Failure modes of fibre reinforced composites: The effects of strain rate and fibre content

O. I. OKOLI
Famu-Fsu College of Engineering, 2525 Pottsdamer Street, Tallahassee, FL32310, USA
G. F. SMITH
Warwick Manufacturing Group, Advanced Technology Centre, University of Warwick, Coventry CV4 7AL, UK

The many aspects of high speed response of fibre reinforced composite materials have received the attention of a large number of investigators. Nevertheless, the understanding of the mechanisms governing failure under high speed loadings remain largely unknown. The effect of rate and fibre content on failure mechanisms was investigated by viewing fractured surfaces of tensile specimens using a scanning electron microscope (SEM). Tensile tests were conducted on a woven glass/epoxy laminate at increasing rates of strain. A second laminate (with random continuous glass reinforcement) was tested in tension at varying fibre volume fractions in order to ascertain the relationship between fibre content and failure mechanisms. The results suggest a brittle tensile failure in fibres of the woven laminate. In addition, the matrix was observed to play a greater role in the failure process as speed was increased, resulting in increased matrix damage and bunch fibre pull-out. The results also indicated that increasing the fibre volume fraction increased the likelihood of a matrix dominated failure mode.

1. Introduction

The number and complexity of fracture mechanisms exhibited by composite materials make the characterisation of their failure mode rather difficult [1]. In designing composites, the engineer is faced with the problem of defining failure with regards to the structure in question. Failure of a structural element may be said to have taken place when it ceases to perform satisfactorily. For instance, a bumper material may be considered as having failed at the point where it can no longer absorb energy on impact. There are cases where a very small deformation may constitute failure, whereas in others, only total fracture or delamination constitutes failure. In composite materials, internal material failure generally initiates long before any change in its macroscopic appearance or behaviour is observed. Fibre reinforced polymer composites are generally heterogeneous on a macroscopic scale. In addition, the individual lamina that constitute a laminated continuous fibre reinforced composite are anisotropic. Thus, unlike metallic materials, composites, have no single, similar self propagating crack. The following forms of internal material failure may be observed separately or jointly in the damage zone, and may result in component failure [2]: Fibre breakage, matrix microcracking, fibre separation (debonding), and delamination.

Generally, the microscopic material response changes well before the macroscopic failure. Thus, depending on the application or design procedure, the failure load could be considered as the load at which material behaviour deviates from linear stress-strain response, or as the load at fracture.

The use of composite materials in safety critical structural applications such as an automotive chassis cross-member leads to uneasiness since the mechanical response in crash applications is not well understood [3–5]. There is a lack of information on the dynamic mechanical behaviour of composite materials. This is due to the difficulty of designing high speed testing machines available to give information on the basic material behaviour rather than on the impact response of a structural element, and the complex interactions between the reinforcing fibres and the matrix [6].

The dynamic behaviour of composites may be better understood by first studying the individual rate dependencies of the constituent materials [6]. Majority of the reported data on polymeric matrix were obtained under compressive loadings. However, some results in tension have been reported [7, 8] and show that increasing strain rate leads to an increase in failure strength. Glass fibres have also been shown to exhibit rate dependence [7, 9]. Furthermore, it has been shown that the mechanical behaviour of composites not only depends on the constituents (fibre and matrix) properties, but also on the fibre/matrix interface [6]. In composites, the interfacial bond between the matrix and the fibre is an important factor influencing the mechanical properties and performance [10]. The interface is responsible for transmitting the load from the matrix to the fibres, which contribute the greater portion of the composite

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strength. As a result, the composite strength is affected by the interfacial condition. The interfacial condition controls the mode of propagation of micro-cracks at the fibre ends. When a strong bond exists between the fibres and the matrix, the cracks do not propagate along the length of the fibres. Consequently, the fibre reinforcement remains effective even after the fibre breaks at several points along its length. A strong bond is also essential for higher transverse strengths and for good environmental performance of composites.

The increasing use of fibre reinforced composites has prompted the need to ascertain the fibre contents necessary to provide the essential mechanical properties. In safety critical applications, it is therefore necessary to investigate the effect of increasing fibre content on the failure mode of the structure.

This work set out to investigate the effect of strain rate and fibre content on the failure modes of fibre reinforced composite materials.

2. Experimental

The apparatus and procedure used to obtain the tensile properties in the two laminates are described below.

