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Original Research

ANALYSIS OF THE PROPERTIES OF ORTHOTROPIC COMPOSITES IN TERMS OF THEIR USE IN AIRFRAME REPAIRS

ANALIZA WŁAŚCIWOŚCI KOMPOZYTÓW ORTOTROPOWYCH W ASPEKCIE ZASTOSOWANIA W NAPRAWACH PŁATOWCÓW

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Abstract

The aim of the research was to determine the basic strength properties of orthotropic composites in terms of their use in the repair of aircraft airframes. The objects of the tests were three types of composites reinforced with carbon fibers: produced using the wet method with a thickness of 2.5 mm, commercial with a thickness of 2 mm and commercial with a thickness of 7.3 mm. Specimens cut out from the first two types of materials were subjected to a static tensile test with a force applied in the direction of the fibers and at an angle of 45°, which enabled the determination of tensile strength and modulus of elasticity. Specimens made of 7.3 mm thick composite were subjected to four-point bending and tensile tests to determine Young's modulus, compression and impact strength, also taking into account two directions of load application. The values of stresses and Young's modulus determined in this way indicate much lower strength and stiffness of orthotropic composites apart from the reinforcement fibers' directions, which is the basis for replacing them with quasi-isotropic composites in repairs of aircraft airframes.

Keywords: orthotropic composite, mechanical properties, impact strength

Streszczenie

Celem badań było wyznaczenie podstawowych właściwości wytrzymałościowych kompozytów ortotropowych w aspekcie wykorzystania ich w naprawach płatowców statków powietrznych. Obiektami badań były trzy rodzaje kompozytów zbrojonych włóknami węglowymi: wytworzony metodą na mokro o grubości 2,5 mm, komercyjny o grubości 2 mm oraz komercyjny o grubości 7,3 mm. Próbki wycięte z dwóch pierwszych rodzajów materiałów poddano statycznej próbie rozciągania siłą przyłożoną w kierunku ułożenia włókien oraz pod kątem 45°, co umożliwiło wyznaczenie wytrzymałości na rozciąganie oraz modułów sprężystości podłużnej. Próbki wykonane z kompozytu o grubości 7,3 mm poddano czteropunktowemu zginaniu oraz próbom rozciągania w celu określenia modułu Younga, ściskania oraz wytrzymałości udarnościowej także z uwzględnieniem dwóch kierunków przyłożenia obciążenia. Wyznaczone w ten sposób wartości naprężeń oraz modułów Younga wskazują na znacznie mniejszą wytrzymałość i sztywność kompozytów ortotropowych poza kierunkami ułożenia włókien zbrojenia, co stanowi podstawę do zastąpienia ich kompozytami quasi-izotropowymi w naprawach płatowców statków powietrznych.

Słowa kluczowe: kompozyt ortotropowy, właściwości mechaniczne, udarność

1. Introduction

Composite construction materials have found application in many industries due to their special properties. They are, among other things, a response to the search for new solutions in the field of materials used in the construction of aircraft airframes. The main purpose of their use is weight reduction and optimization of fuel consumption.

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Therefore composites replace heavier elements made so far in 60-70% of aluminum alloys [1]. In addition to low weight, other advantages of composite materials include corrosion resistance and chemical stability, thermal and electrical conductivity, as well as low coefficient of thermal expansion [2].

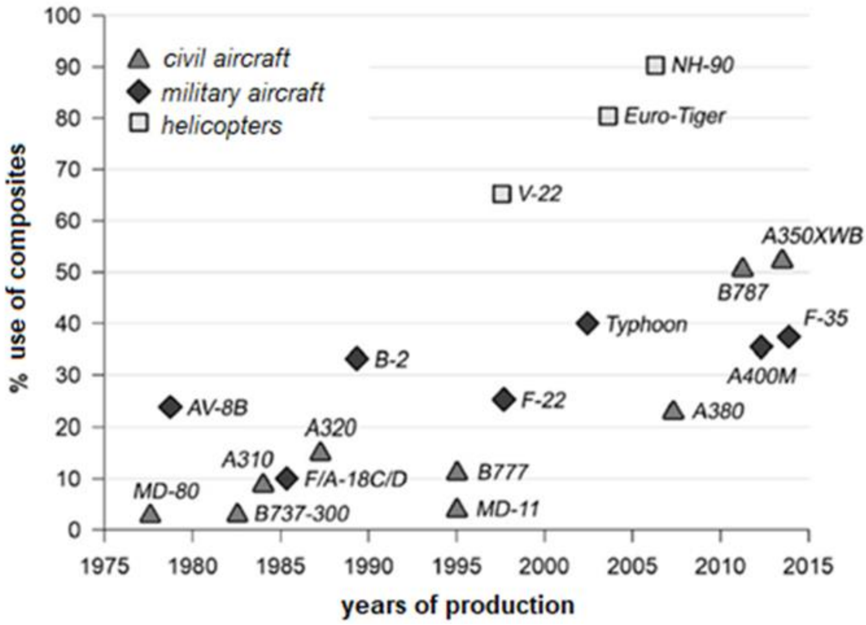


Fig. 1. Mass share of composites in the construction of aircrafts in the years 1975-2015 [5]

