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A Study on Mechanical Strength and Failure of Fabric Reinforced Polymer Composites

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ABSTRACT

The paper presents a study on influence of different fabric weave and fabric orientation on strength properties of fiber reinforced polymer composites. The research concerns materials used in a new type of rotorcraft. Four series of laminates were fabricated with hand forming, using the MGS L285/H285 epoxy resin. Triple-kind experiments were performed: the Shore hardness measurements, tensile strength testing and fractographic analysis. The specimens of different series shown various strength and stiffness characteristics, depending on the type of weave and fabric layup. Three different failure schemes were observed. The Poisson coefficient was different among series, as well, but no understandable link to specimen morphology could be found so far. Fractographic observations suggested intralaminar delamination.

Keywords: delamination, fractography, strength tests, CFRP composite.

INTRODUCTION

Research into composite materials, in which modifications have been made to the arrangement of fibres resulting in a strengthening of their structure, unfortunately requires continuous development work, as well as the use of newer and better composites, with particular emphasis on improving their strength. Composites have gained such a wide popularity in the field of aviation, due to the property of lightness, energy absorption from dynamic phenomena and resistance to external factors. This paper discusses how to conduct research on a new way of preparing composite material.

The purpose of conducting the research was a great interest of the aviation industry carrying out the production of aircraft, which are oriented at the possibility of using these composite materials [1, 2], which very often allow to replace the ones used so far. Researchers are still looking for much better composite materials with better properties, such as a high strength, good fracture toughness, temperature resistance etc. to create better and more reliable flying equipment. Tests about composite materials are carry out at various industry, that allow to obtain measurable benefits in the form of improved reliability of composites element [3–4].

