MECHANICAL AND FAILURE BEHAVIOUR IN CARBON/EPOXY COMPOSITES

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A review of the mechanical properties and failure initiation and propagation in carbon/epoxy composites is presented. The results of the study of the macromechanical static characteristics, non–linear elastic behavior, flexural modulus and shear properties of unidirectional composites (UDC), as well as, of tensile, compression and flexural moduli, strength analysis, edge and hybrid effects in multidirectional composites (MDC) were discussed. A discussion of the non–linear elastic behavior of carbon/epoxy UDC, the flexural moduli of both UDC and MDC, strength analysis and edge effects of laminates is emphasized.

A study of the mechanical properties and failure phenomena of carbon fiber/epoxy resin composites was performed with the aim of understanding the nature and mechanical properties of composites as well as the mechanisms and phenomena of failure initiation and propagation in the composite under mechanical load. This study included the measurement of a set of mechanical properties (static, impact) by several test methods as well as the fractographic observation of failure created in a composite coupon during testing.

The interpretation of the values obtained for the mechanical characteristics was first based on a comparison of the experimental results with values predicted by theory. The investigations included the theoretically based analysis of factors influencing the measured property and the correlation of theoretical statements with the measured macromechanical characteristics and the microstructure of the failure surfaces.

This paper reviews, results and main conclusions of the performed investigations, emphasizing the modest contribution given by this study to this field. The paper is divided into two parts: the first deals with the mechanical properties (tensile, compressive, flexural, shear) and the failure fractography of unidirectional composites, while the second presents investigations related to the mechanical behavior of multidirectional carbon/epoxy and glass/carbon hybrid/polyester composites.

MECHANICAL PROPERTIES AND FAILURE FRACTOGRAPHY OF UDC

Macromechanical static characteristics

A series of static mechanical tests and a fractographic examination of the failure surfaces formed in the tests was performed on unidirectional composites (UDC). The corresponding axial and transverse properties: strength, modulus, Poisson's ratio and failure strain, were determined in 0° and 90° tensile, compression, three point flexural tests (Table 1) [1–4].

All types of fracture surfaces formed in the tests were examined on a scanning electron microscope in order to specify their characteristic features and to attribute them to the failure micromechanisms and microfailure events [1,2].

The obtained results were analyzed with regard to the constituent material properties, to the ir mutual relations and to the relations of the lamination theory. Mechanical testing coupled to fractographic observations of the same samples enable a better understanding of both kinds of investigations.

The values obtained for axial tensile strength and modulus agree well with those calculated by the rule of mixture (ROM) [1, 2]. The axial flexural strength value was somewhat higher than the strength obtained in the tensile test, while the axial flexural modulus (E_F) was remarkably lower than the tensile ($E_F = 0.77\ E_T$). The axial compression modulus and strength were 26–28% lower than the corresponding tensile values.

The main point here was to remark that compressive modulus E_C was lower than tensile modulus E_T, which is a normal consequence of the non–linear elastic behavior of carbon fibres [5,6]. The values obtained for the flexural, tensile and compressive moduli ($E_C < E_F < E_T$) can be explained in a qualitative manner by Jones' relations [7]

$$E_F = 4E_T\,[(E_T/E_C)^{1/2} + 1]^{-2} \qquad (1)$$

$$E_F = 4E_C\,[(E_C/E_T)^{1/2} + 1]^{-2} \qquad (2)$$

The modulus values presented in references [1–4] were evaluated for the variety of strain. Eq. 1. and Eq. 2 were rigorously validated for the modulus values referring to ε_{TF}, ε_{CF} and r_F, points mutually correlated by the equations [7]

$$\varepsilon_{TF} = 4r_F\,[(E_{TF}/E_{CF})^{1/2} + 1]^2 = K_T r_F \qquad (3)$$

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Table 1. UDC static mechanical characteristics

Properties	Strength [MPa]	Modulus [GPa] for $\varepsilon = 3 \times 10^{-3}$	Poisson's ratio	Failure strain [mm/m]
UDC(0)				
Tensile	1467 ± 94	126.7 ± 3.6	0.310 ± 0.010	
Flexural	1660 ± 70	106.5 ± 5.5		16.16 ± 0.50
Compressive	1225 ± 47	102.8 ± 6.6	0.310 ± 0.02	11.10 ± 0.06
In–plane shear	70.3 ± 1.9	3.56 ± 0.06		
Interlaminar shear	118.3 ± 2.5			
UDC(90)				
Tensile	348.6 ± 5.6	8.4 ± 0.5	0.018 ± 0.001	4.98 ± 0.65
Flexural	74.3 ± 7.9	8.0 ± 0.8		9.51 ± 0.84
Compressive	172.6 ± 7.2	11.5 ± 0.5	0.020 ± 0.001	15.19 ± 1.12

