Polskie Towarzystwo Materiałów Kompozytowych
Polish Society of Composite Materials

Kompozyty 11: 1 (2011) 84-89

KOMPOZYTY
COMPOSITES

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Otrzymano (Received) 10.02.2011

COMPARATIVE EXPERIMENTAL TESTING OF SELECTED GLASS-POLYESTER COMPOSITES

The study presents the results of comparative experimental testing of selected glass - polyester layered composites. The composites are symmetric, mixed (fabric - mat reinforcement), manufactured with the contact technology applied for shell segments of composite covers of engineering structures. The base composite is the laminate of a CSM300/4xWR600/CSM300 ply sequence used in the Klimzowiec sewage-treatment plant. Two research problems are considered: 1. the influence of the ply sequence in a glass - polyester composite on its load capacity, 2. the influence of the manufacturing technique of a glass - polyester composite on its load capacity. The comparative testing in problem 1 has been performed for the following laminates: the L-4F-2M laminate (matrix: Polimal 104 T polyester resin (inflammable), ply sequence: CSM300/ 4xWR600/CSM300), the L-2F-5M laminate (matrix: Polimal 104 T polyester resin, ply sequence: CSM300/WR600/ CSM450,300,450/WR600/CSM300). The comparative testing in problem 2 has been conducted for the following laminates: the L-T laminate (matrix: Polimal 104 T polyester resin, ply sequence: 3x(CSM450/WR600)/CSM450), the L-AWTP laminate (matrix: Polimal 104 AWTP polyester resin (with a styrene anti-evaporator additive), ply sequence: 3x(CSM450/WR600)/CSM450). The comparative testing of the load capacity has been limited to bending and interlaminar shear testing in problem 1 and to interlaminar shear testing in problem 2, performed according to the respective standards. In reference to problem 1, it has been pointed out that replacing the fabric core with a mat core considerably increases the strength to bending and the conventional strength to interlaminar shear. In reference to problem 2, it has been shown that adding a styrene anti-evaporator slightly decreases the conventional strength to interlaminar shear.

Keywords: **layered composite, glass-polyester composite, laminate's core modification, styrene's anti-evaporator influence, experimental testing**

PORÓWNAWCZE BADANIA EKSPERYMENTALNE WYBRANYCH KOMPOZYTÓW POLIESTROWO-SZKLANYCH

Przedstawiono wyniki badań eksperymentalnych porównawczych wybranych kompozytów poliestrowo-szklanych warstwowych, symetrycznych, mieszanych, wytworzonych technologią kontaktową stosowaną w przypadku powłokowych segmentów przekryć kompozytowych obiektów inżynierskich. Kompozytem bazowym jest laminat zastosowany w oczyszczalni ścieków Klimzowiec o sekwencji warstw CSM300/4xWR600/CSM300. Rozważono dwa zagadnienia: 1. wpływ sekwencji ułożenia warstw kompozytu poliestrowo-szklanego na jego nośność, 2. wpływ technologii wytwarzania kompozytu poliestrowo-szklanego na jego nośność. W zagadnieniu 1 badania porównawcze przeprowadzono dla następujących laminatów: laminat L-4F-2M (osnowa: Polimal 104 T (uniepalniona), sekwencja warstw: CSM300/4xWR600/CSM300), laminat L-2F-5M (osnowa: Polimal 104 T, sekwencja warstw: CSM300/WR600/ CSM450,300, 450/WR600/CSM300). W zagadnieniu 2 badania porównawcze przeprowadzono dla następujących laminatów: laminat L-T (osnowa: Polimal 104 T, sekwencja warstw: 3x(CSM450/WR600)/CSM450), laminat L-AWTP (osnowa: Polimal 104 AWTP (z dodatkiem blokującym parowanie styrenu), sekwencja warstw: 3x(CSM450/WR600)/ CSM450). Badania porównawcze nośności ograniczono do prób na zginanie i ścinanie międzywarstwowe w przypadku zagadnienia 1 oraz do próby na ścinanie międzywarstwowe w przypadku zagadnienia 2, przeprowadzonych zgodnie z odpowiednimi normami. W przypadku zagadnienia 1 wykazano, że zastąpienie rdzenia tkaninowego rdzeniem matowym znacząco podwyższa wytrzymałość na zginanie oraz umowną wytrzymałość na ścinanie międzywarstwowe. W przypadku zagadnienia 2 wykazano, że zastosowanie dodatku blokującego parowanie styrenu nieznacznie obniża umowną wytrzymałość na ścinanie międzywarstwowe.

