STATIC AND THERMAL BEHAVIOUR OF SHIP STRUCTURE SANDWICH PANELS

by

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Original scientific paper
https://doi.org/10.2298/TSCI190531463B

The mechanical properties of certain flexible core materials of ship structure sandwich panels, having skins made of metallic or composite laminates maybe significantly influenced by the temperature variations that may occur during the operational loading. At the same time, the improving knowledge of the behaviour of these panels in terms of bending strength and other stress/strain related aspects in various harsh conditions increases their superiority in terms of weight-to-strength ratio, high stiffness, easy to manufacture, acoustic, and thermal insulation. In the paper, the behaviour of the ship structural rectangular sandwich panels to the mechanical and thermal loading are presented. The sandwiches have a special core of 20 mm and skins made out of different materials (glass fiber reinforced polyester, steel and aluminum) with a thickness of 3 mm. Analysis consists of the behaviour of the composite sandwich panels in the bending test at constant speed by the three-point method, for three distances between different supports, by measuring the maximum displacement and force applied to the specimens under various thermal fields. The sandwich structures are also thermally analysed, determining their thermal conductivity by the heat flow measurement method. The experimental results are compared with the results obtained by finite element analysis in numerical simulation of all modelling cases.

Key words: *ship structural panels, sandwich composites, thermal analysis, finite element method analysis, bending analysis*

Introduction

The use of composite materials in Romanian shipbuilding is still on the beginning phase. This material kind is used especially for small craft, where not hard loading occurs. The most commonly used materials are fiber composite laminated panels, materials which have the disadvantage of imperfections due to delamination's, thickness variations, inclusions, *etc.*, most often due to using manual manufacturing for fabrication [1-3]. Various combinations of reinforcing elements (metal alloys, plastics, wood, *etc.*) with a role in increasing the compressive/tensile or bending strength and various epoxy resins or polyurethane foams, which give elasticity and hardness, can lead to the production of new composite structures with applicability in the shipbuilding field [4, 5]. In the last decade, modern sandwich panels, made up of a flexible

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core and two sides which are either of metal or composite materials, are widely used in the shipbuilding industry as primary and secondary structural elements precisely for their superior qualities in terms of weight-to-strength ratio, high stiffness, or acoustic and thermal insulation [6, 7].

In the paper, studies on the behavior of three sandwich structures types, having extruded polystyrene of 20 mm thick as core and skins with thickness of 3 mm made of different materials:
– polyester reinforced with glass fiber (PAFS),
– steel, and
– aluminum.

The faces and the core are glued with an adhesive aimed to facilitate mechanical and thermal load transfer between components. This increases the bending stiffness of the structure without adding substantial weight, despite the heterogeneity of the component materials and the totally different properties of the core and skins [8]. The behaviour to bending loading of sandwich (composite-polystyrene-composite) specimens, by three point bending method is analysed. Different loads are applied for the different spacing of the supports, during the analysis. Also, using the SOLID-type finite elements, the thermomechanical behaviour of the three numerical models of sandwich structures is performed.

Since the mechanical properties of certain composite structures with a sandwich panel core may be influenced by the temperature variations that may occur during their operation [9, 10], the experimental thermal analysis is also performed by determining the conductivity thermal method by measuring the heat flow. For the study of thermal effects in the behaviour analysis of sandwich panels, simplified computational models were often considered [11, 12].

Experimentally obtained parameter values are used in finite element numerical models by measuring maximum displacement and force applied on samples in different thermal fields.

When defining sandwich structures, responses due to thermal loading or deformations induced by the thermal field are considered separately from those induced by mechanical loads, even if the interaction between mechanical and thermal loads can lead to a particular behaviour. In this study we present the interactions between mechanical and thermal loads for three different sandwich panels in which the thermal conductivity was determined by the heat flow measurement method for which the concept of heat flow meter is according to ISO 8301:1991 [13].

Determining the bending characteristics using the three-point bending test

The bending characteristics of the composite structure are determined using rectangular-shaped specimens of sandwich plates with two high rigidity skins, made of glass fiber fabrics, called STRATIMAT, having a specific mass of 30 g/m^2, and a core made of extruded polystyrene with a thickness of 20 mm and a density of 30 kg/m^3. Glass fiber impregnation was performed with epoxy resin with a density of 1.1 kg/dm^3 (gelcoat type).

Samples are simply supported, being loaded at mid-span – the three-point bending test. The sample is subjected to bending at a steady speed, pressurised to failure or until the deflection reaches a pre-determined value. During the test, the force applied on the sample and arrow shall be measured.

The method used for determining the bending behaviour of samples and bending resistance, Young's modulus at bending and other aspects of the relation between stress and strain, given the circumstances [14].

The tests were carried out at the room temperature (23 °C) on the universal testing machine, TESTOMETRIC M 350-5AT of 5 kN from within the Department of Manufacturing Engineering from *Dunarea de Jos* University of Galati, fig. 1.

The machine allows relative movement of the pressing lid in relation the supports, at an approximate and adjustable v is the speed, the radius of the pressing lid – r_1 , respectively, the radius of the supports, r_2, have the following values: r_1 = 5±0.1 mm, r_2 = 2±0.2 mm, with a distance between the supports, L, adjustable, fig. 2.

Three specimens type sandwich (210 mm × 26 mm) with core made out of foam with thickness of 20 mm and skins made of composite material epoxy-eglass with thickness of 3 mm have been tested for three point bending. The distance between supports are respectivelly: L = 160 mm, L = 150 mm, L = 140 mm. During tests three speeds have been used (v = 5 mm per minute, v = 50 mm per minute, respectivelly, v = 100 mm per minute). Totally, 27 specimens have been tested.