In recent years, technical progress and high competition on global markets have forced manufacturers to conduct research that can be used in the industry and to seek and implement new and better solutions. High pressure and high expenditures on innovation have led and continue to lead to the creation of new materials and products and to the continuous improvement and increase of efficiency of already known technologies and processes and, what is also very important, to the development of new and better and more modern technologies [10, 12]. The aviation sector is one of the most rapidly growing industries, which is also characterised by high competition. It is also a very demanding industry, which is why the need for modern technologies and materials is so pronounced here. Over the years, various materials such as wood, steel, aluminium and its alloys as well as other metals and their alloys have been used in the manufacture of aircraft structures. With the development of technology, an increase in demand for composite materials has been observed in this sector [11]. Composites are just such modern materials, they are an argument for the constantly growing market demand for materials with more favourable construction and exploitation indices, besides they allow for rational shaping of the required properties. They are called "materials of the 21st century" due to their special properties and the possibility of using them in many areas of industry [10]. At the end of the twentieth century, a very fast, dynamic development of branches of industry involving construction materials and an expressive growth of utility parameters of these materials could be observed [9]. The very numerous ways in which they can be used confirm the need for the individual components to meet the appropriate design requirements. This is confirmed by their use in specialised fields such as aerospace (composite materials used as radiation absorbing materials and in aircraft manufacturing. Composites with such parameters are used in the production of stealth aircraft [16], renewable energy of the wind industry (composite materials are used in wind turbines) [17]. The automotive industry is characterized by an increasing use of composite materials in, among others, powertrain and suspension assemblies, exhaust systems, brake systems and body parts [18]). Production of more and more modern and complicated elements of machine parts and constructions, not only aeronautical ones, creates the necessity of continuous development of production methods and materials. The development of composite materials was initiated in the second half of the 20th century, laminates, or multilayer fibre composites, are still used today. The need to reduce the weight of new types of aircraft while maintaining adequate mechanical strength of many elements creates the necessity to use strong and lightweight construction materials. These requirements are met by more and more frequently used composites based on polymers and metal alloys [2, 5]. A composite is a material formed from a minimum of 2 components with different properties, resulting in better or new properties compared to the components used separately or resulting from the simple addition of these properties, a composite is an externally monolithic material with noticeable boundaries between the individual modules [5]. One must be awared, that during manufacturing process of composites some inevitable defects, such as voids or microcracks may be appear. Moreover, as indicated by some authors [23] voids can induce microcracking in the composite because of stress concentration. Some authors point at risk of delamination and interfacial damage in laminated composite structures, especially in result of low energy impact [21–22]. This reveals a need of identification of various damage forms and mechanisms with fractography and other methods. Composites are high-strength materials and are used to make many structural components in gliders, aircraft, helicopter rotors and even space equipment and rockets. They can take many shapes, are mechanically strong yet lightweight and have high rigidity. In terms of production tonnage or variety of applications, polymer structural composites form an unrivalled large field of global creativity. The use of composites is constantly increasing, as exemplified by the year 2010, when world production amounted to 12.1 million, an increase of 17% over the previous year, 2009. In the popular aircraft such as the Boeing 787 Dreamliner, polymer composites account for as much as 50% of the weight of the entire structure. The use of such materials brings with it a reduction in the weight of the airframe, which contributes to lower fuel consumption and thus lower emissions. Another advantage is that the composite structures do not require as many rivet joints as in the structures using other materials, this brings better aerodynamic properties and reduces the cost of production [5, 7]. The advantage of inorganic and polymeric fibres in comparison to metals and their alloys is lightness, despite their high prices they are often used in aviation and aerospace where the choice of fibre type is influenced by stiffness and strength ratios related to density. Aramid, carbon and boron fibres are currently used in the most responsible composite parts of aircraft [6, 14]. Composites are increasingly used in aircraft construction due to their high strength properties at low density. The first polymer composites used as early as the 1950s were glass fibre reinforced composites. Epoxy resin matrix composites are widely used in glider construction, but have not been used for heavily loaded aircraft structural components due to the low stiffness of glass fibres. The appearance of high-strength and high-stiffness boron and carbon fibres gave a chance to use polymer composites to make entire structural elements as well as to reinforce elements of airframe which were made of metals [13]. At present, it is possible to make integral covers of several metres in length, including stiffening elements. Compared to the same covers made of aluminium alloys, composite covers are 20% lighter. In the prototypes of the YF-23 and YF-22 combat aircraft, composite materials accounted for 30% and 23%, but in series production composites were to account for 40% and 35% of the airframe weight. In aircraft that are produced today, composites can account for up to 65% of the airframe weight. Such extensive use of composites causes the so-called cascade effect, i.e. reduction of the mass of the airframe makes it possible to reduce the area of the stabilisers and wings, and thus reduce the mass. High stiffness of composite materials gives the possibility of various structural problems, such as negative wing haunch in the X-29 aircraft. The advantage of composite materials which are reinforced with fibres is high fatigue strength. Some of the more fatigue resistant fibres are carbon fibres. These fibres are used in composites for the production of passenger and transport aircraft, which should have a long service life, while the change of helicopter blades from metal to glass-epoxy composite made it possible to increase the residual life twice [27].

Another use of composite materials is also seen in the Lockheed Martin F-35 Lightning II single-engine multi-role fighter, where composites occupy 35% of the airframe weight. A CFR-type laminate was used in the load-bearing elements, which are the wing skins, flaps, vertical and horizontal stabiliser, and fuselage. This aircraft pioneered the mass production of aircraft using structural nanocomposites called carbon nanotube reinforced epoxy. The use of composites for this type of aircraft is also strategic, reducing detection by radar stations [8].

In the paper [24] Zachariah and others made a revision of recent trends in composite materials. Based on the research the conclusions were drawn. Perfectly woven fiber fabrics shown a moderate level of isotropy, and woven fabric composites were reported to be resistant to impact damage compared to respective unidirectional counterparts.

Morris and others [25] described the behavior of carbon fabric in dry and wet environments subjected to simulated lightning strike. They analyzed the occurrence of degradation and the effect of hygrothermal aging on carbon fabric. Fractographic (SEM) studies were shown to confirm the conclusions.

