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Mechanical behaviour of carbon and glass hybrid fibre reinforced polyester composites

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Mechanical behaviour of carbon fibre/glass mat/polyester resin hybrid composites of sandwich construction is studied through tension, flexure, impact and post-impact tension tests. Tensile and flexural strength, modulus and failure strain values are compared to the calculated values. Total impact fracture energy and residual (after impact) tensile strength values of hybrid composites are analysed with regard to corresponding values of carbon/polyester composites. Failure of tested coupons was analysed by visual inspection and observation by scanning electron microscopy.

1. Introduction

With the proper hybrid combination of reinforcements, the possibility of controlling many composite properties, at the same time, increases and some disadvantages of composites reinforced by one type of fibre can be improved. So, by introducing plies reinforced by aramid or glass fibres into carbon/plastic laminates, an improvement in composite toughness takes place. The lack of sufficient stiffness is a serious deficiency of glass/plastic composites as a structure material, while carbon/glass/plastic hybrids would possess the satisfactory modulus for structural application.

In the literature [1–3] covering research work in the field of mechanical properties of fibre hybrid reinforced composites, the emphasis is on comparison between measured properties, and the values calculated by model–rule of mixture (ROM). But, due to the wide variety of fibres and resins used, as well as various test coupons and tests used, a direct comparison of data is very difficult and the differences between measured and calculated values are not always of the identical sign for the same property.

Certain properties of hybrid composites (tensile modulus of many hybrids [1, 4], flexural modulus of alternately plied glass–carbon hybrid fibres reinforced epoxy [5] obey the rule of mixture. In some cases the measured value is higher than the ROM value (flexural modulus of sandwich hybrids [1, 4]). For most properties, especially strength [3, 5, 6], the rule of mixture is only an upper bound. All detected deviations of hybrid properties from ROM values, have to be explained separately.

In the study of mechanical and failure behaviour of carbon and glass hybrid fibre reinforced polyester, coupons of sandwich construction, 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. Tensile and flexural properties are compared with the rule of mixture values, while impact fracture energy and residual (after impact) tensile strength are discussed by comparison of the values for coupons of different fibre content ratios, as well as with those of carbon/polyester composites. Failure created in samples during performed tests was studied by visual inspection, as well as by microfractographic observations on a scanning electron microscope. In the explanations of obtained results, microfractographic evidence, recognized failure micromechanisms and fibre–matrix interfaces phenomena have been taken into account.

2. Experimental procedure

Tension, flexure, impact and impact–tension tests were carried out on sandwich samples of unidirectional carbon fibre/glass mat/polyester resin hybrid composites (designation of coupons CGPHM) of different reinforcements content (different ratio of two reinforcements), as well as on samples of unidirectional carbon fibre/polyester resin composites (CPC).

All the tested composites were obtained by hand lay-up, from glass strand mat (GM), produced by GES-Gostivar; polyester resin (PR) Colpoly 720, produced by HINS-Novi Sad and two qualities of high strength carbon fibres (CF). Coupons of hybrid composites CGPHC-1 to CGPHC-9 are made of HTS carbon fibre obtained in our Institute ($\sigma_{CF} = 1950 \pm 550$ MPa, $E_{CF} = 180 \pm 30$ GPa, $e_{CF} = 10.5 \pm 0.3$ mm m^{-1}), while all other tested coupons are made of ENKA, TENAX-HTA carbon fibres.

Composites were characterized (Table I) by determining density, volume fractions of present layers (x for the layers with CF) and volume content of present phases ($\lambda_{CF} = x\lambda$, $\lambda_{GM} = (1-x)\lambda$, $\lambda_{PR} = 1 - \lambda$; λ denoting the volume content of reinforcement in each layer). x and λ were evaluated from mass content of reinforcements and densities of composite, resin, carbon fibre and glass mat.

Methods for mechanical testing were based on American Society for Testing Materials (ASTM) standards: ASTM D-3039 for tension test, ASTM

D-790 for flexure test (three point loading, span to depth ratio 16–32), ASTM D-2344 for short beam flexure test (span to depth ratio 4) and ASTM D-256 for impact test.

