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The Effect of Strain Rate on the Compressive Stress-Strain Properties of PEEK and Epoxy Carbon Fibre Composites

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Abstract. The dynamic compressive behaviour of two AS4 carbon fibre composite systems has been studied at room temperature at strain rates from about 10^{-3} s^{-1} to 10^3 s^{-1} . One system (APC2) had a thermoplastic PEEK matrix, while the other system (EC) had a thermoset epoxy resin matrix. Transverse unidirectional and transverse cross-ply fibre configurations were used for each system. Both configurations showed greater stiffness, linearity and strength at high rates than at low rates, but the high rate behaviour of the APC2 was more complex than that of the EC. The measured Young's modulus values were in good agreement with theoretical predictions.

Résumé. Le comportement sous pression dynamique de deux systèmes de AS4 fibre de carbon transversal a été étudié à température ambiante, entre des vitesses de déformation de 10^{-3} s^{-1} jusqu'à 10^3 s^{-1} . Un composite APC2 avait une matrice PEEK, tandis que l'autre EC avait une matrice de résine époxyde. A des vitesses de déformation élevées les deux composites ont montrés plus de rigidité, linéarité et résistance, mais le comportement du APC2 a vitesse de déformation élevée était plus compliqué que celui du EC. Les valeurs mesurées du module de Young étaient en bon accord avec les prédictions théoriques.

1. INTRODUCTION

Carbon fibre composites have found wide application as structural materials, especially in the aerospace industry [1]. The high strain rate behaviour of such materials is of great importance when there is impact loading. The present paper describes a comparative study of the transverse compressive behaviour of two continuous carbon-fibre systems at high and low strain-rates. One system (APC2) consists of Hercules Magnamite AS4 carbon fibres in a thermoplastic polyetheretherkeytone (PEEK) matrix, while the other system (EC) uses AS4 fibres in a thermoset epoxy resin matrix (type 934, code 89). The fibre volume fraction was 62% for each system. High strain rates were obtained using the split Hopkinson pressure bar (SHPB) technique in which strain rates covering the range of about 10^2 to 10^4 s^{-1} are achievable [2, 3].

2. EXPERIMENTAL METHODS

2.1 The Test Specimens

The test specimens were in the form of small solid cylinders with nominal dimensions of 8 mm diameter by 4 mm thickness cut from 32-ply composite plates. The specimen faces were flat to within $1 \mu\text{m}$ and parallel to about $10 \mu\text{m}$. Two types of transverse fibre configuration were used for each system: (a) transverse unidirectional (TU), in which all the fibres were aligned in the same direction, and (b) transverse cross-ply (TC) in which the fibres were at right angles in alternate plies. For each configuration the direction of the compressive loading was perpendicular to the specimen faces (i.e. to the fibre planes).

2.2 Compression Tests

All experiments were carried out at room temperature using two different types of test equipment: a conventional 50 kN screw-driven Instron machine for low strain rates of about 10^{-3} s^{-1} , and a split Hopkinson pressure bar system for high strain rates of about 10^3 s^{-1} .

2.2.1 The Split Hopkinson Pressure Bar System (SHPB)

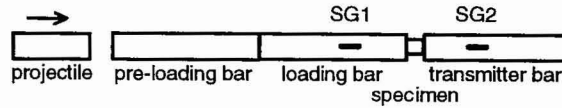


Figure 1: The three-bar SHPB system.

Figure 1 is a schematic diagram of the novel three-bar Loughborough system [4]. The specimen is sandwiched between two 1 m length, high-strength maraging steel bars (the loading and transmitter pressure bars). A pre-loading bar of the same diameter as the pressure bars (12.7 mm), but made of a lower strength steel, is positioned before the loading bar. A 25 cm length steel projectile is fired at the pre-loading bar at speeds up to 35 m s^{-1} from a gas gun. The pre-loading bar dampens the high frequency oscillations on the stress pulse created by the impact; a smooth pulse of amplitude up to 700 MPa and a duration of about $100 \mu\text{s}$ then passes into the actual loading bar. Part of this pulse is reflected from the specimen while the rest passes through into the transmitter bar.

