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SCIENCE

Analytical model of laminar composites having fibre reinforced polyester faces and a polypropylene honeycomb core; experimental testing of the model

Daiva Zeleniakiene*, Vitalis Leisis, and Paulius Griskevicius

Department of Solid Mechanics, Kaunas University of Technology, Kestucio 27, 44025 Kaunas, Lithuania; vitalis.leisis@ktu.lt, paulius.griskevicius@ktu.lt

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Abstract. Experimental study of deformation behaviour of sandwich structures with a honeycomb core in the cases of quasi-static loading was carried out. The object of investigation was the static bending of the sandwich composite used for safety important structures made of woven glass fibre and polyvinylester resin composite facesheets with a polypropylene hexagonal honeycomb core. The results were obtained using equations of laminate theory; modified equations of beam theory were compared to experimental ones. As the analytically obtained results were in good agreement with the experimentally obtained ones, this methodology was used for the strength analysis of the investigated structure. The influence of geometrical parameters on the static behaviour of the sandwich structure was evaluated and their dependence on strength properties of the layered structure was assessed.

Key words: sandwich composite, fibre reinforced plastic, honeycomb, strength analysis.

INTRODUCTION

Sandwich structures are used for safety important objects such as aircrafts, transport means, vessels, and pipes, since they offer great energy absorption potential and increase the flexural inertia without significant weight penalties. By varying the core, the thickness, and the material of the facesheet of the sandwich structures, it is possible to obtain various properties of the structure [1–3].

Sandwich materials have been a topic of many scientific investigations. The behaviour of the sandwich material under crushing loads and the ductile fracture limits are usually determined with the help of compression tests [4]. Cores are the weakest part of sandwich structures and they fail due to shear stress. The shear strength properties of the sandwich core are important in the design of sandwich structures subjected to flexural loading. Three-point bending tests are performed to find the flexural and shear stiffness of sandwich beams [5].

Mechanical behaviour of a regular honeycomb core has been widely studied. Initiators of such research were Gibson and Ashby [6], who laid the base for analytical investigations of regular hexagonal honeycomb deformation behaviour. Later these studies were developed by other authors [7–10]. Triplett and Schonberg [11] analysed the sandwich structure including a honeycomb core by using finite element modelling under static and dynamic loading. Meraghni et al. [12] used the classical laminate theory for core stiffness evaluation. So, various analytical methods are employed for investigation of the mechanical behaviour of sandwich structures. However, the application of theoretical research can be complicated due to very complex structure of a layered composite [13]. It is clear that the mathematical equations derived for one combination of composite materials cannot suit for another combination. The search for a proper analytical methodology is relevant today.

* Corresponding author, daiva.zeleniakiene@ktu.lt

The facesheets resist nearly all of the applied in-plane loads and flatwise bending moments and offer nearly all of the bending stiffness to the sandwich. Examples of widely used facesheet materials are fibre reinforced plastic (FRP) and carbon fibre. Fibre reinforced plastic composite has high stiffness and strength, low weight, corrosion resistance, and electromagnetic neutrality [14–16]. Because of this FRP composites are more and more often used in new modern structures as well as in sandwich composites.

The analysis of recent scientific research showed that investigation of honeycomb sandwich composites is a complicated issue. Numerous studies have been carried out but in some materials combinations are poor.

A numerical finite element analysis of impact energy absorption and impact behaviour of FRP-honeycomb sandwich composite was recently presented by the authors of this study [17,18]. However, the need for quasi-static analysis of this composite is also tangible.

The aim of this study is to apply a suitable analytical methodology to investigation of the static deformation behaviour of sandwich composite made of woven glass fibre and polyvinylester resin composite facesheets and a polypropylene honeycomb core and to evaluate the dependence of geometrical parameters on strength properties of the layered structure.

MATERIALS AND METHODS

The sandwich composite made of woven glass fibre and polyvinylester resin composite facesheets with a polypropylene hexagonal honeycomb core was investigated. Two core thicknesses were used: 10 and 20 mm. Facesheet thicknesses were 1.0, 2.5, and 4.0 mm.

The mechanical properties of component materials were obtained according to applicable standards EN ISO 178:2003 [19], EN ISO 527-1:1994 [20]. Nida Core H8PP honeycomb (USA) was used as the sandwich structure core. The thickness of the honeycomb wall was 0.4 mm. Core compression tests were executed according to the standard EN ISO 844:2007 [21]. The properties of the sandwich structure are presented in Table 1.