The tensile tests were performed according to the method prescribed in ASTM D3039 [11]. Two materials were tested. The first was a 3 mm thick woven glass/epoxy Tufnol 10G/40* composite laminate. The composite had a fibre weight fraction of 70%. The specimens were cut 200 mm by 15 mm. Aluminium tabs 1 mm thick and 50 mm long were locally bonded on to the specimens with an adhesive, leaving a gauge section of 100 mm. Strain gauges were bonded on either side of the specimens to measure the axial and transverse strains on the material during testing. All data were logged on to a personal computer via a data logger. The low speed tensile tests were performed at 4 cross head velocities (1.7, 8.3, 17.0, and 83.0×10^{-2}) mm s^{-1}. Further tests were carried out at high speeds at 4 cross head velocities (10, 100, 1000, 2000 mm s^{-1}).

The second material were locally manufactured Warwick Manufacturing Group (WMG) random continuous glass/epoxy laminates with different fibre volume fractions (15.5, 20.7, 26.9, 38.0 and 41.2%). They were also tested as with the previous material, but at a singular cross head rate of 0.83 mm s^{-1}.

* Tufnol Birmingham, Birmingham B42 2TB, U.K.

3. Results and discussion

The failure modes of composite laminates used in this work will be discussed using photomicrographs.

3.1. Effects of strain rate on failure mode

Fig. 1 shows a magnified fracture surface of a Tufnol laminate tested in tension at a cross-head rate of 1.7×10^{-2} mm s^{-1}. The surface shows individual as well as group (bundle) fibre fracture. This may be attributed to translaminar tensile fracture [12].

The fracture surface is rough with protruding broken fibres. The fibre ends indicate a brittle failure mode. However, there are signs of matrix adhering to the fibres which indicate a good bond in the fibre-matrix interface. This brings about brittle failure in the fibres since interfacial bonding influences the intralamina strength, the interlaminar shear strength and the interlaminar tensile strength [13]. The observed pull-out of fibres is dependent on the bond strength and the load transfer mechanism from matrix to fibre.

Fig. 2 shows a fracture surface of a Tufnol laminate tested in tension at a cross-head rate of 10 mm s^{-1}, with fibre bunch pull-out and signs of matrix adhesion. It was pointed out earlier that fibre-matrix adhesion

Figure 1 Tufnol 10G/40 Laminate showing brittle failure with fibre breakage (× 541).

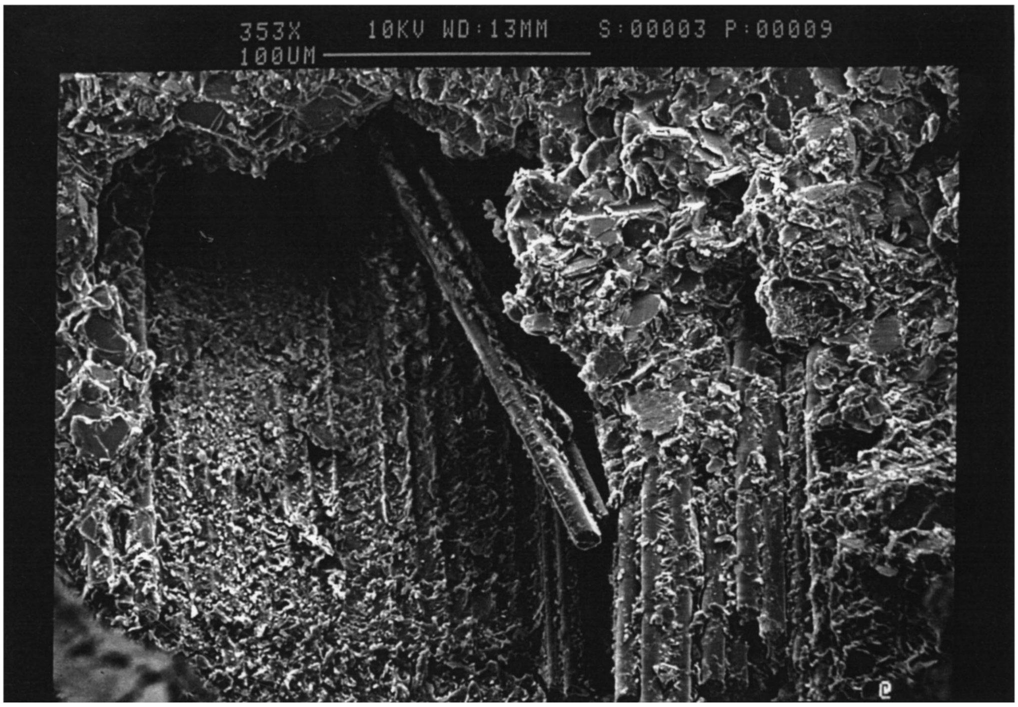

Figure 2 Tufnol 10G/40 Laminate showing fibre bunch pull-out with signs of fibre-matrix adhesion (× 353).