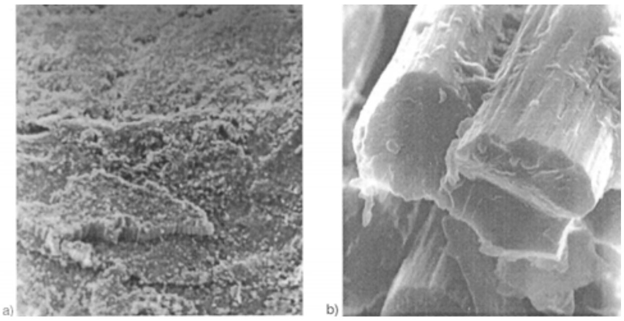

Figure 1. UDC tensile failure
a. Transverse fracture b. Fibre fracture

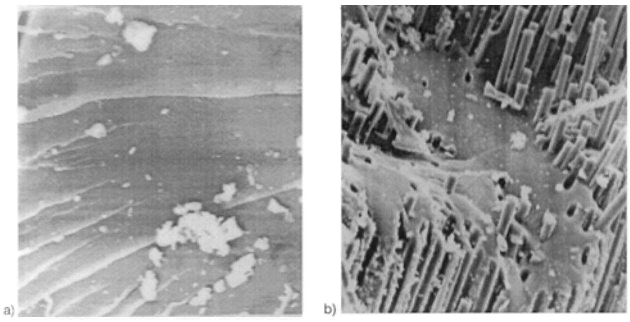

Figure 2. UDC tensile failure
a. Matrix cracking b. Pull–out mechanism

$$\varepsilon_{CF} = 4r_F\,[(E_{CF}/E_{TF})^{1/2} + 1]^2 = K_c r_F \qquad (4)$$

These equations connect the actual flexural strain (r_F) of the UDC bent coupon with the axial strain of the coupon bottom outer fibre under tensile stress (ε_{TF}) and the strain of coupon upper outer fibre under compression stress (ε_{CF}). All these strains arise simultaneously.

A high longitudinal tensile strength value of carbon/epoxy UDC equal to the ROM value was reached with the composite exhibiting a very high interlaminar shear strength value OF 118.3 MPa [1], i.e. a very strong fibre–matrix bond resistant to delamination.

In the longitudinal tensile test, crack propagation transverse to the fibres produces a relatively flat surface traversed by some axial splitting [1]. This fracture mode of the brittle type (Fig.1a), analogous to cleavage fracture in polycrystals, is due to fibre fracture (Fig.1b) and matrix cracking (Fig.2a), as well as to the small contribution of fibre–matrix debonding and the pull–out mechanism of broken fibres (Fig.2b).

In the longitudinal flexure test the sample failure, so–called multiple shear mode fracture, was of a tensile nature originating on the tensile side. Samples failed by crack propagation toward the neutral axis, from one fracture plane to another, producing a rough fibrous structure separated by axial failure surfaces created by interlaminar debonding.

Failure of the macrosurface of axially compressed specimens appeared approximately 45° to the compression axis. Failure surface micrographs show a regularly spaced series of stepwise fractures (Fig. 3a) and some lateral delaminations (Fig. 3b) [4].

Non–linear elastic behavior

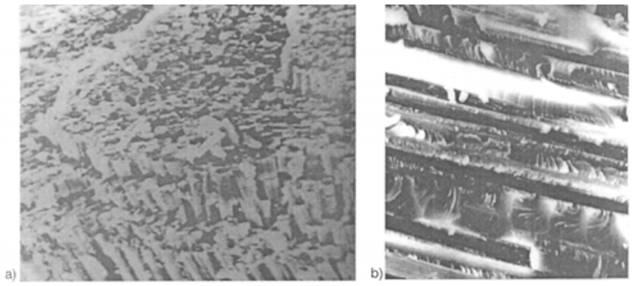

Figure 3. UDC compression failure
a. Stepwise transverse fracture b. Lateral delamination

Carbon fibres and UDC reinforced with carbon fibres are highly anisotropic and their elastic response is non–linear with respect to strain. Our investigations related to this topic [5,6] included the conduction of standard tensile and compression tests, as well as an original modified three point flexure test [9] and, consequently the construction of axial stress–strain plots for UDC in tension and in compression. In the modified three point flexure test, the tensile and compressive strains of the bent coupon outer fibres were measured by strain gauges. From the evaluated stress–strain curves, the tangent modulus values for different strains were calculated and the analytical expression

$$E_{T(C)} = E_Z\,[1 + \gamma_{T(C)}\,\varepsilon_{T(C)}] \qquad (5)$$

for tensile modulus–tensile strain and compression modulus–compressive strain dependencies derived (Table 2).