A three-point bending test was performed in this investigation. A sketch of a sandwich composite under three-point bending showing geometrical parameters is presented in Fig. 1. The dimensions of the bending test specimens were the following: width $b = 100$ mm; facesheet thickness $2t = 2; 5; 8$ mm; core thickness $c = 10; 20$ mm; sandwich thickness $h = 12; 15; 18; 22; 25; 28$ mm; the distance between the two supports $L = 200$ mm. First of all the bending force equal to $F = 0.2$ kN was applied and the deflection δ_{exp} was measured. Next, the bending force was increased until the specimen lost the strength and the maximum value of force $F_{max,exp}$ was measured.

Table 1. Mechanical properties of the sandwich structure component materials

Mechanical property	Facesheet material, FRP	Core material, polypropylene	Honeycomb thickness	
			10 mm	20 mm
Tension strength, MPa	380	–	–	–
Compression strength, MPa	280	–	–	–
Shear strength, MPa	130	–	0.5	0.4–0.6
Young modulus, GPa	19.2	1.75	1.0×10^{-3}	1.0×10^{-3}
Poisson ratio	0.13	0.42	0.05	0.05
Yield stress, MPa	–	24.0	–	–
Shear modulus, MPa	–	620	25	20

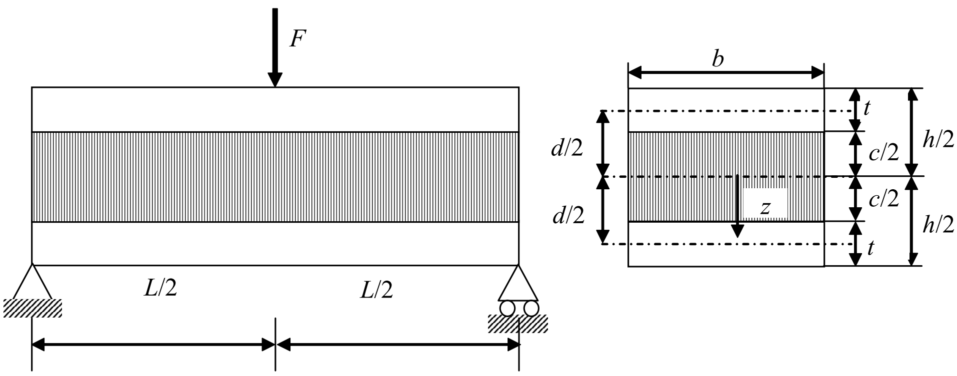

Fig. 1. Geometry of a three-point bending sandwich composite.

The analytical calculation of sandwich structure stresses, deflections, and strains was carried out using equations of the classical laminate theory [22] and modified equations of beam theory [2,4]. Laminate theory does not estimate the shear between layers under bending. Therefore this theory was used only for normal stress and linear strain calculation. Modified equations of beam theory were used as follows [2,4]:

$$\sigma_{\mathrm{f}} = \frac{FLz}{4D} E_{\mathrm{f}} \left(-\frac{h}{2} \le z \le -\frac{c}{2}; \frac{c}{2} \le z \le \frac{h}{2} \right), \quad (1)$$

$$\sigma_{\mathrm{c}} = \frac{FLz}{4D} E_{\mathrm{c}} \left(-\frac{c}{2} \le \frac{c}{2} \right), \quad (2)$$

where σ_{f} and σ_{c} are normal stresses of facesheets and core, respectively; z is the distance from the neutral line; D is the bending stiffness; E_{f} and E_{c} are Young moduli of facesheets and core, respectively.

The maximum deflection of the beam is due to both flexural and shear deformations. Shear deformation dominates in the core. The classical beam theory is not suitable enough for sandwich structures containing a honeycomb core because it does not evaluate the shear. It is namely the low shear stiffness of the honeycomb structure that influences high deflection. For this reason some modifications were made and the approximate expression for the elastic deflection δ can be expressed as [2,4]

$$\delta = \delta_E + \delta_S = \frac{FL^3}{48D} + \frac{FL}{4S}, \quad (3)$$

where δ_E and δ_S are deflections related to bending and shear stiffness, respectively; D is the bending stiffness; S is the shear stiffness. D and S can be expressed as follows [2]:

$$D = \frac{E_{\mathrm{f}} t^3 b}{6} + \frac{E_{\mathrm{f}} t d^2 b}{2} + \frac{E_{\mathrm{c}} b c^3}{12}, \quad (4)$$

$$S = b d G_{\mathrm{c}}, \quad (5)$$

where G_{c} is the shear modulus of core.

