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Original Research

Experimental Study of Mechanical Properties of Selected Polymer Sandwich Composites

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Abstract

The aim of this work was to determine the influence of material and geometric factors of selected sandwich composites on their mechanical properties. The first pair of sandwich materials under consideration were made by the industrial infusion method and consisted of epoxy resin reinforced with 7 layers of glass fabric (skin) with core made of PVC foam or aramid honeycomb. The second pair of materials was prepared manually and consisted of polyester resin reinforced with glass mat (skin) with aramid honeycomb core of varying thicknesses. The aim of this work was to determine the influence of material and geometrical factors of selected sandwich composites on their mechanical properties. The mechanical properties were determined in static bending, compression and tensile tests. In each case, the method of destruction of the tested composite materials was assessed. In the case of composites with epoxy resin skins application of aramid honeycomb core resulted in higher tensile and edgewise compressive strength. For materials with polyester resin skins and honeycomb cores it was found that increase of core thickness yielded higher bending stiffness but the tensile and bending strength were reduced.

Keywords: sandwich composites, mechanical properties, static bending tests, static compression test, static tensile test

1. Introduction

Layered composites are usually made of several layers of fibers, in the form of roving, knitted fabrics, fabrics or mats, which are embedded in a polymer, ceramic or metal matrix (Woźniak & Kukiełka, 2014). Layered composites are classified into the two categories: laminates and sandwich composites.

Laminates are composite materials that consist of a polymer matrix and several layers of fabrics or mats. An example of a laminate is plywood, which, unlike the wood from which it is made, has isotropic properties in the plane of the sheet (Boczkowska et al., 2016).

Sandwich composites are materials consisting of rigid skin and a low-density core. They owe their unique properties by the combination of the best features of two materials with completely different properties. Sandwich structures are characterized by a high stiffness to weight ratio. An example of such composite can be a resonant panel, which consists of high-quality cardboard glued between the skins of a carbon fiber-reinforced polymer composite (Rajczyk & Stachecki, 2011). The core of the sandwich composite can be made of foamed polymer or honeycomb core (this is the most commonly used core). The honeycomb is formed as a result of local sticking of the tapes at specified intervals, and then stretching them in a direction perpendicular to the tape. The cellular disc created in this way is joined with skins on two sides. Skins are most often made of polymer composites, which are reinforced with carbon fibers or glass fabrics (Mayer & Kaczmar, 2008). The resulting sandwich panel is rigid, light and has high compressive and bending strength. Sandwich composites are most often used in the aerospace industry (mainly military), civil engineering (beams, girders) and automotive industry (Grabarski, 2001). Multilayer structures, despite their many advantages, have also a number of disadvantages associated with a variety of modes of destruction. Sandwich composites may be damaged as a result of: buckling, delamination of the core, shearing of the core and local surface depression or buckling of a single cell (Ochelski, 2004).

The properties of sandwich composites strongly depend on the materials used for their core and skins. A sandwich structure requires a specific distribution of internal forces and a system of masses which affect the stability, strength and rigidity of the designed structure. Skins of sandwich composites are usually made of steel, aluminum alloys or fiber reinforced polymer (FRP) composites. Organic materials such as balsa or cork tree were used to build the cores of the first sandwich composites (Sawal et al., 2015). These materials were replaced by artificial materials such as cellular cores or polymeric foams due to excessive cost of production. Today, there are 5 basic types of materials that are used to produce the core of sandwich structures: balsa, PU (polyurethane), PVC (polyvinyl chloride), PET (polyethylene terephthalate) foams and honeycomb cores.

Laminate with balsa is a sandwich composite characterized by very high stiffness, strength, and low weight. Balsa is perfectly compatible with all types of adhesives and resins and is suitable for most production processes.