The same E_Z (zero strain modulus) value 117.96 ± 0.44 GPa from the derived expressions (Table 2) was determined. The γ_T coefficient from the tensile and modified flexural tests are practically the same having the values of 24.06 ± 0.12. The coefficient γ_C from the standard compression test has a higher absolute value (–34.3) than the same coefficient derived from the modified flexural test having the value of (–11.6). Through this study we confirmed the validity of the applied flexural test for measuring the axial modulus in UDC and gave experimental [9] evidence to Harper and Neuman's opinion [8] that the buckling of fibres, as a progressive failure mechanism, can contribute to the strain and modulus values determined from the compression test using Celanese fixtures.

Table 2. Parameters of modulus to strain dependence in carbon epoxy UDC

Test	Property	E_Z (GPa)	$\gamma_{T(C)}$
In tension	tensile [5]	117.8	24.3
	flexural [24]	118.2	23.9
In compression	compressive [5]	117.6	– 34.3
	flexural [24]	117.7	– 11.6

Flexural modulus

The apparent flexural modulus of carbon/epoxy UDC, determined from the ASTM three point flexural test, is of limited validity due to the influence of many factors. These factors were analyzed [10,11] on the basis of theoretical considerations of the stress state in bent coupons, in order to contribute to the proper interpretation of the obtained flexural modulus data, particularly as a function of the strain.

From the standard three point flexure tests of carbon/epoxy UDC coupons, the flexural (tangent) modulus values were determined in the strain range 1 x 10^{-3} – 15 x 10^{-3} mm/m. The shape of the E_F–r_F plot was approximated by two crossing straight lines [10] (Fig. 4). The linear expressions for these lines were derived from the experimental E_F and r_F data, by the linear regression method [10].

The theoretically based analytical expression for the strain (r_F) dependence of the flexural modulus (E_F)

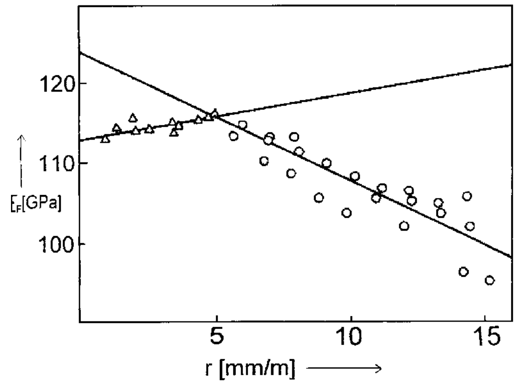

Figure 4. Strain dependence of the flexural modulus

$$E_F = E_Z(1 + \gamma_T K_T r_F)\left[\left(\frac{1 + \gamma_T K_T r_F}{1 + \gamma_C K_C r_F}\right)^{1/2} + 1\right]^{-2} \qquad (6)$$

was derived from the data given in the diagram in Fig. 4. [10], taking into account the following expressions: (i) the Jones relation (eq. 1) describing the change in E_F as a consequence of the displacement of the neutral axis from the beam mid–depth, due to a difference between the E_T and E_C, i.e., between E_{TF} and E_{CF} values; (ii) the analytical expression given by eq. 5 for the variation of the axial moduli of the flexure coupon outer fibres with axial strain; and (iii) the relations between the ε_{TF}, ε_{cf} and r_F values given by eq. 3 and eq. 4.

In eq. 6, γ_T and γ_C are coefficients of the modulus–strain dependence in tension and in compression, while the K_T and K_C parameters are defined by eqs. 3 and 4.

Through a mathematical analysis of the derived analytical form for the strain dependence of the flexural modulus (eq. 6), it was shown that the experimentally obtained shape of the E_F variation with r_F is possible only when the absolute value of the γ_C coefficient is lower than the absolute value of the γ_T coefficient. This is the case of the γ_C coefficient value determined from the data obtained in the modified flexural tests. Higher $|\gamma_C|$ than γ_T values determined from the axial tests were due to a contribution of buckling to the compressive strain of the coupon in the Celanesse jig during the UDC compression test [10].