The incident (loading), reflected and transmitted pulses are recorded by etched-foil resistance strain gauges SG1 and SG2, mounted axially on the surface of the pressure bars at 40 cm from the specimen. SG1 records the incident and reflected pulses without overlap, and the transmitted pulse reaches SG2 at the same time as the reflected pulse arrives at SG1. The strain gauges are connected via bridge circuits to a two-channel digital storage oscilloscope. A microcomputer system is used for analysis of the signals.

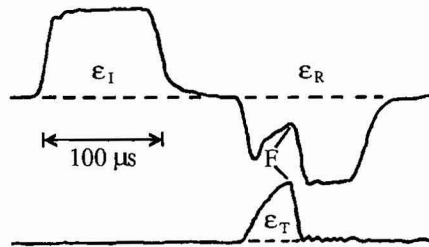


Figure 2: DSO traces for a unidirectional (TU) epoxy composite with a projectile impact speed of 11 m s^{-1} .

Figure 2 shows an oscilloscope display of the strain in the pressure bars as a function of time for a unidirectional (TU) epoxy composite with a projectile impact speed of 11 m s^{-1} . The upper trace indicates the strain pulses in the loading bar (as recorded by SG1). The compressive (positive) incident strain pulse ϵ_I is followed by the tensile (negative) reflected pulse ϵ_R . The lower trace shows the compressive (positive) transmitted strain pulse ϵ_T in the transmitter bar (as recorded by SG2). The occurrence of fracture (F) in the specimen is indicated by the simultaneous abrupt changes in the ϵ_R and ϵ_T pulses about $40 \mu\text{s}$ after they start.

The usual application of one-dimensional wave propagation theory to the SHPB system shows that the engineering values of the specimen stress σ_s and strain rate $\dot{\epsilon}_s$ are proportional to the transmitted and reflected strain pulses respectively. Integration of the reflected pulse then gives the engineering strain ϵ_s . Since $\dot{\epsilon}_s$ varies during the loading, the results in the present paper have been characterised by the average strain rate given by dividing ϵ_s at maximum stress by the time taken to reach that stress.

The engineering values above need to be converted to give the true, or natural, mechanical properties of the materials. By assuming the compressive strains and stresses are positive, then the true specimen strain ϵ is related to the engineering strain ϵ_s by $\epsilon = -\ln(1 - \epsilon_s)$, while the true specimen stress σ is related to the engineering stress σ_s by $\sigma = \sigma_s \exp(-2\nu\epsilon_s)$, where ν is the Poisson's ratio for the specimen. The appropriate values of ν are 0.35 and 0.02 for the TU and TC specimens, respectively [5]. All the stress and strain values presented in this paper are the true values.

3 RESULTS

3.1 SHPB Recordings

The SHPB oscilloscope traces indicate several distinct types of specimen response. As described above, the recording in Figure 2 for a unidirectional (TU) epoxy specimen showed that fracture occurred about $40 \mu\text{s}$ after the start of loading. The analysis of this record indicates a fracture stress of 330 MPa at a strain of 4 % and a strain rate of 940 s^{-1} .

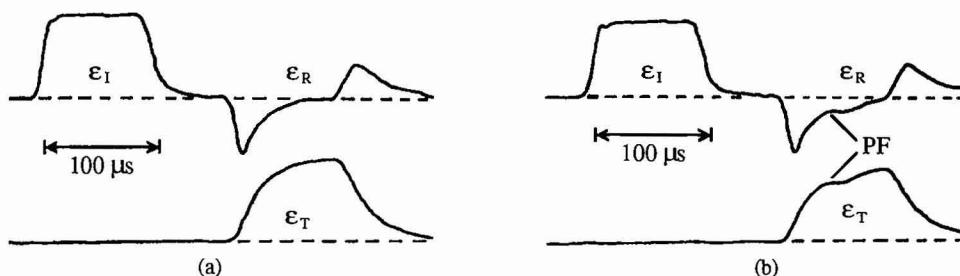


Figure 3: DSO traces for (a) cross-ply (TC) epoxy at projectile speed of 20 m s^{-1} , (b) cross-ply APC2 at speed of 19 m s^{-1} .