brings about brittle failure. Increased damage in the matrix brought about by a combination of the increased test speed and the interfacial bond strength can be observed, and results in the bunch fibre pull-out shown. This bunch fibre pull-out implies that at this loading rate, the fibre-matrix interfacial bond strength was exceeded before the tensile failure strength of the composite was attained. It has been demonstrated, that the tensile modulus of elasticity [9], and tensile strength [7], of glass fibres increases with strain rate. It then follows that the observed rate dependence of the failure strength follows from the increased strength of the glass fibres. In consequence [14, 15], the energy involved in the failure of the FRC specimens as determined from the area under the stress-strain curve, increases with strain rate.

As discussed previously, increasing test speed brings about an increase in fibre tensile strength and tensile modulus, such that the fibre-matrix interfacial bond is exceeded before the tensile failure strength of the composite. As these fibres are pulled out, matrix debonding occurs, resulting in cracking and disintegration of matrix observed in Fig. 3, which is a magnified view of the Tufnol laminate fracture surface tested at 2000 mm s^{-1}.

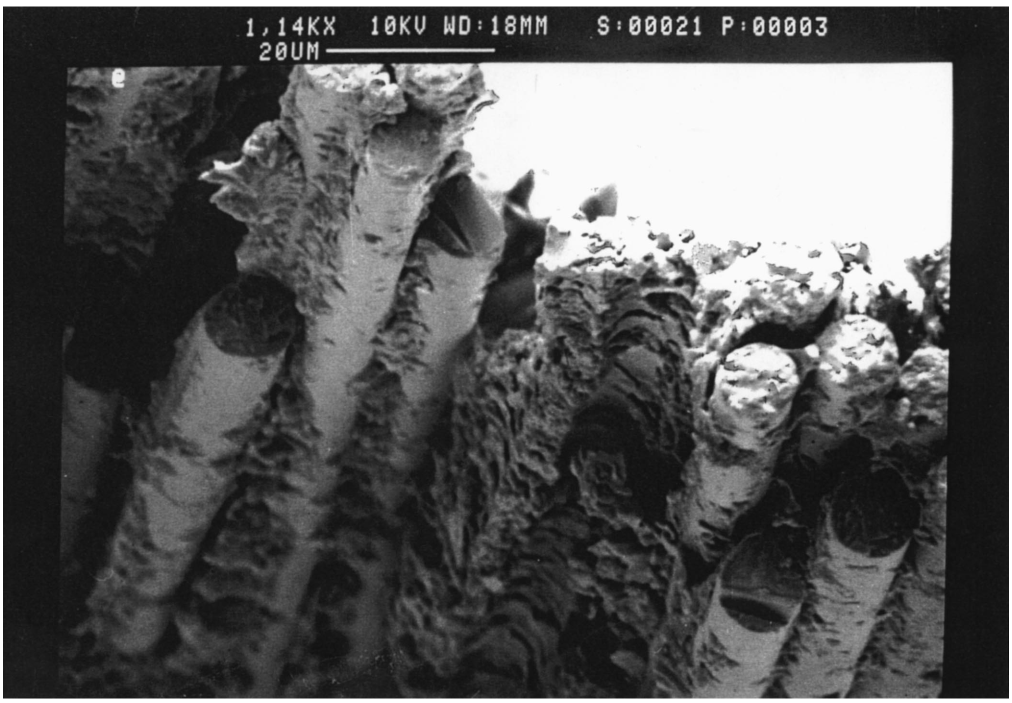

Figure 3 Tufnol 10G/40 Laminate showing exposed fibres indicating matrix delamination and debonding (× 1140).

