INFLUENCE OF FIBRE CROSS-SECTIONAL ASPECT RATIO ON MECHANICAL PROPERTIES OF GLASS FIBRE/EPOXY COMPOSITES

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Summary: A comprehensive experimental study was conducted to identify effects of the fibre cross-sectional aspect ratio on mechanical properties as well as failure modes of glass-fibre/epoxy composites using fibres of three different cross-sectional shapes (round, peanut-shaped and oval). It was found that the fibres of peanut and oval cross-sectional shapes tend to align with the long axis of the cross section perpendicular to the direction of the applied pressure or in the plane of a composite laminate. As a result, many fibres were overlapped with each other, having large contact areas, which act as a path for longitudinal crack propagation. For the composites with fibres of large cross-sectional aspect ratios, a cumulative damage progression with a high failure strain was observed for the tensile and flexure tests in the longitudinal direction. However, the longitudinal tensile modulus and strength were nearly the same for the three composite systems. The transverse strength and strain-to-failure for transverse tensile and flexural tests showed the similar case as those in longitudinal tension and flexure, but the transverse moduli were reduced for composites with fibres of large aspect ratios. A low delamination resistance was also observed for such composite systems reinforced by glass fibres with large fibre cross-sectional aspect ratios, which is attributed to the effect of fibre over-lapping in these composites.

Keywords*:* Glass-fibre/epoxy composites, fibre cross-sectional aspect ratio, fibre-matrix interface, mechanical properties

INTRODUCTION

Most work in the development of composite materials considered fibre-matrix adhesion a necessary factor to ensure good mechanical properties. The sensitivity of the mechanical behaviour of composite materials to fibre-matrix adhesion has long been realised [1-4]. The fibre-matrix adhesion involves very complex physical and chemical mechanisms. The majority of previous efforts was concentrated on the chemical aspect of fibre-matrix adhesion through the use of surface treatments and coatings [5-8]. However, no much attention was paid to the physical aspect of fibre-matrix interaction. One of the most important physical aspects is the geometry of reinforcing fibres, which influences adhesion between fibre and matrix, stress transfer and local mechanisms of failure. In addition to chemical bonding, fibre-matrix bonding strength in shear is largely dependent on the roughness of the fibre surface and the fibre-matrix contact area. Recently glass fibres with deformed cross-sectional shapes were developed, and the aspect ratio of these glass fibres can be as great as four with peanut-shaped and oval cross sections [9]. Since the cross-sectional shapes of these fibres have been

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flattened greatly, the composites reinforced by such kinds of fibres may have some peculiar mechanical properties compared to those reinforced by conventional glass fibres.

MATERIALS

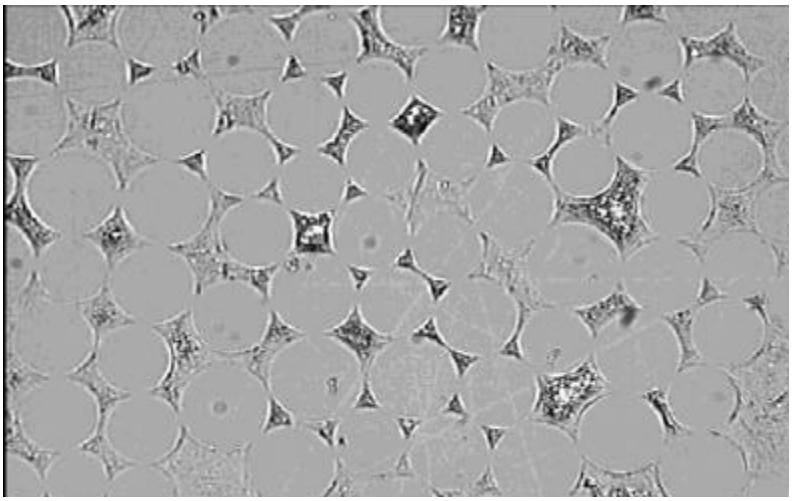
Three types of glass fibres with different cross-sectional aspect ratios were used in this study, KS161-454, KSH081-870 and HISS4-454 (Glass Fibre Research Laboratory, Nittobo, Japan). KS161-454 has a round cross-sectional shape, shown in Fig. 1a. The cross section of KSH081-870 is peanut-shaped with an aspect ratio about 2 and HISS4-454 has an oval cross-sectional shape with an aspect ratio about four (Figs. 1b, 1c). A standard DGEBA epoxy resin (Araldite-F, Ciba-Geigy, Australia) was chosen as the matrix material. The cured Araldite-F epoxy has a tensile modulus of 3.2 GPa and a tensile strength of 70 MPa; the strain-to-failure is about 4.5%. Piperidine was added as the hardener to the epoxy resin with a ratio of 5:100 wt% after degassing the epoxy at 100°C in a vacuum chamber. A commercial SOLVENT 101 epoxy thinner (15 wt%) was mixed with the resin to make its viscosity suitable for impregnating fibres. Composite prepreg sheets were fabricated from the three types of glass fibres and the epoxy resin using a filament-winding machine. The fibre tow was drawn through a resin bath and wound onto a cylindrical mandrel to form a single layer of prepreg. The prepreg was then cut into sheets with dimensions of 280 mm × 250 mm. The laminates were laid-up by hands according to different desired sequences. The composite laminates made from KS161-454, KSH081-870 and HISS4-454 glass fibres were designated as Round/Epoxy, E2/Epoxy, and E4/Epoxy respectively.

