Polskie Towarzystwo Materiałów Kompozytowych
Polish Society of Composite Materials

12: 1 (2012) 60-65

COMPOSITES THEORY AND PRACTICE

Mateusz Kozioł

Silesian University of Technology, Faculty of Materials Engineering and Metallurgy, ul. Z. Krasińskiego 8, 40-019 Katowice, Poland
Central Mining Institute, pl. Gwarków 1, 40-166 Katowice, Poland
Corresponding author: E-mail: Mateusz.Koziol@polsl.pl

Otrzymano (Received) 12.12.2011

THE EFFECT OF REINFORCING FABRIC TYPE ON MECHANICAL PERFORMANCE OF LAMINAR FR EPOXY COMPOSITE

The scope of the study is the experimental evaluation of the effect of the main characteristics of fabrics used as a reinforcement of polymer matrix composites on the mechanical performance of composites. The characteristics taken into consideration are: (1) fibre material - Kevlar, carbon, glass, (2) areal weight - 90 and 300 g/m^2; only for glass fibre, (3) reinforcement form - plain weave fabric, chopped mat; only for glass fibre, (4) weave type - plain, twill; only for carbon fibre, (5) tow size K - 2, 3, 12; only for carbon fibre. Static flexural tests were conducted for all the specimens. The flexural strength (R_g), flexural modulus (E_g) and the strain by maximum load obtained during bending (*Epsilon*) have been determined. It was found that the material of reinforcing fibres has an essential effect on the mechanical performance of a laminate. Laminates reinforced with carbon fibres had/obtained/achieved thegreatest R_g and E_g. Glass-reinforced (GFRP) laminates performed slightly better in comparison to Kevlar-reinforced ones. However, the Kevlar-reinforced laminates showed the highest deformability at high load. An increase in areal weight of a reinforcing fabric causes a growth in the R_g and E_g and a decrease in deformability of a GFRP laminate. The reinforcement form evidently affects the mechanical performance of a laminate. The GFRP 0/90 fabric reinforced laminate showed an R_g half higher in comparison to the equivalent chopped-matt reinforced one. The twill carbon fabric FRP laminate showed a slightly lower R_g and E_g, whilst a bit higher deformability in comparison to the plain weave carbon fabric FRP one. The tow size K practically does not affect the strength or deformability of a CFRP laminate. However, an increase in K causes a drop in the elastic modulus of the composite.

Keywords: laminate, tow size K, areal weight, plain weave, twill weave, carbon fibres, glass fibres, Kevlar