Polymer foams are the cheapest and lightest types of cores. These include PU, PVC and PET foams. Their mechanical properties depend mainly on the density of the material used. Moreover, they are easy to manufacture and process. PU foam is a rigid foam with closed cells. It is used for sandwich elements produced industrially in large quantities. It is used in both simple and complex 3D structures, at room and elevated temperature. PVC foam is cross-linked polymer foam with closed cells. It is characterized by high rigidity, strength and low density. PVC foam is resistant to chemicals, is not brittle, and has very low water absorption. It is compatible with the majority of resins and ideally suits as a basic material for all lightweight sandwich structures which are subject to static or dynamic loads. PET foams are thermoplastic structural foams. They are used for all types of resin connections. Their big advantage is their ease of processing and thermoformability. Due to their beneficial properties – high compressive strength, creep and fatigue resistance – they are used in a wide range of composites.

Honeycomb cores are used in heavily loaded structural elements. They are manufactured from various materials, such as paper or aluminum alloys. Paper cores with a honeycomb structure consist of a series of hexagonal cells joined together. They form a sheet that contains about 95% free space. Due to the unique geometry of honeycomb cores, sandwich composites are characterized by high strength to weight ratio, high rigidity, good fatigue and acoustic properties, thermal and acoustic insulation, resistance to fire, moisture, corrosion, and many others. The unique geometric structure of the honeycomb cores combined with the properties of the materials used, provides unique properties.

The aim of this work was to determine the influence of material and geometrical factors of selected sandwich composites on their mechanical properties. The mechanical properties were determined in static bending, compression and tensile tests. In each case, the method of destruction of the tested composite materials was assessed.

2. Materials and methods

Four types of sandwich materials were adopted for the examination, which in the further part of the paper were marked with numbers from 1 to 4.

Materials 1 and 2: the skins were prepared from a laminate made of glass fabric with a plain weave. Each skin consisted of 7 layers of fabric. The laminate matrix was made of Hexion Epikote Resin L 1100 with a density of 1150 kg/m^3. The average thickness of one skin was 1.4 mm. The materials were made by the industrial infusion method. Infusion moulding is a modern process for manufacturing composite materials. It consists of placing dry reinforcements in a mould covered by a vacuum bag which will then be impregnated with the arrival of resin which is sucked up by the depression created in the mould. This technology allows the production of monolithic parts (low and high thickness), such as sandwich structures. The resin was hardened at 85°C for 2 h. In material number 1, the core was made of PVC foam – Airex C70.55 with a density of 60 kg/m^3, while in material number 2 aramid honeycomb core was used with a thickness of 4 mm and a density of 29 kg/m^3. The average total thickness of sandwich material no. 1 was 6.60 mm and material no. 2 was 6.92 mm.

Materials 3 and 4: the skins were made of glass mat reinforced polyester resin HAVELPOL 1 having a density of 1200 kg/m^3. The average thickness of one skin was 2.8 mm. The aramid honeycomb cores had various thickness: 3 mm in material number 3 and 8 mm in material number 4. The skins were hand-bonded to the core with a two-component epoxy glue – Araldite. Total average thickness of the sandwich material number 3 was 9.10 mm and material number 4 – 14.25 mm.

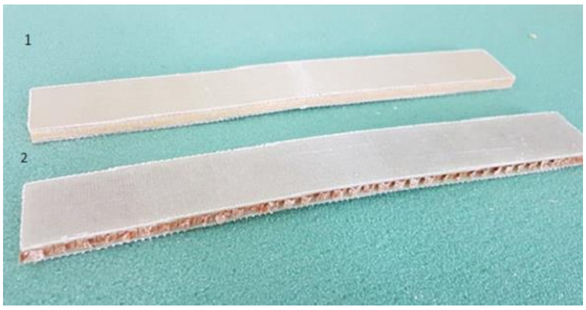


Fig. 1. Sandwich material no. 1 and 2

a) b)