In tension and flexure tests, performed with a M 1185 Instron Universal testing machine, tensile (Table II), flexural (Table III) macromechanical characteristics and interlaminar shear strength values (Table IV) were determined.

In impact tests carried out on unnotched samples (4.5 mm × 10 mm × 60 mm), using Charpy impact tester Zwick M8 (15 J striker energy), total impact fracture energy, U_t, was determined (Table IV).

Impact succeeded by tension tests were carried out on 2.5 mm × 70 mm × 250 mm dimensions laminate plates. Clamped plates were subjected to drop weight impact of 10 J [7] with 15 mm diameter spherical striker. Specimen support during impact was a basic steel plate, with a central 30 mm diameter hole. After impact, tension tests were performed with an Amsler testing machine of 1000 kN capacity, on coupons made of described plates by bonding bevelled tabs to both grip ends. From tension tests of unimpacted and impacted coupons, the decrease in tensile strength due to impact were evaluated (Table V).

Failure of tested coupons was studied by visual inspection and by observation of fracture surfaces on a Jeol scanning microscope, model JSM-35.

3. Results and discussion

3.1. Tensile properties

Tensile modulus results of all the tested composites agree with values calculated by linear rule of mixture (ROM) (Table II), regardless of the characteristics of tested coupons (Table I).

Coupons of carbon fibre/polyester resin composite (CPC) failed during tensile tests at strains lower than carbon fibre failure strain (e_{CF}) and those of carbon fibre/glass mat/polyester resin hybrid composite (CGPHC) at strains remarkably lower than e_{CF} (Table II). Experimental strength of these composites, when expressed as a percentage of ROM values, fully correspond to the failure strain values expressed as a percentage of e_{CF} (Table II). Differences between measured and possible values of strength or failure strain in tested composites are bigger as the coupon depth and carbon fibre content were greater, i.e. as the loads producing final failure of coupons were higher.

Unlike carbon fibre/epoxy resin composites [8, 9] coupons of tested CPC, as well as CGPHC, failed under tensile load levels remarkably lower than those corresponding to theoretical strength values. The shape and quantity of tensile failure of tested CPC coupons were different from those of composites based on epoxy resin [8]. The latter have visible transverse fracture surfaces with some axial splits propagating mainly through the resin [8]. In CPC coupons there is no transverse fracture of noticeable distance. Numerous axial splits have fracture surfaces like those of interlaminar shear delamination (Fig. 1a), with clean fibre surfaces, fibre imprints and cleaved surfaces through the resin in between fibres without many figures characteristic of interlaminar shear in carbon/epoxy composites (Fig. 1a). Overall coupon failure is like that initiated near or under tabs in carbon/epoxy composites, due to improper alignment of the coupon. The deviation of measured strength from ROM value was higher in coupon of CPC, made by lay-up technique where the misalignment of carbon fibres was more pronounced.

The macroscopic aspect of hybrid coupons tensile fracture is different from that of CPC one. Thick hybrid coupons failed near or under tabs. In thin coupons, failure has initiated and propagated along the gauge length, mainly through shell carbon fibre reinforced layers, but the transverse fractures in the

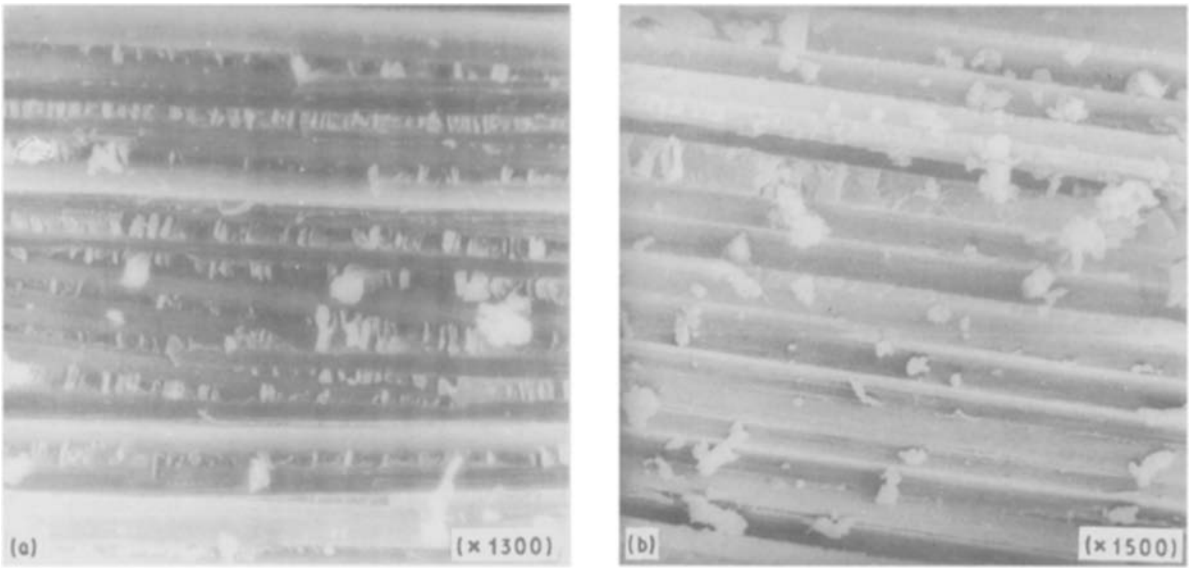
TABLE I General characteristics of tested coupons