Słowa kluczowe: **kompozyt warstwowy, kompozyt poliestrowo-szklany, modyfikacja rdzenia laminatu, wpływ dodatku blokującego parowanie styrenu, badania eksperymentalne**

INTRODUCTION

Shell segments made of GFRP layered composites are widely applied as parts of covers of tanks and canals. The design of rectangular, self-supporting circular, and supported circular covers [1, 2] is based on the first- and second-rank laminate theory [3-7]. Nowadays, designers focus increasingly more attention on the optimization of the ply sequence and the shape of the shell panels as well as on modifications of the manufacturing methods [8].

The study presents the results of comparative experimental testing of selected GFRP composites. The base composite is the laminate of the CSM300/ 4xWR600/CSM300 ply sequence, impregnated with Polimal 104 T polyester resin, used to manufacture of tank covers in the Klimzowiec sewage-treatment plant. Two research problems are considered:

1) the influence of the ply sequence in a glass - polyester composite on its load capacity
2) the influence of the manufacturing technique of a glass - polyester composite on its load capacity

The comparative testing of load capacity has been limited to bending and interlaminar shear testing in problem 1 and to interlaminar shear testing in problem 2, performed according to the following standards:

- PN-EN ISO 14125:2001. Fibre-reinforced structural composites. Determination of properties at bending,
- PN-EN ISO 14130:2001. Fibre-reinforced structural composites. Determination of conventional strength to interlaminar shear using short beam method.

EXPERIMENTAL TESTING

The experimental testing concerns selected glass - polyester layered composites which are symmetric, mixed (fabric - mat reinforcement) and manufactured with the contact technology applied for shell segments of composite covers. The composite components are as follows:

- matrices:
  a) Polimal 104 T poliester resin (inflammable)
  b) Polimal 104 AWTP poliester resin (with a styrene anti-evaporator additive)
- E glass reinforcement:
  a) fabrics of simple weave: WR450, WR600
  b) mats: CSM300, CSM450

The Polimal 104 AWTP polyester resin contains a styrene anti-evaporator additive mostly belonging to the paraffin group. Composite plates impregnated with this resin have to be produced with technological breaks, which may decrease interlaminar adhesion.

The comparative testing in problem 1 has been performed for the following laminates:

- the L-4F-2M laminate:
  matrix: Polimal 104 T polyester resin (inflammable)
  ply sequence: CSM300/ 4xWR600/CSM300
- the L-2F-5M laminate:
  matrix: Polimal 104 T polyester resin
  ply sequence: CSM300/WR600/CSM450,300,450/ WR600/CSM300

The comparative testing in problem 2 has been conducted for the following laminates:

- the L-T laminate:
  matrix: Polimal 104 T polyester resin
  ply sequence: 3x(CSM450/WR600)/CSM450
- the L-AWTP laminate:
  matrix: Polimal 104 AWTP polyester resin (with a styrene's anti-evaporator add) ply sequence: 3x(CSM450/WR600)/CSM450.

The two central layers of the CSM300/4xWR600/ CSM300 laminate, i.e. 2xWR600, have been named 'the fabric core'. The three central layers of the CSM300/WR600/ CSM450, 300,450/WR600/CSM300 laminate, i.e. CSM450,300,450, have been named 'the mat core'. The cores have the same G.P.S. of reinforcement.