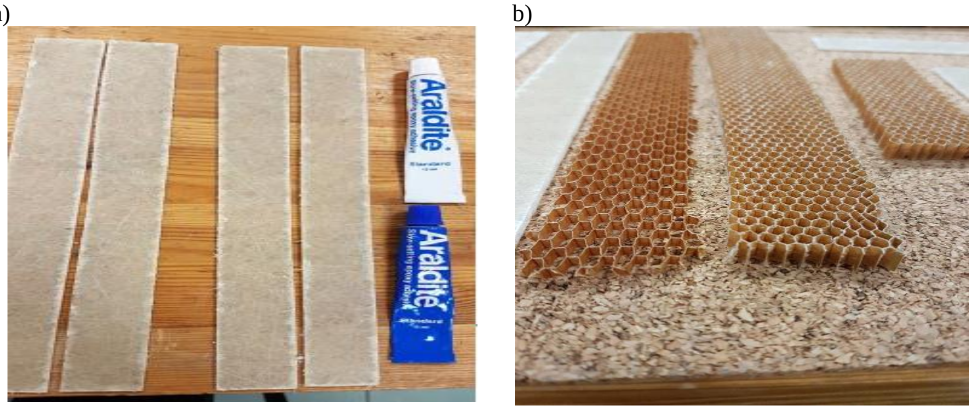


Fig. 2. Materials used to make the sandwich composite no. 3 and 4: a) glass mat reinforced polyester laminate, b) aramid cores, 3 and 8 mm in thickness

The three-point bending test was performed on an Instron 5982 testing machine in accordance with ASTM D7249/D7249M standard (American Society for Testing and Materials, 2012). The machine was equipped with a bending fixture and deflectometer. An extensometer, which measured the deflection, was attached to the deflectometer. During the test, the crosshead displacement [mm], load [N] and deflection of the specimen [mm] were recorded.
From the values recorded during the test, flexural modulus was calculated, using following formula:

$$E_b = \frac{Pl^3}{48fI} \tag{1}$$

where: P – force [N], l – spacing of supports [mm], f – mid-span deflection [mm]; I – moment of inertia of the specimen cross-section [mm^4], which is given by:

$$I = \frac{bh^3}{12} \tag{2}$$

where: b – specimen width [mm], h – specimen thickness.

To verify the values of flexural modulus and to determine the influence of the distance between supports on its value, a second variant of the bending test in terms of elastic deformation was performed, taking three support spacings: 60, 130 and 200 mm. The deflection of samples was measured with the Keyence LK-H052 laser measuring head at 100 Hz sampling frequency.

The static tensile test was carried out on a Zwick UTS 100 testing machine, at the crosshead speed of 2 mm/min (American Society for Testing of Materials, 2010). The values measured during the test were: crosshead displacement [mm], force [N], and elongation [%].

From the values recorded during the test, the ultimate tensile strength was calculated using equation:

$$Rm = \frac{Pmax}{A} \tag{3}$$

where: *Pmax* – maximum force during tensile test [N], *A* – initial cross-sectional area of the skins [mm^2].

The edgewise compression test was performed on an Instron 3382 testing machine according to ASTM C364/C364M standard at a crosshead speed of 2 mm/min (American Society for Testing and Materials, 2017). The values measured during the test were crosshead displacement [mm] and loading force [N] (the test was performed without an extensometer) (American Society for Testing and Materials, 2017). The edgewise compressive strength was calculated from the values recorded during the test using the equation:

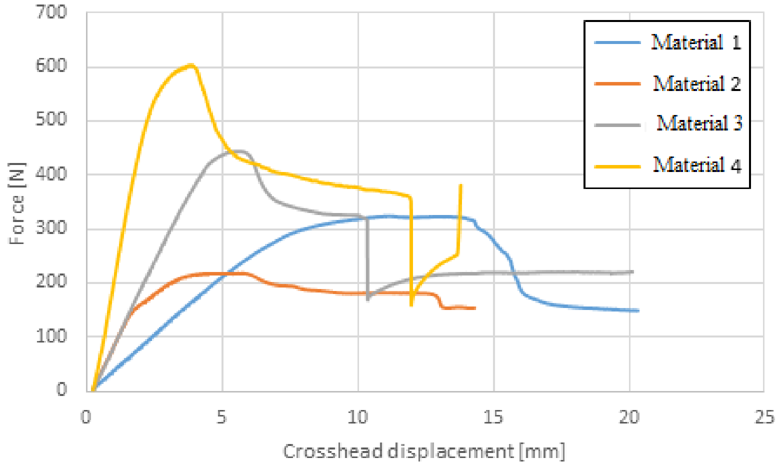
$$R_s = \frac{Pmax}{b(2\,t)} \tag{4}$$

where: *Pmax* – maximum force [N], *b* – specimen width [mm], *t* – skin thickness [mm].