Curing of the composite laminates was conducted in a high performance computer-instrumented autoclave (American Autoclave Co.) using the vacuum bag technique. The curing cycle was 0.6 MPa for 16 hours at 120°C. The fibre volume fraction used in different tests was determined by the matrix ignition loss method (ASTM D2584-68). Table 1 shows tensile properties of glass fibres and fibre volume fractions of different composite systems. Optical photographs of the transverse cross section for unidirectional composite laminates are shown in Fig.1.

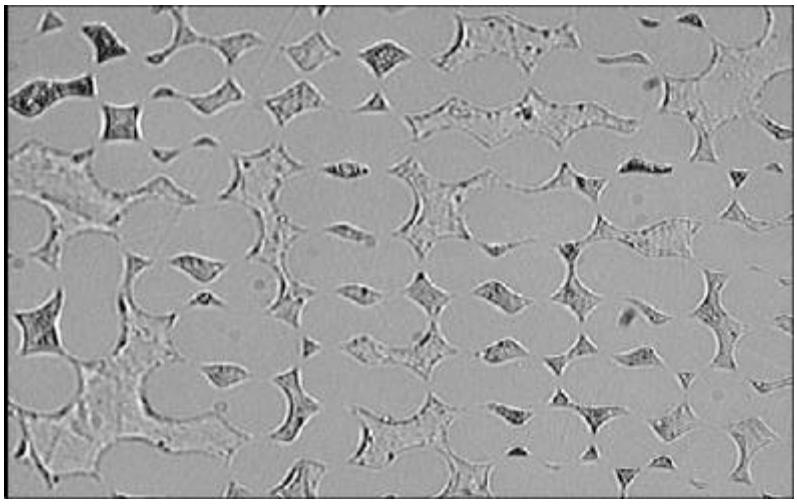
Table 1 Properties of glass fibres and fibre volume fraction of different composite systems

	Average cross-sectional shapes	Fibre cross-sectional aspect ratio	Tensile strength of fibres*, [GPa]	Tensile modulus of fibres*, [GPa]	Composite fibre volume fraction, (%)
KS161-454 (Round/Epoxy)	Round	1	1.93±0.43**	74.0±4.2	69.2±0.3
KSH081-870 (E2/Epoxy)	Peanut-shaped	2	2.07±0.40	77.0±4.5	68.2±1.4
HISS4-454 (E4/Epoxy)	Oval	4	2.07±0.56	75.8±4.1	69.3±0.5