Other types of recording are shown in Figure 3, in which the strain amplifier gain is half that for Figure 2. Figure 3(a) shows traces for a cross-ply (TC) epoxy specimen with a projectile speed of 20 m s^{-1} . No fracture has occurred in this test. There is a continuous smooth increase in ϵ_T and a corresponding smooth decrease in ϵ_R until the loading pulse ϵ_I starts to decrease. Then ϵ_T decreases smoothly, indicating a reduction in specimen stress, and ϵ_R increases to values above the baseline, indicating elastic strain recovery. The maximum stress and strain are 1030 MPa and 8.5 % respectively, at a strain rate of 1450 s^{-1} . Figure 3(b) is for an APC2 cross-ply (TC) specimen with an impact speed of 19 m s^{-1} . The maximum specimen stress and strain are 880 MPa and 10.7 % respectively, at a strain rate of 1610 s^{-1} . There is a partial fracture (PF) after about $40 \mu\text{s}$, as indicated by the discontinuous change in ϵ_T and ϵ_R . However, the specimen does not completely fracture but eventually recovers. This partial fracture is a characteristic of the APC2 and does not occur with the epoxy, where fracture is always sudden and complete.

3.2 Stress-Strain Behaviour

3.2.1 Transverse Unidirectional Specimens (TU)

3.2.1.1 Low Strain Rates Figure 4(a) shows the stress-strain behaviour up to fracture for the epoxy (EC) and APC2 composites at strain rates of 10^{-3} s^{-1} using the Instron. Two sets of curves are plotted to indicate the extreme range of values obtained from at least four separate experiments for each material. The maximum experimental errors are $\pm 4 \text{ MPa}$ in the stress and $\pm 0.1 \%$ in the strain. There is clearly a high degree of consistency in these stress-strain properties. Both composites show linear behaviour up to a strain of about 1 %. The epoxy fractures at a higher flow stress than the APC2, but at a lower strain.

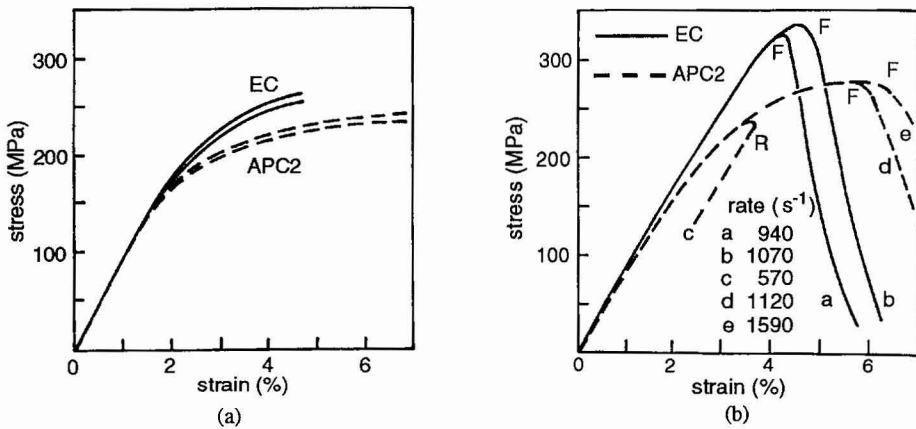


Figure 4: Stress-strain plots for TU composites: (a) 10^{-3} s^{-1} , and (b) high strain rates.

3.2.1.2 High Strain Rates Unlike the Instron tests, the strain rates for the SHPB method cannot be pre-selected since the rate is determined by the projectile impact speed and the relative mechanical impedance of the pressure bars and specimen. Also, because of wave propagation within the specimen, the conventional SHPB analysis can lead to an overestimate of the strain for strains less than about 0.5 %, i.e. in the region of the stress-strain curve where the Young's modulus would be measured. In the following SHPB analyses, a pulse displacement technique has been used to minimise this effect [6].