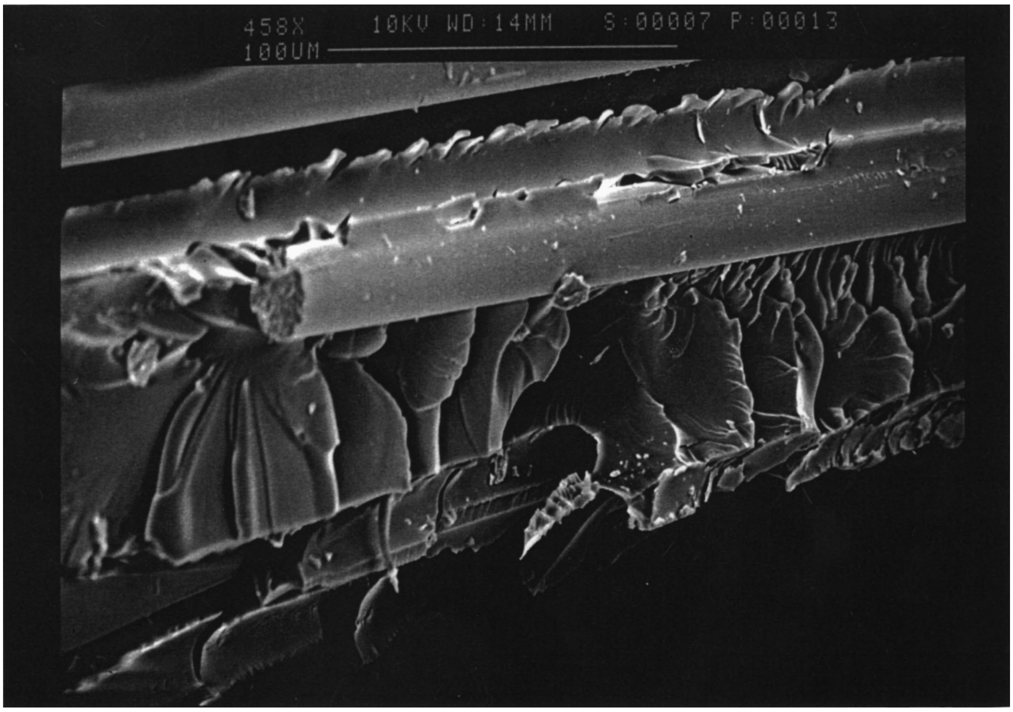

Figure 4 WMG Random Continuous Glass/Epoxy Laminates with 15.5% fibre volume fraction showing fibre pull-out with 'smooth' fibres, indicating fibre-matrix debonding (× 458).

Figure 5 WMG Random Continuous Glass/Epoxy Laminates with 20.7% fibre volume fraction showing delamination with some degree of fibre-matrix adhesion (× 428).

3.2. Effect of fibre volume fraction on failure mode

Fig. 4 shows a magnified fracture surface of a random continuous WMG laminate with 15.5% fibre volume fraction. The visible fibre shows no signs of matrix adhesion, and the matrix exhibits signs of fibre pull-out. The occurrence of fibre pull-out in the matrix indicates that the fibre-matrix bond strength varies across the surface. This implies a variation in the local load transfer mechanisms from matrix to fibre. The broken fibre tip failed in a brittle manner. River marks are also visible, showing the direction of crack propagation in the matrix.

Fig. 5 shows a fracture surface of a WMG laminate with 20.7% fibre volume fraction. Delamination of the matrix can be observed indicating the occurrence of matrix shear failure. The almost 'smooth' nature of the visible fibres suggest very little fibre-matrix interfacial bonding which provides for fibre-matrix debonding. Fig. 6 shows another section of the fracture surface of