WPŁYW RODZAJU WZMOCNIENIA NA WŁAŚCIWOŚCI MECHANICZNE WARSTWOWEGO EPOKSYDOWEGO KOMPOZYTU WŁÓKNISTEGO

Celem pracy jest eksperymentalna ocena wpływu podstawowych cech tkanin wzmacniających na właściwości mechaniczne wytworzonych laminatów o osnowie polimerowej. Cechy tkanin, które wzięto pod uwagę podczas oceny, to: (1) materiał tkaniny - poliaramid, węgiel, szkło, (2) gramatura tkaniny - 90 oraz 300 g/m^2; tylko włókno szklane, (3) postać wzmocnienia - płótno, mata; tylko włókno szklane, (4) rodzaj splotu - płócienny, skośny; tylko włókno węglowe, (5) K tkaniny (ilość elementarnych włókien w paśmie rowingu) - 2, 3 oraz 12; tylko włókno węglowe. Dla wszystkich materiałów przeprowadzono próby zginania statycznego. Wyznaczono: wytrzymałość na zginanie (R_g), moduł przy zginaniu (E_g) oraz odkształcenie względne przy maksymalnym obciążeniu w próbie zginania (Epsilon). Stwierdzono, że materiał włókien wzmacniających ma podstawowe znaczenie dla właściwości wytrzymałościowych i sprężystych kompozytu. Laminat wzmocniony włóknem węglowym wykazał najwyższe R_g oraz E_g spośród badanych. Laminat z włóknem szklanym wykazał wyższy poziom właściwości od kompozytu wzmocnionego poliaramidem. Kompozyt poliaramidowy ma z kolei najwyższą spośród badanych laminatów odkształcalność przy dużym obciążeniu. Wzrost gramatury tkaniny wzmacniającej powoduje polepszenie R_g oraz E_g i jednoczesny spadek odkształcalności laminatu z włóknem szklanym. Postać wzmocnienia bardzo znacząco wpływa na właściwości wytrzymałościowe i sprężyste laminatu wzmacnianego włóknem szklanym. Kompozyt wzmacniany tkaniną krzyżową wykazał R_g o połowę wyższą w porównaniu z ekwiwalentnym laminatem wzmocnionym matą. Laminat wzmocniony satynową tkaniną węglową wykazał nieznacznie niższe wartości R_g oraz E_g, ale nieco wyższą odkształcalność w porównaniu z laminatem wzmocnionym tkaniną płócienną. Wielkość pasma rowingu *K* praktycznie nie ma wpływu na wytrzymałość i odkształcalność laminatu z włóknem węglowym. Jednakże, wzrost K powoduje dość wyraźny spadek modułu kompozytu.

Słowa kluczowe: laminat, wielkość pasma K, gramatura, splot płócienny, splot skośny, włókno węglowe, włókno szklane, kewlar

INTRODUCTION

Technical fabrics used as reinforcements in FRP composite laminates are characterized by a number of specific parameters. The most important are: fibre material, areal weight, reinforcement form (continous or non-continous fibres, twisted strands), weave type and tow size K (line density of individual roving strand). The parameters are of great importance in composites technology - master process engineers usually select them based on their own experience. However, it is not easy to find precise guidelines about all the parameters in scientific literature. The study is to basically clear up the problem.

The strong effect of fibre modulus and strength on a composite mechanical performance is obvious. It results from the rule of mixtures (whose aim is to define the physical properties of composites) - the modulus and strength of the composite depends directly and proportionally on the modulus, strength and volume fraction of the reinforcing fibres [1, 2]. The evaluation of fibre strength is conducted in micromechanical tests of elementary fibres performed for new types of fibres or for fibre-treatment evaluation [2, 3].

The areal weight of the fabric defines the amount (mass) of fibre material within an area unit of the fabric. An increase in areal weight may be obtained by increasing the elementary fibre diameter or - more often - by better packing of the fibre strands within the fabric. Reduction of the unfilled areas within the fabric usually contributes to an increase in the fibre volume fraction of the composite. However, it reduces the deformability of the fabric during the put-to-the-mold or preform assembly operations. High areal weight also results in worse permeability of the fabric, which determines the impregnation rate.

Reinforcement form is the form of fibre strands within the fabric. The fibres in a strand may be continuous in long lengths or cut into several centimeter long fragments (chopped matt); the strands may run parallel to each other or run in various directions: more- (chopped matt) or less- (braided fabric) randomly; fibres within the strand may be paralelly ordered (roving) or twisted (cord, thread).

The continuity of fibres is particularly important for the elastic properties and strength of the composite. When the length of the elementary fibre is shorter than the critical length, the fibre does not reinforce the composite with its full potential - the stress at the interfacial area is higher than the interfacial strength and the fibre is rather pulled-out of the matrix than breaks within its cross-section. Continuous fibres are fibres which are longer than their critical length [2, 4]. However, for glass fibre of 10 μm in diameter, the critical length does not reach 1 mm.

The direction of fibre strands decides about the stiffness and strength of the laminate in particular directions. Reinforcement coefficient η is often (simple cases) used to determine the strength or modulus of the laminate. For a unidirectional layout, $\eta = 1$ in the direction of the fibres; for a cross layout (50% of fibre mass in two transverse directions) $\eta = 1/2$ in the directions of the fibres; for chopped matt $\eta = 1/6$ in any layout plane direction [1, 2, 4, 5].

