oak particles – layer 2).

In previous research were experimentally determined mechanical properties of composite laminas [3, 4]. It was found that wood particle size influences physical, mechanical, acoustic and thermal properties. Laminas obtained with oak particle sizes between 0.4 ÷ 1 mm have optimal characteristics for applications in automotive components.

Properties of materials used in structural optimization process have the average values obtained by experimental methods. The following materials were used: polyester resin composite reinforced with flax fabric (FUP) and polyester resin composite with oak particles (OUP). Strength and the elastic properties of the layers are shown in Table 1.



a) b)

Fig. 2. Normal stresses distribution σ_x median surface of each layer of material (FUP - layer reinforced with natural fibres, OUP - layer reinforced with oak particles)
a) composite with three layers; b) composite with five layers

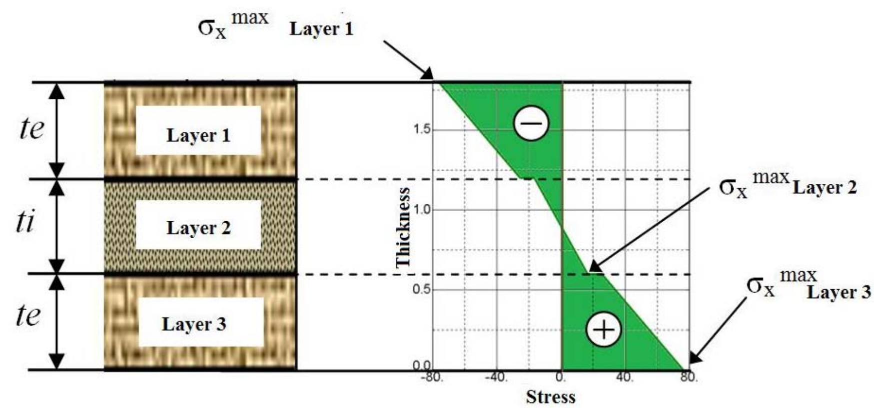


Fig. 3. Normal stresses distribution σ_x on composite thickness

Direction of the weft yarn fabric corresponds to the *x* direction (Fig. 2). Transverse modulus (G) of flax fabric layers was taken from the literature and has a value of 1800 MPa [5, 6]. Poisson's ratio (υ) for materials reinforced with oak particles has a value of 0.37 as determined experimental [7, 8, 9]. Material density (ρ) of each layer was determined by mixture method, knowing the percentage of fiber reinforcement and constituent densities.

Table 1. **Properties of laminas**

Layers	E_1 [MPa]	E_2 [MPa]	σ_{r1} [MPa]	σ_{r2} [MPa]	υ_{12}	G_{12} [MPa]	G_{13} [MPa]	G_{23} [MPa]	ρ [kg/m^3]
FUP	4711	2787	65.32	28.81	0.35	1800	1800	1800	1187
OUP.1	3041	3041	20.72	20.72	0.37	-	-	-	1077

To calculate the maximum bending at middle of board and stresses in each layer in accordance with design variables, we used a program developed in MatLab, adapted from Cerbu [7] based on analytical relations [10].

The following input data were considered for each layer: L_{free} - dimensions of free sides (mm), $L_{supported}$ - dimensions of simply supported sides (mm), p_0 - pressure applied to the surface of plate (MPa), $\sigma_{rst.1}$ - fracture stresses of layer 1 (outside) (MPa), $\sigma_{rst.2}$ - fracture stresses of layer 2 (inside), MPa; ρ_{te} - outer layer density (kg/m^3); ρ_{ti} - inner layer density, (kg/m^3).

The design variables were considered thicknesses of layers and material characteristics: $x_1 = t_e$ – thickness of outer layers (mm); $x_2 = t_i$ - core thickness (mm); $x_3 = \upsilon_e$ – Poisson's coefficient of the outer layer; $x_4 = \upsilon_i$ - Poisson's coefficient of the core layer, $x_5 = E_{1e}$ - longitudinal modulus of outer layer (MPa) and $x_6 = E_{1i}$ - longitudinal modulus of the core layer (MPa).