Shear properties

The in–plane and interlaminar shear characteristics of carbon/epoxy UDC were investigated by several methods [12–14]. The obtained results (Table 3) were analyzed by comparing the values of the same property evaluated by different methods and by their comparison with the literature data. In addition, the used shear methods are discussed in terms of their relative advantages, their validity and suitability for the determination of a given property, as well as in terms of the accuracy and reliability of the obtained results. The

Table 3. Shear characteristics of carbon/epoxy UDC

Test	Coupon stacking geometry	Shear strength [MPa]	Shear modulus [GPa]
In–plane shear characteristics			
Tensile	$(\pm45)_{4S}$	86.8 ± 4.5	4.45 ± 0.09
Compression	$(\pm45)_{4S}$	97.3 ± 1.0	4.51 ± 0.13
Off axis tensile	$(45)_{16T}$	29.7 ± 1.9	4.01 ± 0.16
Off axis compression	$(45)_{16T}$	96.7 ± 1.1	3.51 ± 0.10
Off axis tensile	$(10)_{16T}$	76.8 ± 5.4	4.36 ± 0.30
Interlaminar shear			
Short beam Flexure and flexure	$(0)_{32T}$	105.7 ± 5.1	G_{13} = 4.23 G_{13} = 3.89

appearance of the shear coupling phenomena in the coupon during tests has been analyzed too [12,13].

Reliable G_{12} values were evaluated from the data obtained in tensile and compression tests of $(\pm45)_s$ coupons. The real value of the in–plane shear ultimate strength lies between the τ_{12} values deduced from the tensile and compression tests of the $(\pm45)_{4s}$ coupons. Deviation from the τ_{12} reliable value of the values from the $(\pm45)_{4s}$ coupons axial tests, as well as of the values from all of the performed off–axis tests may be explained by shear coupling phenomena (SCPh) in the non–linear region of materials response, before macroscopic failure takes place. In the UDC coupons exposed to off–axis axial tests SCPh appeared already in the elastic region. The less pronounced intensity of SCPh in the coupons submitted to the 10 degree off–axis test, makes the G_{12} value from these tests close to those from the axial tests of the $(\pm 45)_{4s}$ coupons [15].

The interlaminar shear strength τ_{13} values, determined from both short beam flexure tests [12] and symmetrical tensile–shear (STSh) tests [13] are not correct; first by due to known reasons, and second by because the performed finite element calculations revealed the appearance of a normal stress beside the non–homogeneous shear stress distribution along the shear range in STSh specimens [13].

The Young (E_1, E_2) and shear (G_{12}, G_{13}, G_{23}) moduli of unidirectional carbon/epoxy composites were determined from the flexural modulus data obtained in three point flexure tests with different spans, on coupons of appropriate fibre orientation [14].

For coupons with orthotropic symmetry the form factor for shear γ was determined by Cowper's equation [15]. For anisotropic coupons used for evaluation of the E_2, G_{12} and G_{23} (x=2) data, the coefficient γ was derived from the slope of the linear regression straight line I/E_f-$(d/L)^2$ for the coupons (x=1) and the G_{12} value determined by the tensile tests of the $(\pm45)_{4s}$ coupons [12].

Size effect

The size effect i.e. the decrease of strength with coupon dimensions, in carbon fibre/epoxy resin unidirectional composites was studied by analyzing this effect in carbon fibres as well as in unidirectional composites themselves [26–28]. The carbon fibres were tested applying the single–filament tensile test with different gauge lengths (measured strength and failure strain) [27], while unidirectional composite coupons of different dimensions were tested in standard static tensile tests (measured strength values) [26,28].

The obtained tensile strength results were analyzed according to the Weibull statistical strength theory for brittle materials, by comparing the variation of sample strength (failure strain) during the increase of samples dimensions with the variability scatter of results for individual sample around the mean values.

The performed analysis showed that size effect in carbon fibres the can be fully described by the Weibull statistical theory. However, due to complex failure propagation, composites exhibit a pronounced size effect, however followed by reduced strength variability. It makes the detected composite size effect behaviour deviate from that in brittle materials [28].

MECHANICAL BEHAVIOR OF MDC

Effective tensile, compression and flexural moduli

The apparent modulus values of carbon/epoxy MDC of different stacking geometry, determined from tensile, compression and flexural tests, were correlated with the values calculated by the stiffness matrix relations of the lamination theory [4,16,17]. The values used in the calculations are the values of the main engineering properties of UDC [1] adjusted to the laminate fibre content. Full agreement between the experimental and the calculated values in compression has been claimed [4]. The same was found for the $E_{||}$ values in tension, except for cross–ply laminates (Table 4) [16]. A lower E_x^{exp} than E_x^{cal} value in tension for $(0/90)_{ns}$ coupons was due to the elastic instability, preceding the multiple transverse cracking in 90° plies.

