TIAM kwartalnik naukowo-techniczny
TECHNOLOGIA I AUTOMATYZACJA MONTAŻU
ZESPOŁÓW • MASZYN • URZĄDZEŃ

Jacek Janiszewski[1], **Paweł Przybyłek**[2], **Rafał Bieńczak**[3],
Łukasz Komorek[4], **Miłosz Sobieski zu Schwarzenberg**[5]

DOI: 10.7862/tiam.2022.4.3

THE INFLUENCE OF THE MANUFACTURING METHOD ON THE MECHANICAL PROPERTIES OF THE HONEYCOMB CORE SANDWICH COMPOSITE

WPŁYW METODY WYTWARZANIA NA WŁAŚCIWOŚCI MECHANICZNE KOMPOZYTU PRZEKŁADKOWEGO Z WYPEŁNIACZEM ULOWYM

Abstract

Reducing weight and fuel consumption is one of the main goals of modern aeronautical engineering. The most common materials to achieve this goal are composite layered materials, including the sandwich ones. High strength, stiffness and low density have made sandwich composites one of the fundamental materials of the aerospace industry. Sandwich-structured composites can be manufactured with a variety of methods, differing primarily in the manufacturing time, which translates into an overall cost of making a composite component. The research focused on three methods of manufacturing sandwich composite materials with a honeycomb core, differing in the number of operations, during which it was possible to obtain a finished composite panel (single-phase, two-phase and three-phase methods). The authors manufactured and examined composites with a honeycomb cover and two composite glass fibre-reinforced covers. The composites were made by means of the vacuum bag method. As a result of the conducted study, it was found that composites manufactured with the single-phase method have the shortest manufacture time as well as the lowest material consumption, however their strength properties are the lowest. The two-phase method requires a longer manufacture time and more material consumption, however it makes it possible to obtain a composite with higher strength compared with the single-phase method. The three-phase method has the longest composite manufacture time and the highest material consumption.

Keywords: sandwich composites, composite manufacturing processes, vacuum bagging technique, impact strength, shear strength

Streszczenie

Zmniejszenie masy i zużycia paliwa jest jednym z głównych celów współczesnej inżynierii lotniczej. Najpopularniejsze materiały, które pozwalają osiągnąć ten cel, to materiały kompozytowe warstwowe w tym przekładkowe. Wysoka wytrzymałość, sztywność i niska gęstość, sprawiły, że kompozyty przekładkowe stały się jednym z podstawowych materiałów przemysłu lotniczego. Kompozyty przekładkowe z wypełniaczem strukturalnym mogą być wytwarzane różnymi metodami, różniącymi się przede wszystkim czasem wytwarzania, co przekłada się na ogólny koszt wykonania elementu kompozytowego. W badaniach przeanalizowano trzy metody wytwarzania materiałów kompozytowych przekładkowych w wypełniaczem ulowym różniące się liczbą operacji podczas których uzyskano gotową płytę kompozytową (metoda jednofazowa, dwufazowa i trójfazowa). Wytworzono i badano kompozyty zbudowane z rdzenia ulowego oraz dwóch kompozytowych okładek wzmacnianych włóknami szklanymi. Kompozyty wykonano metodą worka próżniowego. W efekcie przeprowadzonych badań stwierdzono, że kompozyty wytworzone metodą jednofazową cechują się najkrótszym czasem produkcji jak i najmniejszym zużyciem materiałów, ale ich właściwości wytrzymałościowe są najniższe. Dwufazowa metoda wymaga dłuższego czasu produkcji i większego zużycia materiałów, natomiast pozwala uzyskać kompozyt o większej wytrzymałości w porównaniu do metody jednofazowej. Trójfazowa metoda cechuje się najdłuższym czasem wykonania kompozytu i największym zużyciem materiałów.

Słowa kluczowe: kompozyty przekładkowe, metoda wytwarzania kompozytu, technika worka próżniowego, udarność, wytrzymałość na ścinanie

---

[1] MSc. Eng. Jacek Janiszewski, Polish Air Force University, ul. Dywizjonu 303, no 35, 08-530 Dęblin, Poland, e- mail: j.janiszewski@law.mil.pl

[2] Phd. Eng. Paweł Przybyłek, Polish Air Force University, ul. Dywizjonu 303, 35, 08-530 Dęblin, Poland, e-mail: p.przybylek@law.mil.pl, ORCID: 0000-0002-7544-3813.

[3] Eng. Rafał Bieńczak, Polish Air Force University, ul. Dywizjonu 303 No. 35, 08-530 Dęblin, Poland, e-mail: r.bienczak@law.mil.pl

[4] Eng. Łukasz Komorek (corresponding author), Polish Air Force University, ul. Dywizjonu 303 No. 35, 08-530 Dęblin, Poland, e-mail: l.komorek5374@wsosp.edu.pl

[5] Eng. Miłosz Sobieski zu Schwarzenberg, Polish Air Force University, ul. Dywizjonu 303 No. 35, 08-530 Dęblin, Poland, e-mail: m.sobieskizuschwarzenberg4817@wsosp.edu.pl

1. Introduction

At present composites play an increasingly important role in aviation industry as well as in other areas of manufacturing [1, 2]. The most widely used type of such materials in aviation is sandwich structure composites, characterised by high mechanical strength at low density [3, 4]. Honeycomb core sandwich composites are used in different aerospace applications and are becoming the go-to material for critical substructures in rockets, aircraft, jet engines, and propellers, as well as similar non-aerospace structures, such as wind turbine blades [5]. In less sensitive applications, sandwich composites are also used in aircraft heating, ventilation, and air conditioning systems. This type of composites also includes materials with a sandwich structure, which consists of a rigid, low-density core with claddings on the outside. Such a structure ensures extremely high rigidity and a light-weight construction [5, 6].

Multi-layered composite materials can be manufactured by multiple methods. One of the most popular methods for the manufacture of such composites is a technique using the so-called vacuum bagging [7, 8]. Other commonly used techniques are the infusion technique [9], press method [10] and the autoclave technique [11], which however has been losing popularity in recent years due to high production costs and the possibility of replacing it with other production methods [12].