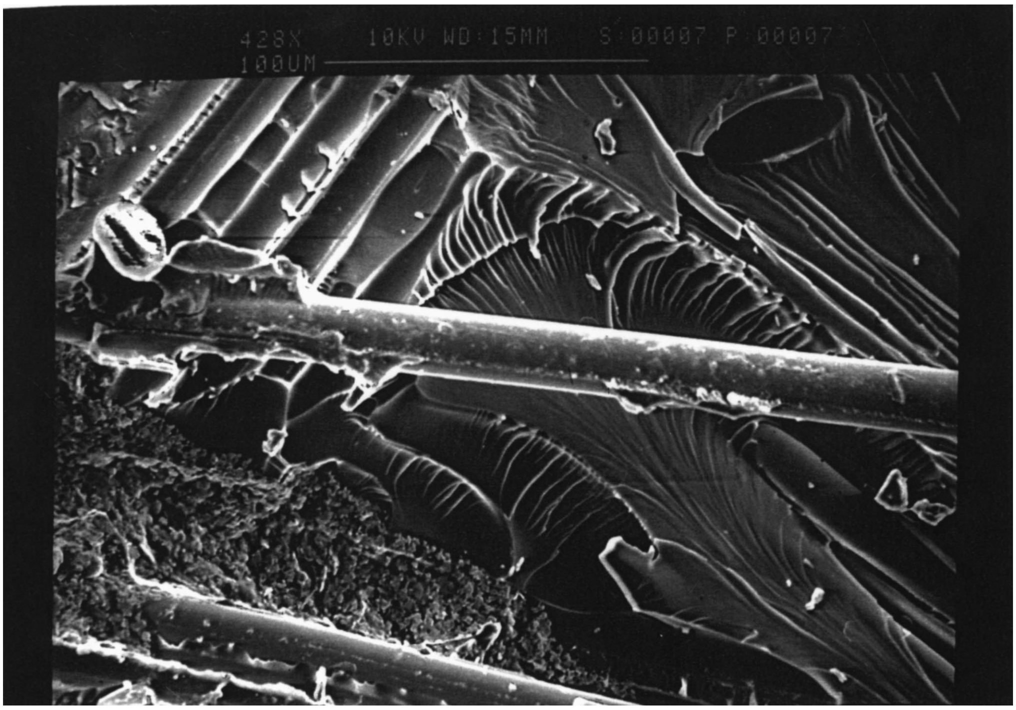

Figure 6 WMG Random Continuous Glass/Epoxy Laminates with 20.7% fibre volume fraction showing areas of fibre-matrix adhesion, fibre pull-out and fibre-matrix debonding (× 428).

the same laminate shown in Fig. 5. The matrix shows river marks, indicating the direction of crack propagation. The matrix also shows areas of fibre-matrix adhesion, fibre pull-out and fibre-matrix debonding. The long fibre pull-out indicates composite toughness. The fore going suggests that the laminate failed by fibre brittle failure and/or matrix failure.

Fig. 7 shows a resin rich layer of the fracture surface of a WMG laminate with 26.9% fibre volume fraction. The resin shows signs of bunch or group fibre pull-out. The protruding fibre, shows signs of a brittle failure. The SEM micrograph of the same laminate at lower magnification (Fig. 8) shows long fibre pull-out, indicating composite toughness. The laminate most likely failed in a matrix dominated mode due to the low fibre content and the resin rich areas which provide for easy matrix crack propagation.

Fracture surface of a WMG laminate with 38% fibre volume fraction is shown in Fig. 9. This clearly shows delamination of the matrix with signs of constituents