Static simple bending of laminates according to standard PN-EN ISO 14125:2001 concerns polymer-matrix composites with termoset or thermoplastic matrices reinforced with glass, carbon or aramide fibres. The orthotropy directions of subsequent plies are parallel to the cubicoid edges of the specimen. The specimen is bent at a respectively chosen constant velocity of the testing machine's traverse, up to breaking or limited strains. During testing, the pressure force and deflection of the beam specimen in 3-point bending are registered. The method is applied to determine the strength to bending, the longitudinal modulus at bending and other features. The standard PN-EN ISO 14125:2001 introduces, among others, the following quantities:

L - a beam span, mm
l - a total length of beam, mm
b, h - beam cross-section dimensions, mm
v - velocity of testing machine's traverse, mm/min
F - a pressure force, N
σ - rated normal stress at bottom surface of specimen cross-section at midspan, MPa
ε - normal strain at bending at bottom surface of specimen cross-section at midspan
R_{fM} - strength to bending, i.e. rated normal stress carried by specimen at maximum pressure force in case of accepted kinds of damage, MPa
s - deflection, mm

In the 3-point bending test, the supports and the central mandrel loading the specimen are located as shown in Figure 1. The radii of the cylindrical surfaces are equal to R_1 = 5±0,2 mm, R_2 = 5±0,2 mm for $h > 3$ mm.

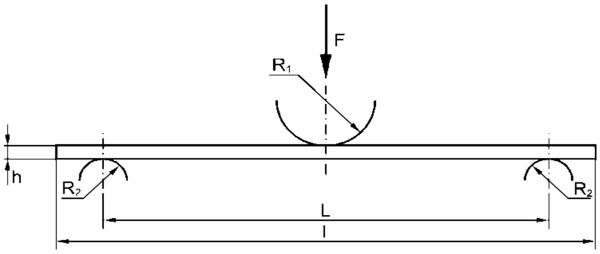

Fig. 1. The 3-point bending test scheme for beam specimen [9]
Rys. 1. Schemat zginania trzypunktowego próbki belkowej [9]

The formed specimens are conditioned before testing over at least 88 h, at temperature of 23 ±2°C and relative humidity of 50 ±10%. The testing is performed in the same conditions. Cubicoid specimens were cut from plate blanks using a water contour band saw. In each test 10 specimens were examined. The remaining testing conditions specified in PN-EN ISO 14125:2001 have been also fulfilled.

The cubicoid specimens being tested on had the dimensions: L = 64 mm, l = 80 mm, b = 15 mm corresponding to class II (plastics reinforced with mats, unwoven fabrics, woven fabrics, as well as mixed forms, e.g. DMC, BMC, SMC and GMT), protecting admissible dimensional tolerances given in PN-EN ISO 14125:2001.

Based on the classic strength of materials, one obtains

$$\sigma = \frac{3FL}{2bh^2}, \quad \varepsilon = \frac{6sh}{L^2}, \tag{1}$$

The static interlaminar shear of a laminate according to standard PN-EN ISO 14130:2001 concerns structural composites with a fibre-reinforced thermoset or thermoplastic matrix. The orthotropy directions of subsequent plies are parallel to the cubicoid edges of the specimen. The specimen is under shear at bending at a respectively chosen constant velocity of the testing machine traverse, up to breaking or limited strains. During testing, the pressure force and deflection of the beam specimen in 3-point bending are registered. The method is applied to determine the strength to interlaminar shear using the short beam method. This method is not applied for exact determination of material constants, but it can be applied for material classification or for quality control. The specimen of a rectangular cross-section is loaded like in the 3-point bending test so that at first interlaminar shear damage appears. The standard PN-EN ISO 14130:2001 introduces, among the others, the following quantities:

τ - conventional shear stress at interlaminar shear, acting at neutral plane of specimen, MPa

R_{13}- conventional strength to interlaminar shear, i.e. value of conventional shear stress at interlaminar shear failure or at maximum pressure force, MPa

The remaining quantities are analogous to those in PN-EN ISO 14125:2001.