The aim of the presented research is to analyse various techniques for the manufacture of sandwich-structured composites. The composites are manufactured by three methods: single-phase, two-phase and three-phase, taking into account such criteria as: time and labour consumption of manufacturing the composite, the amount of material used and the mechanical strength of the obtained composite.

2. Manufacturing of composite panels

2.1. Two-phase method

2.1.1. Making the first phase of the composite

The authors decided to produce a composite, consisting of a honeycomb core and two-layer covers with a glass fabric reinforcement as the test material. The vacuum bag method was used to make the composites.

The composite used a 100 g/m^2 twill glass fabric and a 5 mm thick honeycomb paper core at a density of 29 kg/m^3. The dimensions of the composite panels which were later used for cutting the samples with the water jet method equalled 400 x 800 mm.

The components were manually saturated with L285 resin mixed with H285 hardener. The resin/hardener composition was prepared in a 100:40 weight ratio. It was intended to both connect the core and the covers, and to provide a matrix for the composites which make up the covers.

The manufacture of a composite using the two-phase method generally consists of the following phases [13]:

1. The manufacture of a semi-finished product (core with one cover) by making a composite cover in one phase and bonding it to the honeycomb core with a resin/hardener composition.
2. Making a second cover and combining it with a semi-finished product (covers and a honeycomb core produced in the first phase) into a finished composite panel using the vacuum bag method (Fig. 1).

Fig. 1. Curing the composite in phase I

The honeycomb core was applied to fibreglass fabrics, saturated with the resin composition, and then subjected to a light pressure over the entire surface, using a pressure plate to facilitate the bonding of the covers to the core in the vacuum bag.

Preparing the first phase of the composite using this method makes it possible to achieve a high-quality bond between the cover and the honeycomb filler. The PET foil, over which there is a glass fibre fabric, when spreading the resin makes all the resin seep through the two layers of glass fibre, ensuring solid adhesive bonding with the core. The delamination and the drainage mat located on the honeycomb filler during compression of the composite in the vacuum bag drains an excess resin and air that could degrade the quality of the composite.

A photograph taken with a Tagarno Magnus microscope (Fig. 2) shows an absence of resin in the cells of the honeycomb filler, whereas Fig. 3 shows full seepage of resin through the cover.

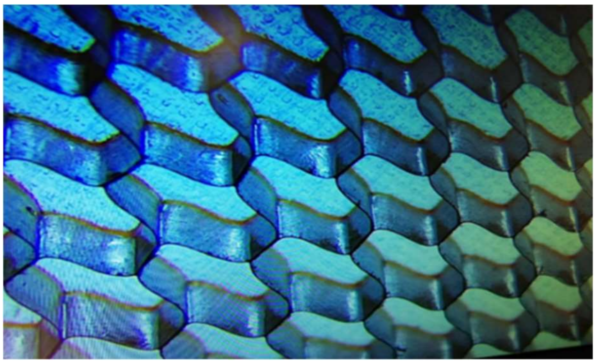

Fig. 2. Microscopic photograph which shows bonding of honeycomb core and cover (x20)

Fig. 3. Hardened composite cover visible from the outside

In the second phase of the composite manufacture, a key factor was to ensure the best possible bonding between the cover and the honeycomb core prepared in the first phase; the cover was prepared in the second phase. A problem in the second phase of the composite manufacture was a limited possibility to drain the excess of resin and air due to the cover enclosing the composite from the top. In order to produce a high-quality composite, a second phase of composite manufacture was proposed, using three different methods, in which a potential solution to this problem was experimentally tested.

2.1.2. The first method to carry out phase II of the composite manufacture

During phase II of the composite manufacture (Fig. 4) with the first method, the main idea was to remove the excess air and resin through a typical perforated separating foil with holes of approximately 0.5 mm in diameter when pressing the soaked layers of glass fabric onto the semi-finished product made in phase I. The method uses the following arrangement of materials:

- 2 layers of glass fabric,
- separation foil with 0.5 mm holes,
- delamination,
- drainage mat.

Fig. 4. Preparation process for phase II of the composite

The foil was to drain excess resin and air from the lower layers, while the delamination was to prevent the drainage mat from sticking to the rest of the materials.

Unfortunately, this attempt proved unsuccessful, as most of the resin, despite the 0.5 mm diameter holes, seeped into the lower layers of the materials, preventing the individual components of the composite from bonding together. Consequently, an insufficient amount of resin resulted in the cover not bonding properly with the honeycomb filler. Numerous discolourations from the seeped resin are visible throughout the delamination surface (Fig. 5).

Fig. 5. Cover peeling off from the semi-product manufactured in phase I

2.1.3. The second method of carrying out phase II of the composite manufacture

When conducting phase II of the composite using the second method, the main assumption was to compare the quality of the composite produced with and without the possibility of removing excess air. For this purpose, a PET foil was prepared (Fig. 6). It was split into two parts: the first one with a mesh consisting of 1,600 holes, each 2 mm in diameter, hand-made, using the drilling technology, and the second one with a uniform net. Consequently, when the first part of the composite (made in the first phase) was pressed against the second part (non-hardened cover), the air that had accumulated between the first part of the composite (made in the first phase) and the second part (non-hardened cover) could be removed through the holes made in the PET film.

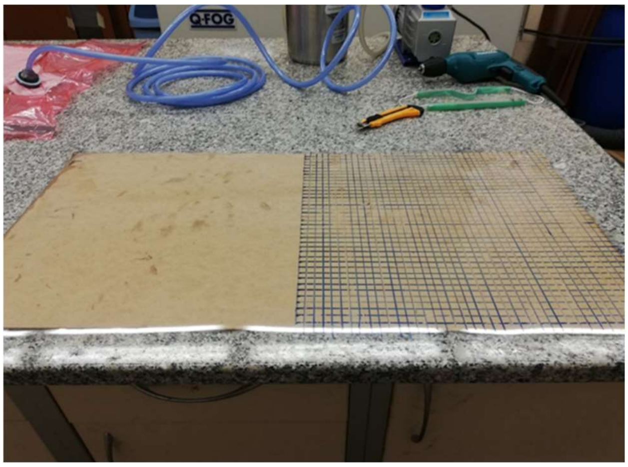

Fig. 6. PET film with a mesh consisting of 1,600 holes

Half of the cover that was laid on the PET film with holes did not stick to the semi-product made in phase I. This was due to the resin seeping into the lower layers of the materials through the previously prepared holes. Half of the cover that was on the uniform part of the PET film had seeped through and bonded properly to the rest of the composite (Fig. 7).