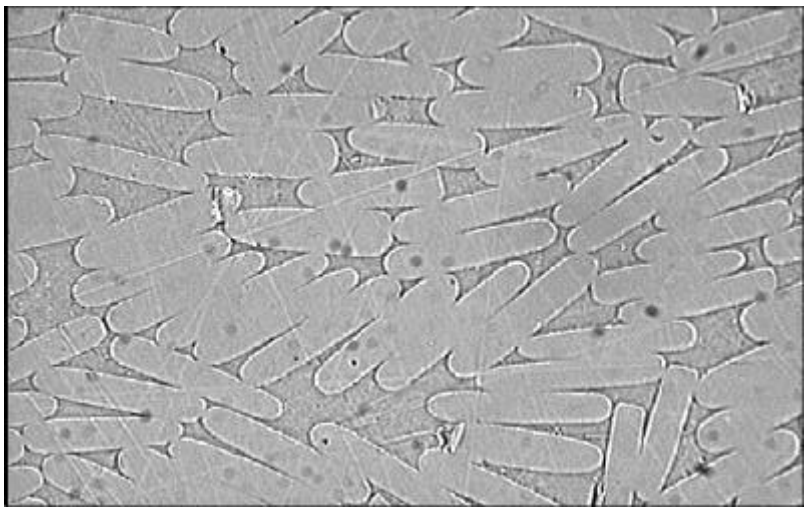
* Measured at a gauge length of 30 mm.
** Standard deviation



(a) Round/Epoxy



(b) E2/Epoxy



(c) E4/Epoxy

Fig.1 Transverse cross section of unidirectional composite laminates showing fibre cross-sectional shapes and fibre alignments in composites

EXPERIMENTAL

The mechanical characterisations of the composites were conducted by longitudinal (0°) and transverse (90°) tension (ASTM D-3039), three-point flexure (ASTM D-790), double cantilever beam (DCB), and end notched flexure (ENF) tests on an Instron 5567 universal testing machine. The crosshead speed for tensile tests was 1 mm/min and an extensometer of a gauge length of 50 mm was used to measure the axial strain. Three-point flexure tests were conducted with a crosshead speed of 2.7 mm/min and the deflection at the mid-span of the specimen was determined from the crosshead displacement. Since the glass/epoxy composites fabricated in this study were quite flexible, a supporting span of 40 mm was adopted for all the three-point flexure tests to ensure the flexural failure of the specimens at the mid-span without excessive deflection.

Mode I and Mode II interlaminar fracture toughness were evaluated using the double cantilever beam (DCB) and end notched flexure16 (ENF) test methods, respectively. A heat-resistant polyimide film of 12.3 μm in thickness was included in the mid-plane of the composite laminates along one edge during hand lay-up to produce a film-induced-crack for DCB and ENF tests. Aluminium loading blocks were bonded on the pre-cracked end of DCB specimens to allow unrestrained rotation during the test. The crack opening displacement (COD) in the DCB specimens was measured in terms of the crosshead displacement. The crack propagation lengths were monitored visually using a travelling microscope with regards to the corresponding COD and the applied load. A crosshead speed of 2 mm/min was used for DCB tests. A high resolution scanning electronic microscope (SEM) was used to examine the post-failure surface of specimens to identify the failure modes in different composite systems.

RESULTS AND DISCUSSION

1. Longitudinal tension and flexure

Typical stress-strain curves are shown in Fig. 2 for longitudinal tensile tests of the three composite systems. The longitudinal flexural tests showed the similar stress-strain curves. A comparison between the longitudinal tensile and flexural properties is shown in Fig. 3. The tensile moduli are nearly the same for all the three composite systems. The values of tensile strength of the three composite systems are also nearly the same, though the fibre breakage

