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The effect of hydrostatic pressure on transverse strength of glass and carbon fibre–epoxy composites

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An attempt was made to measure indirectly the transverse tensile strengths of uniaxially aligned fibre pultrusions by the diametral compression of disc-shaped samples using concave loading anvils. Two types of composite were investigated, containing ~60% V_f of either type AS carbon fibres (CFRP) or S glass fibres (GRP), both in an epoxy resin matrix. Testing was carried out at atmospheric and under superposed hydrostatic pressures, $-H$, extending to 300 MPa. The resultant principal stresses at the disc centre were $\sigma_1 = \sigma_A + H$; $\sigma_2 = H$; $\sigma_3 = -3\sigma_A + H$, where $\sigma_A = 2P/\pi dt$ for a disc of diameter, d, and thickness, t, subjected to a load P. Deviations from linearity in the load–deflection response were detected throughout the pressure range at ~70% and ~90% of the failure load for CFRP and GRP, respectively, and these were associated with resin yielding. The pressure dependence of σ_A, approximately $-0.1 H$, was consistent with a two-parameter yielding criterion predicting hypothetical yield stresses in simple tension and compression of ~81 and −109 MPa, respectively, for both matrix materials. Irrespective of pressure *eventual* fractures took place along the loading diameter, but in the CFRP specimens tested under pressure initial cracks at the disc centres were at ~45° to the loading axis, i.e. on the plane of maximum shear stress. Fractographic observations were consistent with transverse failure taking place by fibre–matrix decohesion in GRP and by resin fracture in CFRP. Other than the atmospheric datum point for CFRP, the pressure dependence of σ_A for failure, σ_F, was also approximately $-0.1 H$. Of the various stress, strain and strain energy criteria for failure examined, only critical tensile strain was found consistent with this pressure dependence.

1. Introduction

The mechanical properties of resin matrix fibrous composites critically depend on the breaking stress of the bond between the fibre and the matrix [1], i.e. debonding or resin yielding. Hydrostatic pressure has been recognized for some time [1–3] as a valuable aid in investigating this problem, starting with the model experiments of Bowden [1] and latterly considered in papers by Piggott and co-workers [2, 3]. These researchers have concentrated on single fibre interactions; it is our thesis [4], however, that the relevant microstructural unit in uniaxially aligned continuous (e.g. pultruded) fibrous composites can be the fibre bundle. Tensile and compressive results on GRP and CFRP tested under superposed hydrostatic pressure have been presented [4–7] to support our model. Resin yielding in carbon–epoxy and debonding in glass–epoxy have been recognized as the relevant microstructural mechanisms for the fibrous bundles. Additionally we have tried to take account of bundle curvature [4–7] in formulating our theory.

Conventional composite tensile and compressive experiments do not measure the fibre–matrix bond strength and thus specialized testing procedures have been developed [8, 9]. To these we would like to add the diametral compression – sometimes referred to as indirect tensile [19] – test performed under superimposed hydrostatic pressure. Experiments are conducted on thin discs loaded in compression along a diameter. Such a test is most commonly used for geological core samples and is sometimes referred to as the Brazilian test [10–14], but has also been used to measure the through thickness strength of GRP pultrusions [19]. For point loading the maximum tensile stress [10] is

$$\sigma_T = \frac{2P}{\pi d t} \qquad (1)$$

where d is the disc diameter, t its thickness and P the compressive load. Concurrently a compressive stress distribution is produced, being minimum at the disc centre and equal to $-3\sigma_T$ perpendicular to the maximum principal tensile stress. Stresses at the centre of the disc are unaltered if the more commonly used distributed loading is used (Fig. 1).