The weave type determines how often the transverse (0/90°) strands of fibres in a 2-directional fabric are mutually interleaved. It mainly affects the deformability of the fabric which is of great importance in technology - fabrics having a thinner interleave (twill) have better deformability and lesser disturbance of strands during the formation of a round-shaped product. However, a decrease in preform stiffness negatively affects the mechanical performance of the laminate [2, 5].

The tow size (line density of fibre strand) designed as "K" determines the amount of elementary fibres within an individual strand, given in thousands. In practice, K is used only for carbon fibres. Analysis of the effect of K on the mechanical properties of laminates is only sporadic. It may be because of the very low influence of K on the elastic modulus (only for very thin laminates) and strength. One of the reasons for using fabrics having different K are aesthetical aspects, for instance in the production of bicycle frames and parts [6].

There are many other parameters affecting laminate strength and stiffness, which are not a subject of the study. The main ones are: strength of bonding between the fibre and matrix [1] - highly affected by the treatment of fibres [7], the presence of unexpected defects and disturbances within the structure - occurring for instance after the introduction of translaminar reinforcement [8-10].

The aim of the study is an attempt to evaluate experimentally the influence of: *material*, *areal weight*, *reinforcement form*, *weave type* and *tow size K* of reinforcing fabric on the mechanical performance of a laminate.

MATERIALS AND INVESTIGATIVE PROCEDURE

Epoxy matrix based laminates were manufactured by the vacuum assisted resin infusion (VARI) method. Reinforcing preforms had been prepared of: glass, carbon and polyaramide (Kevlar®) fibres, in various forms and configurations described in Table 1.

The XP KEVLAR fabric by DUPONT, BGF STANDARD carbon fabrics by BGF and ER 3003 glass fabrics and matt by KROSGLASS were used. The system: EPIDIAN 53 epoxy resin by ORGANIKA SARZYNA + 10% by weight of Z1 TECZA (triethylenetetraamine) hardener, was applied as the matrix in all the laminates. The laminate panels were cured at room temperature for 24 h and additionally after-baked at 55°C for 6 h. All the laminates showed a fibre volume fraction 47÷50% (evaluated by gravimetric method).

The specimens (rectangular 70 x 20 mm) were mechanically cut from panels.

Effort was taken to provide equivalency among the tested materials - all the parameters except the considered ones are kept as similar as possible within the particular considered population. For instance, the twill and plain weave laminates had the same number of layers and areal weight.

TABLE 1. **Reinforcement description and mechanical performance of laminates manufactured and tested within the study**

TABELA 1. **Opis struktury wzmocnienia oraz uzyskane właściwości mechaniczne laminatów wytworzonych i badanych w ramach pracy**

Reinforcement type	Thickness [mm]	R_g [MPa]	*Epsilon* [%]	E_g [GPa]
Kevlar (10 layers); Plain weave 175 g/m^2	2.7	214 ± 15	4.2 ± 0.6	9.9 ± 2.2
Carbon (9 layers); Plain weave 200 g/m^2; 3K	2.78	449 ± 27	1.8 ± 0.1	26.2 ± 2.9
Carbon (9 layers); Twill 200 g/m^2; 3K	2.77	425 ± 7	2.2 ± 0.1	20.5 ± 0.9
Carbon (9 layers); Plain weave 200 g/m^2; 2K	1.95	452 ± 19	1.7 ± 0.1	26.7 ± 2.6
Carbon (9 layers); Plain weave 200 g/m^2; 12K	1.81	435 ± 9	2.3 ± 0.1	21.4 ± 2.5
Glass (6 layers); Plain weave 300 g/m^2	1.34	325 ± 10	3.1 ± 0.2	13.3 ± 1.3
Glass (9 layers); Plain weave 200 g/m^2	1.42	310 ± 8	3.2 ± 0.2	12.0 ± 1.1
Glass (20 layers); Plain weave 90 g/m^2	1.49	291 ± 1	3.4 ± 0.1	11.0 ± 0.4
Glass (6 layers); Chopped matt 300 g/m^2	2.13	208 ± 2	3.4 ± 0.1	7.1 ± 0.3