3. Results and discussion

On the basis of the results of the bending test, it was found that the greatest stiffness and ability to carry bending loads, regardless to the distance between supports, is characterized by material no. 4 and secondly by material no. 3 (Figs. 3a and 4a). This is a result of the higher thickness of these materials in comparison with materials 1 and 2 – the geometric factor is decisive in this case. In turn, the bending strength of materials 3 and 4, expressed as the maximum stress value in the skin, is the lowest, which results from the low strength of the skin reinforced with a glass mat (Figs. 3b and 4b) (Antony et al., 2012). The apparent flexural modulus values are lower for materials 3, 4 in comparison to materials 1 and 2, which confirms the crucial influence of the elastic modulus of the skin (Table 1).

a)



b)

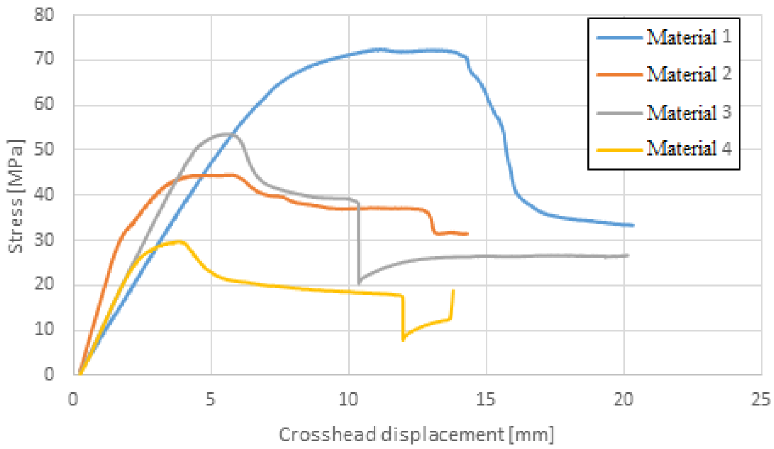


Fig. 3. Bending curves for support spacing of 200 mm: a) force – crosshead displacement, b) stress – crosshead displacement