The test is therefore biaxial and superposition of

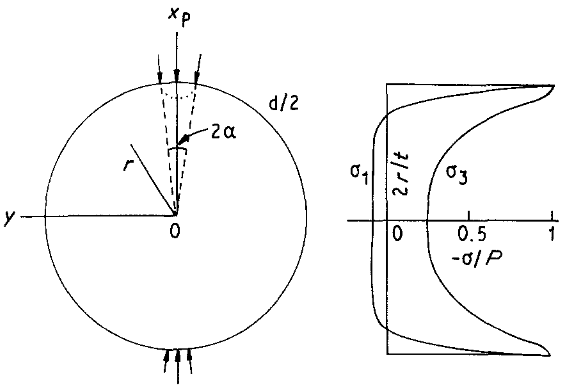

Figure 1 Diametral compression test with loading over 2 α (following Jaeger and Hoskins [10]). Note that at the disc centre $\sigma_3 = -3\sigma_1$ where $\sigma_1 = 2P/\pi dt$.

hydrostatic pressure, $-H$, makes the stress system

$$\sigma_1 = \sigma_T + H$$

$$\sigma_2 = H$$

$$\sigma_3 = -3\sigma_T + H$$

This test was chosen by us primarily because it makes possible investigation of composite rod material perpendicular to the fibre direction. Accordingly our specimens were simply cut transverse to the rod axis; the loading diameter was not important as fibres were perpendicular to all such axes (Fig. 2a). If the test were extended to plate material, sufficiently thick to cut a disc with thickness as its diameter, two testing geometries for interfacial strength become possible: with fibres parallel as well as perpendicular to the loading axis (Fig. 2). The third simple test geometry, fibres perpendicular to loading axis and parallel to the disc faces would measure, in principle, composite tensile strength under complex loading.

2. Experimental procedure

CFRP discs were obtained from nominally 6 mm diameter pultruded rods containing ~60% V_f type of AS carbon fibres in an epoxy resin matrix supplied by Courtaulds Ltd. Samples approximately 2.5 mm thick were cut using a Meyer and Burger diamond slitting machine. GRP discs of similar dimensions were cut from pultrusions containing ~60% V_f of S glass fibres in an epoxy matrix, the material being originally provided by AERE, Harwell. Both sets of samples were from the same batches of material that had been previously used to prepare tensile [6, 7] and compressive [4, 5] test specimens in earlier investigations. As previously [4, 7] testing was carried out on a universal Hedeby machine fitted with a Coleraine pressure cell, the compression rate being 0.1 mm min^{-1}. Experiments were carried out at pressures up to 300 MPa in Plexol, a synthetic diester.

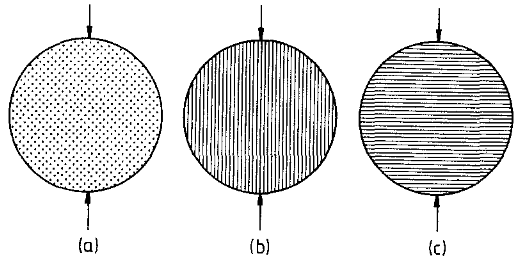

Figure 2 Possible geometries for the diametral compression testing of unidirectionally aligned fibrous composites applying tensile stress (a) and (b) transversely and (c) longitudinally to the fibre axis. Geometry (a) was used in this investigation.

Some samples were mounted in polyester resin, sectioned and polished parallel to the (transverse) tensile axis for observation by reflection optical microscopy. Specimen failure surfaces were examined by scanning electron microscopy.

3. Results

Diametral compression testing resulted in relatively linear load-displacement up to ~70% of the failure load for CFRP and, at approximately the same applied stress, ~90% of the failure load for GRP (Fig. 3). This deviation is associated with resin yielding. Failure in the disc centre was detected by a load drop; the testing machine was then reversed to unload the specimen. Samples were then found not to be broken into two pieces; cracking did not propagate to the circumference. In all the GRP specimens cracking was approximately along the loading diameter (Fig. 4a), as also in the CFRP samples tested at atmospheric pressure (Fig. 4b). Although crack growth was along the loading axis also in the CFRP specimens tested under pressure, initial cracking was approximately at 45° to the loading axis (Fig. 4c), i.e. on the plane of maximum shear stress. To examine the fracture surfaces, (some) specimens were subsequently split. In all cases, regardless of pressure, transverse failure in GRP was by debonding, the fibres on the failure surfaces were "clean" (e.g. Fig. 5a). In contrast, all the fibres on CFRP failure surfaces had epoxide adhering to them (e.g. Fig. 5b).