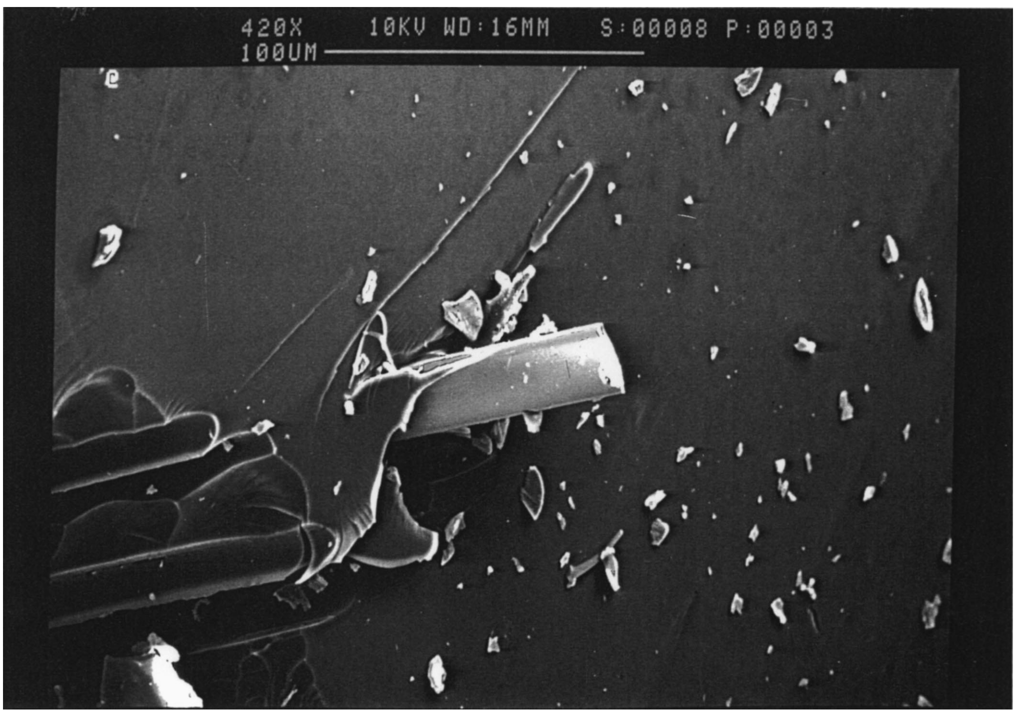

Figure 7 WMG Random Continuous Glass/Epoxy Laminates with 26.9% fibre volume fraction showing fibre pull-out from matrix (× 420).

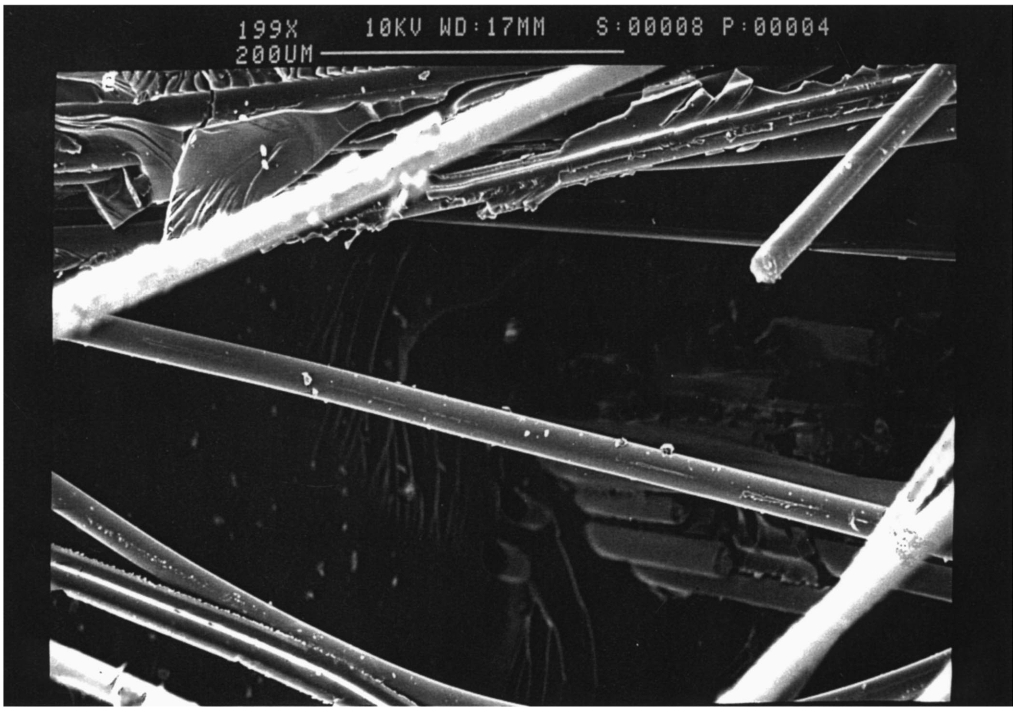

Figure 8 WMG Random Continuous Glass/Epoxy Laminates with 26.9% fibre volume fraction showing matrix with signs of fibre pull-out, and fibres showing no signs of matrix adhesion (× 199).