Generally speaking, there is a lot of research about materials fibre composite but a lack of information on the topic of woven composites used in the aircraft industry, even though some authors [26] describe woven composites but they are used in biomechanical engineering. Additionally, carbon fibers are well established in a competitive market. Application of thin solid layups as tailored interfaces on the carbon fiber surface provide a potential for technical improvement. These technologies can further improve interfacial adhesion and oxidation resistance [15]. An important aspect of the testing methodology is appropriate selection and application of measurement techniques that allow for non-invasive and non-contact in real-time determination of local deformations. Pecho and others looked into the application of structural monitoring. Authors chose RFID methods for detecting defects based on antenna deformation [28].

The analyses of new composite materials performed so far by the authors of the current article haven't been constructively used in design of flying objects (rotorcrafts) up to the moment. On the other hand, systems of arrangement of fiber layups and fiber types analyzed in the paper confirmed their applicability for aircraft structures. The results of the study confirm the possibility of using the respective fabric-reinforced composites in unmanned aerial vehicles and rotorcrafts, in which the main problem is the phenomenon of delamination and other damage. The complexity of the aircraft structure requires usage of materials which properties ensure implementation of tasks associated with the performed flight operations.

METHOD OF PREPARATION

The tested objects were composite samples made in the process of manual lamination using the MGS L285/H285 epoxy resin (Mixing ratio 100:40 – by weight, 100:50 – by volume. Working time 50 min. Curing time 24h at room temperature, followed by 15h at 55°C, cf. www.r-g.de), the parameters of which are collected in the following tables. The specimens were prepared using fabric reinforcement [ECC 40030682 and ECC 40030665]. The reinforcing fabric formed various composite layups – $[0/+90°]_n$ and $[+/- 45°]_n$. Then autoclaving technique was exploited – the batch was covered with a vacuum bag mounted on glued hermetically at the edge of the mould. Hardening of the laminate was carried out at under pressure of -0.9 atm. Next stage of preparation was exposition of the batch to a temperature of 60°C for 8 hours. Subsequently in accordance with the ASTM D3410 standard beam samples were cut out of composite plates (batch). The last step of preparation was sticking tabs to the edges of the beams to provide sufficient grip, as well as to protect samples from damage. Geometrical parameters of the composite specimens are given in Table 1. Specification of uncured epoxy resin is described in Table 2. Detailed material specification is shown in Table 3. Specifications Table 2 and Table 3 were provided by the manufacturer.

There were four series of specimens considered, differing with orientation of fabric at delamination interface, as well as the type of weave. In particular, the A series had twill weave and the 0/45° interface; series B differed with the interface only – 0/90°. The specimens in series C and D had plain weave; theinterface angles were 0/45° and 0/90°, respectively. Such conception of the four series enabled multiaspect considerations of influence of different structural factors on mechanical properties of the new composites.

Hardness measurements

One of the basic engineering assessment of mechanical properties of materials is hardness measurement. In case of FRP composites the hardness parameter must be taken at sufficiently big area of the indent, because of material inhomogeneity (fibers embedded in a resin). For this reason hardness measurements were performed using the Shore's hardness-testing apparatus "M SHORE" D/C/D0 0.5 and were done by pressing a concical indenter with an accurate radius of its tip (Fig. 1). The M SHORE D method is used for hard rubber, hard plastics, polystyrene, acrylic glass,resopal, polymers, rollers, vinyl, rigid thermoplastics,cellulose acetate and so on. Minimum material thickness from 4 till 6 (mm). The

Table 1. Geometrical parameters of the samples

Sample series	Nominal width, *B* [mm]	Thickness, *H* [mm]	Lenght, *L* [mm]
A	24.96	2.00	250.00
B	25.00	2.00	250.00
C	25.00	2.00	250.00
D	25.00	2.00	250.00