The critical applied stresses σ_A at the end of the linear displacement regime and σ_F for failure were evaluated using relation 1 and are presented in Figs 6 and 7 for the pressure range to 300 MPa, σ_2. σ_1 was thus $\sigma_A + H$ at yield and $\sigma_F + H$ at failure with σ_3 always compressive; thus the stressing system, except for a few tests below 100 MPa, was compressive. Nevertheless the failures were extensile – no significant fractographic differences could be detected between σ_1 of 25 (GRP) or 38 (CFRP) MPa on the one hand and −248 (GRP) or −229 (CFRP) MPa on the other.

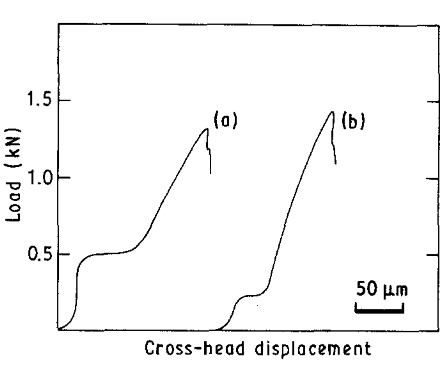

Figure 3 Load–displacement curves for the diametral compression testing of (a) GRP at 250 MPa superposed pressure and (b) CFRP at 50 MPa superposed pressure.