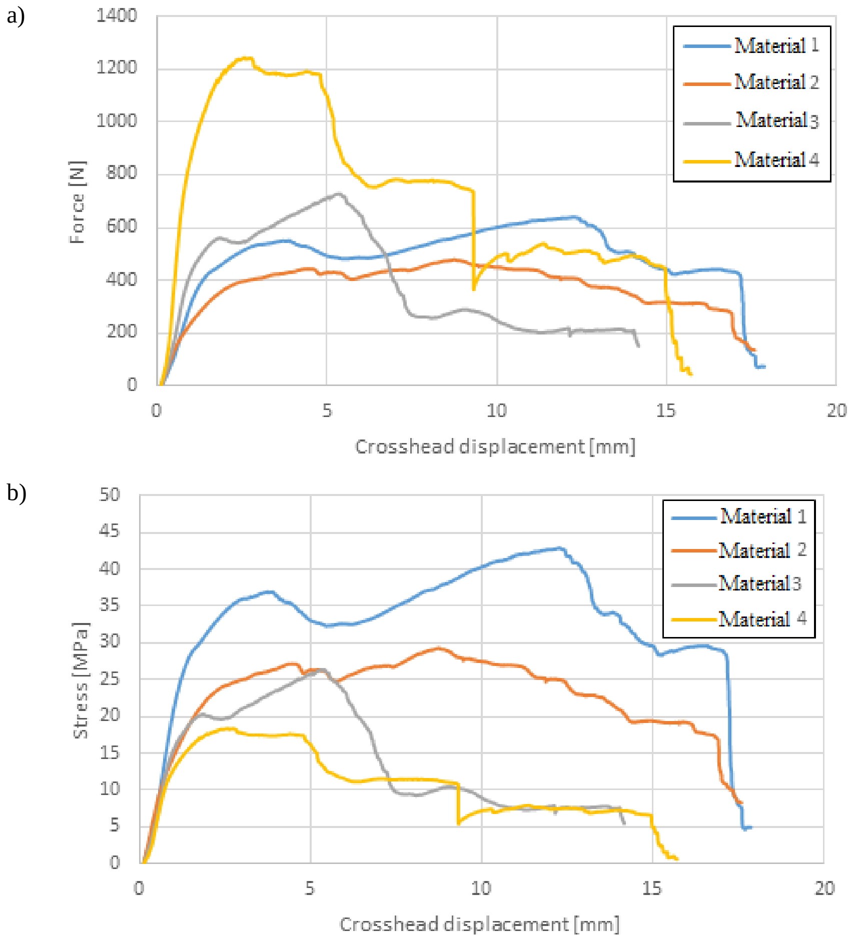


Fig. 4. Bending curves for support spacing of 60 mm: a) force – crosshead displacement, b) stress – crosshead displacement

Table 1. Flexural modulus of sandwich materials determined in two variants of the bending test

Material	Spacing of supports [mm]	Flexural modulus [GPa] (laser sensor measurement)	Flexural modulus [GPa] (deflectometer measurement)
1	60	3.05	3.05
2		2.39	2.32
3		3.88	1.56
4		1.06	0.81
1	130	7.44	-
2		6.21	-
3		4.74	-
4		2.53	-
1	200	10.63	12.05
2		9.63	11.80
3		5.04	5.31
4		3.46	2.63

The values of flexural modulus determined in the classical bend test with the deflection of the sample using a deflectometer were verified in the test during which the deflection was measured using a laser measuring head (Figs. 5a and 5b). In both cases, the determined values of flexural modulus were slightly different (Królicka & Trębacki, 2017). The use of a laser measurement system allows results to be obtained more reliably than in the case of a deflectometer coupled with an extensometer.

It was found that as the distance between supports increases, apparent flexural modulus value also increases. This is due to a change in the ratio between the normal bending and shear stresses, with a change in support spacing (Fig. 6). Calculation of the value of the modulus elasticity in bending requires the use of specimens with a sufficiently large proportion of their length to thickness, which results in minimizing the effect of shear on specimen deformation (Lu et al., 2015). The dominant specimen failure mode in a bending test was the cracking of the skin subjected to tension (Fig. 7).

a) b)

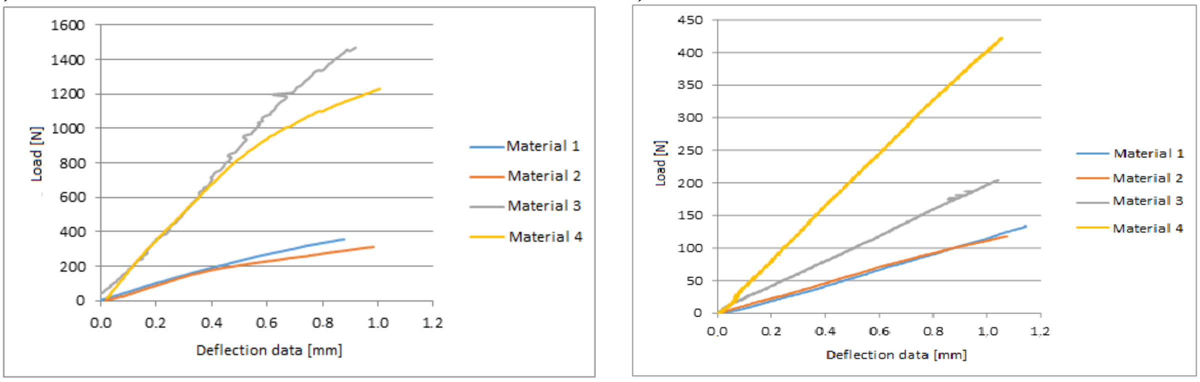


Fig. 5. Load – deflection bending curves measured using laser measuring head for the support spacing of a) 60 mm, b) 130 mm