Table 2. Specifications of uncured epoxy resin

Bending strength	MPa	110–120
Flexural modulus of elasticity	MPa	2700–3300
Tensile strength	MPa	75–85
Compressive strength	MPa	130–150
Elongation	%	5–6.5

Table 3. Carbon fabric data sheet in the four composite series

Type	ECC 40030682		ECC 40030665	
Series mark	A	B	C	D
Interface	0/45° (twill)	0/90° (twill)	0/45° (plain)	0/90° (plain)
Yield	200 tex		200 tex	
Twist	Warp /Weft		Warp /Weft	
Weight	160 g/m²		180 g/m²	
Thickness	0.30 mm		0.35 mm	
Fabric	Carbon		Carbon	

Fig. 1. Hardness-testing machine M SHORE D/C/D0 0.5 with a coniferous plunger

indenter's vertical angle was 30°. For each sample, 10 measurements were performed, each in a different part of the beam. The results are shown in the graphs below (Fig. 2). The time at which the force (F) applied to the indenter was 3 seconds. The test was performed at an ambient temperature of 19°C. No interference by external factors (vibrations, impacts) was recorded. The results of hardness testing for an exemplary series of samples (the A-series) oscilate around 89.5 sh°D (median; maxium 86.1 sh°D, minimum 72 sh°D). The hystogramme (Fig. 2b) shows the majnority of measurements gave hardness values within the range <80, 90> sh°D. The results obtained for the four series of specimens show however various hardness values. Differences in hardness values depended on the structural quality of the composites.

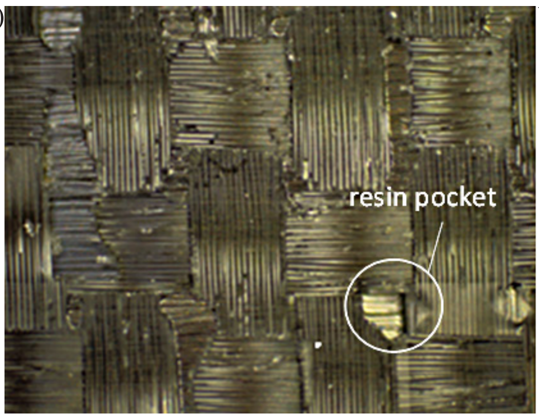
Microscopic examination

Microstructure observations were performed using the "Olympus" BX53M microscope [19]. The main aim of the fractography was to observe possible damage mechanisms. In the pictures (Fig. 3.) one can see the surfaces of delamination in the fabric-reinforced FRP composite. It is obvious that the fracture surface is not a flat plane, as it could be in the composite reinforced with long fibers (especially at a 0//90° interface) [20]. In particular the interwoven fibers seem to brake more easily, which can be treated as intralaminar delamination [21–22]. Also clusters of matrix material – the so called resin pockets – can be observed frequently. On the other hand, some empty spaces (voids) of different size and shape can also be observed (cf. [23]). These phenomena reduce the interlayer toughness and favors damage of the material, such that under external load propagation of pre-existing defects can occur and form delamination.

Strength testing of composites

The tests were carried out with the Instron's 4485 universal strength testing machine (Fig. 4.),

a)



b)

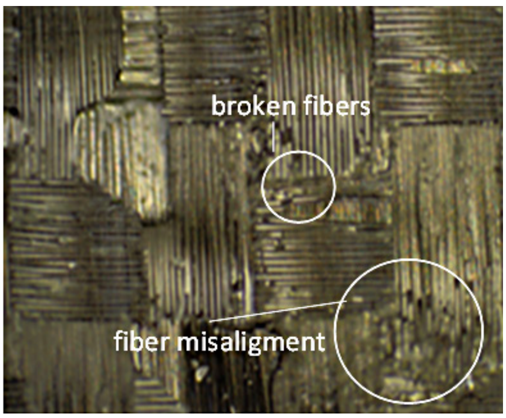


Fig. 2. Results of hardness measurements for chosen composite series: a) individual values, b) distribution of hardness