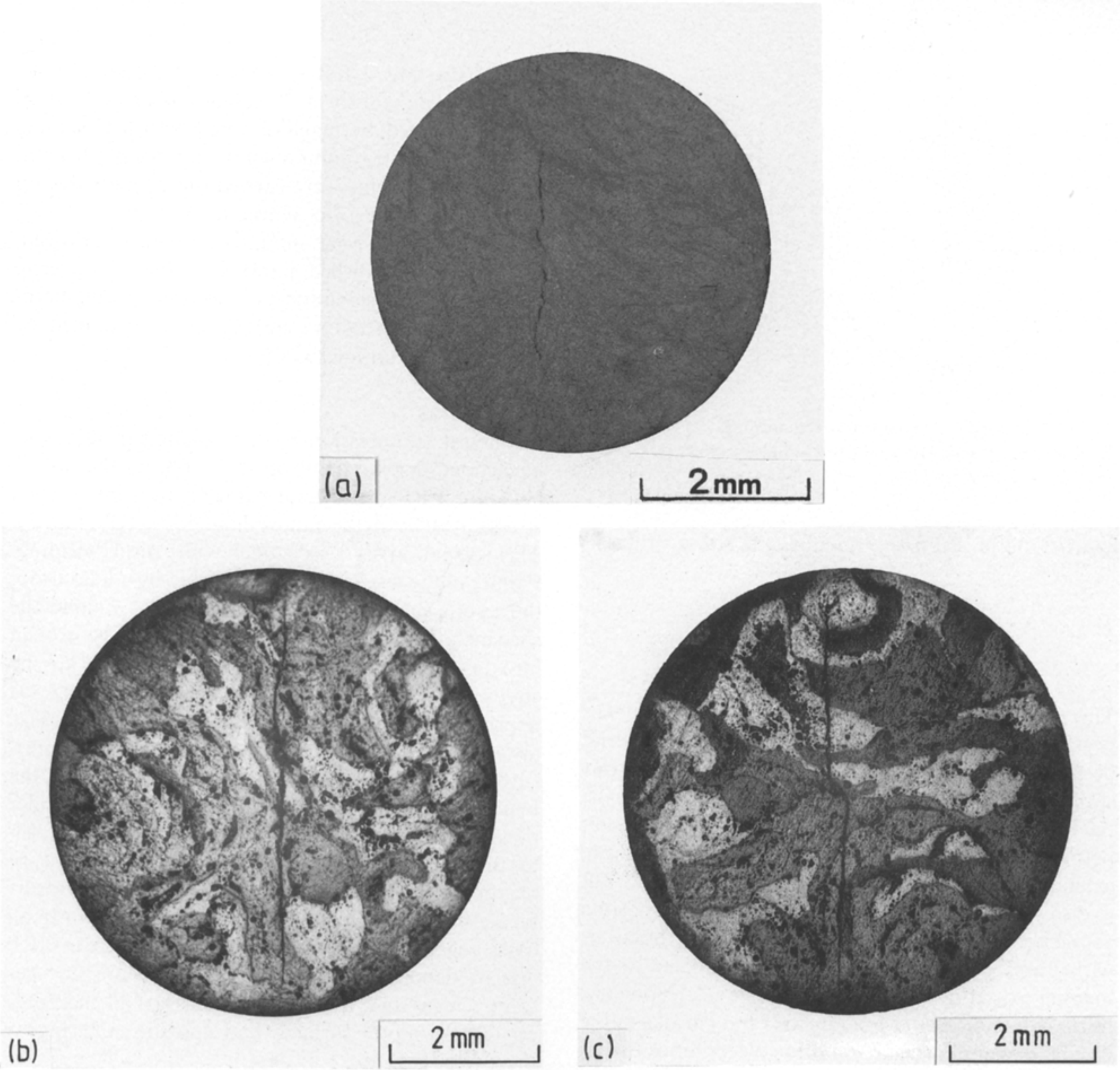

Figure 4 Optical micrographs of the paths of failure in (a) GRP and (b) CFRP discs tested at atmospheric pressure and (c) CFRP disc tested at 200 MPa superposed pressure-showing failure initiation on the plane of maximum shear stress. Note also that in all cases initiation and growth of fracture appeared *not* to have been influenced by microstructural features such as resin rich regions.

4. Discussion

It would appear from the load–deflection behaviour (Fig. 3) that resin yielding preceded failure in all GRP and CFRP specimens at all pressures and therefore the results must be compared to criteria of resin yielding under complex loading. Frequently, as for example in some epoxides, the rato of the compressive, σ_c, to the tensile, σ_t, yield stress is -1.33. Although three-parameter criteria are marginally superior in representing yielding under complex loading [15], it

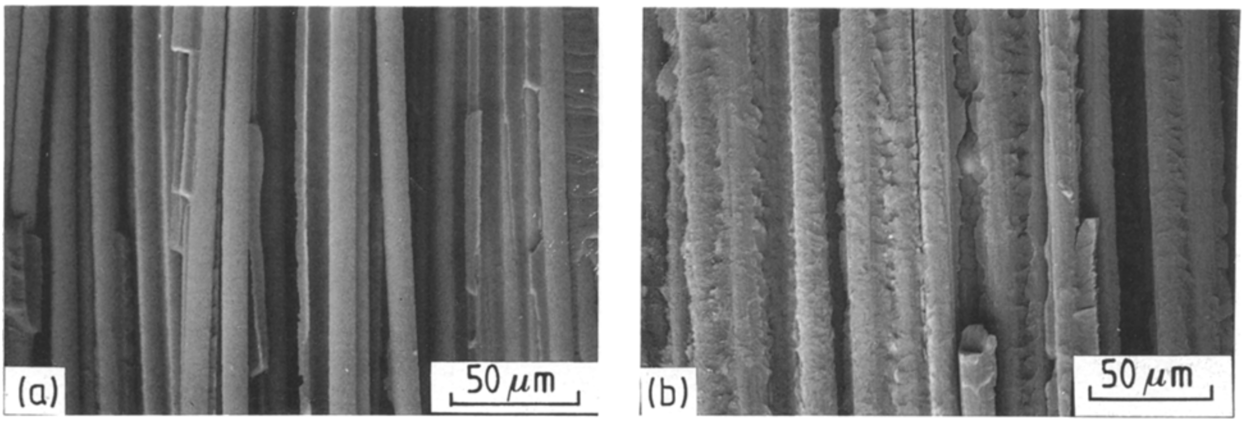

Figure 5 Failure surfaces of (a) GRP and (b) CFRP specimens tested in diametral compression illustrating the adherence of epoxy only to the carbon fibres.

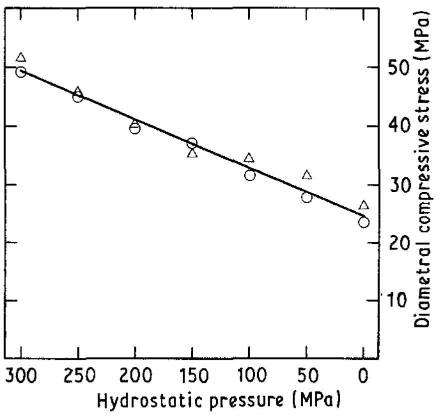

Figure 6 Indirect applied tensile stress, σ_A, at limit of proportionality for: ○ GRP, △ CFRP specimens as a function of superposed hydrostatic pressure, the slope being -0.083.

would be adequate to use a two-parameter pyramidal criterion, i.e.

$$a\sigma_1 + b\sigma_3 = 1 \qquad (2)$$

where $\sigma_t = 1/a$ and $\sigma_c = -1/b$ and which, for this stressing situation reduces to

$$a(\sigma_A + H) + b(-3\sigma_A + H) = 1$$
$$= (a - 3b)\sigma_A + (a + b)H \qquad (3)$$

i.e. a linear dependence of σ_A on H.