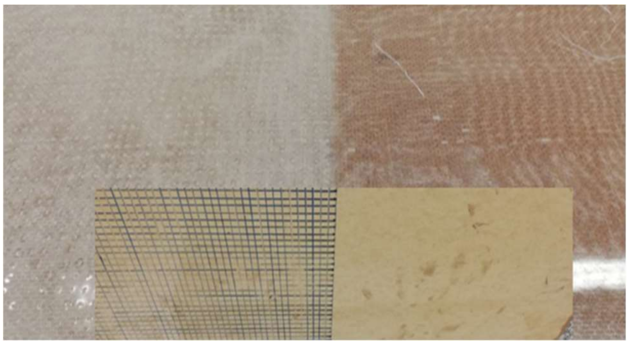

Fig. 7. Left part of composite cured on PET film with holes; right part on uniform film, without holes

2.1.4. Method 3 in conducting phase II in the composite manufacture

Basing on the previous trial, the third method that was used during the process of bonding the composite parts made in the first phase to the cover made in this phase was the application of a uniform PET film over the entire surface of the glass fabric when saturating and curing the cover in the vacuum bag. This allowed the resin to properly soak through all layers of the cover and properly bond the two parts of the composite. The disadvantage was the fact that excess air remained in the composite. However, this method proved to be the best one qualitatively (visual assessment) when producing the two-phase composite (Fig. 8).

Fig. 8. Cover produced in phase II

2.2. Analysis of the mechanical properties of the two-phase composite produced in accordance with the methodology described in section 2.1.4

In order to qualitatively assess the composite, it was decided to carry out static bending, tensile and adhesion tests, as well as dynamic impact and piercing resistance tests. Conducting a bending test of the composite allowed the authors to determine the Young's modulus and bending strength of the manufactured two-phase composite. Five samples, sized 60 x 80 mm, resting freely on supports and positioned 60 mm apart, underwent testing (Fig. 9).

Fig. 9. Sample during a bending test – Zwick/Roell 5kN machine

The test was conducted in accordance with the bending scheme of method A (three-point bending) described in EN ISO 14125 [14].

The obtained results are shown in the graphs (Fig. 10-11).

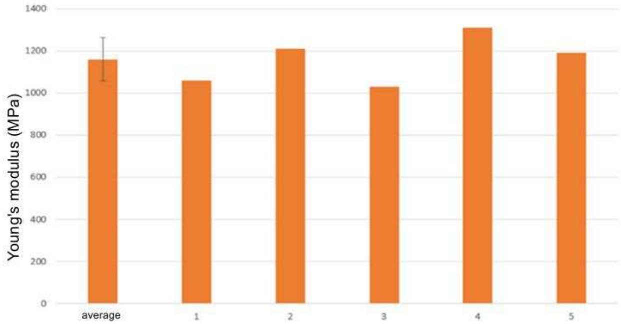

Fig. 10. Young's modulus of two-phase composite samples

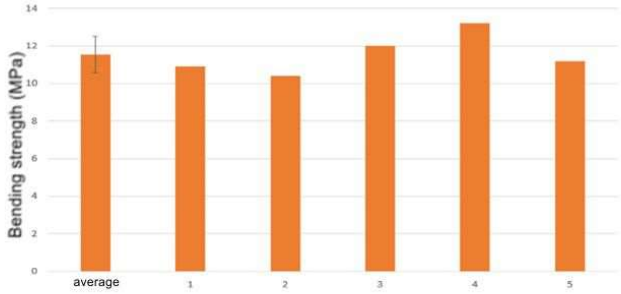

Fig. 11. Bending strength of the two-phase composite

Next, the 60 x 80 mm samples were subjected to a test which examined resistance to penetration. The tests which employed an INSTRON CEAST 9340 drop hammer, had the samples loaded with the following energies: 0.5; 1; 2; 3 and 5 J.

The 0.5 J energy did not damage the composite cover or the honeycomb filler (Fig. 12).

Fig. 12. View of sample loaded with 0.5 J

A load of 1 J caused a slight deformation and cracking of the cover in one part of the sample (Fig. 13).

An energy of 2 J caused the cover to deform and break in three directions propagating from the point of load application (Fig. 14).

Fig. 13. View of sample loaded surface with 1 J

Fig. 14. View of sample loaded surface with 2 J

Loading with an energy of 3 J resulted in a significant indentation and a crack in the composite structure on the side of the load application, propagating in four perpendicular directions (Fig. 15).

Fig. 15. View of sample loaded surface with 3 J

At a load of 5 J, it is possible to observe very deep indentations in the composite and cracking of the cover in four directions (perpendicular), propagating from the point of load application. It is also noticeable, unlike other loading energies, that the cover peels away from the core at the edges of the sample (Fig. 16). It is worth noting that no damage is visible on the bottom cover.

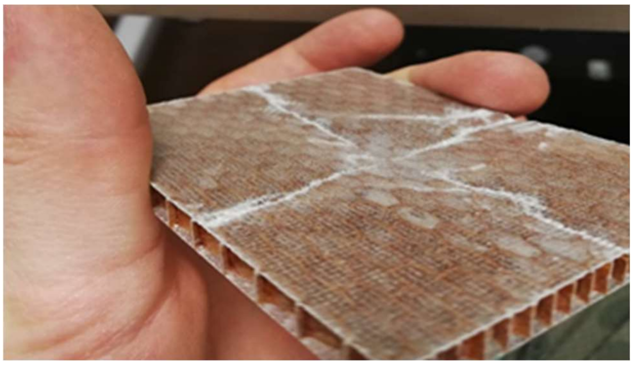

Fig. 16. View of sample loaded surface with 5 J

After the impact tests, the samples were subjected to bending in order to determine the residual bending strength. The obtained results are shown in Fig. 17.