Flexural tests were performed in accordance to the PN EN ISO 14125:2001 standard. An INSTRON 4469 testing machine was used. The fixed test conditions were: loading bar speed v = 10 mm/min, load cell 5 kN, support bars span L = 60 mm. Nine specimens were tested for each measure point.

The determined characteristics are: flexural strength (R_g), flexural modulus (E_g), strain by maximum flexural load (*Epsilon*). The Epsilon was determined according to Formula 1:

$$Epsilon = \frac{6 \cdot f_{F\max} \cdot h}{L^2} \quad (1)$$

where: f_{Fmax} - deflection by maximum load during bending test, mm, h - height (thickness) of the specimen, mm, L - support bars span, mm.

RESULTS AND DISCUSSION

The experimental results for all the specimens tested in the flexural tests are presented in Table 1. A comparison of the R_g, E_g and *Epsilon* of the laminates reinforced with fibres made of various materials is presented in Figure 1.

According to characteristics of the applied fibres (Table 2) and literature predictions for plain weave fabrics with equal distribution of reinforcement in transverse directions [2, 11], the carbon-reinforced laminates showed the lowest deformability (*Epsilon*) from among the tested composites.

TABLE 2. **Mechanical characteristics of fibres reinforcing tested laminates - manufacturers' data**

TABELA 2. **Charakterystyki mechaniczne włókien wzmacniających stosowanych w badanych laminatach - dane producentów**

Fibre material	R_m [MPa]	*E* (tensile) [GPa]	ε (max) [%]
Glass (KROSGLASS ER 3003)	2440	74	1,9
Carbon (BGF STANDARD)	2600	370	0,5
Kevlar (DUPONT XP)	2790	129	2

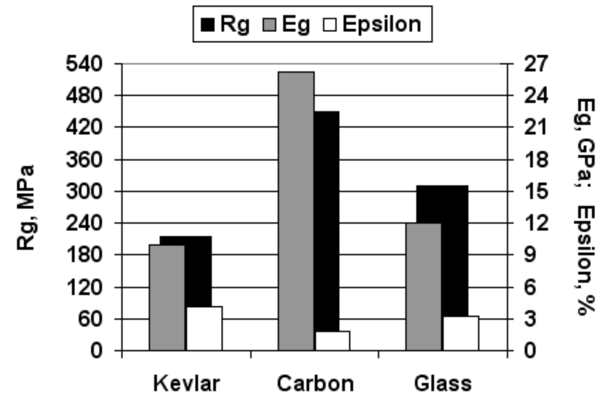

Fig. 1. R_g, E_g, *Epsilon* of the laminates dependent on material of reinforcing fabric

Rys. 1. R_g, E_g, *Epsilon* badanych laminatów w zależności od materiału tkaniny

Furthermore, the larger E_g for the carbon-reinforced laminate, in comparison to the glass- and Kevlar-reinforced ones, is in accordance with the predictions. However, the difference in R_g between the carbon-, glass- and - especially - Kevlar-reinforced laminates is very big. The low performance of the Kevlar-reinforced laminate was unexpected in particular. Only its relatively high deformability (*Epsilon*) is in accordance with the predictions. However, the obtained results present a reasonable level and do not differ considerably from literature data. Moreover, significant dispersion of the E_g and R_g values for similar materials occur in different studies - it especially concerns composites.