Due to their high stiffness, immediate and fatigue strength, composites reinforced with carbon fibers with matrixes based on polymer thermosetting resins (CFRP) are the most widely used in aviation [4]. Reinforcement in this type of composite may take the form of roving strips, fabrics, mats or short fibers, e.g. milled or chopped. A large part of composite materials exposes the properties of an orthotropic material, which means that its properties change in directions perpendicular to each other. Typical types of orthotropic composite reinforcement are shown in Figure 2.

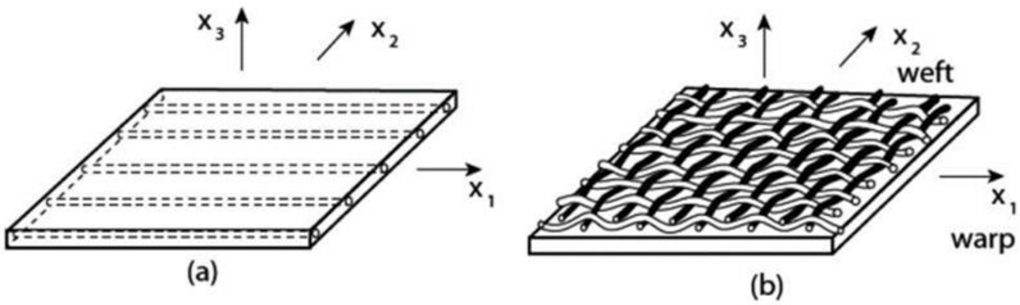


Fig. 2. Directions of orthotropy of the composite reinforced: a) unidirectional, b) fabric [3]

In the case of unidirectional fibers (Figure 2a), the stiffness and strength in the x_1 direction of the fiber are greater than in the x_2 and x_3 directions transverse to it. The fabric presented in Figure 2b is more balanced - it has similar properties in the x_1 and x_2 directions. However, the flat fiber arrangement of 0-90° is the reason for the lower strength in the x_3 direction. Such fabric-reinforced composites, in which the weight of the warp is comparable to the weight of the weft, are the most commonly used type of orthotropic composite [5, 6]. The properties of the composite depend so strongly on the direction of reinforcement orientation due to the fact that the strength of carbon fibers is up to 100 times greater than that of the polymer matrix [7].

The complexity of the internal structure of composite materials is an important factor influencing the fact that elements made of them are subject to damage at various stages of use, which most often include cracks and delamination. Damage can be local or affect the entire element, and it is caused by permanent, fatigue or impact loads. The main operational problems of composites are directly related to their damage - difficulties in detecting low-energy damage (BVID - Barely Visible Impact Damage) [8, 9, 10], in selecting a repair method due to the limited possibility of mechanical processing (cutting [11] and drilling [12, 13]), as well as in the design of joints (especially with the use of mechanical fasteners [14, 15]).

The aim of the research was to determine the strength of polymer carbon composites with orthotropic properties in various directions and to determine their modulus of elasticity. The third type of CFRP composite was also subjected to compression and bending strength tests, as well as impact tests. An attempt was made to analyze the obtained results in terms of the use of orthotropic composite in the repair of airframe structures.

2. Research materials and methods

Composite No. 1

The first stage of the experimental part was the production of a carbon composite. For this purpose, a carbon fabric with a weight of 206 g/m^2, epoxy resin for laminating L285 with a density of 1.19 g/cm^3 and a slow-curing hardener 287 were used. As part of the composite manufacturing process, 12 layers of fabric saturated with a mixture of resin and hardener mixed in a ratio of 100:40 were stacked on top of each other. Excess resin was removed with a roller. The obtained structure was subjected to a force of 40 kN for 30 minutes (pressures of about 0.68 MPa) and then cured for 5 hours in a dryer at 80°C. The effect of the lamination was a composite plate with dimensions close to a square, from which individual specimens were then cut out. Appropriate calculations were carried out (Table 1) in order to theoretically estimate the Young's modulus of the composite material.