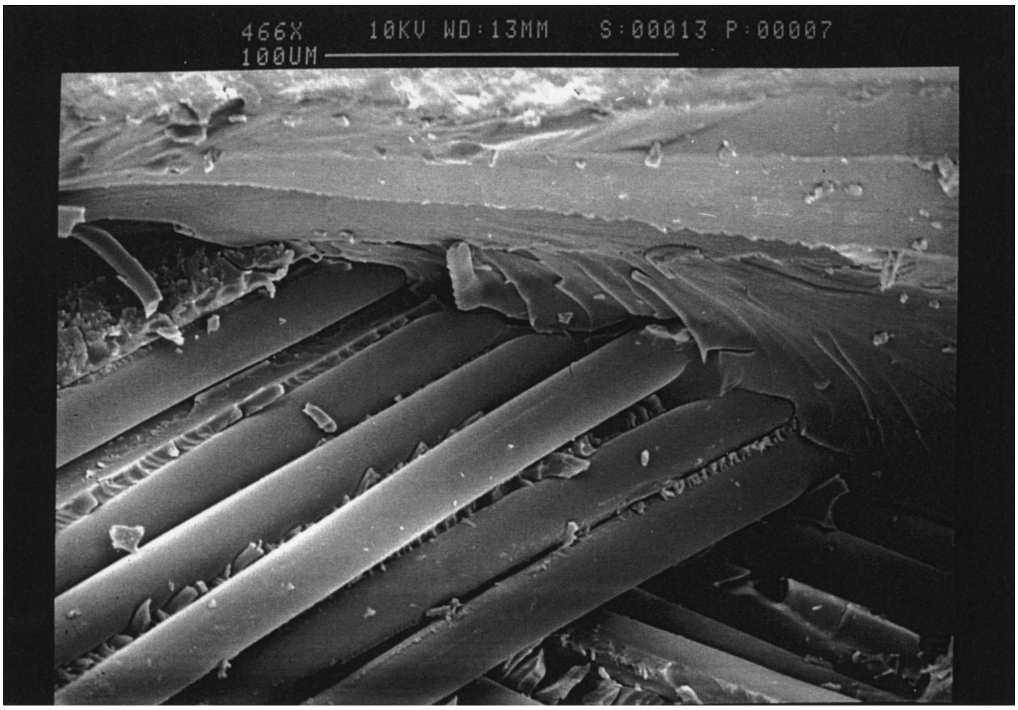

Figure 9 WMG Random Continuous Glass/Epoxy Laminates with 38% fibre volume fraction showing debonded fibres projecting from matrix (× 466).

debonding. The presence of river marks can be observed, indicating the direction of crack propagation through the matrix. The protruding fibres exhibit no signs of matrix adhesion implying fibre pull-out as can be observed in Fig. 10 which shows a different magnified view of the same laminate. This Figure exhibits distinct river marks, indicating extensive matrix damage. The foregoing suggest that the laminate has failed by fibre brittle failure and/or matrix shear failure.

Fig. 11 shows a magnified fracture surface of a WMG laminate with 41.2% fibre volume fraction. It was reported [2] that composites with fibre volume fractions (40–50%) commonly exhibit brittle failure with fibre pull-out. This trend can be observed in Fig. 11. The broken fibre ends are flat indicating brittle failure, and signs of fibre pull-out can be found in the matrix. Traces of matrix adhesion can be observed on the fibres. However, Fig. 12 shows a different section of the same fracture