Shear stress was calculated according to the following equation [2]:

$$\tau = \frac{F}{2D} \left[\frac{E_{\mathrm{f}} t d}{2} + \frac{E_{\mathrm{c}}}{2} \left(\frac{c^2}{4} - z^2 \right) \right]. \quad (6)$$

The facesheet strength was assessed according to the expression

$$\sigma_{\mathrm{f}} \le \sigma_U, \quad (7)$$

where σ_U is facesheet strength, either tension strength σ_{Ut} for the bottom facesheet or compression strength σ_{Uc} for the top facesheet.

The honeycomb core shear strength was obtained using the expression

$$\tau \le \tau_U, \quad (8)$$

where τ_U is core shear strength.

Employing eqs (1) and (7), the maximum force for facesheets was derived as follows:

$$F_{\mathrm{max,f}} = 4D\sigma_U \left(E_{\mathrm{f}} L \frac{h}{2} \right)^{-1}, \quad (9)$$

and, using eqs (6) and (8), the maximum force for the core was derived as follows:

$$F_{\mathrm{max,c}} = 4D\tau_U \left(E_{\mathrm{f}} t d + E_{\mathrm{c}} \frac{c^2}{2} \right)^{-1}. \quad (10)$$

F_{max} represents such a force case in which the failure of separate layers of the sandwich structure can occur. Using eqs (9) and (10), the bending force F_{max} was calculated and its dependence on facesheet thickness $2t$ was found. The specimen model dimensions were chosen the same as these used in the experiment for maximum force measurement.

RESULTS AND DISCUSSION

The influence of facesheet thickness on the deflection of the investigated sandwich structure is presented in Fig. 2. The analytically obtained results were in good agreement with the experimentally obtained ones both in the case of 10 and 20 mm thick sandwich structures. As obvious from Fig. 2, in the case of a low facesheet thickness ($2t = 2$ mm and $2t = 1$ mm for $c = 10$ mm and for $c = 20$ mm, respectively) bending stiffness significantly influences the deflection. With the increase in facesheet thickness above these values, the deflection δ decreases and asymptotically approaches the value of deflection related to shear stiffness δ_S.

Using the above methodology, both the normal and shear stress distribution in the cross section of the sandwich structure was examined. The results showed that the same values of normal stresses were obtained by equations of laminate theory and beam theory. Normal strain is distributed linearly in the cross section, but normal stress acts only in the facesheets. The honeycomb core sustains a very insignificant part of normal stress. As shear stress analysis showed, it acts only in the honeycomb core and is uniform throughout the thickness of the core. That is due to too low core stiffness which does not affect the bending stiffness of the sandwich structure. As seen from eq. (4), the third component has a very low value and its influence is very low as well.