A comparison of the R_g, E_g and *Epsilon* of the laminates reinforced with glass fabrics having the same volume fraction with various areal weights is presented in Figure 2. However, to gain those conditions, diversification in the number of layers was necessary and a slight difference in the laminate thickness occurred - Table 1. The influence of areal weight (and number of layers) of the fabric on the strength and elastic properties of the laminate results from the packing of elementary fibres within the laminate structure. Fibres laid out in a square arrangement (towards cross-section) may encompass a maximum of 78.5% of the laminate volume. For a hexagonal arrangement it is 90.65% [5]. In real laminates, the structure is disturbed after a technological process. However, the fibres are arranged rather in a hexagonal manner (Fig. 3).

The packing of the fibres within the strand is similar for various areal weights of fabric. An increase in areal weight is obtained rather by better packing of the strands in an area unit of the fabric, alternately by an increase in elementary fibre diameter. An increase in areal weight of the fabric layer improves the packing of the fibres in comparison to a layer having a lower areal weight due to a decrease in volume of empty areas between the strands. Moreover, an increase in the number of layers - necessary to obtain an equivalent fibre volume fraction - for a low-areal-weight fabric results in additional interlaminar areas and increases the thickness of the laminate and probability of delamination. It also causes a decrease in the fibre volume fraction, despite the use of the same technology and manufacturing conditions.

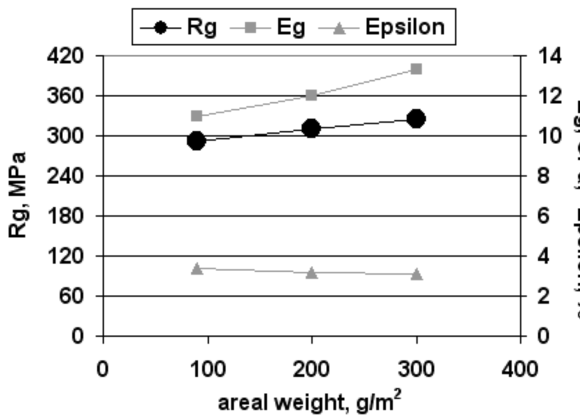

Fig. 2. R_g, E_g, Epsilon of glass fibre laminates in dependence on areal weight of reinforcing fabric

Rys. 2. R_g, E_g, Epsilon badanych laminatów z włóknem szklanym w zależności od gramatury tkaniny

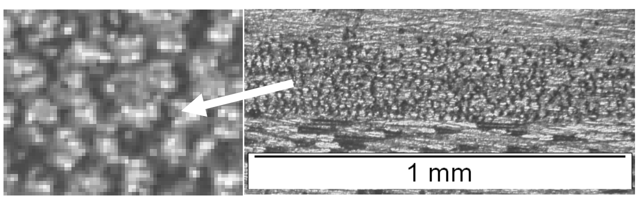

Fig. 3. Cross-section of laminate structure reinforced with cross-weave fabric. Arrangement of elementary fibres in strands transverse to image surface is visible

Rys. 3. Przekrój wycinka struktury laminatu o wzmocnieniu tkaniną krzyżową. Widoczne ułożenie elementarnych włókien w pasmach prostopadłych do powierzchni obrazu

The differences in strength of the tested material having a different areal weight of reinforcing fabric amounted to about 10%, whilst the difference in the modulus is about 20%. The deformability practically did not change (Fig. 2). In study [12], it was found that an increase in areal weight of flax fabric improves the tensile elastic modulus, however, it did not affect the strength.

If there are no special technological indications to apply to well-deformable reinforcing structures, then fabrics having the highest possible areal weight should rather be used.

A comparison of the R_g, E_g and *Epsilon* of the laminates reinforced with glass plain-woven fabric and glass chopped strand matt having the same areal weight is presented in Figure 4.