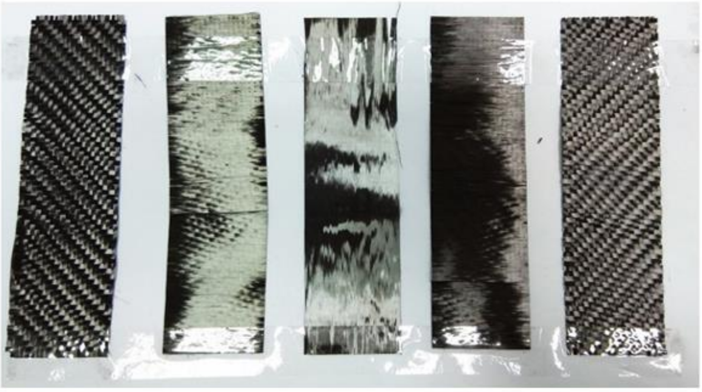
Table 1. Algorithm for determining the Young's modulus of the composite

Plate dimensions	a = 237.8 mm b = 247.4 mm c = 2.492 mm
Carbon fabric weight	$g = 206\ \frac{\text{g}}{\text{m}^2}$
Young's modulus of carbon fiber	E_w = 230 GPa
Number of layers of carbon fabric	n = 12
Resin density	$\rho_ż = 1.19\ \frac{\text{g}}{\text{cm}^3}$
Young's modulus of resin	$E_ż$ = 3.15 GPa
Plate weight	m_k = 202.82 g
Plate volume	$V_k = \text{a} \times \text{b} \times \text{c} = 146.61\ \text{cm}^2$
Plate density	$\rho_k = \frac{m_k}{V_k} = 1.38\ \frac{\text{g}}{\text{cm}^3}$
The surface area of plate	$S_k = a \times b = 0.0588\ \text{m}^2$
The surface of area of the worn carbon fabric	$S_t = n \times S_k = 0.706\ \text{m}^2$
Carbon fibers weight	$m_w = S_t \times g = 145.43\ \text{g}$
Resin weight	$m_ż = m_k - m_w = 57.39\ \text{g}$
Carbon fibers mass fraction	$w_w = \frac{m_w}{m_k} = 0.72$
Resin mass fraction	$w_ż = 1 - w_w = 0.28$
Resin volume	$V_ż = \frac{m_ż}{\rho_ż} = 48.23\ \text{cm}^3$
Resin volume fraction	$u_ż = \frac{V_ż}{V_k} = 0.33$
Carbon fibers volume fraction	$u_w = 1 - u_ż = 0.67$
Carbon fibers density	$\rho_w = \frac{m_w}{u_w \times V_k} = 1.48\ \frac{\text{g}}{\text{cm}^3}$
Young's modulus (theoretical) of the plate	$E_{k\ theoretical} = \frac{(E_w \times u_w)}{2} + (E_ż \times u_ż) = 78.21\ \text{GPa}$

Composite No. 2

The second tested type of composite was a commercial carbon-epoxy composite with a multi-layer reinforcement structure. It consisted of 5 layers shown in Figure 3. The outer layers were in the form of carbon fiber fabrics, and the inner ones - roving, i.e. bundles of continuous, untwisted fibers.

a)



b)

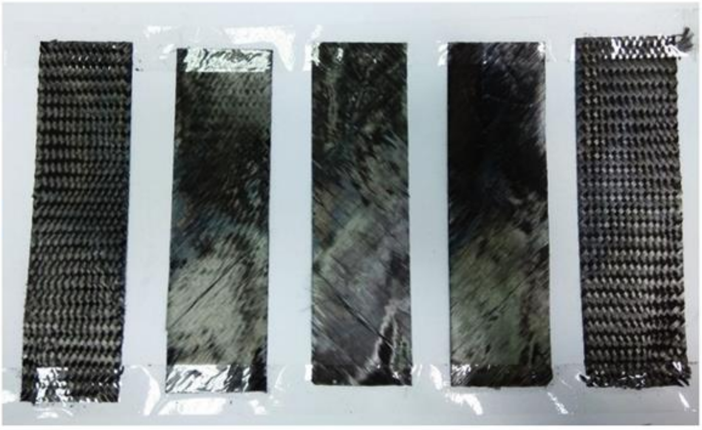


Fig. 3. Individual layers of reinforcement of a composite material with a multi-layer reinforcement structure oriented (a) in parallel (b) at an angle of 45°

Specimens with the dimensions listed in Table 2 were cut out of the composites to carry out a static tensile test using the Hung Ta HT-2402 universal testing machine. The aim of the study was to determine the tensile strength of composite materials (breaking stresses), as well as to determine the actual values of the modulus of elasticity.

Composite No. 3

The third object of research was a composite produced in an autoclave in the Silesian Science and Technology Center of the Aviation Industry Sp. z o.o. based on carbon prepreg GG 204T g/m^2 IMP 503 ZHT, 7.3 mm thick, consisting of 25 layers arranged according to the scheme $[0°]_{25}$. The board was produced at a pressure of 400 kPa and a temperature of 120 °C. For the study of Young's modulus 17 mm wide specimens were cut out of the composite.