The plot of all the resin yielding data (Fig. 5) approximates to a linear H dependence with a slope of -0.082 and intercept of 25 MPa. These correspond to hypothetical yield stresses of 81 and -109 MPa in tension and compression, i.e. a ratio of -1.35, in accord with epoxy behaviour [15].

The critical stages of transverse tensile failure in these uniaxially aligned fibre–epoxy composites take place within the resin for CFRP and at the fibre (bundle)–matrix interfaces in GRP. We are, therefore, looking for pressure dependent fracture criteria of the resin for CFRP and interface fracture criteria for the GRP, as the two mechanism types were found to operate regardless of the hydrostatic pressure superposed. Recently Chua and Piggott [9] have suggested energy, rather than stress or strain, criteria for transverse tensile failure and accordingly strain ε, and energy, W, calculations were carried out. Literature values for the elastic constants of fibres and resins were used and any possible pressure dependences for these were neglected. $W = \frac{1}{2}(\sigma_1\varepsilon_1 + \sigma_2\varepsilon_2 + \sigma_3\varepsilon_3)$ increases with $-H$ as expected – since the hydrostatic component of W, $W(H)$, is obviously pressure dependent. It has, however, long been suggested [16] that when the hydrostatic component of stress, σ_H, is compressive, the relevant energy is deviatoric strain energy, $W(D)$. For $\sigma_H = \frac{1}{3}(\sigma_1 + \sigma_2 + \sigma_3)$ the relevant strains and $W(H)$ were evaluated and $W(D)$ calculated. The deviatoric strain energy was also seen to increase with $-H$ and thus energy criteria were discounted.

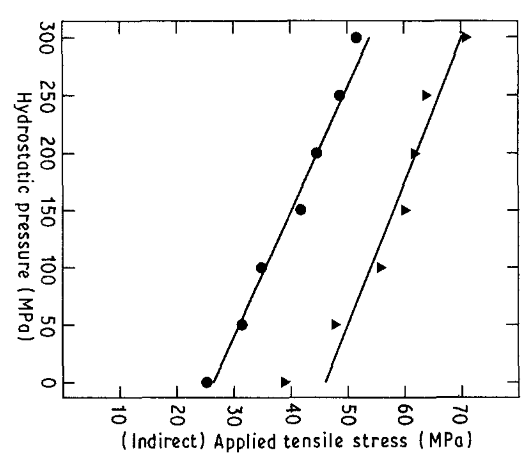

Figure 7 Indirect applied tensile stresses at fracture, σ_F, for GRP and CFRP specimens tested under superposed hydrostatic pressure. The best fit line for GRP has a slope of -0.091 and (ignoring the atmospheric pressure results) the slope is -0.081 for CFRP.

Accordingly stress and deviatoric stress criteria were then examined. It should be pointed out that a complex stress system, especially when extensile failure occurs when all the principal stresses, though unequal, are compressive, gives us an opportunity to search for a criterion relevant to a particular type of failure regardless of mode of loading. Thus, although for debonding, a constant tensile stress is the obvious candidate, it had to be discounted as in our system it became negative for GRP at 50 MPa superposed pressure. Noting that decohesion starts in a composite already under hydrostatic pressure it seemed reasonable to consider the maximum deviatoric tensile stress, $\sigma_D = \sigma_1 - \sigma_H$. For the biaxial stress system

$$\sigma_1 = \sigma_A + H, \quad \sigma_2 = H, \quad \sigma_3 = -3\sigma_A + H,$$
$$\text{so } \sigma_D = \tfrac{5}{3}\sigma_A$$

i.e. σ_A independent of H is postulated. Constant deviatoric strain requires also essentially pressure independent σ_A – so these two criteria had also to be discounted.