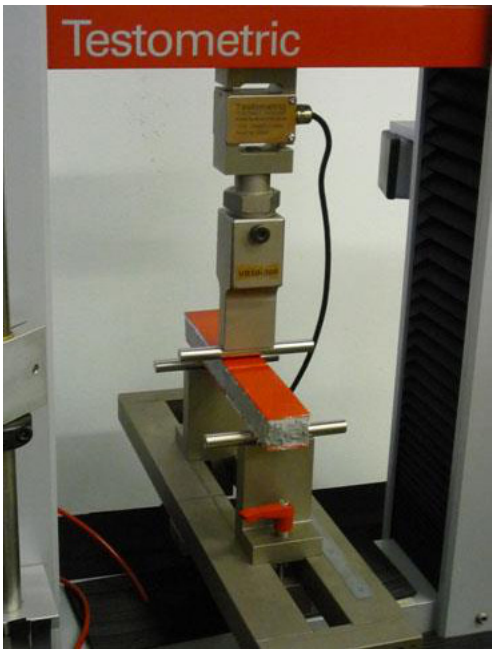


Figure 1. Testing device for bending in three points contact

The samples from the sandwich panel have been used for testing, fig. 3, with a uniform rectangular section, according to the data presented in tab. 1 and fig. 4.

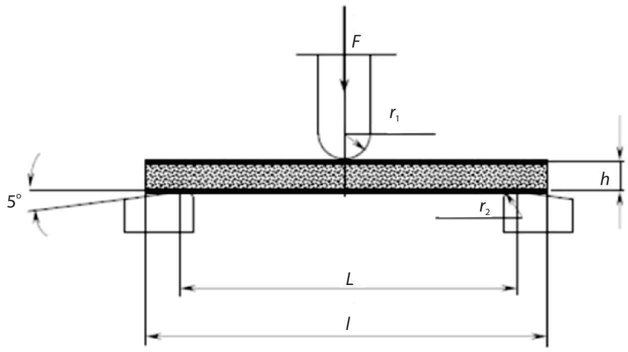


Figure 2. Principle of the three-point-bending test

Figure 3. Samples of 210 mm × 30 mm × 26 mm

Table 1. Dimensions of the samples and lengths of supports

Sample type	Number of samples	Length, l [mm]	Length between supports, L [mm]	Width, b [mm]	Height, h [mm]
Sp1	3	210	160	30	26
Sp2	3	210	150	30	26
Sp3	3	210	140	30	26

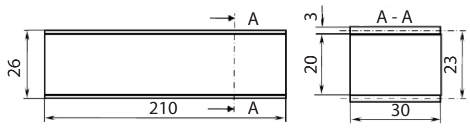


Figure 4. Geometry of the sample used in three-point-bending test

In order to study the influence of the speed test, three speed test values have been taken into account, namely: 5, 50, respectively, 100 mm per minute. For each speed three samples have been tested. In fig. 5 the force-displacement model for various speeds (v = 5 mm per minute, v = 50 mm per minute, respectivelly, v = 100 mm per minute) for specimen Type 1, tab. 1, with distance between supports L = 160 mm, is illustrated. In fig. 6 the force-displacement model for specimens from tab. 1, at speed v = 5 mm per minute.

In order to study the influence of the length between the supports on the mechanical behaviour, three different lengths, have been considered as namely: 140 mm, 150 mm, and 160 mm. These tests were conducted at a speed of 5mm per minute at the ambient temperature, 23 °C. For each length, three samples have been tested. Figure 6 presents the force variation depending on displacement, for v = 50 mm per minute. For example, the values of the Young's modulus, for a length between supports L = 160 mm, are shown in tab. 2.

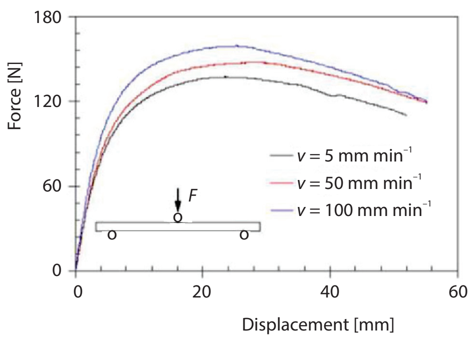


Figure 5. Force/displacement/speed test values, L = 160 mm

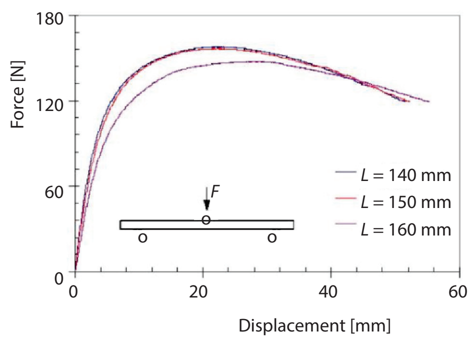


Figure 6. Force/displacement/length of supports, v = 5 mm per minute

Table 2. Results of the three-point-bending tests

Test No.	Speed, v [mm·min^{-1}]	Length between supports, L [mm]	Young's modulus at bending, [MPa]
1	5	160	0.36235
2	50	160	0.38756
3	100	160	0.41025

Static analysis of samples in composite sandwich panels using the finite element method

For sandwich-type panels, given the polystyrene core, of the same thickness (20 mm), and the polymeric composite skins such as epoxy-eglass, aluminum, respectively steel, their mechanical behaviour being analysed. The cases were analysed, according to data from tab. 3.