Dimensions of specimens for strength tests prepared from the above-mentioned composites are shown in Table 2.

Table 2. Dimensions of specimens prepared for strength tests

Dimension	Width	Thickness
Composite No. 1	25.0 mm	2.5 mm
Composite No. 2	40.0 mm	2.0 mm
Composite No. 3	17.0 mm	7.3 mm

The 3542-025M-025-HT2 (Epsilon) extensometer with a measuring base of 25 mm was used to determine the modulus of elasticity. For better fastening of specimens with a thickness of 2 and 2.5 mm in the handles of the machine, folding handles were laminated to their ends made of 3 layers of glass fabric.

Additional specimens of 60 x 250 mm were cut out of the composite board with a thickness of 7.3 mm using the Water Jet method. The composite specimens were subjected to four-point bending (Fig. 4) on the Zwick Roell Z100 testing machine in order to determine the bending loads and failure stresses.

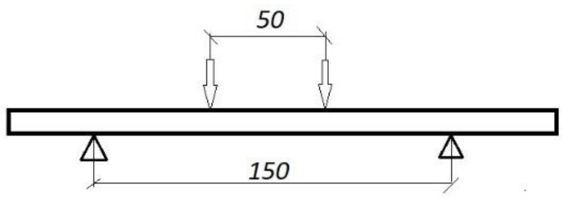


Fig. 4. Scheme of four-point bending

As part of the experiment, the tensile and compressive strength of this composite were also determined. Modulus of elasticity was determined during compression in the x_3 direction (perpendicular to the surface of the material).

In order to test the tensile strength in the x_3 direction, square elements of the composite with dimensions of 16 x 16 mm were bonded into the sockets of steel cylindrical specimens with adhesive DP 420 (Fig. 5). After the joints had hardened, the specimens were axisymmetrically stretched to determine the joint destructive force.

Fig. 5. View of the specimen after testing the strength of the composite in the x_3 direction

To test the modulus and compressive strength in the x_3 direction, 7 cubes of 27 x 27 mm with holes of 10.1 mm in diameter were bonded together (Fig. 6). A specimen with a height of 52 mm was obtained, which was loaded with a force of up to 250,000 N, recording the dependence of the displacement of the machine traverse as a function of force. In addition, the stiffness characteristics of the Instron 8802 testing machine were determined by compressing its plates without a specimen, which allowed to calculate the value of the modulus of elasticity in x_3 direction. Then, the specimen was loaded in a machine with a larger measuring range - the ZDM100000 tensile machine, leading to its destruction.

The impact strength tests of composite No. 3 were carried out on specimens with a square cross-section of 7.3 x 7.3 mm and a length of 60 mm (Fig. 7). The specimens were cut out in the direction of the fibers and at an angle of 45°. The tests were carried out on the impact hammer SW-5 with the speed of 3.8 m/s and the energy of 50 J in the plane of laying the composite layers and in the plane of the cross--section of the composite.

Fig. 6. Cube cut out of 7.3 mm thick composite

Fig. 7. Specimens for impact tests a) in the plane of laying composite layers b) in the cross-sectional plane of the composite

3. Research results

The use of an extensometer made it possible to determine the values of the modulus of longitudinal elasticity of the tested composites. Young's modulus of composites was determined taking into account two basic load variants of composite specimens: variant A - load applied parallel to the direction of the reinforcement fibers and variant B - load applied at an angle of 45° to the reinforcement (specimens cut at an angle).