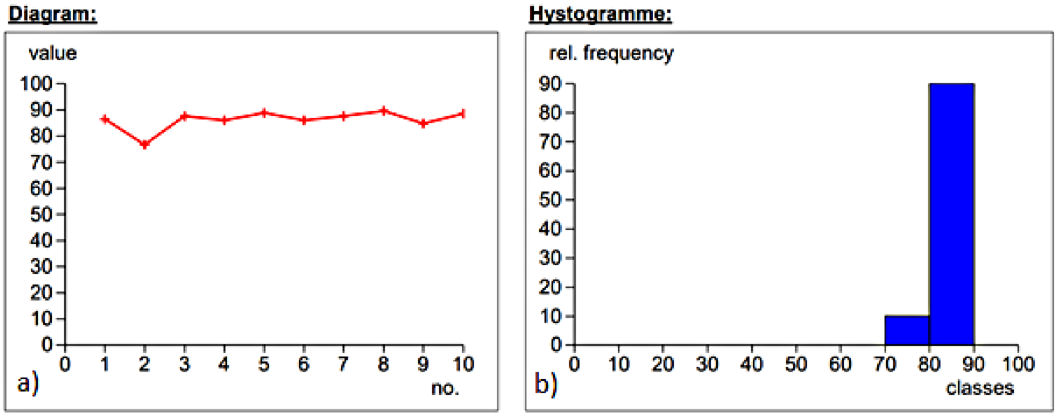


Fig. 3. Microstructure of composite ECC 40030682 wave twill

Table 4. INSTRON 4485 performance characteristics

Parameter	Value/range
Maximum load	200 kN
Operating speed	0.01–1500 mm/min
Workspace	double
Measurement accuracy	+/- 0.5%
Measurement of the narrows	up to 40 mm
Initial sample length	10–100 mm

equipped with a special fixture for tensile tests. In Table 4 parameters of the used press are present.

A specially designed fixture providing tensile load has been used during testing. Mechanical properties of the FRP laminates were determined during tensile tests according to the ASTM D3039 Standard. In order to obtain the Young modulus, Kirchhoff modulus and Poisson ratio different balanced layups of laminates (0/45° and 0/90°) were manufactured.The beam specimens were equipped with strain gauges and eventually subjected to the standardized strength tests.

Fig. 4. INSTRON 4485 universal testing machine

RESULTS AND DISCUSSION

The respective tables contain results of strength tests performed in accordance with the ASTM D3039 Standard. In particular, ultimate tensile load, ultimate strength, apparent longitudinal stiffness and Poisson coefficient are given. In Table 5 the outcomes received for the specimens of series A are collected.

In Tables 6–8 the results of the strength test performed on the B-, C- and D-series composites are shown, respectively. For better visibility and comparison of the results diagrams are given in Table 9. In Figure 5 a comparison of tensile strength values is provided.

It can be noticed that the highest tensile strength revealed the samples of the series D – plain weave arranged in a crossed way 0/90°. The second highest value belongs to series A – twill weave 0/45°. In the remaining two groups of samples (B, C) mean values of tensile strength were significantly lower that the former two; they also differ slightly one from another: 15.7 kN for series B and 11.8 kN for series C. However, the error bars indicate that the difference is not significant.