The supports and the central mandrel (Fig. 1) fulfil the conditions as in the bending test. The examined cubicoid specimens have the dimensions: L = 20 mm, l = 40 mm, b = 20 mm adhering to admissible dimensional tolerances given in PN-EN ISO 14130:2001. The remaining conditions in the shear test are analogous to those in the bending test. Based on the classic strength of materials, one obtains

$$\tau = \frac{3F}{4bh} \tag{2}$$

PROBLEM 1. RESULTS AND DISCUSSION

The bending test of the L-4F-2M, L-2F-5M specimens is illustrated in Figures 2-5 for the representative samples. The interlaminar shear of specimens made of the same laminates is presented in Figures 6-9 also for the representative samples. The final results for the average values and standard deviations of the examined strengths are set up in Tables 1 and 2.

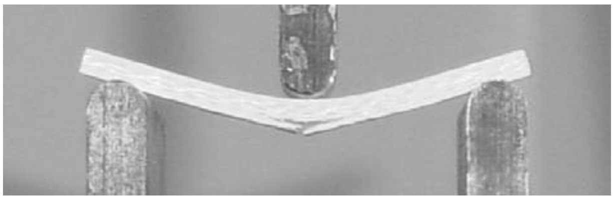

Fig. 2. Bent specimen No. 6 made of L-4F-2M laminate at end moment

Rys. 2. Zginana próbka nr 6 z laminatu L-4F-2M w chwili końcowej

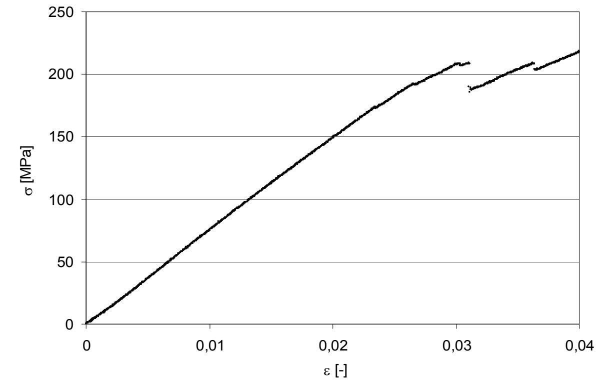

Fig. 3. σ-ε diagram related to bending of specimen No. 6 made of L-4F-2M laminate

Rys. 3. Wykres σ-ε odpowiadający zginaniu próbki nr 6 z laminatu L-4F-2M

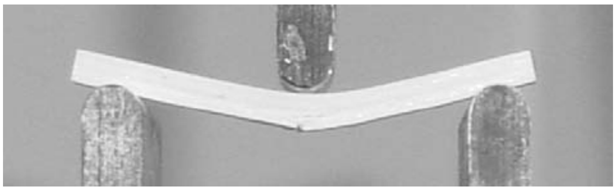

Fig. 4. Bent specimen No. 4 made of L-2F-5M laminate at end moment

Rys. 4. Zginana próbka nr 4 z laminatu L-2F-5M w chwili końcowej

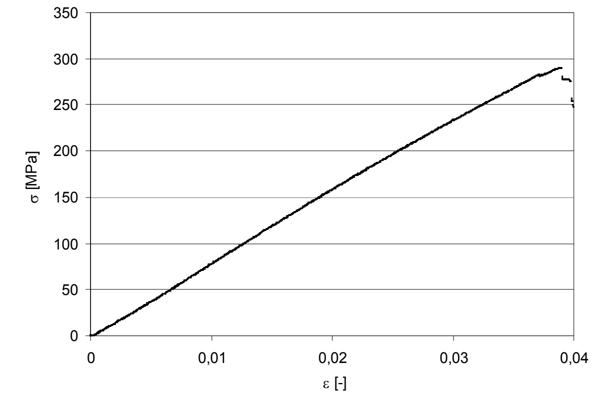

Fig. 5. σ-ε diagram related to bending of specimen No. 4 made of L-2F-5M laminate