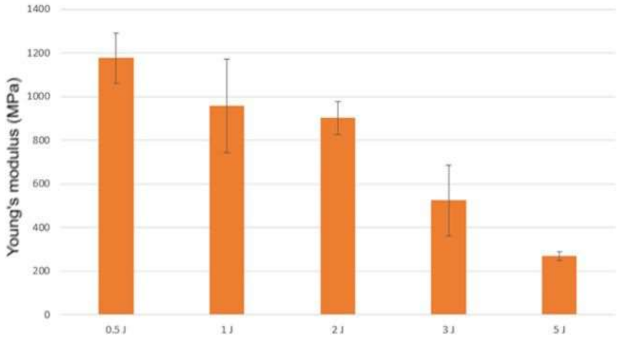

Fig. 17. Average residual bending strength of samples after an impact load

A loading energy of 0.5 J did not reduce the bending strength of the two-phase composite. At energies of 1 J and 2 J, a decrease in bending strength of approximately 200 MPa is apparent. An energy load of 3 J results in a twofold decrease in bending strength. Loading with an energy of 5 J results in a drastic decrease in bending strength in relation to other energies, due to damage to the composite structure and detachment of the cover from the honeycomb core.

Another examination was a tensile test, which involved axial sample stretching. The average value of the Young's modulus of the tested composite was 807 MPa, while the average tensile strength was 18.3 MPa.

The next test was an impact test using a pendulum hammer, with both plane (Fig. 18a) and edge (Fig. 18b) loading of the sample. The obtained results have been presented in Table 1.

Fig. 18. Impact test under: a) plane loading, b) edge loading

Table 1. Impact strength

Impact strength (plane loading) (kJ/m^2)		Impact strength (edge loading) (kJ/m^2)	
3.97		7.21	
4.39		6.87	
4.07		6.97	
3.91		6.78	
4.12		6.22	
4.52		5.99	
4.31		5.61	
3.92		6.17	
Average	4.24	Average	6.32

A significantly higher impact strength of the edge-loaded composite can be observed, which is probably related to a higher impact strength of the edge-loaded covers. The final test of the composite was to examine adhesion between the cover and the core of the two-phase composite. The test was an attempt to determine the shear strength between the covers and the core. In order to investigate these properties, strength tests were performed on samples prepared from the composite with a shape similar to overlap samples, in which two flat elements glued together by a core were stretched in the core plane (Fig. 19). The test results are shown in Table 2.

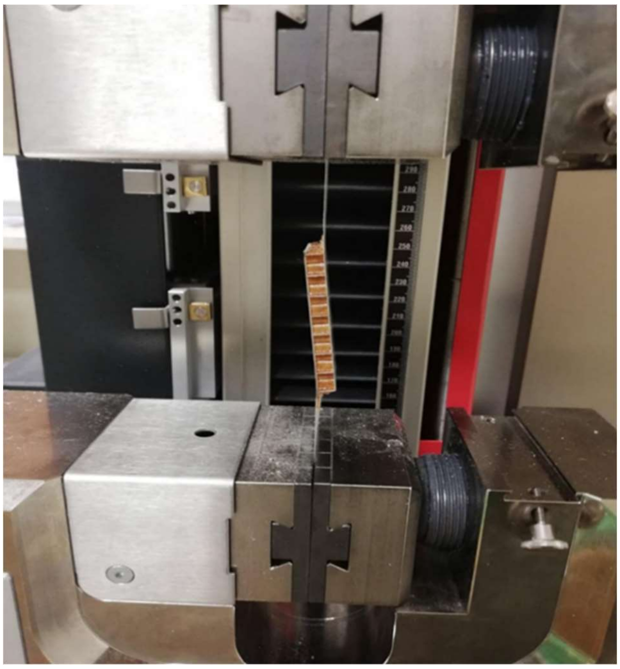

Fig. 19. Scheme of the adhesion test between cover and core

Table 2. Adhesion test findings of a two-phase composite

Sample	Shear strength (MPa)	Load capacity (N)
1	0.350	438
2	0.353	441
3	0.316	395
4	0.453	566
5	0.286	367

3. Analysis of the manufacture of sandwich composite materials, using a single-phase method

3.1. Single-phase composite manufacturing

In the single-phase method, analogous to the two-phase method, the vacuum bag method was used. The single-phase manufactured composite is characterised by the bonding of the core with the covers also made at this stage. Practically, this means that one curing process of the composite in the vacuum bag leads to a finished composite.

The same materials were used to produce the composite in one phase and in the two-phase method.

The manufacture of the composite using the single-phase method began by saturating two layers of glass fibre fabric with resin. Next, the saturated fabric layers had a honeycomb filler applied. The next step was to encapsulate the composite with two layers of fibreglass fabric saturated in resin. The uncured composite, prepared in such a way, was placed in a vacuum bag (Fig. 20-21).

Fig. 20. Composite arrangement

The order of materials when curing in the vacuum bag was as follows:

- fibreboard,
- drainage mat,
- PET film,
- 2 layers of glass fabric,
- honeycomb core
- 2 layers of glass fabric,
- PET film,
- drainage mat,
- fibreboard.

Fig. 21. Sealing off the vacuum bag

The composite produced by means of the single-phase method was characterised by the correct bonding of the covers and the honeycomb filler, as well as uniform curing of the composite covers over the entire surface. The covers were characterised by satisfactory stiffness and high quality. Nevertheless, due to a small possibility of removing excess air, air bubbles remained in some areas. Slight discolouration was caused by residual air and the loss of some of the resin from the saturated glass fibre in the curing process inside the vacuum bag. The resin-soaked fibreglass fabrics of the upper cover leaked some of the resin to the lower cover under the influence of gravity. However, these were small amounts of resin, because the composite was still bonded properly and the cover had appropriate stiffness and hardness during the surface inspection (Fig. 22).