Coupons	Test	Coupon depth (mm)	Density ($kg\,m^{-3}$)	x	λ	λx
CPC-1	T	1.8	1360	1	0.347	0.347
CPC-2	T	0.8	1390	1	0.376	0.376
CPC-3	F	1.4	1350	1	0.335	0.335
CPC-4	I	4.7	1370	1	0.371	0.371
CEC-1(x)	I	4.5		1	0.603	0.603
CPC-5	I-T	2.1	1360	1	0.347	0.347
CPC-6	I-T	2.2	1390	1	0.383	0.383
CGPHC-1	T, F	1.7	1410	0.298	0.213	0.064
CGPHC-2	T, F	1.7	1450	0.278	0.227	0.063
CGPHC-3	T, F	1.6	1450	0.296	0.233	0.069
CGPHC-4	T, F	3.2	1400	0.511	0.242	0.138
CGPHC-5	T, F	2.9	1390	0.634	0.281	0.178
CGPHC-6	T, F	2.1	1390	0.664	0.297	0.197
CGPHC-7	T, F	6.0	1390	0.866	0.276	0.239
CGPHC-8	T, F	7.3	1370	0.830	0.334	0.277
CGPHC-9	T, F	8.0	1360	0.845	0.354	0.303
CGPHC-10	I	4.4	1508	0.572	0.364	0.208
CGPHC-11	I	4.3	1446	0.797	0.344	0.274
CGPHC-12	I	4.0	1385	0.655	0.223	0.146
CGPHC-13	I-T	2.3	1560	0.409	0.374	0.153
CGPHC-14	I-T	2.8	1580	0.613	0.465	0.285

TABLE II Tensile characteristics

Coupons	Strength		Modulus		Failure strain	
	(MPa)	(%CS)[a]	(GPa)	(%CM)[b]	($mm\,m^{-1}$)	(%e_{CF})
CPC-1	859.6 ± 66.4	71.0	84.10 ± 0.7	100.1	10.23 ± 0.22	73.1
CPC-2	1039.4 ± 29.7	81.3	90.0 ± 1.8	88.8	11.43 ± 0.33	81.6
CGPHC-1	114.5 ± 13.8	51.9	20.2 ± 1.6	196.2	5.74 ± 1.69	54.76
CGPHC-2	113.2 ± 26.1	50.2	19.4 ± 3.8	90.2	5.28 ± 0.57	50.3
CGPHC-3	131.2 ± 24.2	55.2	23.6 ± 1.1	104.4	5.71 ± 0.85	54.4
CGPHC-4	173.4 ± 19.3	49.8	35.4 ± 3.7	110.5	5.00 ± 0.58	47.6
CGPHC-5	215.1 ± 32.1	50.4	37.2 ± 2.1	95.4	5.29 ± 0.94	50.4
CGPHC-6	245.3 ± 34.3	53.1	46.3 ± 3.6	109.2	5.72 ± 0.68	54.5
CGPHC-7	184.5 ± 22.8	35.6	48.5 ± 6.3	103.6	3.65 ± 0.14	34.8
CGPHC-8	232.1 ± 29.4	38.9	54.0 ± 0.8	98.9	4.14 ± 0.64	39.4
CGPHC-9	268.1 ± 25.0	41.4	60.1 ± 4.1	101.5	4.36 ± 0.07	41.5