Rys. 5. Wykres σ-ε odpowiadający zginaniu próbki nr 4 z laminatu L-2F-5M

The damage mechanisms of the examined laminates in both tests are typical and compatible with the theoretical prediction. In the bending test, subsequent layers crack starting from the bottom layer. Replacing the fabric core in the L-4F-2M laminate with the mat core in the L-2F-5M laminate has resulted in increasing the laminate thickness by 35%, as well as increasing the strength to bending (the average values) by 24% at the same level of the relative standard deviation (16%). Below the strength to bending, the laminates behave approximately linearly elastically. The effective Young's modulus is greater by 8% for the L-2F-5M laminate (with the mat core) compared to the L-4F-2M material.

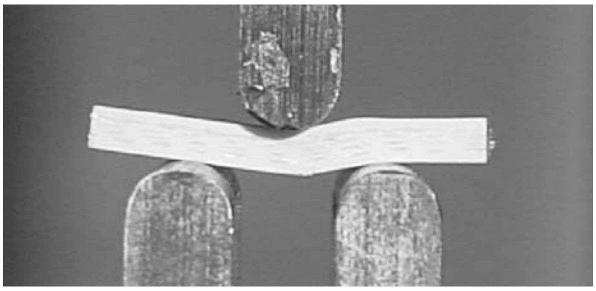

Fig. 6. Interlaminar shear of specimen No. 7 made of L-4F-2M laminate at end moment

Rys. 6. Ścinanie międzywarstwowe próbki nr 7 z laminatu L-4F-2M w chwili końcowej

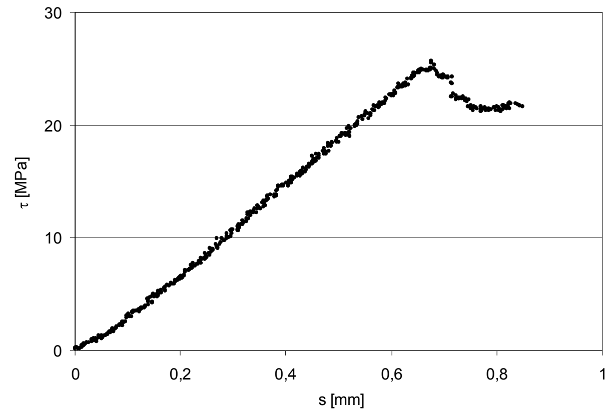

Fig. 7. τ-s diagram related to interlaminar shear of specimen No. 7 made of L-4F-2M laminate

Rys. 7. Wykres τ-s odpowiadający ścinaniu międzywarstwowemu próbki nr 7 z laminatu L-4F-2M

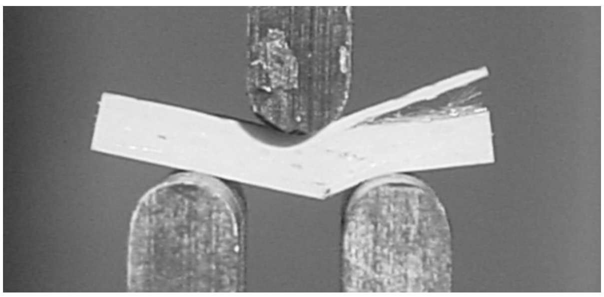

Fig. 8. Interlaminar shear of specimen No. 1 made of L-2F-5M laminate at end moment

Rys. 8. Ścinanie międzywarstwowe próbki nr 1 z laminatu L-2F-5M w chwili końcowej