Figure 4(b) shows examples of stress-strain plots for the epoxy and APC2 composites, as a function of strain rate. The epoxy curves overlap and are reasonably linear up to fracture (F), the fracture stress being higher for the higher strain rate experiment. Curve (a) is the analysis of the experiment corresponding to Figure 2. The APC2 curve (c) shows that no fracture has occurred, and the specimen has recovered elastically (R). At the higher rates corresponding to curves (d) and (e), the specimens have fractured and, just as for the epoxy, the higher the strain rate the greater is the fracture stress.

3.2.2 Transverse Cross-Ply Specimens (TC)

3.2.2.1 Low Strain Rates Figure 5(a) shows stress-strain results up to fracture for the epoxy (EC) and APC2, at strain rates of 10^{-3} s^{-1} . Two sets of curves are plotted for each material to indicate the extreme range of values. The maximum experimental errors are $\pm 10 \text{ MPa}$ in the stress and $\pm 0.2 \%$ in the strain. The stress-strain behaviour is almost linear up to fracture for both materials. On average, the epoxy is stiffer than the APC2 but fractures at lower values of stress and strain.

3.2.2.2 High Strain Rates Figure 5(b) shows stress-strain plots for the epoxy and APC2, as a function of strain rate. The epoxy curve (b) is the analysis corresponding to Figure 3(a), while the APC2 curve (f) corresponds to Figure 3(b). The epoxy shows very consistent behaviour: all the results overlap within experimental error up to their respective values of maximum stress indicating that there is no measurable variation in the stiffness over this range of strain rate. There is elastic recovery in cases (a) and (b), whereas there is complete brittle fracture in cases (c) and (d). The APC2 results indicate a more complex behaviour. Curve (e) indicates elastic behaviour followed by elastic recovery. The higher strain rate curve (f) shows that there is a partial fracture followed an increase in stress and then elastic recovery, i.e. the specimen did not disintegrate. A further increase in the strain rate causes an initial partial fracture followed by a large increase in stress up the point of complete fracture (curve g). At the highest strain rate used, the partial fracture is delayed but then is very shortly followed by complete fracture (curve h).

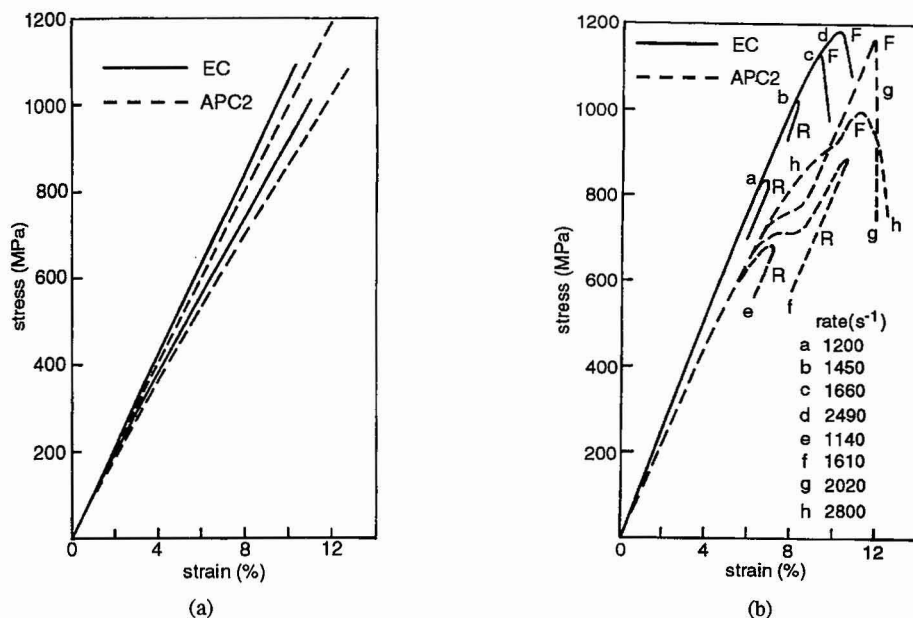


Figure 5: Stress-strain plots for TC composites: (a) 10^{-3} s^{-1} , and (b) high strain rates.