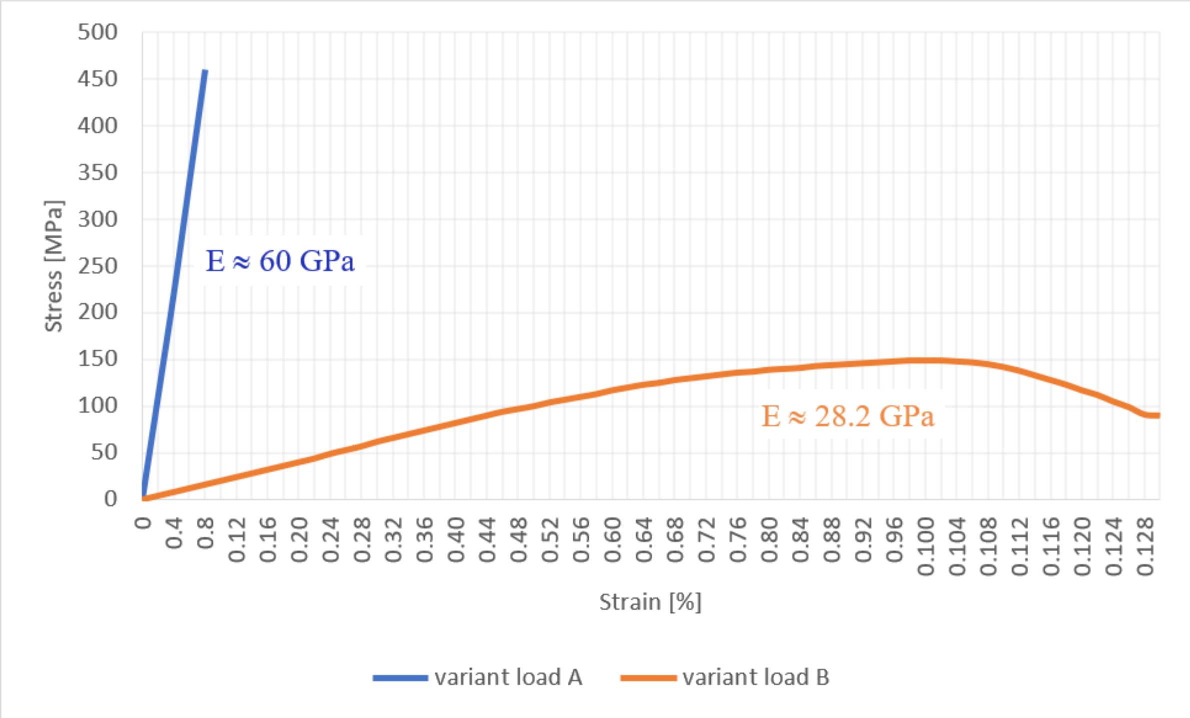


Fig. 8. Curves σ = σ(ε) of composite No. 1

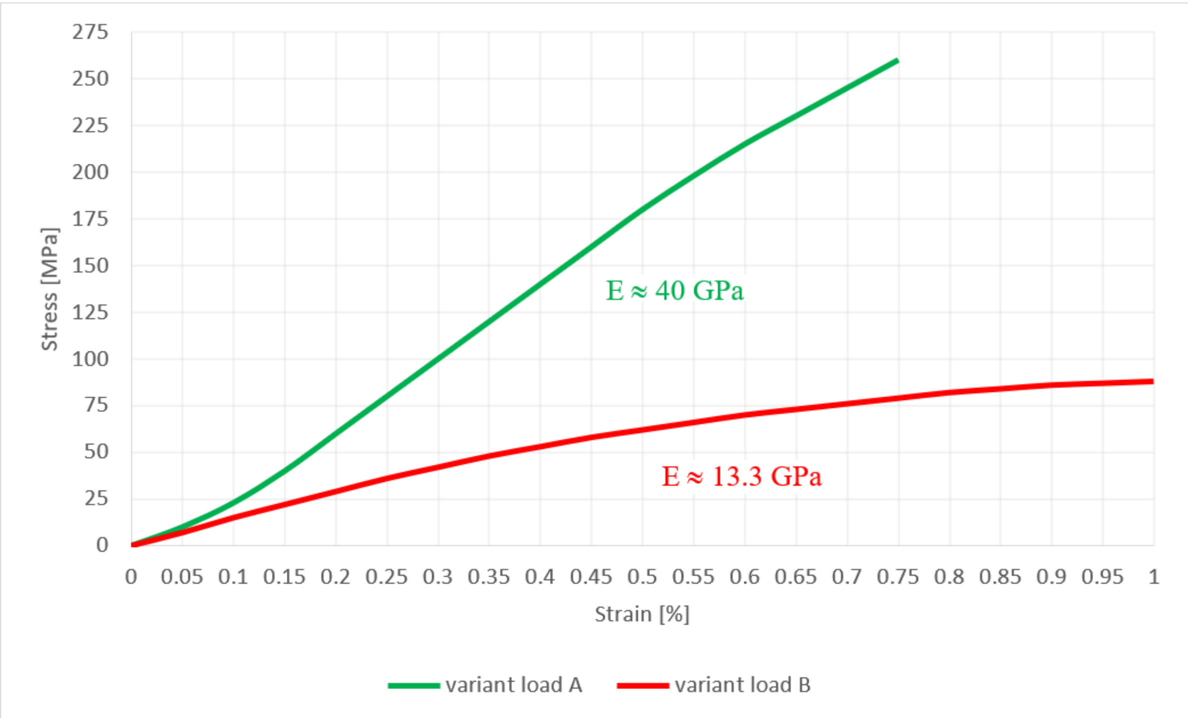


Fig. 9. Curves σ = σ(ε) of composite No. 2

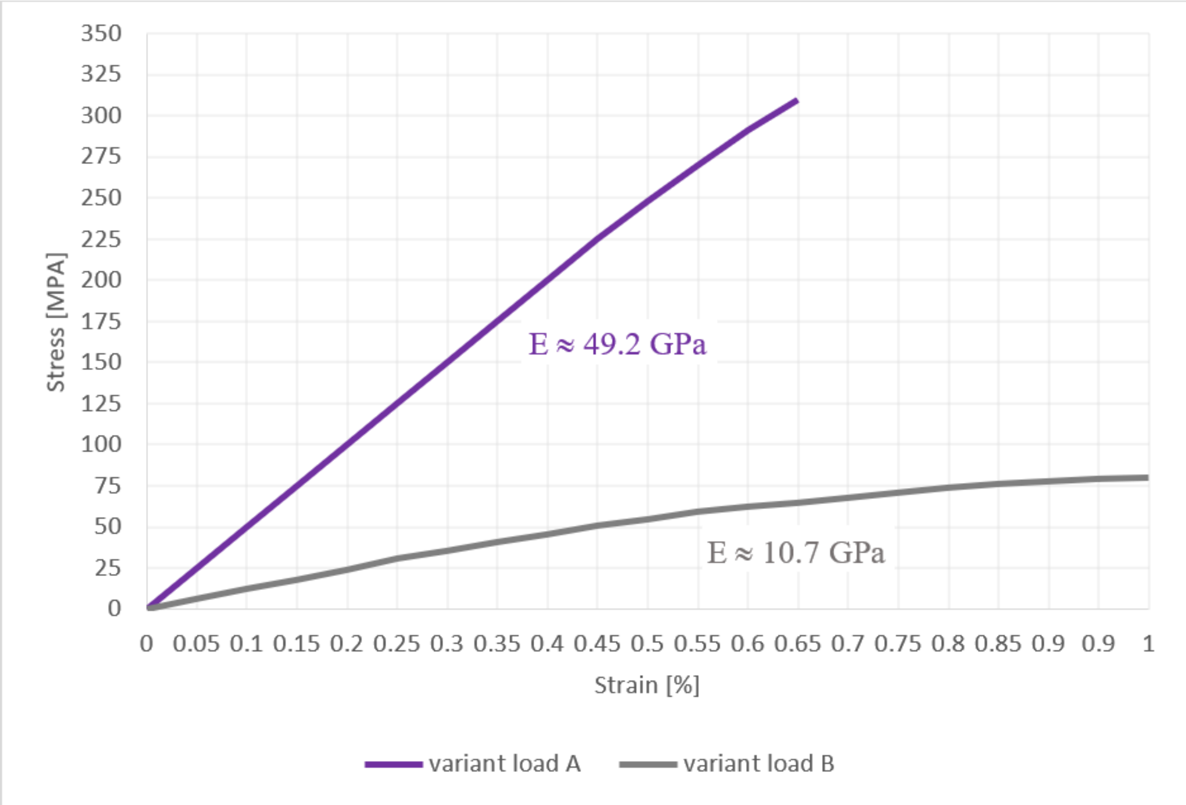


Fig. 10. Curves σ = σ(ε) of composite No. 3

The tensile strength significantly depends on the direction of the load. For loads directed at an angle of 45° (variant B) in relation to the fiber arrangement, the strength is at least twice as low as the strength of the material loaded along the fibers (variant A).