After converting the ultimate loads to the ultimate strengths (using the calculated values of cross-section area of respective specimens), it

Table 5. Results of tensile strength tests for A-series specimens

Specimen series	Cross - Section area A [mm^2]	Ultimate tensile load F [N]	Ultimate strenght σ_u [MPa]	Apparent longitudinal stiffness (Tangent Young Modulus) E_A [GPa]	Poisson Coeff. v [-]
A1	49.90	25878.93	517.58	2.71	0.01
A2	49.80	26879.83	501.01	1.81	0.01
A5	50.00	25501.15	510.02	1.75	0.01
Mean value	49.90	26086.64	509.54	2.09	0.01

Table 6. Results of tensile strength tests for B-series specimens

Specimen series	Cross - Section area A [mm^2]	Ultimate tensile load F [N]	Ultimate strenght σ_u [MPa]	Modułus Kirchoff G [GPa]	Poisson Coeff. v [-]
B1	50.00	18425.05	368.50	3.54	0.43
B2	50.00	21413.91	428.29	2.80	0.35
B5	49.80	13101.54	262.03	2.41	0.37
Mean value	49.93	17646.83	352.94	2.95	0.38

Table 7. Results of tensile strength tests for C-series specimens

Specimen series	Cross - Section area A [mm^2]	Ultimate tensile load F [N]	Ultimate strenght σ_u [MPa]	Apparent longitudinal stiffness (Tangent Young Modulus) E_A [GPa]	Poisson Coeff. v [-]
C1	50.00	11813.33	236.27	5.64	0.32
C2	50.00	6267.50	125.35	5.23	0.35
C5	48.00	12914.32	304.46	6.15	0.25
Mean value	49.30	10331.72	222.03	5.67	0.31

Table 8. Results of tensile strength tests for D-series specimens

Specimen series	Cross - Section area A [mm^2]	Ultimate tensile load F [N]	Ultimate strenght σ_u [MPa]	Modułus Kirchoff G [GPa]	Poisson Coeff. v [-]
D2	50.00	37766.71	755.33	3.02	0.01
D3	50.00	34199.92	684.01	2.42	0.02
D5	48.00	33539.11	670.80	2.32	0.01
D6	49.80	34555.44	691.10	2.61	0.02
Mean value	49.45	35015.30	700.31	2.60	0.015

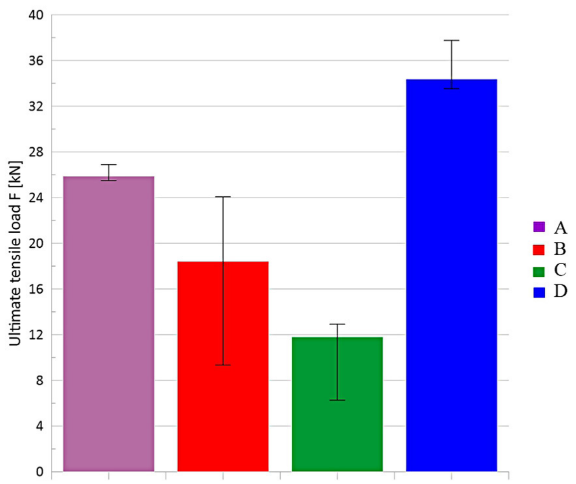


Fig. 5. Comparison of ultimate tensile loads for four series of specimens

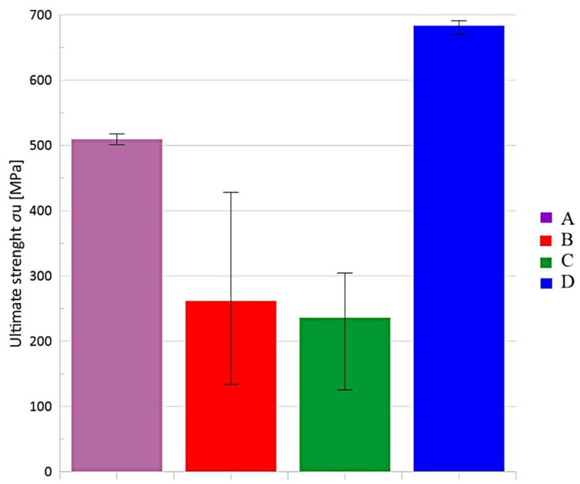
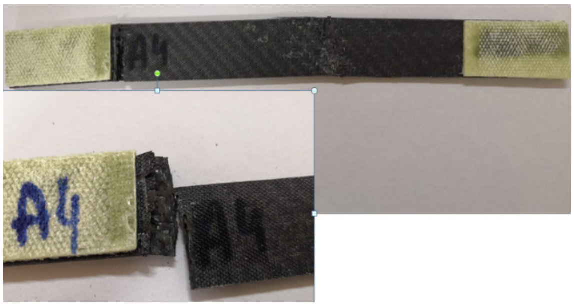
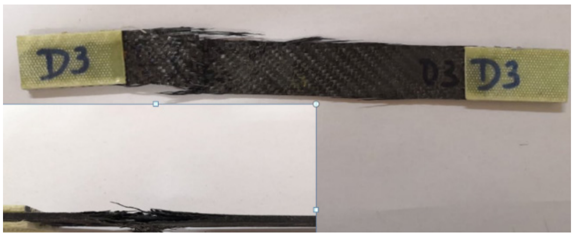