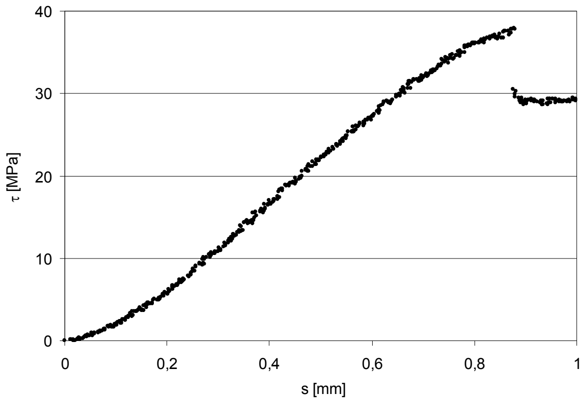

Fig. 9. τ-s diagram related to interlaminar shear of specimen No. 1 made of L-2F-5M laminate

Rys. 9. Wykres τ-s odpowiadający ścinaniu międzywarstwowemu próbki nr 1 z laminatu L-2F-5M

TABLE 1. **Final results from bending tests in problem 1**
TABELA 1. **Wyniki końcowe testów zginania w zagadnieniu 1**

Laminate	H, mm	R_{fM}, MPa	$\sigma(R_{fM})$, MPa
L-4F-2M	4.3	210	33
L-2F-5M	5.8	260	43

TABLE 2. **Final results from interlaminate shear tests in problem 1**
TABELA 2. **Wyniki końcowe testów ścinania międzywarstwowego w zagadnieniu 1**

Laminate	H, mm	R_{13}, MPa	$\sigma(R_{13})$, MPa
L-4F-2M	4.4	25	1.5
L-2F-5M	6.0	37	1.0

The main damage mechanism in interlaminar shear test is the interlaminar shear in the central mandrel - support section at the "weaker" side of the beam specimen. This mechanism differs from that suggested in standard PN-EN ISO 14130:2001 but is compatible with the classic strength of materials (note that no shear forces appear outside the support). After the conventional strength to interlaminar shear has been reached, a slow decrease in the load capacity is observed for the fabric-core laminate, while for the mat-core laminate, rapid dropping is detected. After replacing the fabric core in the L-4F-2M laminate with the mat core in the L-2F-5M laminate, the average strength R_{13} increases by 48%. The relative standard deviation of this strength equals 6% for the fabric core and 3% for the mat core.

PROBLEM 2. RESULTS AND DISCUSSION

The main damage mechanism in the shear tests of L-T and L-AWTP laminates is the interlaminar shear between the mandrel and the support at the "weaker" side of the beam specimen. This mechanism satisfies the classic materials mechanics principles. After the conventional strength to interlaminar shear has been reached, a slow decrease in load capacity in both composites is observed but a styrene anti-evaporator additive can induce rapid local decreases in the capacity. The average value of the strength R_{13} drops by 2% after adding the styrene anti-evaporator (Tab. 3). A slight increase of the standard deviation of this strength is detected, from 2% for the L-T laminate to 5% for the L-AWTP laminate. Summing up, a styrene anti-evaporator additive slightly decreases the resistance of the mixed laminate to interlaminar shear.

TABLE 3. **Final results from interlaminar shear tests in problem 2**

TABELA 3. **Wyniki końcowe testów ścinania międzywarstwowego w zagadnieniu 2**

Laminate	h, mm	R_{13}, MPa	$\sigma(R_{13})$, MPa
L-T	6.3	33.2	0.7
L-AWTP	6.6	32.4	1.6