[a] Calculated strength
[b] Calculated modulus



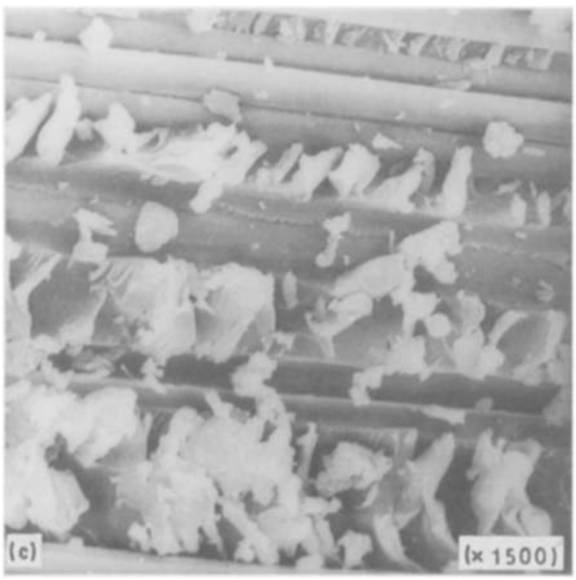


Figure 1 Delamination microfractographs (a) carbon fibre–epoxy resin [8]; (b) carbon fibre–polyester resin; (c) glass fibre–polyester resin.

two present carbon fibre layers were never one *vis-a-vis* other.

The transverse fractures in the two present carbon fibre layers do not coincide, this indicates the misalignment of fibre directions within them. It is evident that the direction of load application does not coincide with fibre direction in at least one of the two present layers. This was the reason for: stress concentration appearing in the coupon during testing; premature failure initiation and pronounced reduction of hybrid coupon strength.

The microscopic aspect of tensile failure in carbon/polyester composites, with an important contribution from axial fibre–matrix decohesions, is identical to that of carbon fibre reinforced layers in CGPHC. There is no doubt that the strength decrease of CPC and CGPHC in tensile testing is due to interface decohesion as a failure initiation mechanism.

3.2. Flexural properties

With thick coupons of hybrid composites (of higher carbon fibre content) flexure tested at lower span to depth ratio (16 and 12), E_f values smaller than ROM ones resulted (Table III). For hybrid composite thin

TABLE III Flexural characteristics

Coupons	Span to depth ratio	Strength		Modulus		Failure strain	
		(MPa)	(%CS)[a]	(GPa)	(%CM)[b]	($mm\,m^{-1}$)	(% e_{CF})
CPC-3	32	833.1 ± 58.3	71.6	80.6 ± 13.2	99.4	10.47 ± 0.97	74.8
CGPHC-1	32	293.6 ± 21.3	100.1	25.2 ± 2.1	120.0	12.49 ± 1.06	118.9
CGPHC-2	32	305.8 ± 58.6	100.5	24.5 ± 1.4	111.0	12.03 ± 1.43	114.6
CGPHC-3	32	296.2 ± 28.7	94.2	28.5 ± 1.4	126.1	10.75 ± 1.11	102.4
CGPHC-4	32	336.8 ± 23.2	89.4	33.2 ± 2.0	103.8	10.61 ± 0.99	101.0
CGPHC-5	32	424.7 ± 58.6	96.5	43.1 ± 4.3	110.5	10.97 ± 0.23	104.5
CGPHC-6	32	563.9 ± 64.3	120.5	52.9 ± 4.2	124.8	11.15 ± 0.98	106.2
CGPHC-7	16	371.0 ± 67.5	76.9	38.0 ± 8.1	81.2	10.02 ± 0.92	95.4
CGPHC-8	12	303.0 ± 57.6	54.3	46.4 ± 2.1	85.0	6.69 ± 1.48	63.7
CGPHC-9	12	260.4 ± 45.4	43.6	53.4 ± 5.1	90.2	5.10 ± 0.92	48.6

[a] Calculated strength
[b] Calculated modulus

coupons, submitted to flexure at a span to depth ratio equal to 32, experimental E_f values exceeded ROM values.