4. DISCUSSION

4.1 Stress-Strain Behaviour

Figure 4 shows that for the unidirectional (TU) composites the strain to fracture for the epoxy composite is virtually the same under low and high strain rate conditions, whereas the fracture strain is reduced at high rates for the PEEK composite. At the high strain rates, there is an increase in stiffness for both types of composite and a significant increase in the fracture stress, resulting in a greater fracture energy.

Figure 5 for the cross-ply (TC) materials indicates that the strain corresponding to complete fracture is approximately the same at low and high strain rates. The general shapes of the stress-strain plots for the epoxy are similar at high and low rates, i.e. the behaviour is virtually linear up to fracture. However, the stress at fracture is greater for the highest strain rates, giving a greater fracture energy. The significant difference between the APC2 plots at low and high strain rates indicates a more complex fracture process at high rates. At high strain rates there are partial fractures which occur at much lower stresses than the fracture stresses in the quasistatic tests. These partial fractures begin at higher stresses as the strain rate is increased. At the highest rates the fracture energy is comparable with the quasistatic values.

4.2 Modulus Variation

A theoretical estimate of the transverse Young's modulus of each composite has been made by applying the Halpin-Tsai equation [7], using published values of the quasistatic modulus of the matrix materials and of the transverse modulus of the carbon fibre, 4.0 GPa and 16.7 GPa respectively [5]. The predicted low strain rate modulus for both the epoxy and APC2 unidirectional composites is then 9.4 GPa, whereas it is 10.5 GPa for the cross-ply composites; both of these values are in excellent agreement with those measured in the present study (9.3 ± 0.5 GPa and 10.4 ± 0.5 GPa, respectively).

The measured modulus values show an increase at high strain rates. This increase must be attributable to the viscoelastic matrix since the modulus of the carbon fibres is not expected to change. A theoretical estimate has again been made using the Halpin-Tsai equation but with a higher value for the matrix

modulus appropriate to the high rate conditions. Such calculations show that for every 10 % increase in the matrix modulus there would be a 4 % increase in the modulus of the composite.

The strain rate sensitivity of several polymers was investigated by Parry et al [8] using a cylindrical wave propagation technique to obtain high rates. For example, they showed that as the strain rate was increased from 10^{-3} s^{-1} to 10^3 s^{-1} , there was a modulus increase of about 100 % for high density polyethylene but only 25 % for nylon. The higher the quasistatic modulus of the material, the smaller was the modulus increase at high strain rates. The quasistatic moduli of the epoxy and PEEK matrices are similar to that of nylon. If the increase in the matrix modulus is then assumed to be 25 % at high strain rates, then the increase in the composite modulus should be about 10 %, as explained above. The present experiments indicate an increase of about 5 % for the unidirectional composites and about 14 % for the cross-ply types. These results are in quite reasonable agreement with prediction. However, as mentioned above, because of wave propagation effects during the first few microseconds of loading, it is possible to overestimate the strain in the first 0.5 % of the recording and this can lead to an underestimate of the modulus. This is a more important consideration for the unidirectional composites since they start to become non-linear at much lower strains than the cross-ply.

The increase in the modulus values with strain rate for the epoxy composite, as reported in this paper, are not very different from those obtained by Daniel et al [9]. They conducted experiments, using a servohydraulic machine, on a similar type of transverse unidirectional epoxy composite, and found an increase in modulus of about 20 % when the strain rate was increased from about 10^{-4} s^{-1} to 5 s^{-1} .

5. CONCLUSIONS

The investigation has shown that the principal difference between the epoxy and the PEEK composites is the more linear, brittle behaviour of the epoxy type which leads to sudden fracture at lower levels of strain. For the cross-ply composites at high strain rates, the stress-strain behaviour of the PEEK type was more complex than that of the epoxy. At high strain rates, both types of material have increased Young's modulus values which are in reasonable agreement with theoretical prediction.

Acknowledgments

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