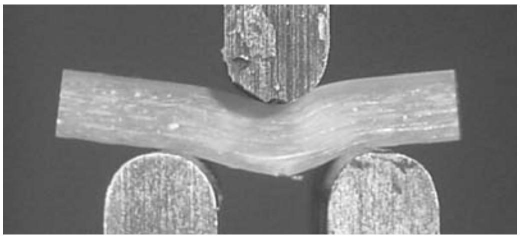

Fig. 10. Interlaminar shear of selected specimen made of L-T laminate

Rys. 10. Ścinanie międzywarstwowe wybranej próbki z laminatu L-T

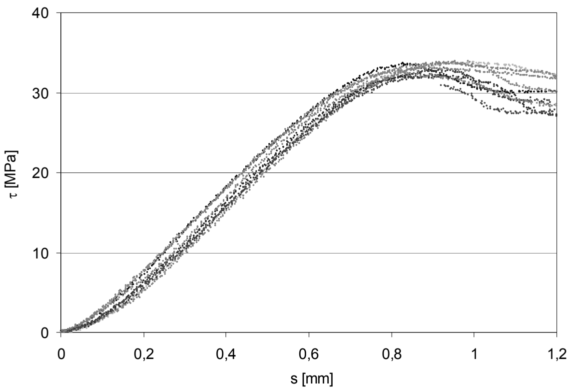

Fig. 11. τ-s diagrams corresponding to interlaminar shear of specimens No. 1-10 made of L-T laminate

Rys. 11. Wykresy τ-s odpowiadające ścinaniu międzywarstwowemu próbek 1-10 z laminatu L-T

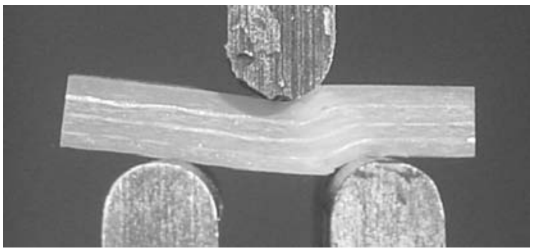

Fig. 12. Interlaminar shear of selected specimen made of L-AWTP laminate

Rys. 12. Ścinanie międzywarstwowe wybranej próbki z laminatu L-AWTP

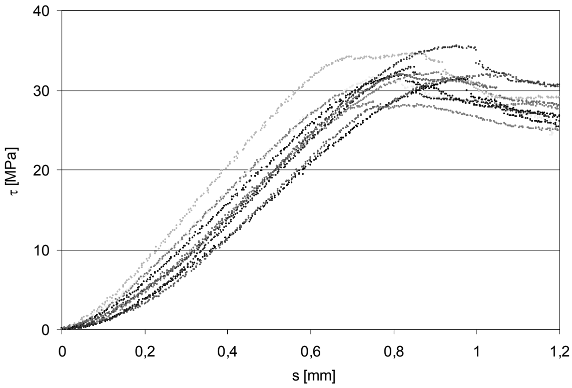

Fig. 13. τ-s diagrams corresponding to interlaminar shear of specimens No. 1-10 made of L-AWTP laminate

Rys. 13. Wykresy τ-s odpowiadające ścinaniu międzywarstwowemu próbek 1-10 z laminatu L-AWTP

CONCLUSIONS

The damage mechanisms of the L-4F-2M and L-2F-5M laminates in both tests are in accordance to the principles of the classic strength of materials. Replacing the fabric core in the L-4F-2M laminate with the mat core in the L-2F-5M laminate has caused a valuable increase in the load capacity. The average value of the strength to bending has increased by 24%, whereas the average value of the strength to interlaminar shear - by 48%. Thus, layered composites with mat cores should be preferred in practice, particularly in manufacturing shell covers of CE structures.

The damage mechanism of the L-T and L-AWTP laminates in the interlaminar shear test also coincides with the principles of the classic strength of materials. The average value of the conventional strength to interlaminar shear of the mixed laminate decreases by 2% after adding the styrene anti-evaporator.

The optimisation of sequences of laminate layers, resulting in valuable strengthening of laminates, should be performed in a large number of combinations using numerical methods based on laminate theories, the finite element method, standard tests and CAE software such as MSC.MARC or LS-DYNA. Experimental tests should be only used for the verification and validation of the numerical results.

Acknowledgment

The study is a part of the research and development project No. O R00 0097 12, financed by the Ministry of Science and Higher Education, Poland. This support is gratefully acknowledged.

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