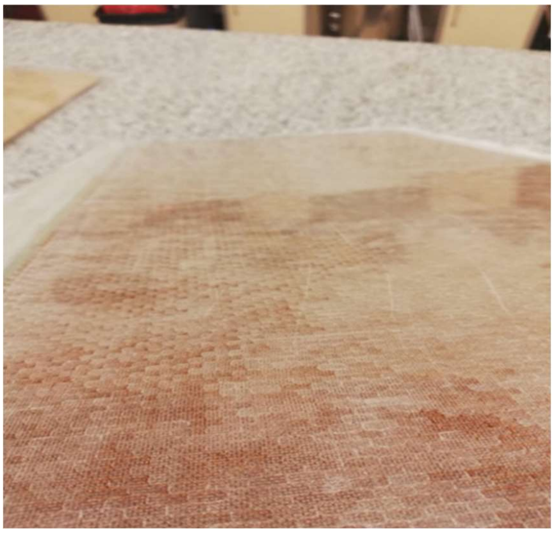

Fig. 22. Composite manufactured with a single-phase method

3.2. Analysis of mechanical properties of the single-phase composite

The bending test of the composite was carried out in a three-point bending test by means of a Zwick/Roell 5 kN universal testing machine. The test was conducted in accordance with the bending scheme of method A described in PN-EN ISO 14125. The obtained results have been shown in Table 3.

Table 3. Results of a single-phase composite bending strength test

Sample	Young's modulus (MPa)	Bending strength (MPa)
1	814	8.14
2	770	9.46
3	1020	10.30
4	805	10.40
5	974	10.10
Average	877	9.68

The samples were then subjected to an impact test. Similarly to the samples made by means of the two-phase method, the test was performed with following energy: 0.5; 1; 2; 3; 5 J, using the INSTRON CEAST 9340 system.

An energy of 0.5 J caused minor deformation in the cover and minimal indentation (Fig. 23).

Fig. 23. View of a single-phase sample loaded with 0.5 J

The 1 J energy caused damage to the cover in two places and indentation of the honeycomb core (Fig. 24).

Fig. 24. Image of a single-phase sample loaded with 1 J

An energy of 2 J caused three branching cracks in the cover, propagating from the point of load application, as well as a large indentation of the honeycomb filler (Fig. 25).

Fig. 25. View of a single-phase sample loaded with 2 J

An energy of 3 J caused three branching cracks in the cover, propagating from the point of load application, as well as a large indentation of the honeycomb filler (Fig. 25). The massive indentations of the honeycomb filler caused its fracture (Fig. 26).

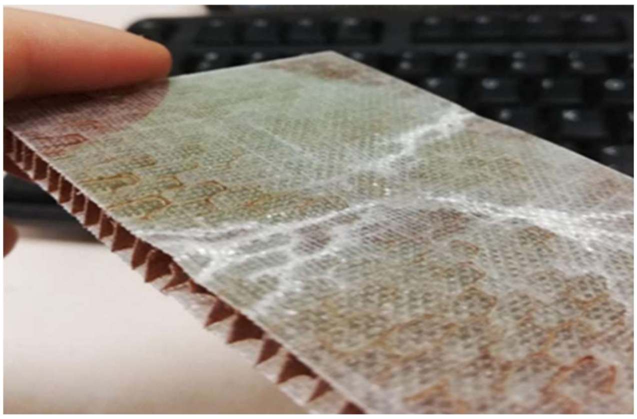

Fig. 26. Damage to a single-phase sample loaded with 3 J

An energy of 5 J caused extensive damage to the cover over the entire surface and detachment of the cover from its filler over 70 per cent of the surface (Fig. 27).

Fig. 27. Damage to a single-phase sample loaded with 5 J

After the load tests, the samples were subjected to bending in order to determine the residual bending strength. The obtained results have been presented in Table 4.

The bending strength of the single-phase composite did not deteriorate after the impact load of 0.5 J. The load of 1 J resulted in a decrease in bending strength of 200 MPa. However, at an impact energy of 2 J, the bending strength value dropped by approximately five times. The loading energies of 3 J and 5 J caused complete damage to the composite structure (detachment of the covers from the honeycomb core, fracture of the honeycomb core), therefore the strength characteristics after these tests were so low. The results obtained have been presented in the graph (Fig. 28).

Another examination was a tensile test, whose results have been shown in Fig. 29-30.

Table 4. Results of bending test after impact loading

Sample	Energy of load (J)	Bending strength (MPa)
1	0.5	10.30
2		10.40
3		10.10
4	1	8.16
5		9.87
6		7.72
7	2	3.12
8		2.60
9		0.77
10	3	0.81
11		3.11
12		1.11
13	5	0.36
14		1.51
15		1.36

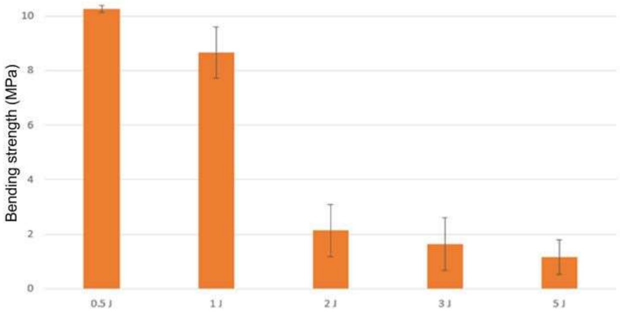

Fig. 28. Average residual bending strength of samples after examining the impact strength.