The structural optimization was performed in case of three objective functions - maximizing stiffness, flexural maximizing in case of minimizing mass, minimizing material density.

2.1. Minimizing material density

Minimizing composite mass can be achieved in two directions: either by reducing the thickness of the component layers, either by reducing the density of each layer to an established thickness. The two components were varied according to Table 2 using the optimization program.

Table 2. **Optimize component of material density**

Input data	Design variables	Objective function	Constraints
L_{free} = 400 mm; $L_{supported}$ = 200 mm; ρ_{te} = 1187 kg/m^3; ρ_{ti} = 1077 kg/m^3	t_e =(0,40; 0,45; 0,50…2,40) mm; t_i = (0,40; 0,45; 0,50…2,80) mm	minρ= $\rho(t_{e1}, t_{e2}, \dots t_{en}, t_{i1}, t_{i2}, \dots t_{in})$; minρ=$(2\cdot L_{free}\cdot L_{supported}\cdot\rho_{te} + L_{free}\cdot L_{supported}\cdot\rho_{ti})/(L_{free}\cdot L_{supported}\cdot(2\cdot t_e+t_i))$	$0,40 \le t_e \le 2,40$ mm; $0,40 \le t_i \le 2,80$ mm;

In figure 4 it can be seen that the function minρ reaches a minimum when it is used a core layer (t_i) with a large thickness compared to the thickness of the outer layer

(t_e).

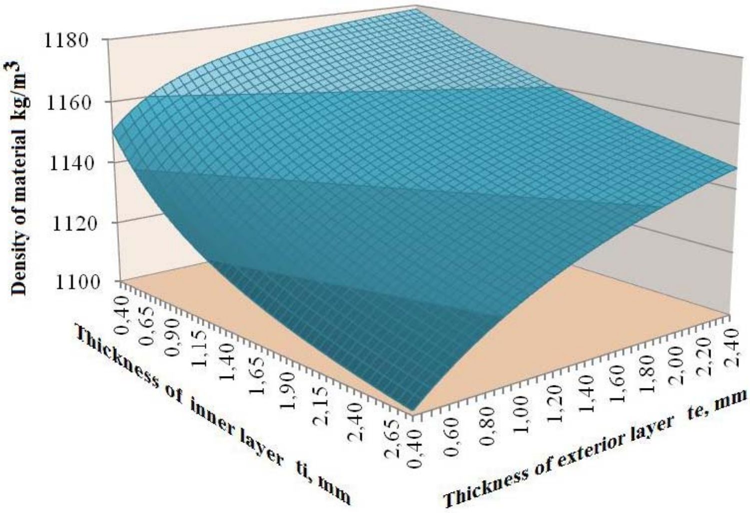


Fig. 4. Variation of density composite depending on the thickness of layers (t_i, t_e)

2.2. Maximizing stiffness

Laminated plate stiffness *(R)*, expressed by the value of maximum deflection (w_{0max}) in the middle of it, and depends on layer thickness and material characteristics thereof. Thus, in this analysis were defined as design variables layers thicknesses (t_e, t_i) and elastic characteristics (E_1 and υ) (Table 3).

Table 3. **Optimize components of stiffness (*R*)**

Input data	Design variables	Objective function	Constraints
p_0 = 0.0005 MPa; L_{free} = 400 mm; $L_{supported}$= 200 mm; E_{1e}.=4711 MPa; E_{1i}=3041MPa; υ_e = 0.35; υ_i = 0.37;	t_e=(0,40;0,45; ,50…2,40) mm; t_i=(0,40;0,45; 0,50…2,80) mm; E_{1e} = (800; 1000; 1200… 16000) MPa; E_{1i} = (800; 1000; 1200… 16000) MPa; υ_e=(2,25; 2,26; 2,27 …4,5); υ_i=(2,25;2,26; 2,27…4,5);	max$R$ = minw_0 max (t_e, t_i, E_{1e}, E_{1i}, υ_e, υ_i)	$0,40 \le t_e \le 2,40$ mm; $0,40 \le t_i \le 2,80$ mm; $800 \le E_{1e} \le 16000$ MPa; $800 \le E_{1i} \le 16000$ MPa; $2,25 \le \upsilon_e \le 4,5$; $2,25 \le \upsilon_i \le 4,5$; $w_0$max ≤ 40 mm.