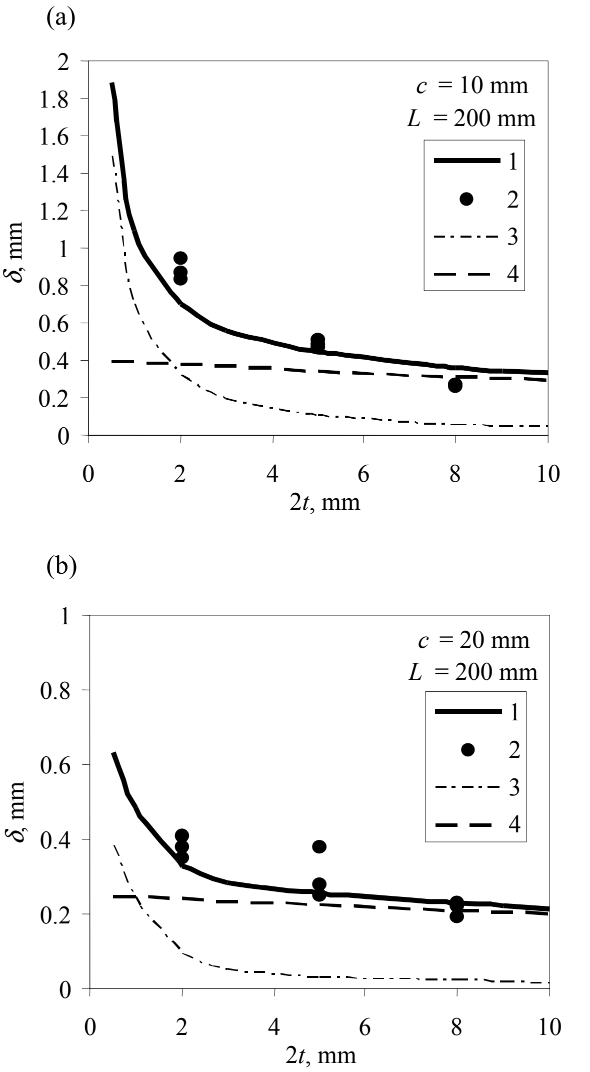

Fig. 2. Influence of facesheet thickness $2t$ on the deflection of the sandwich structure with a honeycomb core of 10 mm (a) and 20 mm (b); 1 – deflection δ, 2 – experimental deflection δ_{exp}, 3 – deflection related to bending stiffness δ_E, 4 – deflections related to shear stiffness δ_S.

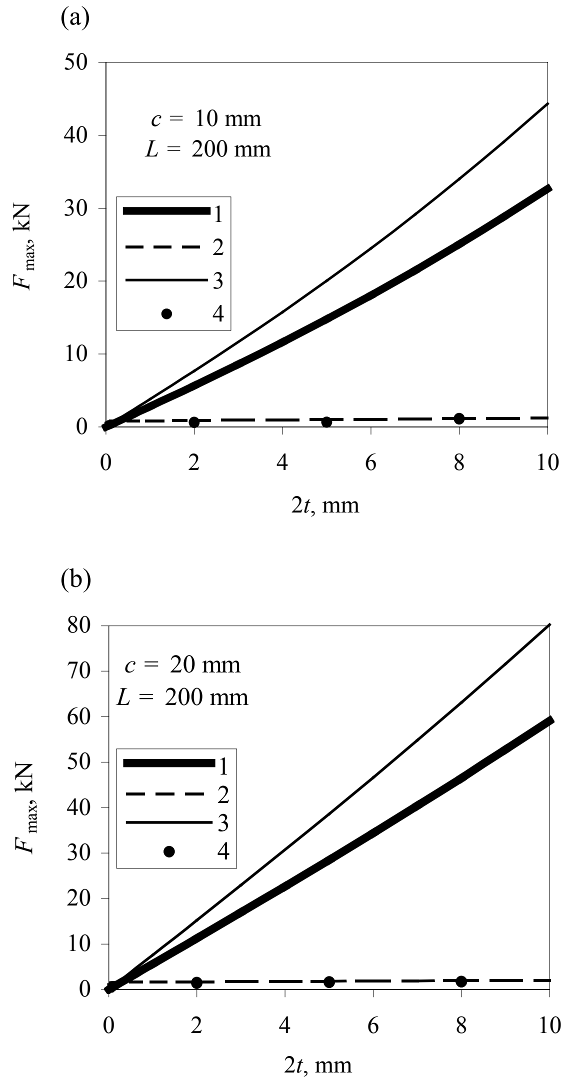

Fig. 3. Influence of facesheet thickness $2t$ on the bending force $F_{\max}$ of the sandwich structure with a honeycomb core of 10 mm (a) and 20 mm (b); 1 – top facesheet $F_{\max,\mathrm{f}}$, 2 – honeycomb core $F_{\max,\mathrm{c}}$, 3 – bottom facesheet $F_{\max,\mathrm{f}}$, 4 – experimentally tested values $F_{\max,\mathrm{exp}}$.