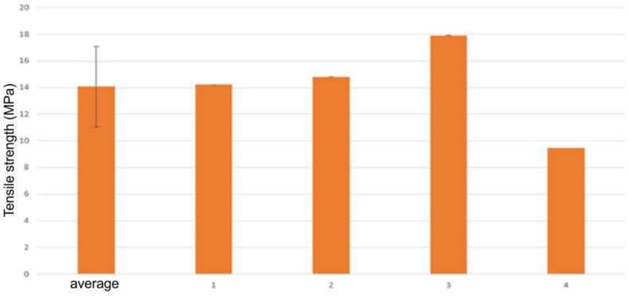

Fig. 29. Tensile strength of a single-phase composite

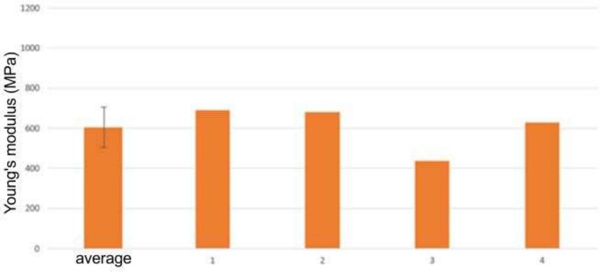

Fig. 30. Longitudinal modulus of elasticity of a single-phase composite

Next, the composites were subjected to an impact test using a pendulum hammer, with both plane and edge loading of the sample. The obtained results have been presented in Table 5.

Table 5. Research findings

Impact strength of planes (kJ/m^2)		Impact strength of edges (kJ/m^2)	
3.14		4.79	
3.52		4.83	
3.21		4.45	
2.97		3.92	
3.17		4.82	
2.91		3.84	
2.83		4.63	
3.76		4.31	
3.29		4.12	
2.77		4.86	
Average	3.16	Average	4.46

When analysing the results, it is noticeable that the impact strength of the edge-impacted composite is significantly higher compared to plane-impacted samples.

The final test of the composite was to examine adhesion between the cover and the core of the two-phase composite (Fig. 31) The test was carried out analogously to the two-phase composite. The test results are shown in Table 6.

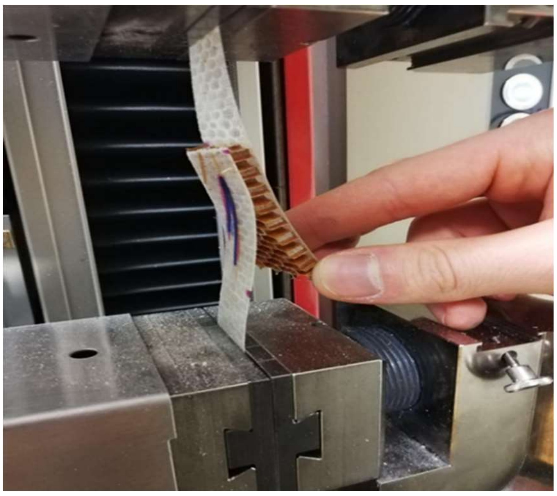

Fig. 31. Adhesion test between cover and core – Zwick/Roell 5 kN machine

Table 6. Adhesion test results of a two-phase composite

Number of sample	Shear strength (MPa)	Load capacity (N)
1	0.390	487
2	0.158	197
3	0.328	410
4	0.254	318
5	0.283	354

4. Analysis of the manufacture of sandwich composite materials using a three-phase method

4.1. The first method to run phase III in manufacturing a composite

The composite produced with the three-phase method has the longest manufacture time compared to the one- and two-phase methods. The process consists of the manufacture of glass fabric composite covers in Phases I and II. The third phase involves bonding the cured covers to the honeycomb core. The manufacture of the composite in each phase of this method requires the use of a drainage mat, PET film and delamination, making it the most costly of all the methods researched. The unquestionable advantage of this method is the fact that the covers are manufactured independently of each other, preventing excess air in the composite and ensuring good saturation of the covers. An additional advantage is also the fact that in one- or two-phase manufacture, at least two persons are required to produce such a composite. On the other hand, in the three-phase method, one person is able to handle every stage of the composite production.

Fig. 32. Preparation of composite covers

The manufacture of a composite using the two-phase method consists of the following phases:

1. Manufacture of the first cover from two resin-saturated fibreglass layers, using the vacuum bag method (Fig. 32).
2. Manufacture of a second cover from two layers of resin-saturated fibreglass, using the vacuum bag method.
3. Gluing the honeycomb filler covers together with a resin composition, using the vacuum bag technique.

In the process of making Phase I and Phase II covers by means of the vacuum bag method, the key element is to ensure the best possible saturation of the fabrics and removal of excess air. In order to achieve such effects, the following sequence of materials was used in the manufacturing process of the composite cover: drainage mat, delamination, two layers of glass fibre, PET film, drainage mat, fibreboard. (Fig. 33).

Fig. 33. Materials put together to make the cover (1st and 2nd phase)

The two covers, produced in such a way, owing to good saturation of the fabrics and the removal of excess air, were characterised by good stiffness and high quality (Fig. 34).

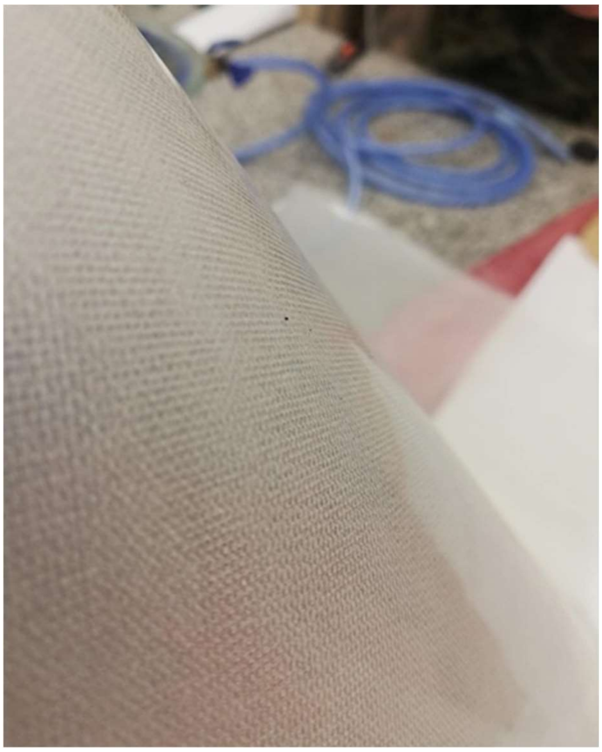

Fig. 34. Cover manufactured in phase I of composite preparation, using the three-phase method

Once the composite covers had been manufactured, the next step was to glue them to the honeycomb core. It was assumed that the composites cured in Phases I and II, i.e. the covers made in such a manner, had a homogeneous structure; after soaking them in resin in Phase III there would be no risk of the resin seeping into the lower layers of the materials, therefore only a drainage mat and a fibreboard were used under the composite covers. Unfortunately, the assumption of homogeneity of the covers turned out to be wrong and resulted in the composite covers sticking together with the drainage mat (Fig. 35).