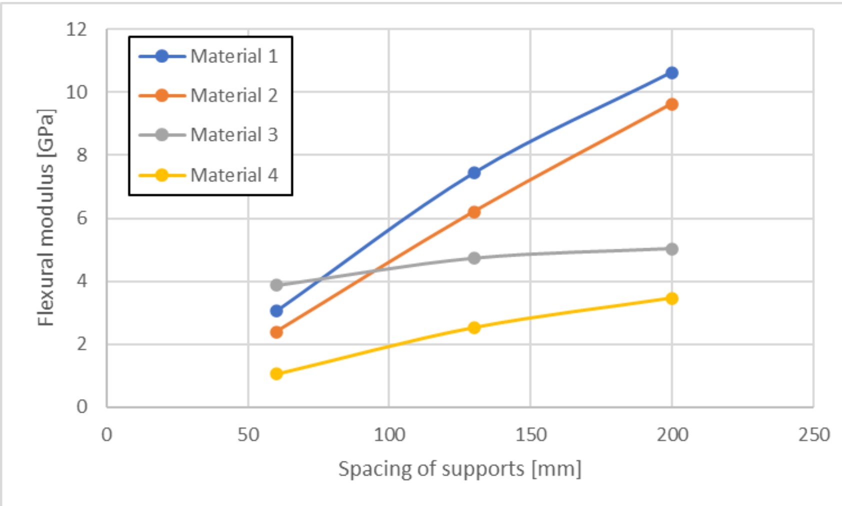


Fig. 6. The influence of supports spacing in the bending test on the value of the flexural modulus of elasticity

It was found that skin material and connection between cores and skin have significant influence on flexural modulus (Arbaoui et al., 2014). Higher values of flexural modulus for materials 1 and 2, which were increasing markedly with increasing supports spacing, resulted mainly from the higher stiffness of the reinforcement applied. More firm and stronger connection between skin and core obtained in industrial process was an additional factor enhancing flexural modulus of these materials.

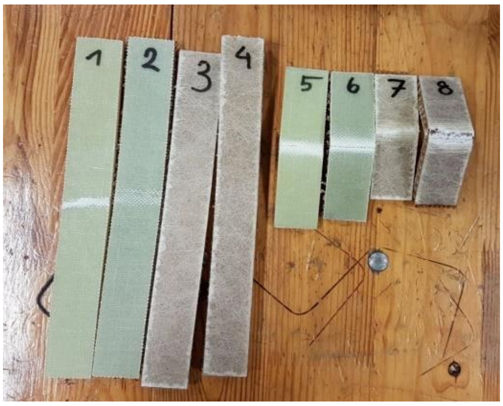


Fig. 7. Samples after three-point bending test

As a result of the tensile and compression tests, the tensile strength and compressive strength (Table 2) were determined for materials 1-4, referring the load values to the cross-section of the skins themselves. It was assumed that the direct contribution of the core to the carrying of such loads is minimal. However, it may affect the deformation of the skin, which causes differences in the stiffness of individual materials (e.g., 1 and 2 in tension) despite the use of the same skin material. In both tests, the highest tensile and compressive strength was obtained for materials 1 and 2 and the lowest for material 4 (Figs. 8, 9). This is due to the decisive influence of the skin material properties on the resultant properties of the sandwich material in this loading mode. Although the skin material of sandwich materials 1 and 2 was the same, different tensile and compressive strength values were obtained. This is related to the different materials of their cores: the material with a honeycomb core has a higher load-carrying capacity than the material with a foam core, which makes it more resistant. Material 4, with the highest thickness, had the lowest compression and tensile strength, which may be caused by the irregular distribution of the glue between the skin and the core and by not gluing them together precisely. The particularly large difference in tensile strength between materials 3 and 4, despite the use of the same skin material, is due to the difficulty in implementing the right way to introduce the load into a thick specimen. The specimen slipped out of the grip of the testing machine and the increase in gripping force caused crushing of the specimen, so the stress distribution in the specimen was different from the uniaxial tensile state, which caused its earlier failure.