The reason for higher E_f^{exp} values of CGPHC-1 to CGPHC-6 coupons is due to the bigger contribution of outer carbon fibre reinforced layers, stiffness to modulus value of a sandwich beam as a whole [10].

Lower experimental values of flexural modulus for CGPHC-7–CGPHC-9 coupons are the consequence of a low span to depth ratio. It generated shear stresses, which caused additional displacement and thus yielded lower moduli. Low span to depth ratios are not sufficient and failure occurs in the outer fibre of the specimens, due to the bending moment only. As a consequence, the flexural strength and failure strain of these coupons also became low. Flexural strengths deduced from the tests on thin coupons (1.5–3.2 mm), with a span to depth ratio of 32 (Table III) for hybrid composites approach ROM values, while for CPC coupon represents only 72% of ROM value.

The decrease of σ_f value of CPC coupon has to be connected with fibre–matrix decohesion appearance, while the hybrid flexural strength values emerge from two tendencies: one, just mentioned, of decrease due to decohesion appearance and another one, of increase, due to enhancement of failure strain. Failure strain measured in flexural test on CGPHC coupons, with 35–70% volume fraction of glass mat reinforced core (CGPHC-1–CGPHC-6) exceeded that of carbon fibre (Table III). Such positive hybrid effect is known in the literature [11–14] from tension and flexure tests. In our flexure experiments, like in Manders and Bader's [14], it is bigger in coupons with higher glass mat to carbon fibre content ratio.

Explanations attributing failure strain enhancement of hybrid composites to residual thermal stresses [8], in our case, does not look reliable enough. Low curing temperature indicates that there must be other factors for the strain enhancement.

In flexural tests, coupons failed by crack initiation from side stresses at tension. Transverse crack propagated through the carbon fibre layer toward the glass mat reinforced core, where it ended near the midplane. In coupons of highest GM to CF content ratio (CGPHC-1–CGPHC-3) there are no longitudinal splits, neither cracking of upper layer stressed in compression. Both of these failures are present in coupons with lower GM to CF content ratio, especially in thick CGPHC-6–CGPHC-9 coupons.

Although, the macroscopic view of failure differs in coupons tested in tension and those tested in flexure tests, failure microfractographs of these two coupon groups are not essentially different. In both coupon groups the main failure micromechanisms manifested by known microstructure features are: debonding through fibre–matrix interfaces (carbon fibre–matrix and glass fibre–matrix), resin cleavage along fibres, resin cracking transverse to fibres, breakage and pull out of carbon fibres, delamination through interlayer surface. Carbon fibre–polyester resin interfaces of low bond strength, debonded easily without resin traces on fibre surfaces, while glass fibre–polyester resin decohesion micrographs show much resin collected on fibres and numerous branched figures in the resin between fibres (Fig. 1c).

3.3. Impact behaviour

In impact tests for all the examined composites, relatively high, [15–18], U_t values were determined (Table IV), when compared to those measured for carbon/epoxy composites.

To assess reasons for the difference between measured U_t values for carbon fibre composites, with polyester (CPC) and with epoxide resin (CEC), U_t values for these composites are calculated by

$$U_t^{cal} = \frac{1}{2}\frac{\sigma^2}{E}L \quad (1)$$

from corresponding composites values of tensile strength, σ and modulus, E, for span $L = 0.04$ m in Charpy test. By comparing U_t^{cal} values for CPC ($371.5\ kJ\,m^{-2}$) and CEC coupons ($329.2\ kJ\,m^{-2}$) one would expect higher experimental U_t values for carbon/polyester composite. However, established differences of U_t values for these two composites (Table V) cannot be explained by higher failure strain of carbon fibre in composites with polyester resin, or by the difference in toughness between polyester and epoxide resins. Comparative failure observations, as well as interlaminar shear strengths of polyester and epoxy resin based composites (Table IV), suggest that

TABLE IV Total impact fracture energy, U_t, and interlaminar shear strength values, τ_{ILS}