A disagreement between E_x^{exp} and E_x^{cal} in flexure is evident, when, according to the Euler–Bernouli beam bend theory, E_F was taken to be equal to E_T (Table 5) [17]. An agreement between E_x^{exp} and E_x^{cal} was achieved

Table 4. Experimental and calculated E_x and ν_{xy} values of MDC from tensile tests

MDC	E_x(GPa)		ν_{xy}	
	exp.	cal.	exp.	cal
$(\pm45)_{4S}$	15.68 ± 0.26	16.06	0.737 ± 0.001	0.773
$(0/90)_{4S}$	68.71 ± 1.44	72.56	0.042 ± 0.004	0.043
$(\pm45/02)_{4S}$	66.18 ± 1.49	67.69	0.661 ± 0.016	0.695
$(\pm45/0/90)_{4S}$	48.50 ± 1.40	47.35	0.296 ± 0.009	0.315

only for the tested MDC without angle–ply layers [17], when the corrections for the following effects were included in the calculation: (i) the decreasing effect of shear deformation [11]; (ii) the effect due to the difference between E_{TF} and E_{CF} (Eq.1) and due to the variation of E_{TF} and E_{CF} with strain (Eq. 5); (iii) the effect of different contributions of present laminae moduli to the apparent E_F value, depending on the ply distance from the mid–plane. Our analysis has shown that Whitney, Browning and Mair's model [18], derived from the constitutive relations for bending, represents the best way to describe the influence of the stacking sequence effect on the E_F of MDC without angle–ply layers. It has been shown that by this analysis the flexural tests of MDC coupons with angle–ply payers make of no sense.

Table 5. Experimental and calculated E_X and r_X values of MDC from flexural tests

MDC	E_X(GPa)		r_X	
	exp.	cal.	exp.	cal.
$(\pm45)_{4s}$	19.28	16.37	32.32	30.29
$(0/90)_{4s}$	20.73	19.06	32.60	31.07
$(\pm45/02)_{4s}$	22.41	18.15	34.02	29.45
$(\pm45/0/90)_{4s}$	25.24	19.45	31.36	26.93

Strength analysis

The strength analysis for symmetrically balanced MDC coupons of different stacking geometry, subjected to tensile and compression tests, was performed [4,16], according to Halpin's mathematical model of laminate elastic behavior [19], using stiffness matrices calculations.

By comparing the calculated stress values for all the present laminae, corresponding to the measured laminate strength, with the strength values of the laminae, the lamina of first failure appearance was anticipated. In compression [4], as well as, in tension [16] they are: 90° ply for $(0/90)_{ns}$ and $(\pm45/O_2/9O)_{ns}$ laminates and ±45° plies for $(\pm45/O_2)_s$ laminate. Namely, the conclusion derived formally from the results of tensile strength analysis, when as a shear strength of ±45° plies one takes the ultimate shear strength value, should indicate the first failure appearance in 0° ply of the $(\pm45/O_2)_{ns}$ coupon. However, the shear strength value, much lower than the ultimate one, is responsible for the first failure appearance. The surface micrographic view of the transverse fracture of bent MDC coupons [16] confirms the conclusions for tensile strength analysis.

Edge effects

The standard test document recommends a large enough width of a MDC coupon for tensile strength measurements. This is due to the effect of normal σ_z and shear τ_{xz} interlaminar stresses induced near the coupon free edges, as a consequence of different elastic properties of the adjacent plies [21]. These stresses may cause premature or postponed failure of the MDC coupons. Evidence of the effect of free edge induced interlaminar stresses was observed on failure SEM microfractographs (Fig. 5) of thick carbon/epoxy laminate coupons of the stacking geometry $(\pm45/O_2\ \pm45/0/90)_{3s}$. These coupons were examined in tensile tests [20]. The axial intralaminar fracture throughout the mid–plane plies was generated as a consequence of the action of the very high tensile interlaminar stress σ_Z, induced near the free edges of the 7 mm thick coupons. Otherwise, fracture of this type is practically impossible to pro–duce in the UDC(90) coupon examined in axial tests.