Static behaviour of sandwich structures has been studied, with characteristics of the material according to tab. 4, when the loads have the following values: F_1 = 60 N, F_2 = 90 N, F_3 = 120 N, and F_4 = 150 N. In the tab. 4, the materials characteristic used for the sandwich skins steel-core-steel (ST-core-ST), aluminum-core-aluminum (AL-core-AL), Composite glass fiber/epoxy resin-core-Composite glass fiber/epoxy resin (CO-core-CO) and for core, are given.

Table 3. Samples with sandwich-type structure, subjected to SOLID-type modelling

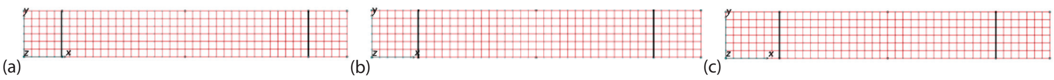
Upper plate 1, thickness 3 mm	Core, thickness 20 mm	Lower plate 2, thickness 3 mm
Steel	Extruded polystyrene	Steel
Glass fiber and epoxy	Extruded polystyrene	Glass fiber and epoxy
Aluminum	Extruded polystyrene	Aluminum

Table 4. Material characteristics of sandwich-type structures

Material	Used for	Type of sandwich	Characteristics
Steel	Skin	ST-core-ST	$E_x = 2.1\cdot10^{11}$ Pa, $\mu_{xy} = 0.3$, $\rho = 7860$ kg/m^3
Aluminum	Skin	AL-core-AL	$E_x = 0.72\cdot10^{11}$ Pa, $G_{xy} = 0.27\cdot10^{11}$ Pa $\rho = 0.27\cdot10^4$ kg/m^3, $\mu_{xy} = 0.33$
Composite – E-glass fiber and epoxy resin	Skin	CO-core-CO	$E_x = 35\cdot10^8$ Pa, $Ey = E_z = 9\cdot10^9$ Pa $\mu_{xy} = \mu_{xz} =0.28$, $\mu_{xz} = 0.4$, $\rho = 1850$ kg/m^3 $G_{xy} = G_{xz} = 47\cdot10^8$ Pa, $G_{yz} = 35\cdot10^8$ Pa
Extruded polystyrene	Core	–	$E_x = 0.67\cdot10^6$ Pa, $\mu_{xy} = 0.01$, $\rho = 80$ kg/m^3

In order to determine the behaviour of composite sandwich panels, using FEM, SOLID-type elements have been used.

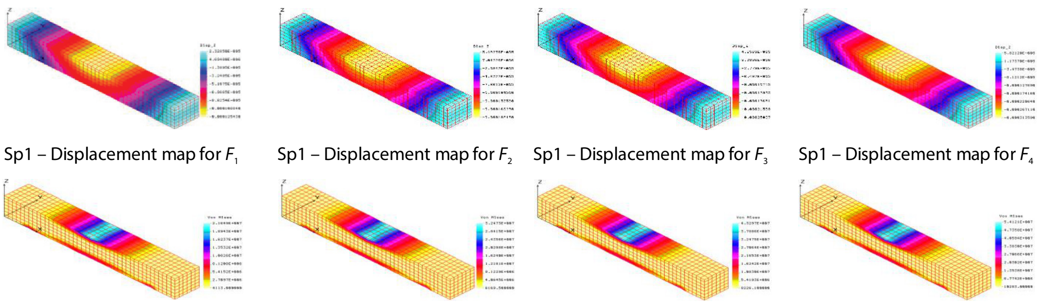
Figure 7 presents the joints of the sample, taking into consideration the length of supports $L = 160$ mm, 150 mm, 140 mm.



(a) (b) (c)

Figure 7. Loading of the structure, length between supports: (a) $L = 160$ mm, (b) 150 mm, and (c) $L = 140$ mm

Following the finite element analysis, maximum displacement w_z [m] and equivalent stresses were determined when the samples were loaded with $F_1 = 60$ N, $F_2 = 90$ N, $F_3 = 120$ N, and $F_4 = 150$ N. Thus, Figures 8-10 present the maps of displacements and the equivalent stress for loads for F_1, F_2, F_3, and F_4, for sandwich structures with skins made of steel, composite



Sp1 – Displacement map for F_1 Sp1 – Displacement map for F_2 Sp1 – Displacement map for F_3 Sp1 – Displacement map for F_4

Sp1 – Stress map for F_1 Sp1 – Stress map for F_2 Sp1 – Stress map for F_3 Sp1 – Stress map for F_4

Figure 8. Maximum displacements and equivalent stress maps at sample loading Sp1 (ST-core-ST) with stress values of F_1, F_2, F_3, and F_4 – length between supports $L = 160$ mm