Fig. 6. Comparison of ultimate strength among specimen series

Table 9. Fracture forms for different specimens

Specimen series	Fracture form	Description
A		One can see the way of destruction of a specimen viewed in a layout adapted to the LAT (Lateral – Angled – Top) scheme of failure location (see ASTM D3039).The well visiblefibre breakage characterizes brittle fracture.
B		Depicts a typical XGM (Explosive – Grip – Middle) damage scheme, since this phenomenon is characteristic for composite failure at very high loads, when samples explode into ragged fibers.
C		The XGM failure scheme appears also in specimens with the 0/45^{o} layup. On contrary, when plain weave with 0/90 layup is considered, not all layers seem to break. This means that three different schemes of failure can be observed for the considered composites, depending on both the layup, as well as the weave type.
D		In this case we can notice the DGM (edge Delamination – Grip – Multi mode) scheme. The fibers didn't break they only have stretched fibers.

was possible to obtain more accurate comparison of strength of the four series of composite. This way a general statement could be formulated that the tensile strength shaped as follows: D,A,B,C (Fig. 6) – counting from the highest to the lowest.

Comparison of values of the apparent tensile Young modulus (E_A) leads to slightly different conclusions - with respect to the specimen series order. Namely, the highest value of E_A was achieved for series C specimens (5.64 GPa); in other words: the samples of this group were characterized by the highest tensile stiffness. Other groups of samples had similar mean values of the Young modulus, whereby in the series B and D these values were almost identical (2.61 GPa and 2.42 GPa, respectively) (Fig. 7).

Comparing the values of Poisson coefficient, significant differences in the values of this parameter between the pairs of series (A, D) and (B, C) were found. In particular, the values of Poisson coefficient for the first pair were 0.01 and 0.02, respectively. In the second pair of series, the values were much higher – 0.35 for series B and 0.32 for series C; this difference is however non-significant (Fig. 8).

Summing-up, it can be concluded from Figs 7 and 8 that higher stiffness of the composites can be achieved by using the plain fabric with 0/45^{o} layup (series C), but it can result in quite high lateral contraction. On the other hand, high Poisson ratio value for the twill fabric appears