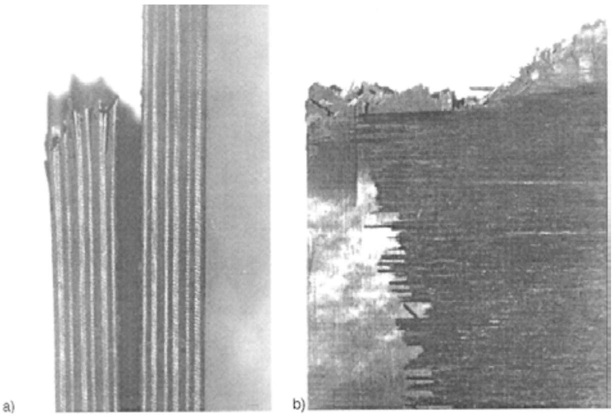

Figure 5. Failure of thick carbon/epoxy $(\pm45/O_2\pm45/0/90)_{3s}$ laminate coupons

In the scope of the study of the edge interlaminar stresses effect on laminate strength, carbon/epoxy and glass/polyester symmetric balanced multidirectional composites of differe–nt stacking geometry were tested in tension and the effective values of the strength and failure strain were derived [30,31]. The method developed by Kasapogou and Lagas [32], based on force and moment equilibrium and on the principle of minimization of complementary energy Π_c was used for the calculation of edge induced interlaminar stresses. (The complementary energy represents the difference between the total strain energy and the total strain work in the load direction). By the applying this method, the three dimensional state of stress for all the interlayers present in the tested laminates was calculated. So, the edge induced interlaminar stresses (σ_Z, τ_{XZ}) and the complementary energy values were calculated at the coupon free–edges. For the interior of the coupon, where only the in–plane state of stress is present, the in–plane stress values and the complementary energy were calculated by classical laminate plate theory (CLPT).

Due to the tensor nature of the stress components, a direct correlation between the values of the interlaminar stresses and the longitudinal strength values does not allow assessment F the edge effects on laminate strength. The edge induced interlaminar stresses can lead to delamination in the interlayer of the laminate at in–plane loads, which are lower than the loads at which the laminate would fail if only in–plane fracture was the failure mechanism.

In cross–ply laminates ($(0/90)_s$ and $(90/0)_s$), near the free edges, only normal interlaminar stress can appear in the interlayers. Due to the appearance of this stress, the strain component ε_Z changes, it increases or decreases. If due to the application of load P_x, the strain component ε_Z increases at the coupon edge in a interlayer. It may induce the splitting of that interlayer. Taking that into account, the effect of the edge the induced normal stress in cross–ply laminates was assessed looking for the change of ε_Z in the interlayer at the coupon edge (Fig. 6a). In the boundary region, where the normal interlaminar stress appeared in $(0/90)_s$ laminates, the value of ε_Z decreased at the edge in regard to the interior of the coupon, while in the $(90/0)_s$ one the ε_Z value became higher, thus initiating delamination in the present 90/0 interlayers thus inducing the decrease of σ_x^{exp}. Contrary to that, edge induced normal interlaminar stress in the $(0/90)_s$ laminate coupons did not cause the initiation of delamination in the present 0/90 interlayers nor a decrease of the tensile strength of the $(0/90)_s$ laminate. The calculated of ε_Z values in the 0/90 interlayer along the (2b) of the cross–ply after a slight increase show an evident decrease at the coupon free edge (Fig. 6b).

In other tested laminates, due to differences in the both shear and normal interlaminar stresses are induced elastic properties of adjacent plies in the edge region. Then a direct correlation of the calculated edge interlaminar strain or stresses with the measured strength values can not help to assess the effect of edge interlaminar stresses on the strength values because of the tensorial nature of the stress components.

There the effect of edge induced interlaminar stresses on σ_X was assessed by correlating the Π_c values in the present interlayers at the coupon edges and in the interior of the coupons (Table 6) with the appearance of cracks in the interlayers of the tested coupon.

Table 6. Complementary energy in the interlayer of the tested MDC coupons

Stacking geometry	Interlayer	Π_c^{CLTP} [kJ/m^3]	Π_c^{EDGE} [kJ/m^3]
$(\pm45)_s$	45/–45	–1	18
$(90/0)_s$	90/0	40 to –30	80
	0/0	–30	210
$(0/90)_s$	0/90	–28 to 40	–30
	90/90	40	–18
$(0_{0.9}/\pm45)_s$	0/45	160 to –80	54
	45/–45	–80	258
	–45/–45	–80	280
$(\pm45/0_{1.9})_s$	45/–45	–225	75
	–45/0	–225 to 200	75 to 10
	0/0	200	300
$(0_{1.2}/45/90_{1.2}/45)_s$	0/45	6 to –150	17 to 10
	45/90	–150 to 225	500 to 425
	90/–45	225 to –150	375 to 475
	–45/–45	–150	70
$(45/90_{0.9}/–45/0_{0.9})_s$	45/90	–150 to 290	500 to 450
	90/–45	290 to –175	525 to 600
	–45/0	–150 to 16	20 to –75
	0/0	16	15