Table 2. Tensile strength and edgewise compressive strength of the materials 1-4

Material	Maximum tensile force [N]	Tensile strength [MPa]	Maximum compressive force [N]	Edgewise compressive strength [MPa]
1	23163	268	22358	133
2	32579	379	23595	140
3	9222	54.9	21007	62.5
4	6141	36.6	16464	49.0

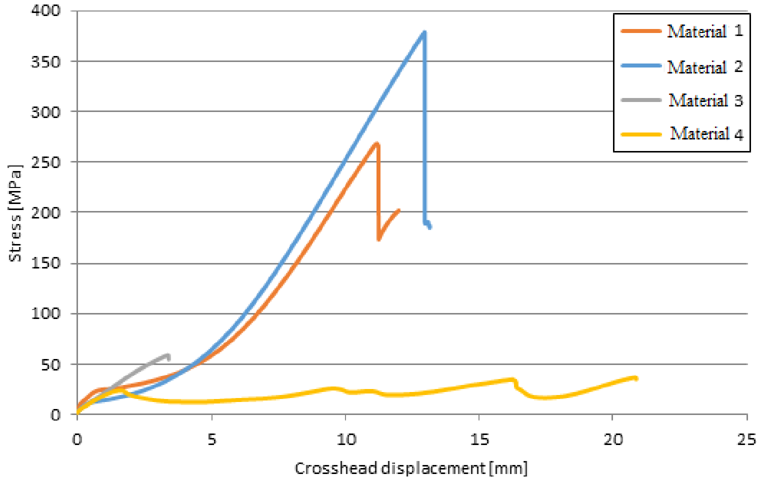


Fig. 8. Tensile stress – crosshead displacement curve

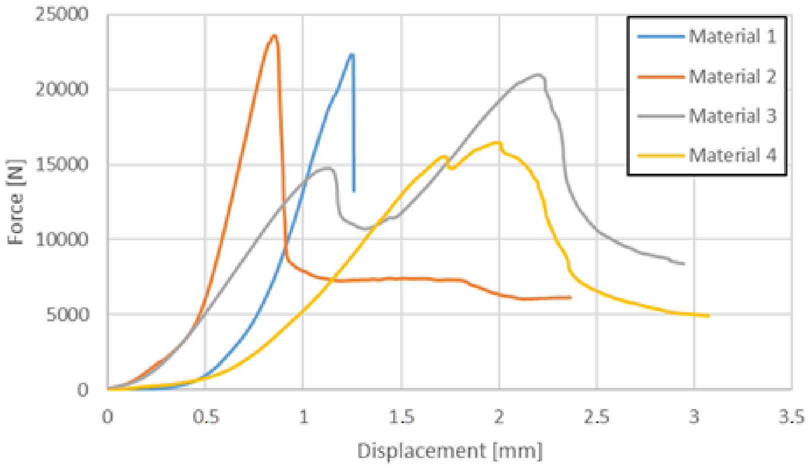


Fig. 9. Force – displacement curves in edgewise compression test

Materials 1, 2, and 4 in the tensile test were damaged by breaking the skin at a short distance from the machine grips (Fig. 10a). Only material 3 was damaged in the gauge length. In the edgewise compression test, the specimens failed by cracking the skin (ASTM C364 code F) (Fig. 10b) (Muc & Nogowczyk, 2005; Greń et al., 2008). The results of the tensile and edgewise compression tests of the sandwich materials in the direction parallel to the plane of the element showed that the type of core material has some influence on the resulting stiffness of the sandwich element, especially in tension (materials 1 and 2). On the other hand, the effect of the core thickness with the same skin material and core material is insignificant (materials 3 and 4) (Banghai et al., 2015).

a) b)