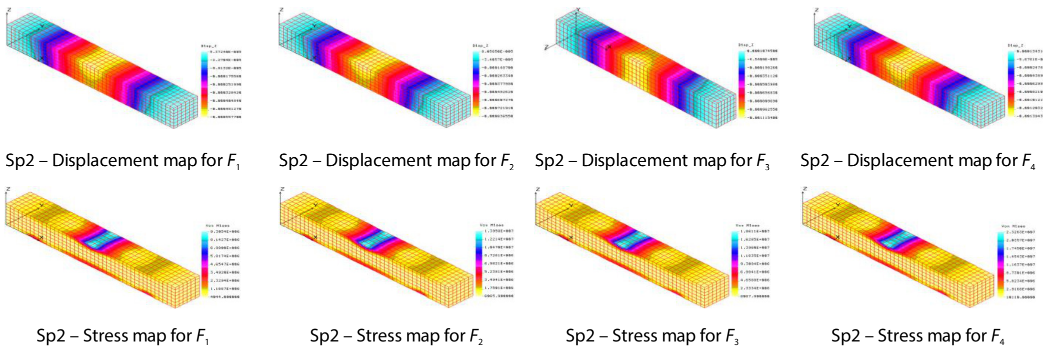


Figure 9. Maximum displacements and equivalent stress maps at sample loading Sp2 (CO-core-CO) with stress values of F_1, F_2, F_3, and F_4 – length between supports L = 150 mm

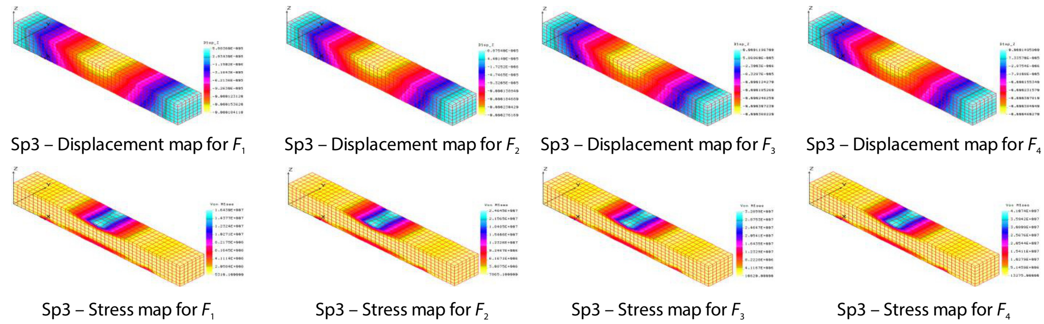


Figure 10. Maximum displacements and equivalent stress maps at sample loading Sp3 (Al-core-Al) with stress values of F_1, F_2, F_3, and F_4 – length between supports L = 140 mm

materials, aluminum, with a length of support of L = 160 mm, 150 mm, and 140 mm. As it is seen, the maximum displacement occurs in the section placed on $X = 0.5L$. The maximum displacement value is dependent of the force magnitude. Due to the fact the SOLID elements have been used, the influence of shearing on the bending deformations is very present.

These observations are also available for the equivalent stresses map, where the shear stresses amount in the total equivalent stresses is significant.

Figures 11-13 present the $w_{\max}$ and σ_{ech} variation for all shaped loads and samples.

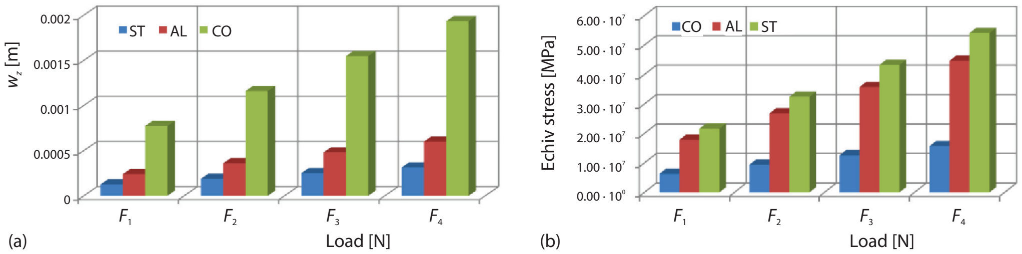


Figure 11. The Sp1 – Maximum displacement variation and equivalent stress variation depending on the load; (a) Sp1 – maximum displacement variation *vs*. load and (b) Sp1 – equivalent sress variation *vs*. load

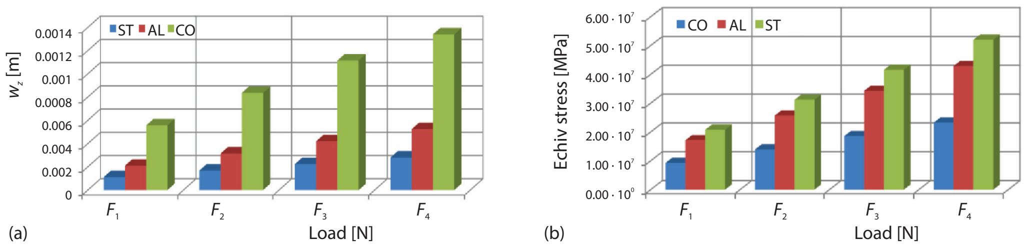


Figure 12. The Sp2 – Maximum displacement variation and equivalent stress variation depending on the load; (a) Sp2 – maximum displacement variation *vs.* load and (b) Sp2 – equivalent sress variation *vs.* load

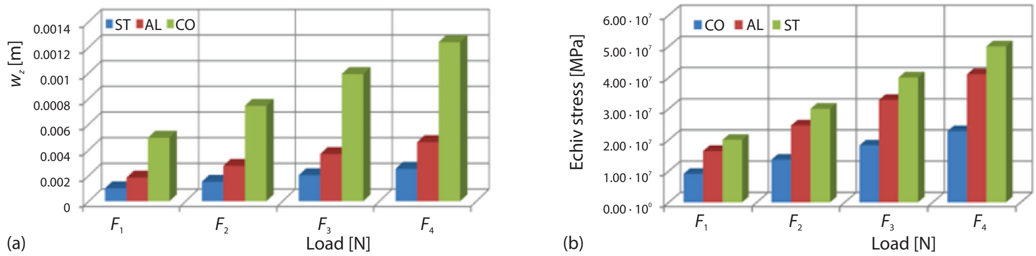


Figure 13. The Sp3 – Maximum displacement variation and equivalent stress variation depending on the load; (a) Sp3 – maximum displacement variation *vs.* load and (b) Sp3 – equivalent sress variation *vs.* load

Regarding the influence of the distance between supports upon the maximum displacement values, respectively, the equivalent stress, these are presented in figs. 14-16.