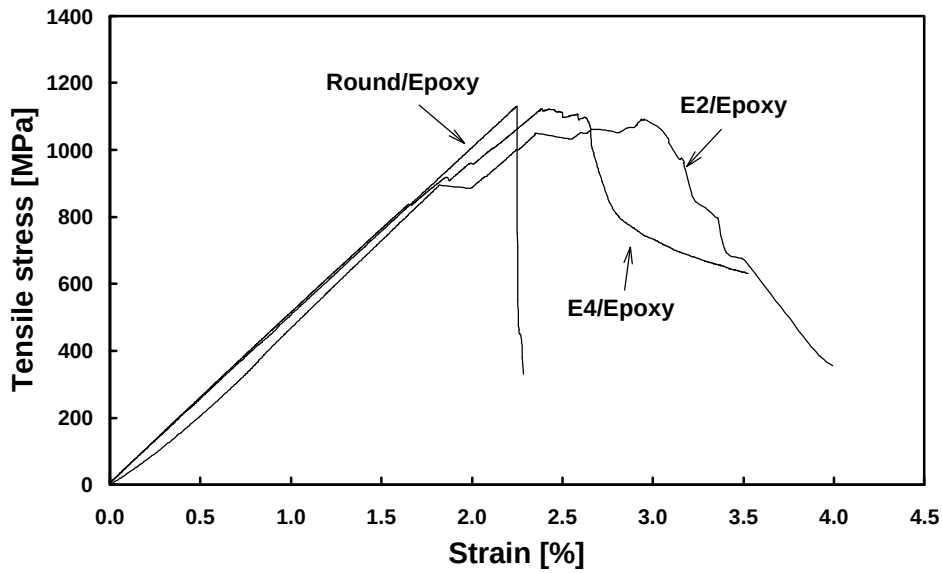
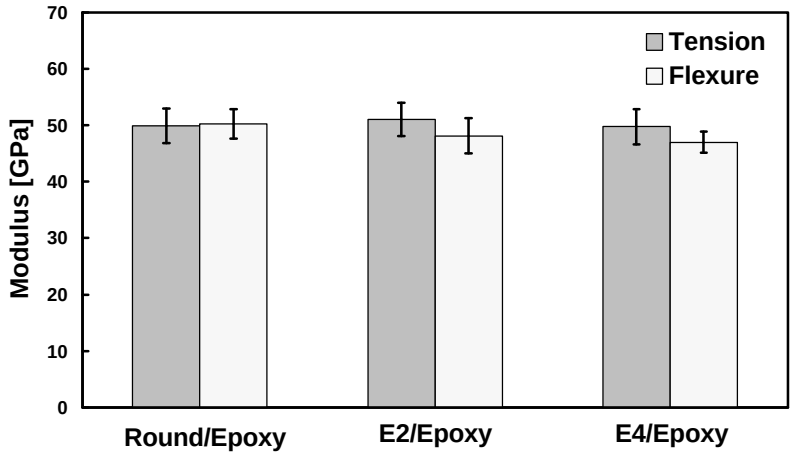
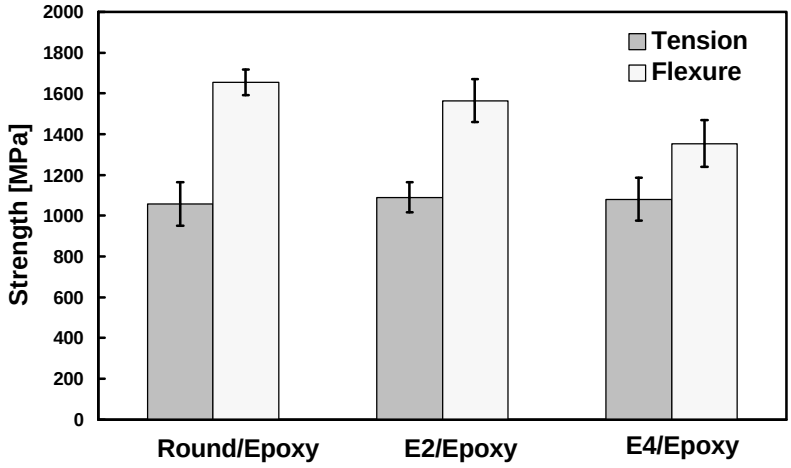


Fig.2 Typical stress-strain curves for longitudinal tension of the three composite systems

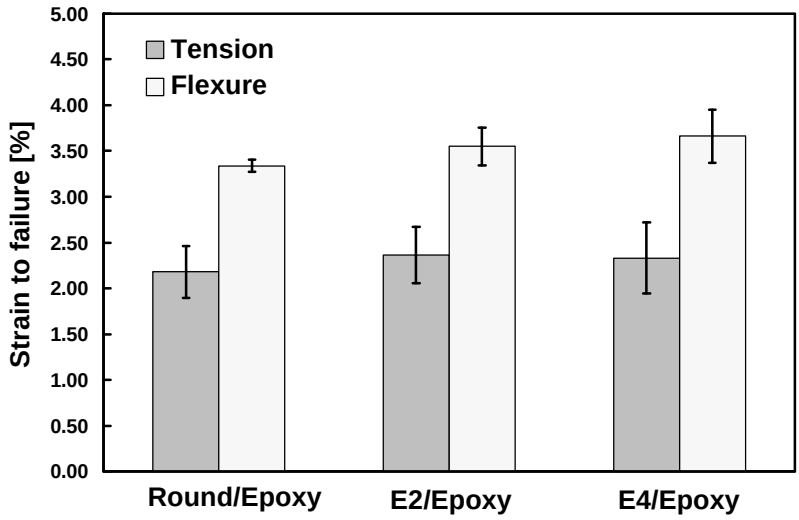
occurred for E2/Epoxy and E4/Epoxy before the peak stress was reached. Consequently, the values of the strain-to-failure were slightly increased for E2/Epoxy and E4/Epoxy.