Coupons	λ (%$_v$)		$\frac{1-x}{x}$	U_t (kJ m^{-2})	U_t^{cor} (kJ m^{-2})	τ_{ILS}
	CF	GM				
CPC-4	37.1	0	0	184.7 ± 15.7	184.7 ± 15.7	32.8 ± 1.8
CEC [15]	60.3	0	0	84.3 ± 3.7	89.4 ± 3.9	107.5 ± 5.1
CGPHC-10	20.8	15.6	0.75	188.6 ± 29.0	203.3 ± 31.3	27.4 ± 0.8
CGPHC-11	27.4	7.0	0.25	171.1 ± 32.6	187.9 ± 35.8	27.4 ± 2.7
CGPHC-12	14.6	7.7	0.53	130.3 ± 41.2	160.3 ± 50.7	25.3 ± 3.5

TABLE V Virgin, σ_v, and residual (after impact) strength, σ_R

Coupons	λ (%$_v$)		$\frac{1-x}{x}$	σ_v	σ_R	
	CF	GM		(MPa)	(MPa)	(%σ_v)
CPC-5	34.7	0	0	859.6 ± 66.4	681.5 ± 40.5	79.3
CPC-6	38.3	0	0	891.3 ± 50.5	682.6 ± 38.7	76.6
CGPHC-13	15.3	22.2	1.44	459.0 ± 25.0	555.0 ± 34.7	94.7
CGPHC-14	28.5	18.0	0.63	555.0 ± 24.7	499.3 ± 22.2	90.0

the reason for the impact behaviour of these two composites is due to different interfacial fibre–matrix behaviour of the two resins in interaction with carbon fibres. Due to the low bond strength of CF–PR interface, in PR based composites, longitudinal delamination is a dominant mechanism of impact failure. Impact failure of ER based composite is less pronounced and less delaminations are present in it. Just as in the intensive delaminations of CF–PR based composites, the reasons for high measured U_t values have to be found.

To eliminate the thickness effect, the obtained U_t values are adjusted to the same thickness, using [16] experimental correlation

$$U_t^{cor} = U_{to}^{exp} \frac{d_o}{d} \quad (2)$$

Comparing U_t values of tested composites (Table IV) with approximatively equal reinforcement contents (36.0 ± 1.1%$_v$), the highest U_t value have coupons with highest GM to CF content ratio $[(1-x)/x]$, proving that the increase of GM content in hybrid combination with CF gives rise to the impact behaviour improvement. The lowest U_t value is measured in CGPHC-12 coupons with smallest reinforcement content.

The presence of interlayer surfaces in hybrid composite tested coupons of small dimensions, due to edge effects, induces interlaminar stresses and reduces short beam bend test strength, but obviously not the measured U_t value.

Improvement of impact behaviour with the presence of glass mat and the increase of its content, in the composite based on carbon fibre and polyester resin, can be seen from registered residual tensile strengths of coupons previously impacted by falling weight (Table V). Tensile strength reduction due to an impact of 10 J is smaller for hybrid than for composites reinforced with only carbon fibres, and residual strength expressed in percentages of virgin strength has a higher value for hybrid composites with bigger values of GM to CG content ratios.

4. Conclusions

Tensile moduli of tested composites agree with values calculated by the rule of mixture. Tensile failure strain and strength results, lower than possible values, indicating that during tensile loading a premature fracture of coupon, initiated by numerous carbon fibre-matrix interface decohesions, took place.

Due to the higher contribution of shell layers modulus to the flexural modulus of sandwich hybrid beam, measured values of the latter are higher than the ROM values, if the span to depth ratio in the test is high enough.

A positive hybrid effect, i.e. failure strain enhancement is stated in flexure tests on sandwich coupons with a high glass mat to carbon fibre content ratio.

Flexural strength of hybrid composites approaching ROM values emerge from two tendencies: one of decrease, due to decohesion appearance and another of increase, due to enhancement of failure strain.

Total impact fracture energy values of tested composites (CPC and CGPHC), are high in relation to that of carbon/epoxy coupons, and are due to intensive impact failure with carbon fibre – matrix decohesion as a dominant mechanism.

Improvement of impact behaviour with the presence of glass mat and with an increase of its content, in the composites based on carbon fibre and polyester resin, is manifested by U_t and after impact residual tensile strength values of tested composites.

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