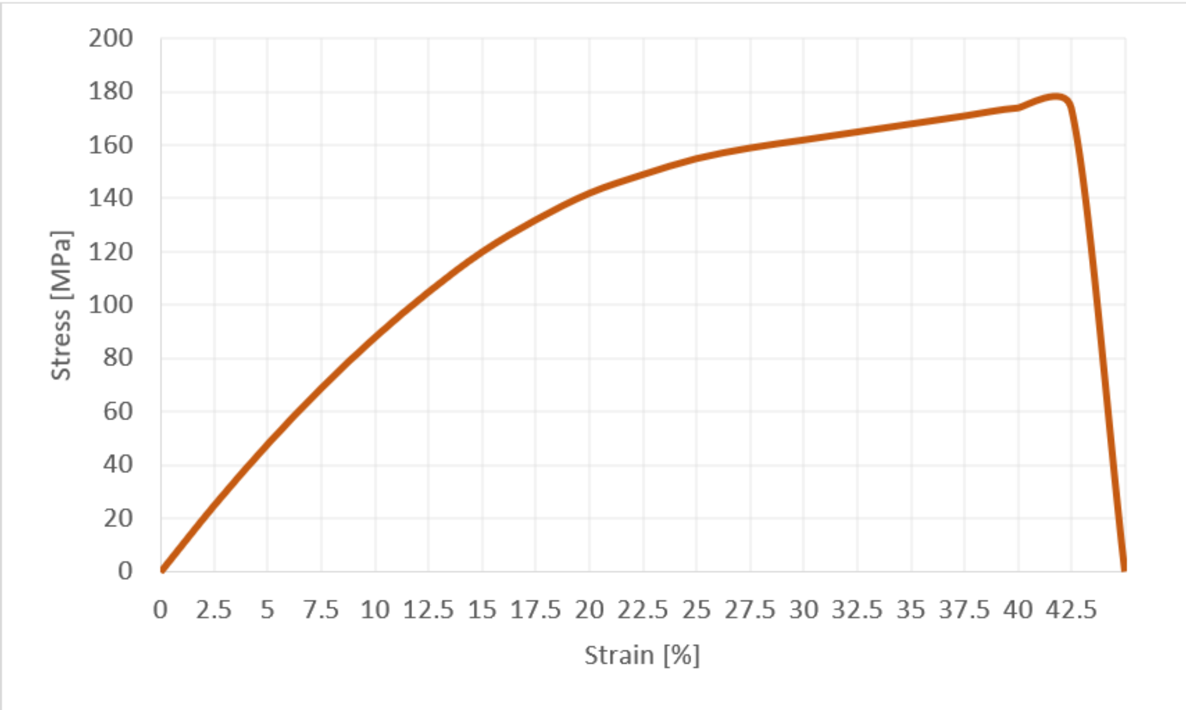


Fig. 11. Curve σ = σ(ε) of composite No. 3 in the load variant B in the entire range of deformations (without using an extensometer)

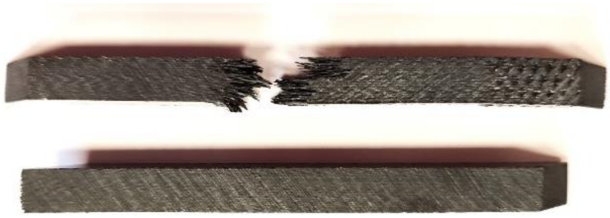


Fig. 12. Destruction of composite No. 3 in variant B

The strength of composites No. 1 and 2 is presented in table 3.

Table 3. Tensile strength of composites loaded in different directions

Load variant	Strength [MPa]	
	Composite No. 1	Composite No. 2
A	766.80	344.45
B	148.00	160.51

The result of three measurements of four-point bending of specimens from composite No. 3 is the average value of the destructive force, which was 14.133 kN, which corresponds to the maximum positive and negative normal stresses in the bending specimen of 663 MPa.

$$\sigma = \frac{M_g}{W} = \frac{7166.5 \times 50 \times 6}{60 \times 7.3^2} = 663 \text{ MPa} \qquad (1)$$

On the basis of axial-symmetric tensile tests of 5 specimens, the tensile strength of the composite in the direction perpendicular to the arrangement of fabric layers was determined to be 24.04 ± 3.85 MPa. This is the stress level corresponding to the tensile strength of epoxy matrixes.

Based on the obtained two compression curves (specimen compression and machine stiffness characteristics), the value of Young's modulus of the tested orthotropic composite was calculated in the x_3 direction, which is 6240 MPa. Using the ZDM100000 testing machine with a larger measuring range, the value of breaking stress equal to about 340 MPa was determined. The destruction consisted in crushing one element of the specimen (Fig. 13).