In figure 5 is represented the variation of maximum deflection (w_{0max}) depends on the thickness of layers. It can be seen that the stiffness of the plate increases with layer thickness. Stiffness of the composite material is influenced by the thickness of laminas and elastic characteristics of them, for this reason is recommended to use for outer lamina materials with superior properties.

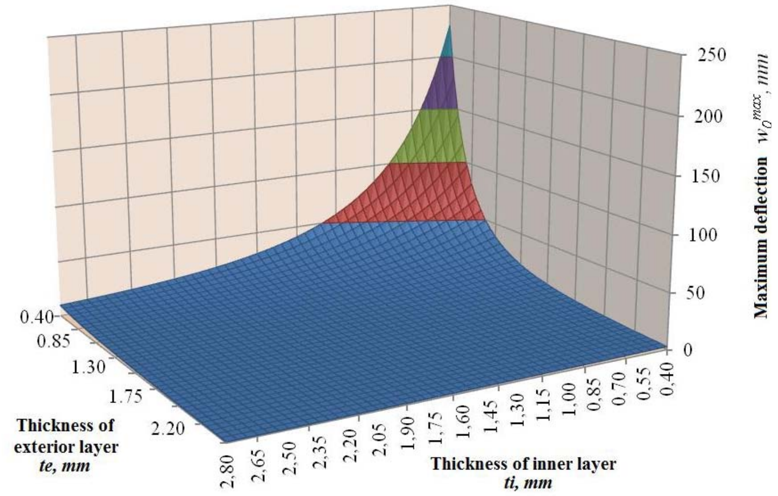


Fig. 5. Variation of maximum deflection with thickness of layers

In figure 6 and 7 it is observed that the maximum stress in the outer layers and the core layer are influenced by layer thickness. With increasing of layers thickness, the maximum stresses decreased.

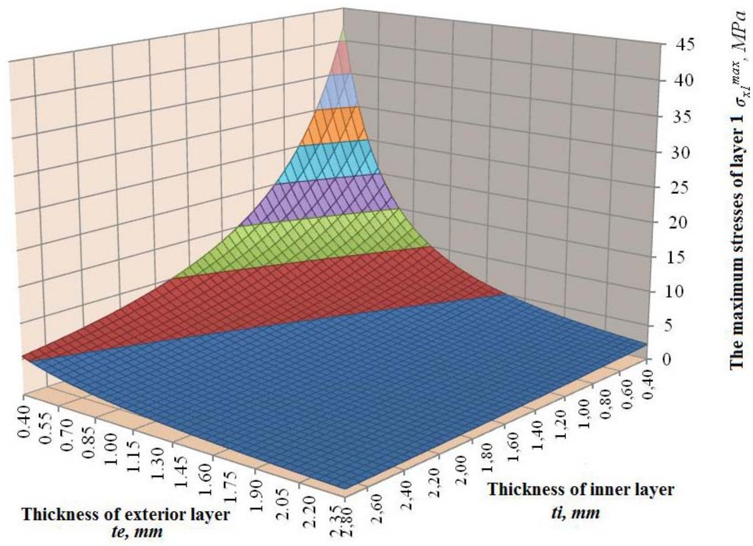


Fig. 6. Variation of maximum stresses in the outer layers depending on the thickness of layers

In Figures 8 and 9 are presented the maximum deflection (w_{0max}) variations depending on the longitudinal elastic moduli on 1 direction and the Poisson's coefficient of the material for each layer. It can be noticed that that the outer layers must have a high rigidity.