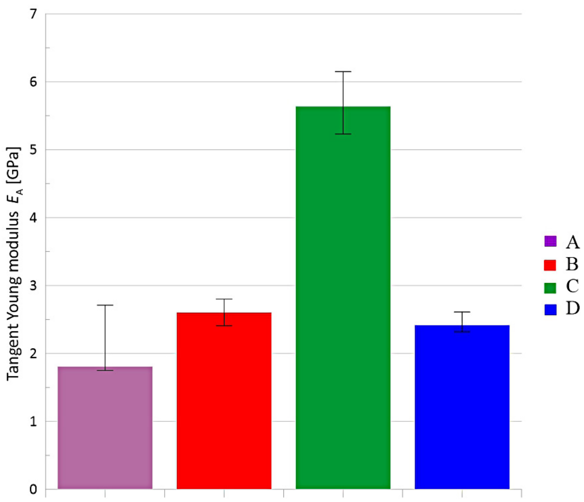


Fig. 7. Comparison of tangent young modulus among specimen series

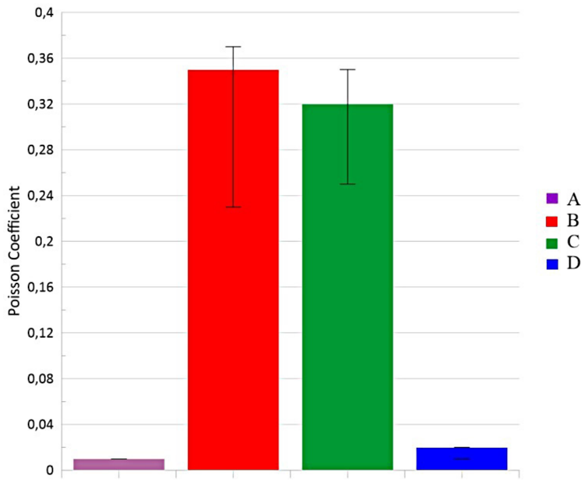


Fig. 8. Comparison of Poisson coefficient among specimens

at ply arrangement 0/90° (series B). This means that the final decision on the choice of a specific fabric, as well as its layup in a composite is the responsibility of a designer. If in some construction significant transverse contraction is acceptable (Poisson ratio of 0.3), one can consider using specimens from series C (plain weave arrangement 0/45°), for which tensile ultimate strength is about 236 MPa, it is about 1/3 of the strength of specimens from series D, but these specimens were characterized by the highest stiffness (5.64 GPa). Obviously, the least favorable configuration is demonstrated by the B-series (twill weave arrangement 0/90°), due to the significant value of Poisson ratio and low stiffness (strength is comparable to series C).

CONCLUSIONS

In the paper research on four series of fabric reinforced composite laminates was described. The specimens varied with the type of weave, as well as the fabric orientation in a layup. The strength tests ended with specimens failure following three different schemes, depending on both the layup and the weave type. The highest tensile strength was the characteristic of the crossed-fabric plain-weave laminate, followed by slightly weaker 0/45° twill-fabric composite. The remaining laminate series turned out to be much weaker than the former two. Concerning the apparent tensile Young modulus, the highest value was achieved for the laminates reinforced with the plain-weave fabric misoriented by 45°. Other composites had practically the same stiffness. While speaking of Poisson coefficient, very small values were obtained for two series of composites, however no apparent dependency on the weave, nor fabric orientation could be found – further studies are necesary. It can be also noticed, that the plain weave of the reinforcing fabric together with the 0/45° layup results in higher stifness of a composite; at the same time the lateral contraction can be high. The appropriate choice of a specific fabric, as well as its layup is up to a designer, depending on the concrete needs. In particular, the design process of rotorcraft structures must be performed thoroughly, because of signigicant risk of delamination.

Composites especially carbon fibre composites are very light weight comparing with high strenght to weight ratio but their mechanical properties depend on ply thickness and the stacking sequence. In addition, fractographic observation revealed that fracture surface was not a flat plane; the broken fibers formed intralaminar delamination. On the other hand, additional defects – resin pockets and voids – were also present. This objects are usually lack of stress concentration and a such may nucleate crack propagation. These observations suggest that fracture toughness of the considered fabric reinforced composites could increase, as well as lead to a surmise of easier cleavage. This ambiguity could be explained in further studies in the field which are planned.

With the development of new engineering materials comes the need for better and more accurate methods to check materials from the microscale through the mesoscale to macroscale observations.

Non-distructive methods like RFID Tag Antenna Deformation allow for non-invasive in real time determination of local deformations. This method can be the basis for further and deeper research for composite to identification of cracks and observation of damage propagation.

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