Fig. 13. The form of destruction of a compressed specimen element

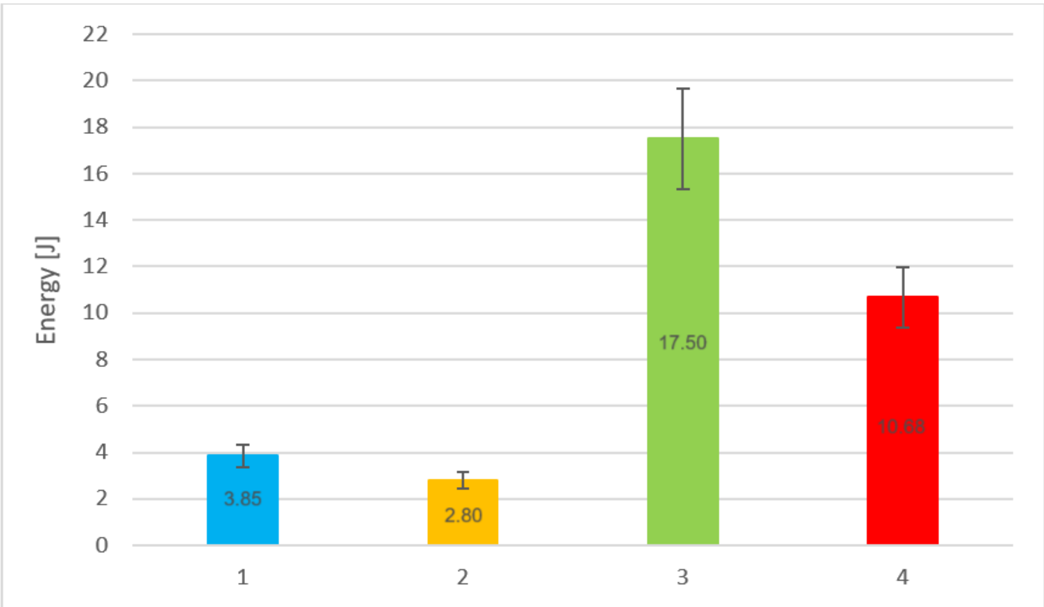


Fig. 14. Values of the energy of destruction of composite no. 3 during the impact test:
1. Load variant A perpendicular to the composite surface, 2. Load variant A perpendicular to the composite cross-section,
3. Load variant B perpendicular to the composite surface, 4. Load variant B perpendicular to the cross section of the composite

Impact tests using the SW-5 impact hammer of composite No. 3 tested in both load variants consisted in hitting both into the surface of the composite as well as into the cross-sectional area. The obtained values of the destruction energy are presented in the diagram in Figure 14.

4. Analysis of the results and discussion

Table 4 summarizes the mechanical properties of the tested composites. The obtained values of the modulus of elasticity and strength correspond by an order of magnitude to the values for carbon fiber-reinforced composites presented by other authors [18].

Table 4. Mechanical properties of the tested composites

Load variant	Composite	Strength [MPa]	Young's modulus [GPa]
A	No. 1	766.8	60.0
B		148.0	28.2
A	No. 2	344.5	40.0
B		160.5	13.3
A	No. 3	663.0	49.2
B		178.5	10.7

The difference between the calculated theoretical value of Young's modulus of composite No. 1 comes from the fact that the analytical calculations assumed that the fibers are perfectly parallel to the load. The experimentally obtained tensile diagrams $\sigma=\sigma(\varepsilon)$ in the direction of fiber orientation show that the stiffness of the composite increases slightly with increasing load. (Fig. 9), which may indicate fiber straightening.

The initial stiffness of the composites in variant B is several times lower than the stiffness in load variant A and clearly decreases with the increase of strain. Researchers in other publications also point out differences in the strength of orthotropic composites depending on the orientation of carbon fibers as a source of possible problems [5].

The failure of the loaded composite in variant A is rapid and cracking occurs in a plane perpendicular to the load. The failure of composites loaded in variant B is characterized by large deformations resulting from the slippage of fibers arranged at an angle of 45°. Therefore, the assessment of the strength of the composites in variant B is less accurate.

The highest strength and stiffness of the wet-produced composite No. 1 resulted from high curing pressures (greater than those obtained in autoclaves), the use of which allowed to obtain a large volume fraction of fibers (about 67%). Research shows that the volume fraction of carbon fibers in the range of 60-70% provides the most optimal mechanical properties [19].

The tests showed that the tensile strength of the composite in the x_3 direction (the direction of laying successive layers of the laminate) is even lower than the tensile strength of epoxy resins. This proves poor cohesion of the epoxy matrix used and poor adhesion to carbon fibers. The lack of reinforcement fibers makes this direction most susceptible to rheological phenomena [14]. The elastic modulus in the x_3 direction is 6.24 GPa, which is consistent with literature data [18].

Exceptionally large differences in the values of the destruction energy of composite No. 3 occur when it is loaded dynamically in different directions. The specimens showed more than four times higher impact strength in load variant B. The maximum impact strength was about 328 kJ/m^2, which is a relatively high value. Exemplary results of other tests of a twelve-layer CFRP composite show a Charpy impact strength slightly above 200 kJ/m^2 [20]. It follows that the impact strength of composites depends significantly on the direction of fiber arrangement in relation to the direction of the impact load.

5. Conclusions

- Large differences in mechanical properties (strength, Young's modulus) of orthotropic composites depending on the load direction make their use in repairs of metal (isotropic) airframe structures unjustified.
- In the case of composite structures, their use would be justified if it concerned fabricated elements made of orthotropic composites, for which the direction of the reinforcement is known. Quasi-isotropic composites seem to be more suitable for repairing metal structures, which can be obtained by rotating successive layers of fabrics against each other.
- The calculation of the Young's modulus of composite materials based on the knowledge of the volume fraction of their components is subject to a large inaccuracy. It results from the fact that the modules of carbon fibers used in fabrics can vary significantly and from the fact that the fibers in fabrics are not perfectly regular.
- Orthotropic composites have the lowest strength properties (tensile strength, Young's modulus) in the x_3 direction (perpendicular to the fabric laying surface). The determined tensile strength in this direction (interlayer strength) is lower than that of typical epoxy resins.
- The highest impact strength is shown by orthotropic composites loaded dynamically in the

variant B. This useful feature of the composite material could be used in the production of collision protection parts, e.g. bumpers.

Acknowledgments

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