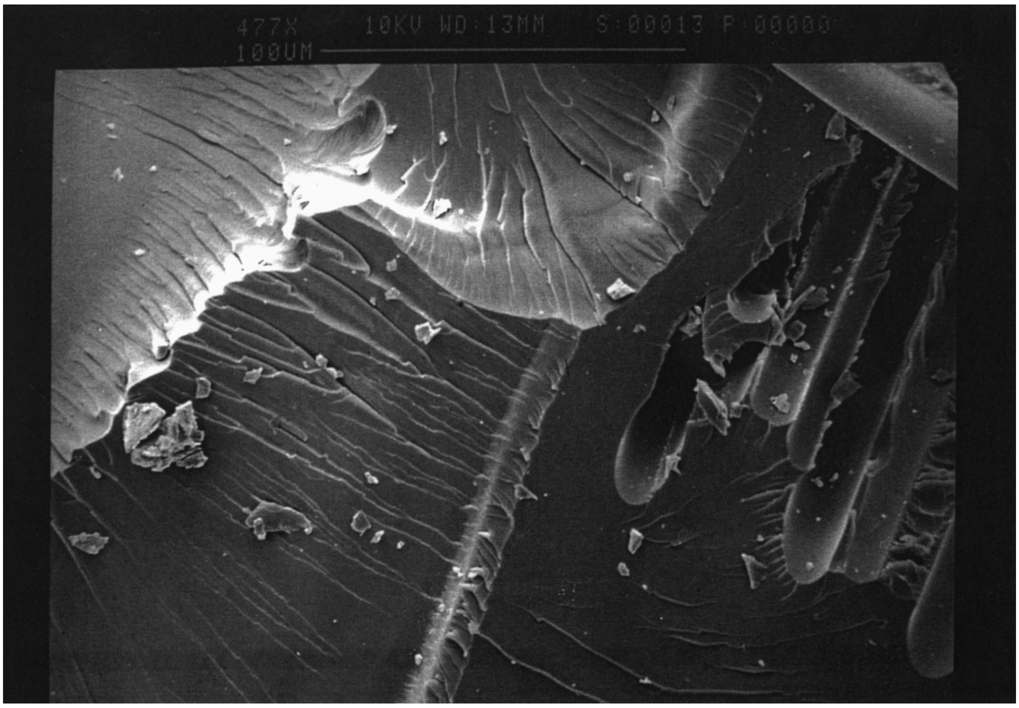

Figure 10 WMG Random Continuous Glass/Epoxy Laminates with 38% fibre volume fraction showing matrix with signs of fibre pull-out (× 477).

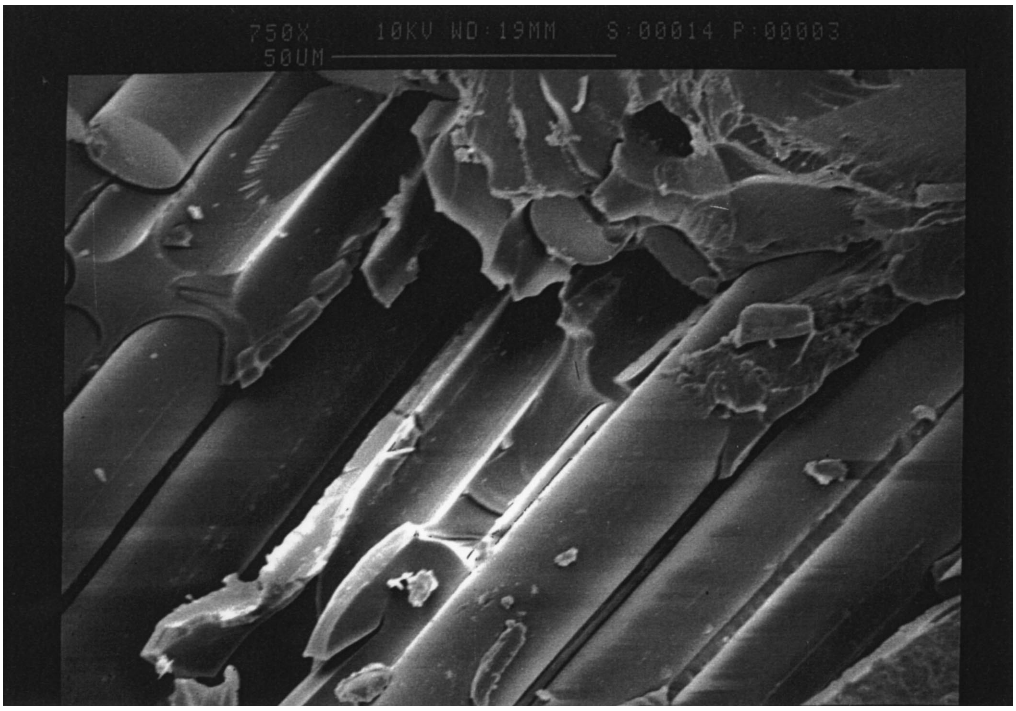

Figure 11 WMG Random Continuous Glass/Epoxy Laminates with 41.2% fibre volume fraction showing matrix exhibiting signs of fibre pull-out and fibres showing little matrix adhesion (× 750).

surface where matrix delamination and cracking can be observed with river marks, indicating the direction of crack propagation through the matrix. This suggests that the composite failed by fibre brittle failure with fibre pull-out and matrix failure.

4. Conclusions

The failure mode in the laminates evaluated, changes from fibre brittle failure with fibre pull out at quasi-static cross-head rates, to brittle failure with considerable matrix damage preceding final fracture as the cross-head rates increases from intermediate to high.

The random continuous (WMG) laminates exhibited a brittle failure mode with fibre pull-out, and in most cases, matrix shear failure. The only laminate that failed solely in a fibre dominated mode was the one with the lowest (15.5%) fibre volume fraction. This suggests that as fibre volume fraction is increased, the matrix plays a greater role in the failure process. That is, the likelihood of a matrix dominated failure mode increases.

Figure 12 WMG Random Continuous Glass/Epoxy Laminates with 41.2% fibre volume fraction showing crack running through debonded matrix (× 366).

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