(a) Modulus



(b) Strength



(c) Strain-to failure

Fig. 3 Comparison between longitudinal tensile and flexural properties of three types of glass fibre/epoxy composites

The failure behaviour of E2/Epoxy and E4/Epoxy tensile specimens was different from that of Round/Epoxy specimens. For the Round/Epoxy system, when the applied stress reaches the maximum, fibre breakage appears and the failure of the specimen happens suddenly, followed by the stress decrease abruptly to zero. However, the failure of the E2/Epoxy and E4/Epoxy tensile specimens undergoes a cumulative damage progression process. When the breakage of some fibres occurs, the remaining fibres still withhold some load, followed by subsequent breakage of more fibres.

For the three composite systems studied in this work, the reinforcing fibres have the almost identical tensile properties, differing only in their cross-sectional shapes. The tensile specimens of the composites also have the similar fibre volume fractions (Table 1). However, microstructures of the composites are quite different from each other. When the fibre cross-sectional shape is round, the epoxy resin can easily impregnate the fibres and make the fibres in the composite have less contact areas with each other (Fig.1a). However, for E2/Epoxy and E4/Epoxy, the fibres have the preferred alignment because of the fibre rotation during fabrication of the prepreg and composite laminates. In the processes of making prepreg and curing composites, the pressure is applied perpendicularly onto the plane of prepreg or laminates, and the fibres in the prepreg or laminates will rotate in the liquid resin to some extent due to the resin transverse flow, so that the long axis of the fibre cross section tends to be perpendicular to the direction of the applied pressure. As a result, there are many fibres overlapped with each other with large contact areas as shown in Fig. 1b and 1c. In such areas the matrix resin is too thin to play the role for stress transfer, so that these areas become weak bonding places.

2. Transverse tension and flexure

Typical transversal tensile stress-strain curves for three types of glass fibre/epoxy composites are shown in Fig. 4. The transverse flexural stress-strain curves are similar with those of the transverse tension. A comparison of transversal tensile and flexural properties of three types of glass fibre/epoxy composites is presented in Fig. 5.