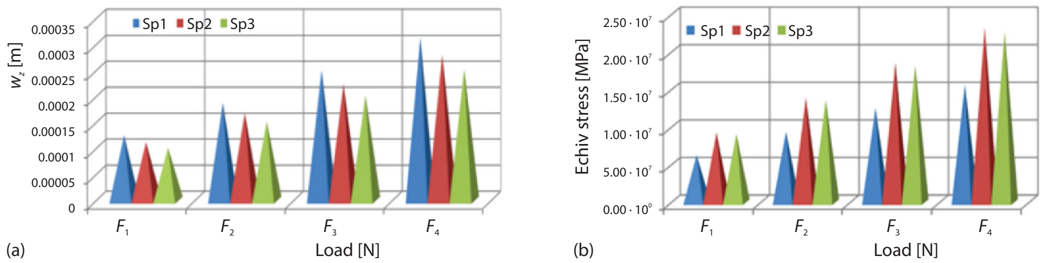


Figure 14. The ST – Maximum displacement variation and equivalent stress variation *vs.* load – samples with skins made of steel; (a) ST – maximum displacement variation *vs.* load and (b) ST – equivalent sress variation *vs.* load

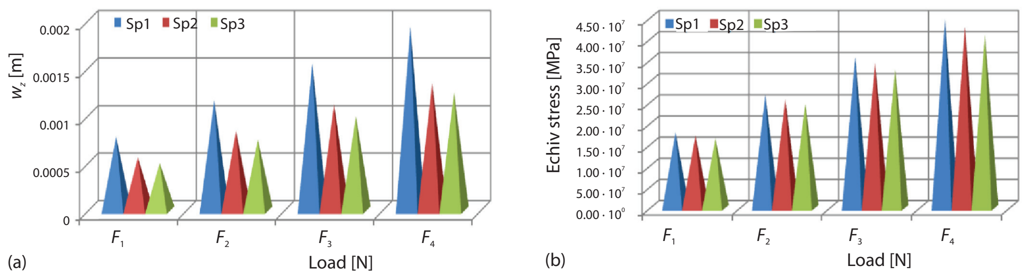
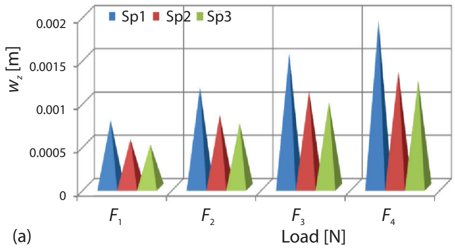


Figure 15. The Al – Maximum displacement variation and equivalent stress variation *vs.* load – samples with skins made of aluminum; (a) AL – maximum displacement variation *vs.* load and (b) AL – equivalent sress variation *vs.* load



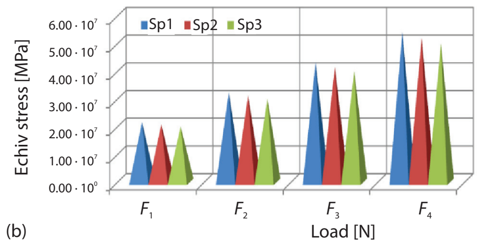


Figure 16. The CO – Maximum displacement variation and equivalent stress variation vs. load – samples with skins made of composite; (a) CO – maximum displacement variation *vs.* load and (b) CO – equivalent sress variation *vs.* load

Determining the thermal characteristics of composite sandwich structures

To determine the thermal characteristics of the sandwich structures, the thermal conductivity is analysed firstly.

Three specimens have been tested from the point of view of thermal conductivity (dimensions 300 × 300 mm, core made of foam with thickness of 20 mm and skins made of epoxy-eglass, aluminum, respectivelly, steel, with thickness of 3 mm). The specimens are the same as those analysed in sections *Determining the bending characteristics using the three-point bending test* and *Thermal analysis with finite elements*, tab. 5. Each sample under test is placed between a hot plate and the heat flowmeter which is attached to a cold plate. The apparatus is surrounded by insulation. The hot and cold plates are maintained at suitable constant temperatures, measured by surface thermocouples. A calibration constant for the individual apparatus is derived from testing a sample of known constant thermal conductivity. By measuring the heat flowmeter output and the mean temperature of the test sample, the thermal conductivity is calculated using this calibration constant. The Hilton B480 unit [15] is based on the heat flowmeter method described. ISO 8301:1991 gives the range of sample sizes that can be used with this method of conductivity measurement [13]. The Hilton B480 unit is capable of holding samples of 300 × 300 mm and 75 mm thickness, fig. 17.