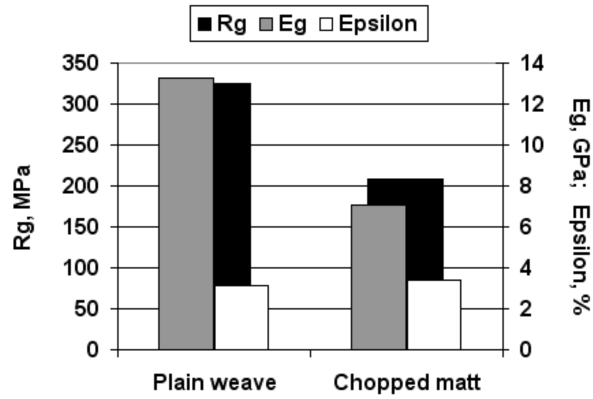

Fig. 4. R_g, E_g, *Epsilon* of glass fibre laminates in dependence on a reinforcement form

Rys. 4. R_g, E_g, Epsilon badanych laminatów z włóknem szklanym w zależności od postaci wzmocnienia

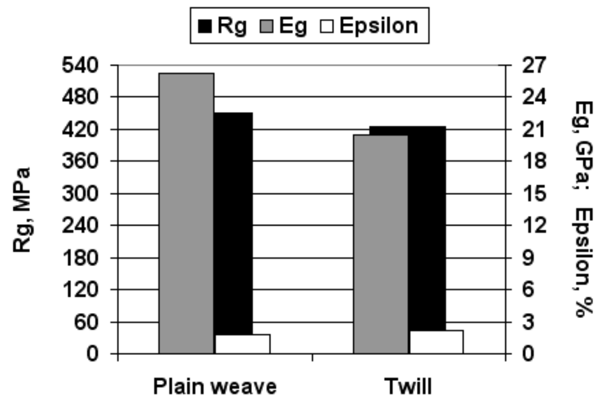

Fig. 5. R_g, E_g, *Epsilon* of carbon fibre laminates in dependence on a weave of reinforcing fabric

Rys. 5. R_g, E_g, *Epsilon* badanych laminatów z włóknem węglowym w zależności od splotu tkaniny

The influence of the reinforcement form (woven fabric, chopped matt) on the mechanical performance of the laminate results from the *reinforcement coefficient*. The value of the coefficient depends mainly on the layout direction of the fibres but also on their continuity. For instance, in study [13] where notches were purposely implemented within the near-surface layers of composite specimens (however, the sections between the notches were considerably longer than the critical length of the fibre L_{kr}), the authors found that the lack of fibre continuity negatively affects the efficiency of the reinforcement.

The obtained experimental results are in accordance with the theoretical predictions. However, the difference in mechanical properties is not as big as the theoretical difference in the reinforcement coefficients. The laminate reinforced with plain-woven fabric showed about a 100% higher E_g and about 60% higher R_g in comparison to the laminate reinforced with chopped matt which, however, showed significantly higher deformability.

If the main load directions are well identified in the composite product design, then reinforcing fabrics with properly oriented (uni- or two-dimensional) fibres are applied first. Chopped matts are applied for preservation against unexpected loads from various directions or for the stiffening of composite walls.

A comparison of the R_g, E_g and *Epsilon* of the laminates reinforced with twill- and plain-woven carbon fabric having the same areal weight is presented in Figure 5. The results confirmed that the laminate reinforced with twill-woven fabric has a significantly lower modulus (by about 20%) and only slightly lower strength in comparison to the laminate reinforced with plain-woven fabric. However, it showed about a 25% higher deformability (which corresponds to the decrease in modulus). The observed trends are in accordance with the theoretical predictions.

The weave type also significantly affects other mechanical properties of laminates. It was found in study [13] that CFRP laminates reinforced with twill-woven fabric show lower mode I and mode II delamination toughness in comparison to equivalent laminates reinforced with unidirectional fabric. However (paradoxically) the laminate with twill-woven reinforcement showed lesser damage area after impact tests and higher residual strength - instant and fatigue as well. In study [14] it was found that twill-woven reinforcing layers slightly improve mode I and II delamination toughness (increase in crack propagation energy) when adjacent to plain-woven or unidirectional layers.