Fig. 35. Bonding of drainage mat and composite cover

This was caused by resin seepage through the holes in the covers when the composite was pressed in the vacuum bag. The photo (Fig. 36) shows holes in the covers through which the resin seeped, leading to bonding with the drainage mat.

Fig. 36. Holes visible in the composite cover

4.2. The second method to run phase III of the composite manufacture

Learning from the erroneous assumptions in the first attempt to produce a three-phase composite, in the second method it was decided to use PET film and delamination. Their use does not pose the risk of the covers sticking to any of the materials. It also ensures good resin seepage and drainage of excess resin when pressing in the vacuum bag (Fig. 37).

Fig. 37. Layers used in phase III of the composite

Unfortunately, this method also proved unsuitable for the manufacture of the composite. When pressing the composite layers together in the vacuum bag, the holes in the covers led to the absorption of most resin by the delamination. This was assumed to be the case when manufacturing the composite using this method, however unexpectedly a lot of resin was absorbed by the delamination, which was only designed to drain the excess resin (Fig. 39-39).

Fig. 38. View of the composite surface

Unfortunately, due to limited possibilities, as the three-phase composite manufacture method appears to be the longest and most time-consuming technique, it was not possible to prepare more composites using this method and expose them to strength testing. Also, testing both three-phase composites was considered unreliable due to the significant imperfections of these materials.

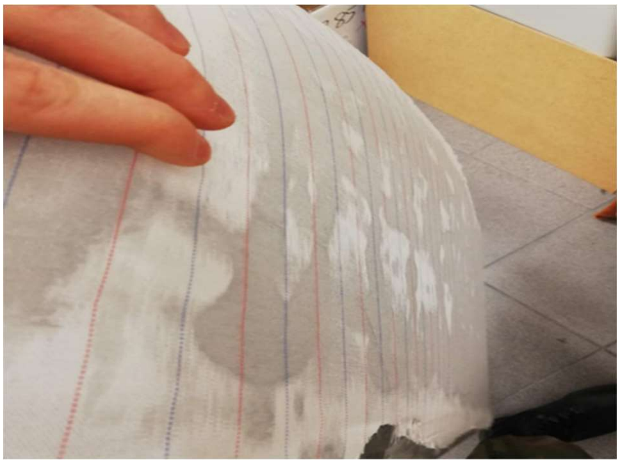

Fig. 39. Resin mostly absorbed by delamination

5. Comparison of properties of the manufactured composites

5.1. Comparison of the composite manufacturing process

Each method of preparing sandwich composite materials is characterised by a different manufacture time, amount of materials required and difficulty of the manufacture. The two-phase method is characterised by the need to consume materials in two phases. In order to prepare the first phase, the following are needed: a drainage mat, PET film, delamination. Once the materials had been used, they cannot be re-used in phase II, so again the following items are needed for phase II: a drainage mat and PET film. When comparing this method with the single-phase composite manufacturing technology, it is important to note significantly higher material consumption. The single-phase method only requires the use of a drainage mat, delamination and PET film in one phase of production rather than two. The three-phase method is the one that consumes the largest amounts of materials, since in the first, second and third phases all the above-mentioned materials are used and they can be used once only.

The manufacture time of the composites with these different methods also varied significantly. The three-phase method was the technique requiring the longest manufacture time, as it took approximately two hours to make each cover in phase I and phase II. Besides it is necessary to add a minimum curing time for each phase in the vacuum bag, equal to six hours. The preparation of phase III required one hour, thus the total composite manufacture time, using the three-phase method, was equal to 23 hours.

The use of the single-phase method was characterised by the preparation time of components equal to 3 hours. When adding the curing time in the vacuum bag, which was six hours, it appeared that the total manufacture time was nine hours. Compared to the three-phase method, the techniques vary noticeably.

When producing the composite using the two-phase method, the preparation process for both the first and second phases took two hours each. It is also necessary to add six hours for the curing process of the composite in the vacuum bag for the first and the second phase. Therefore, the total manufacture time for the two-phase composite was 16 hours.

By contrasting the time and effort involved in preparing the composite with the successive methods, it can be concluded that the method which was the most challenging was the single-phase method, as it required at least two persons in the manufacture process. The process of preparing two covers at the same time and arranging the materials appropriately in the composite manufacture was the most demanding of all methods. The two-phase method also required two persons in the manufacture process, however, it required less work in the preparation of the individual composite components compared to the single-phase method. When producing the composite using the three-phase method, one person was sufficient in the production process, which is a significant advantage of this method.

5.2. Comparison of mechanical properties of single-phase and two-phase composites

As indicated by the results of the strength tests of the single- and two-phase composites, the two-phase composites had significantly higher mechanical strength in all tests. The average Young's modulus at bending for the two-phase composites was 1,160 MPa, while the average bending strength was 11.54 MPa. In the single-phase composites, the average Young's modulus was 25% lower at 876 MPa, while the average bending strength was 9.68 MPa, 16% lower, i.e. it was 16 % lower.

The mean longitudinal modulus of elasticity for the two-phase composites determined during the static tensile test was 812.25 MPa, while the modulus of elasticity for the single-phase composite was equal to 608.75 MPa. The difference in the modulus value between the two composites is 203.5 MPa. The average tensile strength of the two-phase composite was 18.175 MPa; for the single-phase composite it was 14.095 MPa, therefore it was 23% lower.