Table 5. Dimensions and thermal properties of sandwich structures

Item No.	Sandwich material	Dimension [mm^2]	Thermal conductivity, λ [Wm^{-1}K^{-1}]	Thermal resistance, R [m^{2}KW^{-1}]
1	ST-core-ST	300 × 300	0.043	0.604
2	Al-core-Al	300 × 300	0.049	0.53
3	CO-core-CO	300 × 300	0.036	0.722

Figure 17. The Hilton B480 unit and samples 300 × 300 × 26 mm

The Fourier eq. (1) provides the relationship between the parameters of the test samples and the sections:

$$q = \lambda A \frac{\Delta T}{\Delta x} \tag{1}$$

where q [W] and T [K] are the heat flow and temperature difference across the sample, respectively, A [m^2] is the area through which the heat flows, x [m] – the thickness, and λ [Wm^{-1}K^{-1}] – the thermal conductivity of samples.

The thermal conductivity λ is determined with equation [15]:

$$\lambda = \frac{x\left(\left[k_1 + \left(k_2 \overline{T}\right)\right] + \left\{\left[k_3 + \left(k_4 \overline{T}\right)\right] HFM\right\} + \left\{\left[k_5 + \left(k_6 \overline{T}\right)\right] HFM^2\right\}\right)}{\Delta T} \tag{2}$$

where x [m] is the sample thickness, k_1, k_2, k_3, k_4, k_5, k_6, are calibration constants, HFM [mV] is the heat flowmeter output, $\overline{T}$ [K] – the mean temperature, and ΔT [K] – the temperature difference between the hot plate temperature and the cold plate temperature.

In the measurement, upper and lower plates were constantly heated at 60 °C and cooled at 20 °C, respectively, tab. 5. The values of thermal conductivity and thermal resistance that are experimentally determined are used in thermal analysis with FEM, described in section *Thermal analysis with finite elements.*

Thermal analysis with finite elements

To analyse the thermal behaviour of the sandwich structures FEM analysis has been used (module COSMOS FFE Thermal). Heat transfer can be divided into heat conduction, heat convection, and heat radiation.

In the simulation, thermal conductivity, density and specific heat capacity of materials are all critical parameters to describe the transient process and the heat conduction process along the sandwich structure is governed by the following PDE:

$$\rho C \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_z \frac{\partial T}{\partial z}\right) + Q \tag{3}$$

where T is temperature, t – the time, ρ – the density, C – the specific heat, k_x, k_y, k_z – the thermal conductivities in global X-, Y-, and Z-directions, respectively, and Q – the volumetric heat generation rate.

The material properties play an important role of achieving an accurate prediction of the heat transfer process. The characterization of the parameters used in the finite element should be carefully conducted. Firstly, it is noted that ρ, C, and k of sandwich structure may change with temperature. However, as the variation of these parameters is minor when the temperature is between –20 °C and 20 °C, it is assumed that these parameters are independent of temperature in the simulation. However the heat conduction is the major part of the heat transfer process along the sandwich structure, k is one of the most important thermal properties that require a careful evaluation.

In the numerical analysis only thermal conduction has been considered as thermal transfer mechanism, because heat convection, and heat radiation is negligible for the range of temperature used in analysis.

Three sandwich-type structures with extruded polystyrene and skins of various materials are subjected to modelling, ST-core-ST, AL-core-AL, CO-core-CO. In modelling, one of the

Table 6. Temperatures associated to thermal modelling of sandwich structures

ΔT_1 [°C]	ΔT_2 [°C]	ΔT_3 [°C]	ΔT_4 [°C]
20	20	20	20
10	0	–10	–20

skins is considered to be at a temperature of 20 °C, since the other skin establishing temperatures is of 10 °C, 0 °C to –10 °C, –20 °C, respectively, tab. 6, fig. 18.

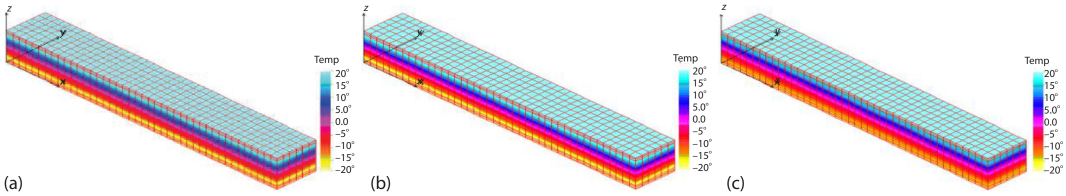


Figure 18. Fields of the temperatures for sandwich structures with skins made of ST, AL, CO-ΔT_4

As a result of thermal modelling for composite sandwich structures, values of the temperatures at the three layers of the composite structures have been presented for cases of thermal load ΔT_1-ΔT_4, Figures 19-22 present variations of these temperatures *vs.* the position z [m] of the point across thickness. Temperatures in 12 points of contact have been registered on the thickness of the laminated.