The cause of strength deterioration and increase in deformability of the twill-woven reinforced laminate may be local buckling in the in-plane direction, due to a lower number of "holding points" (interleaving points) in comparison to plain-woven reinforcement. Even a very low deflection of fibre strands from the load direction may affect the failure progress. For instance, a significant difference in crack propagation through the laminate between a pre-preg fabric and unidirectional non-crimp fabric with a low number of translaminar interleaves was observed in study [10]. Some slight disturbation caused by the interleaves made the failure progress more energy-absorbing. However, the strength of the unidirectional material was lower in comparison to the pre-preg based one, due to the disturbed parllelism of the reinforcing strands.

A comparison of the R_g, E_g and *Epsilon* of the laminates reinforced with carbon fabric having various tow size K and the same areal weight is presented in Figure 6.

The obtained results confirm that K has almost no influence on the strength or deformability of the laminate. However, the E_g of the laminate shows an almost 20% decrease with K growing from 2 to 12. Such behavior is very disadvantageous for advanced structures and is not in accordance with the theoretical predictions. Wide strands of fibres reveal a low possibility for deformation (lower "flexibility") during movement in comparison to narrower strands (having lower K). It increases the probability of strand damage and breakage of elementary fibres during preform assembly, layout in the mold or contact saturation. A narrow strand may displace in such situations but the array of the fibres remains preserved within the strand. However, when K is higher, the average amount of such deflected strands is lower - the strands may easily be damaged but they are difficult to deflect.

A significant advantage of woven fabrics having a high K is also lower participation of crimped strand sections in comparison to fabrics having a lower K - Figure 7 [15].

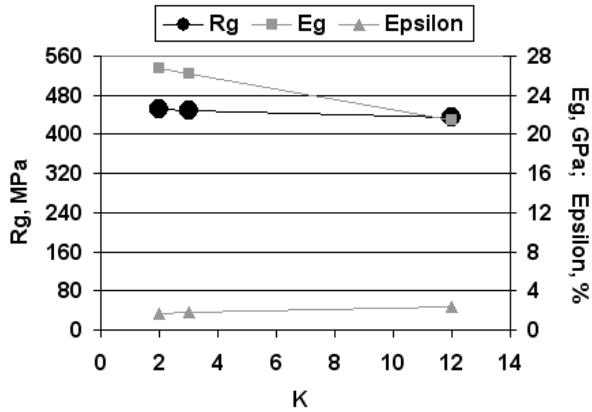

Fig. 6. R_g, E_g, *Epsilon* of carbon fibre laminates in dependence on K of reinforcing fabric

Rys. 6. R_g, E_g, *Epsilon* badanych laminatów z włóknem węglowym w zależności od K tkaniny

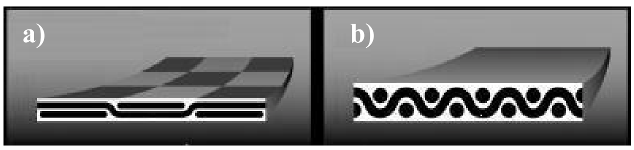

Fig. 7. Schema of fabric cross-section: a) high tow size K, b) low tow size K [14]

Rys. 7. Schemat ideowy przekroju tkaniny o dużej (a) oraz małej (b) szerokości pasma rowingu K [15]

It should cause an improvement in the strength and stiffness of a laminate having a higher K. However, with a higher K (lower amount of wider strands), a crack initiated in the beginning of the destruction process has fewer strands "boundary lines" to pass when it moves through the fabric layer - therefore it will advance faster (reinforcing effect will be reduced).

The obtained results showed that the disadvantages of a high K have a slightly greater effect on the mechanical performance of a laminate than advantageous mechanisms (at least within the tested fabrics and K values). A significant advantage of a high K is a much lower thickness of laminate - e.g. the 12K laminate is 1/3 thinner than the 2K one (Table 1). However, from the mechanical performance point of view, the application of a fabric having a low K is rather recommended.