The influence of facesheet thickness on the maximum bending force, which represents the force case in which the failure of separate layers of the sandwich structure can occur, is presented in Fig. 3a for the core thickness of 10 mm and in Fig. 3b for the core thickness of 20 mm. The results show that in practically all cases the failure begins in the honeycomb core due to shear stress and the failure of facesheets occurs only afterwards. The first top facesheet is failed due to compress stress the limit strength of which is lower than the tension one (see Table 1). Only in the case of very thin facesheets $2t = 0.2 \div 0.4$ mm, it is possible that the failure occurs first in facesheets and then in the core. As seen in Fig. 3, these results were confirmed by the experimental test. This means that the specimen is failed as the core shear strength is reached, but the facesheets experience only 2–10% of their strength and the possibilities of laminates are not availed. Therefore eqs (9) and (10) were compared and the dependence of the possible core shear strength on the thickness of facesheets and distance between supports was calculated (see Fig. 4). The core shear strength can be changed by varying core material, core wall thickness, geometry of the cell, and other parameters. If the needed core strength is ensured, the limit state of the whole composite occurs at the same time both in the core and facesheets. Figure 4 shows that for an optimal sandwich structure the core shear strength should be chosen

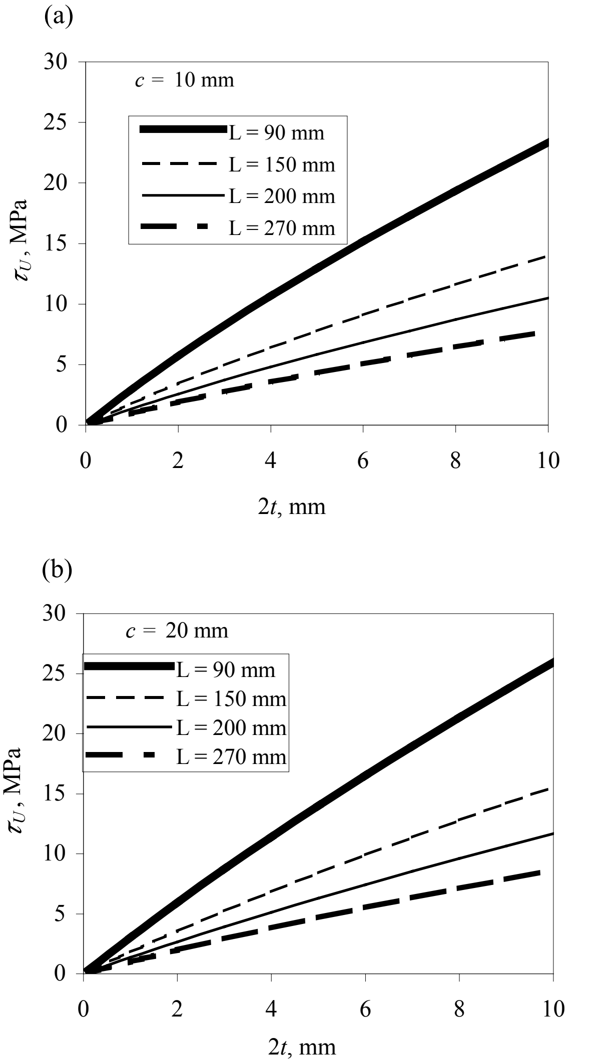

Fig. 4. Dependence of core shear strength τ_U on facesheet thickness $2t$ and distance between supports L with the honeycomb core thickness of $c = 10$ mm (a) and $c = 20$ mm (b).