A test carried out on a pendulum hammer to estimate the ability of the composites to carry dynamic loads by determining their impact strength, made it possible to specify the average impact strength for two-phase composites plane loaded to equal 4.239 kJ/m^2, which was 26% higher than the impact strength specified when the single-phase composite was loaded onto its plane. For edge-loaded two-phase composite samples, the impact strength was 6,322 kJ/m^2 and was thus 30% higher than the impact strength determined with edge-loading of the single-phase composite. The single-phase composite had an impact strength of 3.157 kJ/m^2 for plane-impacted samples, while for the edge-impacted samples this value was equal to 4.457 kJ/m^2.

The final test of the composite was to examine adhesion between the cover and the core of the two-phase composite. The test was an attempt to determine the bonding strength between the covers and the core. The average value of the destructive forces for the two-phase composite was equal to 441.4 N, however, the value for the single-phase composites was 353.2 N, i.e. it was 20 % lower.

All the conducted strength tests indicate better mechanical properties of the two-phase composite. It featured higher bending strength, tensile strength, better impact strength and adhesion between the cover and the honeycomb core. The obtained results prove that the two-phase method achieves a mechanically stronger composite, while the single-phase composites are created at a lower cost and in a shorter time; however, they are worse than two-phase composites in terms of their strength. A factor that determines the inferior mechanical properties of the single-phase composite is the phenomenon of losing some of the resin under the influence of gravity by the freshly saturated layers of glass fabric located on top of the composite. The resin seeps into the second composite cover, which results in one of the covers not being sufficiently saturated with resin. Nevertheless, the amount of resin remaining in the cover allows the covers to cure properly and bond to the honeycomb core. This method can, therefore, be used when a large number of composites need to be produced, with the least amount of auxiliary materials and in a short manufacture time. The two-phase method, on the other hand, achieves a mechanically stronger composite using more material and a longer production time.

6. Conclusions

Based on the experiment, the following conclusions were drawn:

1. The composites made with the single-phase method are characterised by the shortest manufacture time as well as the lowest material consumption;
2. The results of the strength tests indicate that mechanical strength is a significant drawback in the manufacture of a single-phase composite;
3. The two-phase method requires a longer manufacture time and more material consumption, however,

it makes it possible to prepare a composite with higher strength compared with the single-phase method;

4. The three-phase method requires the longest composite manufacture time has the highest material consumption of all the methods;
5. The two-layer covers with fibreglass reinforcement, prepared using the vacuum bag method, do not have a uniform structure. This causes the resin to seep into the other layers of the composite during the bonding process of the covers to the core inside the vacuum bag, during the three-phase method.
6. In the process of curing the composite in a vacuum bag, the resin-soaked glass fibre should be on a PET film or some other uniform material without holes. The use of a material with holes causes the resin to seep into the lower layers of the components, resulting in improper bonding of the composite.

References

1. Boczkowska A., Krzesiński G. 2016. Composites and techniques of their production. Oficyna Wydawnicza Politechniki Warszawskiej. Warszawa.
2. Królikowski W. 2012. Polymer structural composites. Wydawnictwo Naukowe PWN, Warszawa.
3. Ochelski S. 2018. Experimental methods of mechanics of structural composites, WNT. Warszawa.
4. Castane B., Bouvet C., Ginot M., 2020 Review of composite sandwich structure in aeronautic applications, Composites Part C: Open Access, Vol 1, 2020, 100004, https://doi.org/10.1016/j.jcomc.2020.100004.
5. Thomsen O. 2009. Sandwich Materials for Wind Turbine Blades – Present and Future. Journal of Sandwich Structures & Materials 11. 7-26. 10.1177/1099636208099710.
6. Krishnasamy S., Muthukumar C., Thiagamanin S., Rangappa S, Siengchin S. 2022. Sandwich Composites: Fabrication and Characterization. CRC Press.
7. Komorek A., Przybyłek P., Szczepaniak R., Godzimirski J., Rośkowicz M., Imiłowski S. 2022. The Influence of Low-Energy Impact Loads on the Properties of the Sandwich Composite with a Foam Core. Polymers. 14. 1566. https://doi.org/10.3390/polym14081566.
8. Mouritz A.P. 2012. Introduction to Aerospace Materials. Woodhead Publishing.
9. Ostwal R.S., Dumre A., Takalkar A., Mb A., Krishnan R., Padmanabhan, 2014. Influence of Post Curing on the Flexural Properties of a Rigid Polyurethane or Polyisocynurate Foam-Glass/Epoxy Face Sheet Sandwich Composite. International Journal of ChemTech Research. 6(6):974-4290.
10. Reuterlöv S., 2002. Cost effective infusion of sandwich composites for marine applications, Reinforced Plastics, 46(12), 2002, 30-34, doi.org/10.1016/S0034-3617(02)80224-7.
11. Krzyżak A., Mazur M., Gajewski M., Drozd K., Komorek A., Przybyłek P. 2016. Sandwich Structured Composites for Aeronautics: Methods of Manufacturing Affecting Some Mechanical Properties, International Journal of Aerospace Engineering, vol. 2016, Article ID 7816912, 10 pages,. https://doi.org/10.1155/2016/7816912
12. Calabrese L., Di Bella G., Fiore V., 2016. Manufacture of marine composite sandwich structures, Editor(s): Graham-Jones J., Summerscales J. in Woodhead Publishing Series in Composites Science and Engineering, Marine Applications of Advanced Fibre-Reinforced Composites, Woodhead Publishing, pp. 57-78, doi.org/10.1016/B978-1-78242-250-1.00003-X.
13. Menta N.S., Chandrashekhara V.G., Berkel K., Sha T.R., Wu J., Pfitzinger P. 2012. Out-of-Autoclave Sandwich Structure: Processing Study. International SAMPE Technical Conference, 48.
14. Khan A. S. 1996. International Journal of Plasticity. University of Maryland Baltimore County. Baltimore.
15. 4125:2001/A1:2011 – Kompozyty tworzywowe wzmocnione włóknem – Oznaczanie właściwości przy zginaniu.