CONCLUSIONS

1. The material of reinforcing fibres has an essential effect on the mechanical performance of a laminate. Laminates reinforced with carbon fibres have the biggest R_g and E_g. Glass-reinforced (GFRP) laminates were slightly better in comparison to Kevlar-reinforced ones. However, the Kevlar-reinforced laminates showed the greatest deformability at high load.
2. An increase in areal weight of reinforcing fabric causes growth in the R_g and E_g and a decrease in the deformability of a GFRP laminate.
3. The reinforcement form strongly affects the mechanical performance of a laminate. A 0/90 glass fabric reinforced laminate showed an R_g half higher than the equivalent chopped-matt reinforced one.
4. The twill carbon fabric reinforced laminate showed slightly lower R_g and E_g, whilst a bit higher deformability in comparison to the plain weave carbon fabric FRP one.
5. The tow size K practically does not affect the strength or deformability of a CFRP laminate. However, an increase in K causes a drop in the elastic modulus of the composite.

Acknowledgements

The study has been partially financed by the National Centre for Research and Development (NCBiR) of The Republic of Poland in the scope of a research project realized within the LIDER program.

The author would like to thank inż. Artur Jarosz for his help in realizing the technological part of the study.

REFERENCES

[1] Hyla I., Sleziona J. Composites, Elements of mechanics and design, Wydawnictwo Politechniki Śląskiej, Gliwice 2004 (in Polish).
[2] Śleziona J., Podstawy technologii kompozytów, Wydawnictwo Politechniki Śląskiej, Gliwice 1998.
[3] Park J.-M., Kim D.-S., Kim S.-R., Improvement of interfacial adhesion and nondestructive damage evaluation for plasma-treated PBO and Kevlar fibers/epoxy composites using micromechanical techniques and surface wettability, Journal of Colloid and Interface Science 2003, 264, 431-445.
[4] Hyla I., Wybrane zagadnienia z inżynierii materiałów kompozytowych, PWN, Warszawa 1978.
[5] Hyla I., Elementy mechaniki kompozytów, Wydawnictwo Politechniki Śląskiej, Gliwice 1995.
[6] http://www.fitwerx.com/splash (access 04.01.2012).
[7] Nakai A., Osada T., Hamada H., Takeda N., Role of surface treatment in textile composites, Composites: Part A 2001, 32, 487-498.
[8] Kozioł M., Śleziona J., Właściwości mechaniczne zszywanych laminatów żywica poliestrowa - włókno szklane, Kompozyty 2006, 6, 2, 14-20.
[9] Mouritz A.P., Cox B.N., A mechanistic interpretation of the comparative in-plane mechanical properties of 3D woven, stitched and pinned composites, Composites, 2010, 41A, 709-728.
[10] Bibo G.A., Hogg P.J., Influence of reinforcement architecture on damage mechanisms and residual strength of glass-fibre/epoxy composite systems, Composites Science and Technology 1998, 58, 803-813.
[11] Leda H., Kompozyty polimerowe z włóknami ciągłymi, Wydawnictwo Politechniki Poznańskiej, Poznań 2000.
[12] Di Bella G., Fiore V., Valenza A., Effect of areal weight and chemical treatment on the mechanical propertiesof bidirectional flax fabrics reinforced composites, Materials and Design 2010, 31, 4098-4103.
[13] Vallons K., Behaeghe A., Lomov S.V., Verpoest I., Impact and post-impact properties of a carbon fibre non-crimp fabric and a twill weave composite, Composites 2010, Part A, 41, 1019-1026.
[14] Hadavinia H., Ghasemnejad H., Effects of Mode-I and Mode-II interlaminar fracture toughness on the energy absorption of CFRP twill/weave composite box sections, Composite Structures 2009, 89, 303-314.
[15] http://www.oxeon.se (access 04.01.2012).