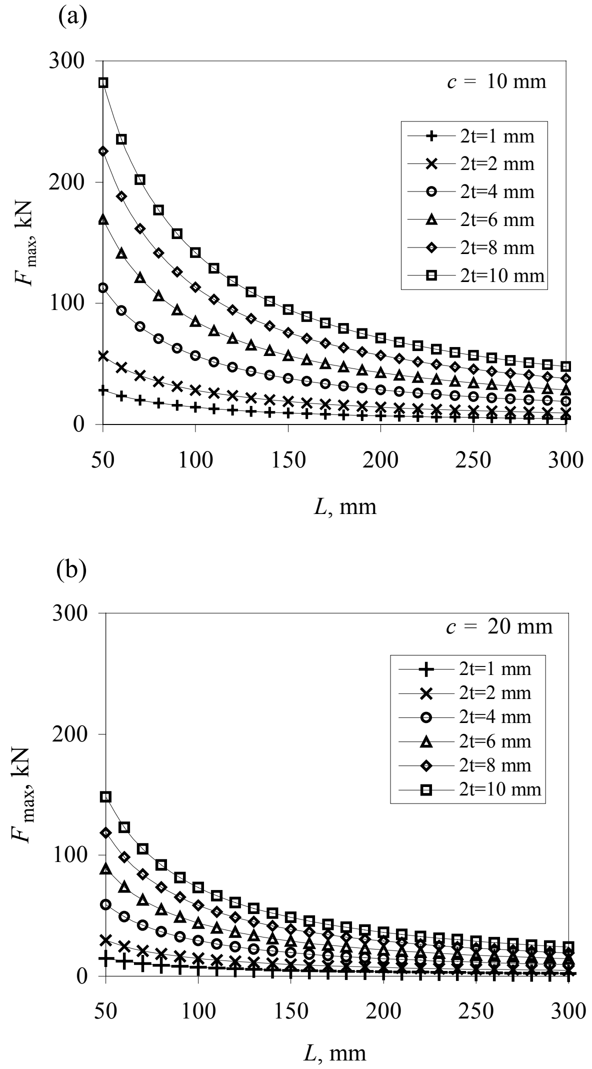

Fig. 5. Dependence of the maximum force $F_{\max}$ on the distance between supports L and facesheet thickness $2t$ with the honeycomb core thickness of $c = 10$ mm (a) and $c = 20$ mm (b).

according to facesheet thickness and the distance between supports; it increases as facesheet thickness increases and the distance between supports decreases.

Using the results of the above analysis, the dependence of the maximum bending force on both the distance between supports and facesheet thickness was derived. It was deduced that the dependence can be defined by a simple equation, as the coefficient of determination is very high $R^2 = 1$, as follows:

$$F_{\max} = 2733tL^{-0.992}, \text{ as } c = 10 \text{ mm}, \quad (11)$$

$$F_{\max} = 1572tL^{-1.0153}, \text{ as } c = 20 \text{ mm}. \quad (12)$$

The graphical expression of eqs (11) and (12), in particular values of $2t$ and L, is presented in Fig. 5a, b, respectively. These equations have a practical application. They can be used for the design of safety important objects made of the sandwich composite of woven glass fibre and polyvinylester resin facesheets and a polypropylene hexagonal honeycomb core.

CONCLUSIONS

- Strength analysis under quasi-static loading of the sandwich composite made of woven glass fibre and polyvinylester resin composite facesheets and a polypropylene hexagonal honeycomb core that can be used for safety important structures was carried out.
- The influence of facesheet thickness on the deflection was investigated in both analytical and experi-

mental ways. The obtained results are in good agreement. The relationships between facesheet thickness and total deflection, deflection related to bending stiffness, deflections related to shear stiffness of the sandwich structure with a honeycomb core of 10 and 20 mm were established.

- The normal and shear stress distribution in the cross section of the sandwich structure was studied. It was found that normal strain is distributed linearly in the cross section, but normal stress acts only in the facesheets. Shear stress acts only in the honeycomb core and is uniform throughout the thickness of the core.
- Analysis of the maximum bending force showed that the failure occurred in the honeycomb core due to shear stress and only after this the failure in facesheets began. The proposed experimentally confirmed equations gave the value for shear strength of the honeycomb core, enabling effective usage of strength resources of laminate materials.
- Based on the applied methodology and analytical investigation, the dependence of the maximum bending force on both the distance between supports and facesheet thickness was derived. The simple equations established have direct practical application.

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Kiudarmeeritud polüesterpinnaga ja polüpropüleenist kärgtäidisega laminaatkomposiitide analüütiline mudel ning selle eksperimentaalne katsetamine

Daiva Zeleniakiene, Vitalis Leisis ja Paulius Griskevicius

Uuriti kärgtäidisega *sandwich*-struktuuride deformatsioonikäitumist kvaasistaatilise koormuse olukorras. Katsetati kootud klaaskiudkanga ja polüvinüülestervaigu komposiidist pealiskihi ning polüpropüleenist kuusnurkse kärgtäidisega struktuuride staatilist paindekäitumist. Laminaadi teooria võrrandite ja tala teooria modifitseeritud võrrandite abil saadud tulemusi võrreldi eksperimentaalsetega. Kokkulangevus rakendatud metoodikaga oli hea. Uuritavatele struktuuridele tehti ka tugevusanalüüs. Hinnati geomeetriliste parameetrite mõju *sandwich*-struktuuride staatilisele käitumisele ja kihiliste struktuuride tugevusomadustele.