Although the stress system was entirely compressive at hydrostatic stresses above ~ 50 MPa, failures were extensile and therefore an attempt was made to evaluate strain. For elastic deformation

$$\varepsilon_1 = \frac{\sigma_1}{E_t} - \frac{\nu_{lt}\sigma_2}{E_l} - \frac{\nu_{tt}\sigma_3}{E_t} \qquad (4)$$

where E_l, E_t, ν_{lt} and ν_{tt} are the longitudinal and transverse Young's moduli and Poisson's ratios. In our experiments load–displacement beyond σ_A was not linear – but approximately so. Accordingly the stresses calculated from given strains will be overestimated and values of Poisson's ratio may appear too high.

With these reservations and assuming that for CFRP $E_l \approx 10E_t$, for GRP $E_l \simeq 5E_t$ and $\nu_{tt} \simeq 2\nu_{lt}$ [17, 18]

$$\varepsilon_1 \simeq \frac{\sigma_A + H}{E_t} - \frac{\nu_{lt}H}{10E_t} - \nu_{tt}\frac{(-3\sigma_A + H)}{E_t} \quad \text{for CFRP}$$

or

$$E_t\,\varepsilon_1 \simeq \sigma_A(1 + 3\nu_{tt}) + H(1 - 1.05\nu_{tt})$$

i.e.

$$\sigma_A = \frac{E_t\varepsilon_1}{1 + 3\nu_{tt}} - \frac{1 - 1.05\nu_{tt}}{1 + 3\nu_{tt}}H \quad \text{for CFRP} \qquad (5a)$$

and

$$\sigma_A \approx \frac{E_t \varepsilon_1}{1 + 3\nu_{tt}} - \frac{1 - 1.1\nu_{tt}}{1 + 3\nu_{tt}} H \quad \text{for GRP} \quad (5b)$$

implying a linear dependence of σ_A on H. This is in qualitative agreement (Fig. 7) with the failure data on GRP and CFRP respectively, except for the atmospheric CFRP datum point. It may be that a different criterion is applicable for atmospheric fracture of CFRP specimens; the failure initiation process was certainly different and apparently similar to that in GRP (Fig. 4).

Considering first the GRP data, it is to be noted that for a slope of -0.09, ν_{tt} evaluates to 0.66 and the transverse tensile strain prior to interfacial failure to ~1.5%. Assuming linear behaviour and the same ε_1 criterion, the atmospheric transverse adhesive strength (in GRP) evaluates to ~78 MPa, similar to the previously estimated tensile yield strength. For the CFRP pressure data, the slope is -0.081 and therefore $\nu_{tt} \approx 0.68$. The critical strain evaluates to ~2.4%, but this cannot be easily translated to a hypothetical atmospheric tensile strain and strength of the resin. Failure initiated on the plane of maximum shear stress may also be associated with a pressure dependent critical shear stress – in a manner not dissimilar to the yielding of polymers.

The atmospheric CFRP datum point (Fig. 7) was not consistent with the criterion relating to the data for CFRP under pressure. The failure initiation process, Fig. 4b, resembled that for GRP (Fig. 4a). The absolute value of σ_F was somewhat higher than for yield and also for failure in GRP. Using the observed value of σ_F (biaxial), for the same tensile strain, σ_F (uniaxial) evaluates to ~113 MPa, probably not unrealistic for epoxide as a thin layer. It is to be noted, however, that, whereas in all the biaxial/triaxial tests σ_H was negative, it is positive for uniaxial tension and a different failure criterion may operate (for GRP as well as CFRP). It may well be that then the resin behaviour is brittle and the upper bound for atmospheric transverse tensile strength is the tensile yield strength, ~80 MPa.

Using the yielding hypothesis, critical transverse tensile stresses were also evaluated using the total strain and deviatoric strain energy criteria. Differences between them for the cases of biaxial and simple tensile tests were small and the (hypothetical) transverse tensile strength worked out at ~94 MPa. Thus, as it is not possible to identify the atmospheric transverse failure criterion in CFRP, it is tentatively concluded that the value of the (probably) brittle fracture strength of the epoxide, as a thin layer in CFRP, is in the range 80 to 113 MPa.

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