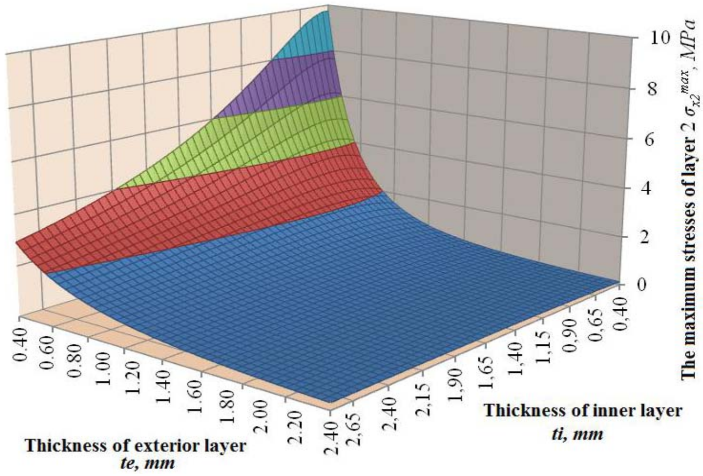


Fig. 7. Variation of maximum stresses in the core layer depending on the thicknesses of layers

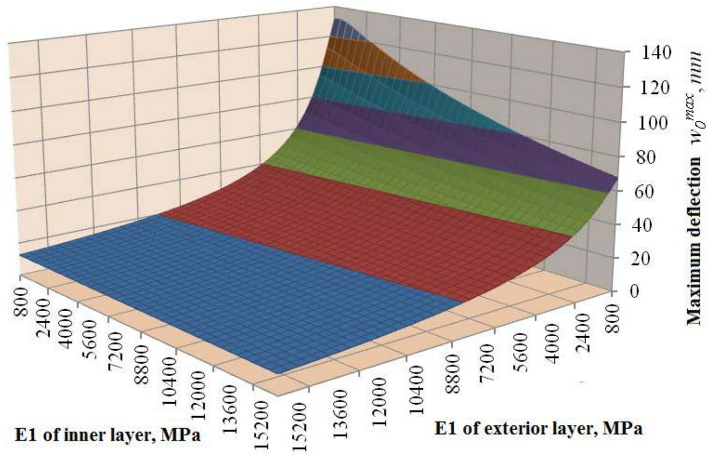


Fig. 8. Variation of maximum deflection depending on the longitudinal modulus

2.3. Flexural strength maximizing in case of minimizing mass

This feature aims to provide an optimal correlation between layers thickness and stiffness of the structure. This will cause the phenomenon of simultaneous destruction of layers which is advantageous for both automotive manufacturers and for those who exploit them.

Above analytical modeling showed that increasing the thickness of the outer layer lead on an improvement stiffness and flexural strength (S_{ti}) of lignocellulosic composite. However, due to technological restrictions related to pre-thickness layers of fabric reinforced with natural fibers and their higher density, value of thickness is restricted up to 0.6 mm. In Table 4 are presented the parameters of optimization.