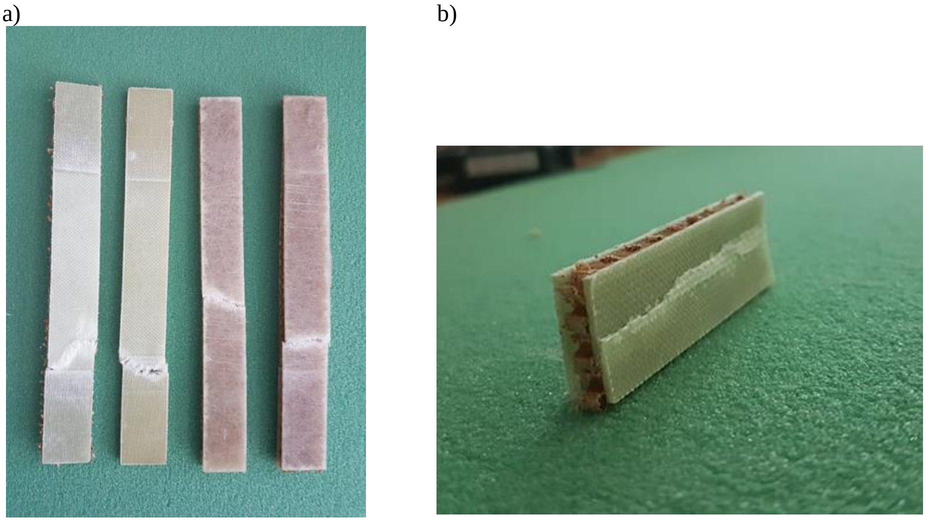


Fig. 10. a) Samples after the tensile test (from the left - material 1, material 2, material 3, material 4), b) specimen of the material no. 2 after compression test – cracked skin

4. Summary and conclusions

Based on the analysis of the obtained results of own research, the following observations and conclusions were formulated:

- Based on the results of the bending test, it was found that the highest stiffness and ability to carry bending loads, regardless of the distance between supports, is characterized by material no. 4, and secondly by material no. 3 – the thickness of the sandwich material is decisive in this case.
- Skins reinforced with glass fabric can carry much higher stress than skins reinforced with glass mats.
- The result values of flexural modulus of sandwich materials, calculated in a classical bend test and a bend test during which the deflection arrow was measured with a laser measuring head, differs slightly.
- As the distance between supports increases, the apparent flexural bending modulus value for all materials increases, due to reduced effect of shear stresses.
- As a result of the bending test, the samples were damaged due to cracking of the stretched skin
- The highest compressive and tensile strength was obtained for material 2 (laminate reinforced with glass fabric/cell core), while the lowest for material 4 (laminate reinforced with glass mat/thicker cell core).
- The honeycomb cell core material has a higher load-bearing capacity in the plane of the sandwich element than the polymer foam core material.
- The lowest tensile and compressive strength of material 4 was probably due to the uneven sticking of the core and skin. The sample slid out of the strength machine's grip, and the increase of pressure force in the grip caused its crushing, hence the stress distribution in the sample deviated from the uniaxial, causing its earlier destruction.
- In the edgewise compression test, the samples were damaged by cracking of the facesheets.

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Badania Właściwości Mechanicznych Wybranych Polimerowych Kompozytów Przekładkowych

Streszczenie

Celem pracy było określenie wpływu czynników materiałowych i geometrycznych wybranych kompozytów przekładkowych na ich właściwości mechaniczne. Pierwsza badana para materiałów przekładkowych została wykonana metodą infuzji przemysłowej i składała się z żywicy epoksydowej wzmocnionej 7 warstwami tkaniny szklanej (okładki) z rdzeniem z pianki PVC lub aramidowego plastra miodu. Druga para materiałów została przygotowana ręcznie i składała się z żywicy poliestrowej wzmocnionej matą szklaną (okładki) z rdzeniem aramidowym o strukturze plastra miodu o różnej grubości. Celem pracy było określenie wpływu czynników materiałowych i geometrycznych wybranych kompozytów przekładkowych na ich właściwości mechaniczne. Właściwości mechaniczne określono w próbach statycznych zginania, ściskania i rozciągania. W każdym przypadku oceniono sposób niszczenia badanych materiałów kompozytowych. W przypadku kompozytów z okładkami z żywicy epoksydowej zastosowanie rdzenia aramidowego o strukturze plastra miodu spowodowało zwiększenie wytrzymałości na rozciąganie i ściskanie. W przypadku materiałów z okładkami z żywicy poliestrowej i rdzeniami o strukturze plastra miodu stwierdzono, że zwiększenie grubości rdzenia dawało większą sztywność zginania, ale wytrzymałość na rozciąganie i zginanie uległy zmniejszeniu.

Słowa kluczowe: kompozyty przekładkowe, właściwości mechaniczne, próby statyczne zginania, próby statyczne ściskania, próby statyczne rozciągania