It was observed [30,31] that in the tested laminates the increase of the Π_c^{EDGE} value in relation to that Π_c^{CLTP} value induced the appearance of decohesion in the tested coupons. These cracks in the inter layers caused the premature failure of the composites at loads which were lower than those when edge interlaminar stresses did not appear. In $(0/90)_s$ laminate coupons, during tensile tests, delamination was not observed in the present 0/90 interlayers. For these coupons Π_c^{EDGE} had lower value than Π_c^{CLTP}. On the basis of this study it was concluded that edge induced interlaminar stresses have a negative influence on MDC coupon strength when

$$\Pi_c^{EDGE} > \Pi_c^{CLPT}.$$

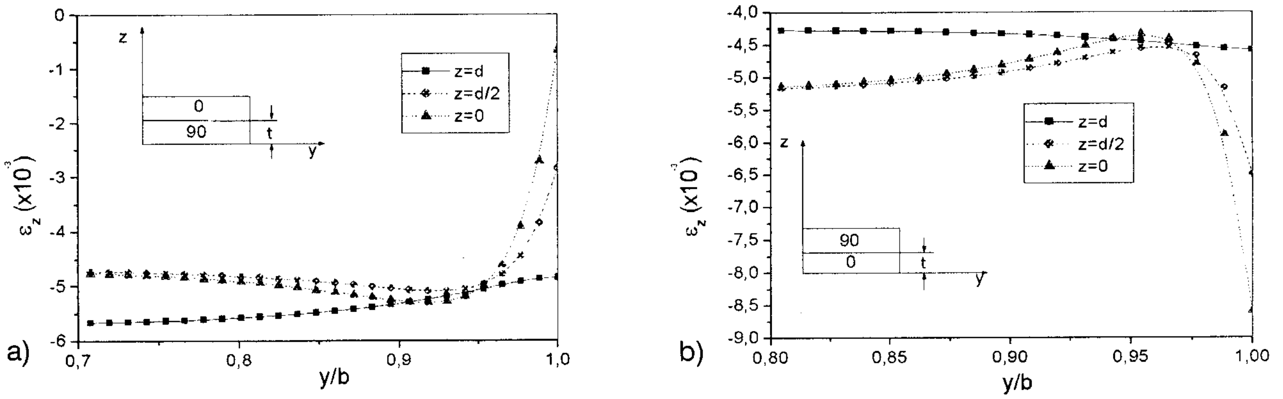

Figure 6. Variation of the ε_Z strain component along the coupon width in cross–ply laminates a) $(90/0)_{4s}$ laminate b) $(0/90)_{4s}$ laminate

Hybrid effects in glass and carbon fibres/polyester composites

Sandwich coupons of carbon and glass hybrid fibre reinforced polyesters with continuous carbon fibres as a shell and glass mat as a core reinforcement, have been tested for tension, flexure, impact and post–impact tension [22]. The tensile moduli of the tested composites agree with the rule of mixture (ROM) calculated values. The tensile failure strain and strength results, lower than possible values, indicate premature fracture of the coupons, initiated by numerous carbon fibre–matrix interface decohesions. Due to the higher contribution of the shell layer modulus to the flexural modulus of a sandwich hybrid beam, the measured values of the latter are higher than the ROM values. A positive hybrid effect, i.e. failure strain enhancement, was found in flexure tests on sandwich coupons with a high glass mat to carbon fibre content ratio.

Since the upper shell made of carbon/polyester composite (CPC), being under compression stress, has a lower modulus than the lower shell made also of CPC, stressed in tension, "hybrid effects" flexural modulus is higher than the ROM value and the flexural failure strain is higher than that of carbon fibre can be explained by the effect of bent coupon neutral axis displacement, due to the higher axial modulus of the lower shell layer than that of the upper one.

The total impact fracture energy values of the tested composites are high compared to those of carbon/epoxy coupons, and are due to intensive impact failure with carbon fibre – matrix dec–ohesion as the dominant mechanism. The improvement of impact behavior in the presence of glass mat and with an increase of its content in composites based on carbon fibre and polyester resin, is manifested by the total impact fracture energy and the after impact residual tensile strength values of the tested composites.