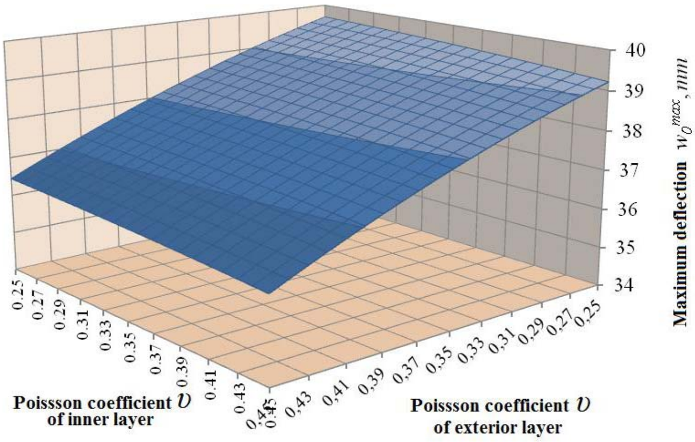


Fig. 9. Variation of maximum deflection depending on Poisson's coefficient

Table 4. **Flexural optimization components**

Input data	Design variables	Objective function	Constraints
t_e = 0,6 mm; L_{free} = 400 mm; $L_{supported}$ = 200 mm; E_{1e} = 4711 MPa; E_{1i} =3041 MPa; υ_e = 0.35; υ_i = 0.37; $\sigma_{rst.1}$ =65.32 MPa; $\sigma_{rst.2}$ = 20,72 MPa;	t_i = (0,40; 0,45; 0,50…2,80) mm; p_0 = (0,0005…0,005) MPa	$S_{ti} = \sigma(t_i, p_0)$, $minS_{ti} \cong \left\|\left(\sigma_{xst.1}^{max} - \sigma_{rst.1}\right) + \left(\sigma_{xst.2}^{max} - \sigma_{rst.2}\right)\right\|$	0,40≤ t_i≤ 2,80 mm; $\sigma_{xst.1}^{max} \le \sigma_{rst.1}$; $\sigma_{xst.2}^{max} \le \sigma_{rst.2}$.

Figures 10 and 11 shows the variation of flexural strength $minS_{ti}$ depending on the layers thickness. It can be noticed that flexural strength reaches the minimum for value of 1.025 *mm* core thickness. For technological reasons, the optimum value of core thickness is round 1*mm*.

3. CONCLUSION

Structural optimization of the materials used in automotive construction provides outstanding benefits society. An increased weight of a vehicle requires additional resources of raw materials, energy to be moved and additional costs of recycling.

In this paper were approached aspects related to lignocellulosic composites used in automotive structures. Optimization presented in this paper is based on experimental data obtained by the authors and shown on papers [3, 4, 7, 8, 9]. Minimizing weight composite structures used in automotive construction can be achieved by varying layer thickness so that the layered structure destruction due to mechanical stress occur simultaneously in all layers and not successively. Destruction of layered structure occurred in the core layer does not influence major strength and stiffness characteristics of the whole structure. Following optimization of the cross section of stratification consisting of three laminas showed that the optimum thickness of the core layer reinforced with oak particles is 2.2 *mm*.

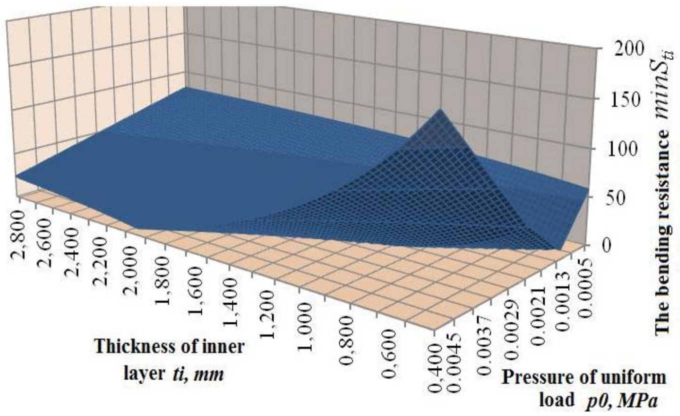


Fig. 10. Variation of minS_{ti} depending on the thickness of the core and the pressure applied to the plate

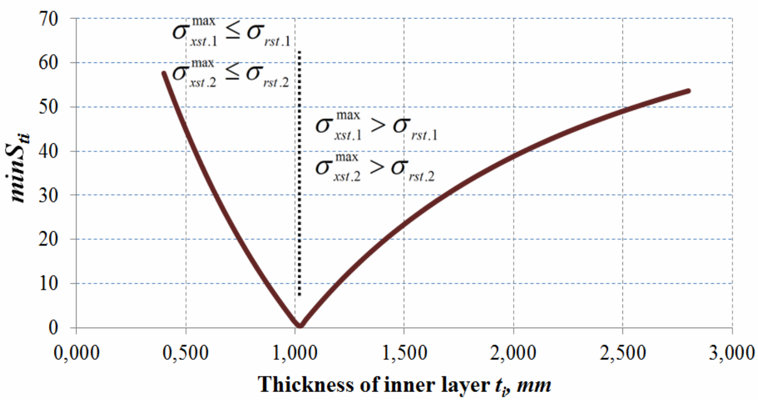


Fig. 11. Variation of flexural strength min$S$ versus thickness of inner layer

Experimental tests on samples combined with modern methods of calculation and analysis of state of tension and deformations from mechanical structures allow fast design and optimization of analyzed structures.

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