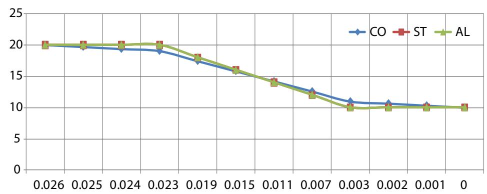


Figure 19. Temperature variations for ΔT_1

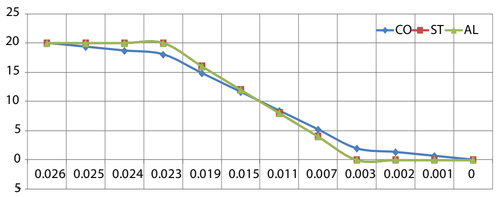


Figure 20. Temperature variations for ΔT_2

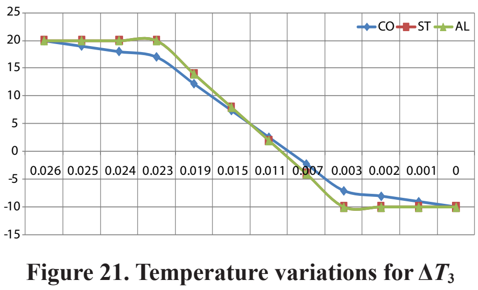


Figure 21. Temperature variations for ΔT_3

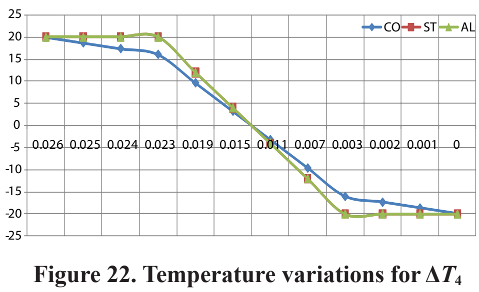


Figure 22. Temperature variations for ΔT_4

Differences arising from thermal modelling of the samples, in order to highlight the variation of heat transfer between the two skins made of the same material, at different temperatures, across the core of polystyrene, can be explained in terms of the order of expansion coefficient for steel, aluminum and composite. It can be noticed that the expansion coefficient for metals is in the order of 10^2, while the composite is in the order of 10^{-2}.

Results and discussion

Determining the bending characteristics using the three-point bending test

The sandwich panels, with foam core have the ratio bending stiffness/strength and weight much more than classical materials. This feature is needed and is used in ship structures building where in last decades composite materials have been used more and more.

The bending tests have been performed only on sandwich specimens type beams because the testing norms are more clear for this type of specimen [14].

Finally, during the experimental analysis of three points bending that has been used to determine the mechanical characteristics, the following observations have been performed.

The increasing of testing speed (v = 5 mm per minute, v = 50 mm per minute, v = 100 mm per minute) leads to the increasing of bending force (see fig, 5, with L = 160 mm). In the same time, the increasing of the distance between supports (L = 140 mm, L = 150 mm, L = 160 mm) leads to the decreasing of bending force, to obtain the same stiffness (see fig. 6, with v = 5 mm per minute).

Static analysis of samples in composite sandwich panels using the finite element method

The results from the three points bending four force magnitudes (F_1 = 60 N, F_2 = 90 N, F_3 = 120 N, F_4 = 150 N) and three distances between supports (L = 140 mm, L = 150 mm, L = 160 mm) have been used for the FEM analysis of the three sandwich specimens (ST-core-ST, AL-core-AL, CO-core-CO).

By analysing the results obtained from the static modelling, one can state that the maximum displacement increases directly proportional to the forces, having low value, in the case of the specimen made of sandwich-type composite with faces made of steel and high value, in the case of the specimen made of sandwich-type composite with faces made of composite. This occurs because the displacement depends inversely proportional to the Young's modulus of the material, figs. 8-10.

The biggest values of the displacements have been obtained in the case of force F_4 = 150 N applied on the sandwich structure type CO-core-CO and distance between supports L = 160 mm. The smallest value of the displacements have been obtained in the case of force F_1 = 60 N applied on the sandwich structure type ST-core-ST and distance between supports L = 140 mm, see figs. 11-13.

The biggest values of the equivalent stress have been obtained in the case of force F_4 = 150 N applied on the sandwich structure type ST-core-ST and distance between supports L = 160 mm. Opposite, the smallest value of the equivalent stress have been obtained in the case of force F_1 = 60 N applied on the sandwich structure type CO-core-CO and distance between supports L = 140 mm, see figs. 11-13).

According to the displacements analysis for each sandwich structure, *vs.* skins material, we have observed that for the sandwich structures type ST-core-ST the biggest values of the displacements have been obtained in the case of force F_4 = 150 N applied on the sandwich structure and distance between supports L = 160 mm. The smallest value of the displacements have been obtained in the case of force F_1 = 60 N applied on the sandwich structure and distance between supports L = 140 mm, see fig. 14. The same observations are available for sandwich structures type AL-core-AL and CO-core-CO, see figs. 15 and 16. Similar observations can be made also for the equivalent stress for each sandwich structure.

Thermal analysis with finite elements

From the point of view of thermal loading, the severe case is observed at ΔT_4, where the difference of temperature between the both skins is of 40 °C. The temperatures field for the three sandwich type structures loaded at ΔT_4 is illustrated in fig. 18.

The best behaviour from the point of view of thermal loading is observed at the structure ST-core-ST. A slow variation of the temperature so within the layer made of steel (ST) and within the foam core is observed. This case is due to the small thermal conductivity of the both steel skins (ST) compared with the high conductivity of the aluminum skins (AL) and composite skins (CO), see figs. 19-22.

From performed measurements, the composite panel with the structure type CO-core-CO has low thermal conductivity and high thermal resistance, compared to the other two structures.

Conclusions

In the paper, the behaviour of the sandwich structures under the mechanical loading and thermal loading is treated. The both loadings are separate treated, even in the case that the interaction between mechanical and thermal loadings can lead to special behaviour.

The cumulative effect given by the modelling and optimising of the three composite materials in the present study (ST-core-ST, AL-core-AL, CO-core-CO) is based on the previous results obtained in [16]. Following to the static modelling, it has been observed that equivalent stresses increase since the temperatures differences are increasing, having a small value in the case of sandwich samples with skins made out of composite materials and a high value in the case of samples with skins made out of steel. Also, a modification of the skins materials gives the sandwich structure rigidity. As the thickness of the core increases, the thermal analysis shows a different behaviour in the case of sandwich type composite panels in terms of the temperature distribution over the thickness of the layer structures. From the previous performed measurements [16], the CO-core-CO specimens have low thermal conductivity and high thermal resistance, compared to the other two structures.