CONCLUSIONS SUMMARY

The macroscopic static characteristics (modulus, Poisson's ratio, strength and failure strain) in tension, compression, flexure and shear for carbon/epoxy UDC were determined. Theoretically founded explanations of the obtained results for these properties have been offered and the reliability of the obtained values assessed. Proper interpretation of the flexural modulus data was based on the analysis of factors influencing the measured E_F value. An original analytical expression for the dependence of the UDC flexural modulus on flexural strain was derived during this study.

A modified three point flexure test, as a valuable test method for the determination of elastic moduli in tension and in compression, was introduced.

During the application of three point flexure tests with different spans for the simultaneous determination of axial and shear moduli, it was found that the use of the form factor for shear, calculated by means of Timoshenko's theory, for anisotropic coupons without orthotropic symmetry around the x–axis, was not appropriate.

The non–linear elastic behavior of carbon/epoxy UDC was studied by means of axial and modified flexure tests. The linear dependence for axial moduli (dependence) on strain were derived. A more reliable dependence was derived from the modified flexural than from the standard compression tests for the compression modulus.

The effective values of tensile, compression and flexural moduli for MDC of different stacking geometry were correlated with the values calculated using the relations of the lamination theory. For tensile and compression moduli, a disagreement between the experimental and the calculated values was recorded only in the case of tensile test of the $(0/90)_{ns}$ laminate. By introducing appropriate corrections in the calculations, it was possible to give a proper interpretation only of the effective flexural modulus value of MDC without angle–ply layers.

By tensile and compression strength analysis performed according to Halpin's model of laminate elastic behavior, the laminae of first failure appearance were anticipated. The microfractographic view of transverse fracture of bent MDC coupons confirmed the findings of the tensile strength analysis.

The effect of edge induced interlaminar stresses on the effective strength values of MDC with different stacking geometry was studied. This effect was assessed by correlating the complementary energy values in the present interlayers at the coupon edges and in correlating the complementary energy values near the free edges and in the interior of the coupon with the appearance of cracks in the interlayers of the tested coupon.

It was concluded that edge induced interlaminar stresses had a negative influence on MDC coupon strength when the complementary energy was higher near the free edges than in the interior of the coupon. In that case the edge interlaminar stresses induced the appearance of cracks in the interlayers of the tested coupon, causing in this way premature destruction of the composite.

During the study of the mechanical behavior of carbon and glass fibre hybrid reinforced polyesters of sandwich construction, a flexural modulus higher than the ROM value and a flexural failure strain higher than that of carbon fibre were recorded. These "hybrid effects" were explained by the effect of bent coupon neutral axis displacement, due to the higher axial modulus of the lower shell layer than that of the upper one.

The effect of edge induced interlaminar stresses on laminate strength was assessed by correlating the Π_c values of the present interlayers at the coupon edges Π_c^{EDGE} and in the interior of the coupons Π_c^{CLTP} with strength values and with the appearance or absence of delaminations in the present interlayers [30,31]. In the tested laminates, increase of the Π_c^{EDGE} value in relation to that of Π_c^{CLTP} induced the appearance of decohesions in the interlayers and probably a decrease of the experimental value of the coupons strength.

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IZVOD

MEHANIČKO PONAŠANJE I PONAŠANJE PRI RAZARANJU KOMPOZITA KARBON/EPOKSID

(Pregledni rad)

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Dat je pregled rezultata i zaključaka istraživanja, kao i doprinos autora razumevanju mehaničkih svojstava i fenomena iniciranja i prostiranja loma u kompozitima karbonska vlakna/epoksidna matrica. U ovom radu su razmatrani rezultati proučavanja makromehaničkih statičkih karakteristika, nelinearnog elastičnog ponašanja, modula savijanja i karakteristika smicanja unidirekcionih kompozita, kao i modula kompresije i savijanja, analize čvrstoće i ivičnih i hibridnih efekata u multidirekcionim kompozitima. Posebno su istaknuti zaključci autora koji se tiču nelinearnog elastičnog ponašanja unidirekcionih kompozita karbon/epoksid, modula savijanja unidirekcionih i multidirekcionih kompozita, kao i analize čvrstoće i ivičnih efekata laminata.

Ključne reči: UDC • MDC • Karbonska vlakna • Epoksidna matrica • Mehanička svojstva • Razaranje •
Key words: UDC • MDC • Carbon fibre • Epoxy resin • Mechanical properties • Failure •