The general conclusion, both from the previous studies and from the present work, shows that, for all structures, the highest temperature is at the base of foam, which is characterized by low conductivity. Thus, CO-core-CO sandwich structures are recommended to be used in ship structures and various other applications, as insulating materials, when are operating at low temperatures.

As a result of static modelling, it can be noticed that the equivalent stress also increases directly proportional to the applied stress, having low value in the case of a test-piece made of composite sandwich-type panel with skins made of composite and high value in the case of the test-piece made of sandwich-type composite with faces made of steel. This occurs because the equivalent stress depends directly proportional to the Young's modulus of the material.

As a result of static modelling, when taking into account the distance between the supports, it can be noticed, as it should, that the higher the maximum displacement value, the longer the distance between supports, regardless of the nature of the skins of the composite sandwich-type samples. As a result of static modelling, when taking into account the distance between the supports, it can be noticed, as it should, that the higher the equivalent stress value, the longer the distance between supports, regardless of the nature of the skins of the composite sandwich-type samples. From the three-point-bending test, it has been noticed that increasing the speed test leads to an increase in the bending force, and also an increase in the length between the supports leads to a decrease in the bending force. Also, a change in the materials of the skins offers a higher stiffness and rigidity of the panel, but with the addition of a heavier weight than in the case of composite structures. Thermal analysis shows different behaviour of composite sandwich-type panels in terms of temperature distribution on thickness of layer structures.

Due to high conductivity of the skins made of aluminum and steel, the temperature variation in these layers is insignificant. For all three structures, the highest temperature is at the core of the polystyrene, which is characterised by low conductivity. In terms of heat, the CO-core-CO structure behaves best at big temperature differences on the skins of the structure. Thus, the sandwich-type structures with faces made of composite are recommended to be used as insulating material, in various applications, at low temperatures. It remains, however, the obvious conclusion that sandwich structures, in most applications, have greater strength, better thermal insulation and acoustic backing, compared with conventional materials.

References

[1] Grabian, J., *et al*., The Role of Innovative Composite Materials in the Safe and Efficient Operation of Floating Marine Structures, *Scientific Journals of the Maritime University of Szczecin*, *52* (2017), 124, pp. 23-29
[2] Selvaraju, S., Ilaiyavel, S., Applications of Composites in Marine Industry, J*ournal of Engineering Research and Studies*, *II* (2011), II, pp. 89-91
[3] Tabacu, S., *et al.*, Structural Performances of Thermoplastic Manufactured Parts, *Mat. Plast*., *45* (2008), 1, pp. 113-118
[4] Mavhungu, S. T., *et al*., Aluminum Matrix Composites for Industrial Use: Advances and Trends, *Procedia Manufacturing*, *7* (2017), 1, pp. 178-182
[5] Lancaster, L., *et al*., Utilization of Agro-Industrial Waste in Metal Matrix Composites: Towards Sustainability, International Journal of Environmental, Ecological, Geomatics, *Earth Science and Engineering*, *7* (2013), 1, pp. 25-33
[6] Rayjade, G. R., *et al*., Study of Composite Sandwich Structure and Bending Characteristics – A Review, *International Journal of Current Engineering and Technology*, *5* (2015), 2, pp. 797-802
[7] Frostig, Y., Thomsen, O. T., Non-Linear Thermal Response of Sandwich Panels with a Flexible Core and Temperature Dependent Mechanical Propertie's, *Composites: Part B*, *39* (2008), 1, pp. 165-184
[8] Beznea, E. F., *et al*., Parametric Study of Experimental and Numerical Simulation of Sandwich Composite Structures Flexural Behaviour, *Materiale Plastice*, *54* (2017), 4, pp. 682-688
[9] Thomas, M., *et al*., An Experimental Device for the Simultaneous Estimation of the Thermal Conductivity 3-D Tensor and the Specific Heat of Orthotropic Composite Materials, *Compos. Sci. Technol*., *53* (2010.), 23-24, pp. 5487-5498
[10] Matine, A., *et al*., Thermal Properties of Composite Materials: Effective Conductivity Tensor and Edge Effects, *Journal of Physics: Conference Series*, *395* (2012), Sept., 012014
[11] Tsekmes, I. A., *et al*., Thermal Conductivity of Polymeric Composites: A Review, *Proceedings*, IEEE International Conference on Solid Dielectrics, Bologna, Italy
[12] Villiere, M., *et al*., Experimental Determination and Modelling of Thermal Conductivity Tensor of Carbon/Epoxy Composite, *Composites: Part A*, *46* (2013), Mar., pp. 60-68
[13] ***, ISO 8301, Thermal Insulation – Determination of Steady-State Thermal Resistance and Related Properties – Heat Flow Meter Apparatus, 1991
[14] ***, SR EN ISO 178, Plastics, Determination of flexural properties
[15] ***, Hilton 480 unit Instruction manual
[16] Beznea, E. F., *et al*., Influence of the Thermal Field on Static Behaviour of Sandwich Structures, *Materiale Plastice*, *56* (2019), 1, pp. 110-114

Paper submitted: May 31, 2019
Paper revised: December 7, 2019
Paper accepted: December 14, 2019

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