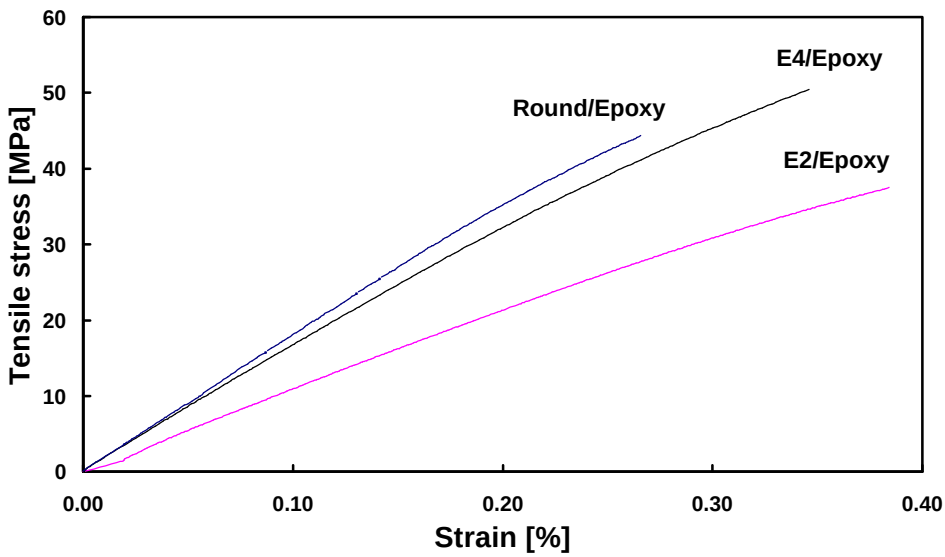
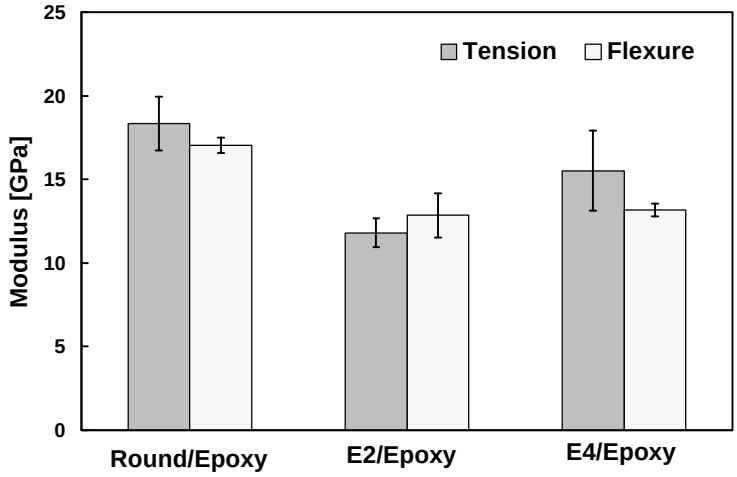
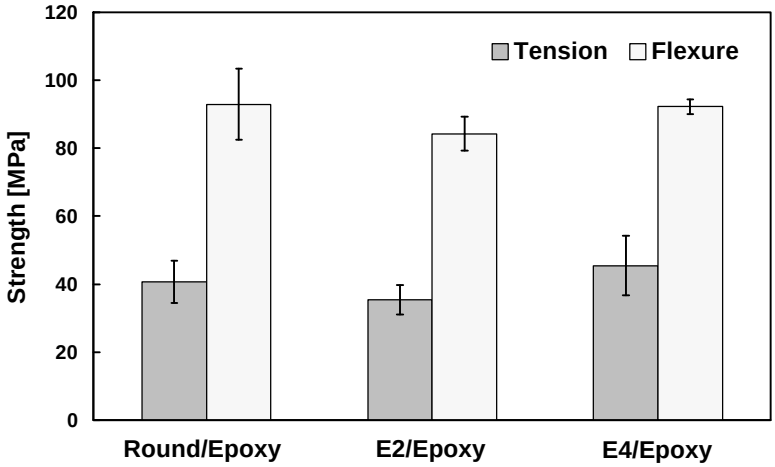


Fig. 4 Typical transversal tensile stress-strain curves for three types of glass fibre/epoxy composites

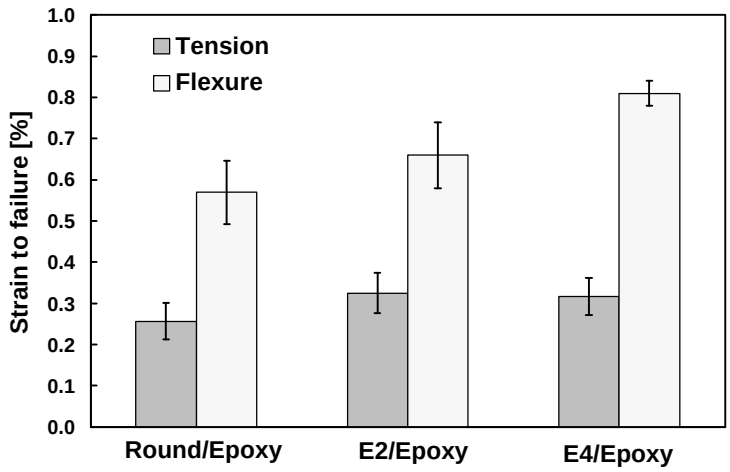
Similar to the longitudinal tension and flexure, the differences in transverse tensile and flexure strengths are marginal among the three composite systems. The strains-to-failure for E2/Epoxy and E4/Epoxy are higher than that of Round/Epoxy, while the transverse tensile and flexural moduli for E2/Epoxy and E4/Epoxy are lower than that of Round/Epoxy.



(a) Modulus



(b) Strength



(c) Strain-to-failure

Fig. 5 Comparison of transversal tensile and flexural properties of three types of glass fibre/epoxy composites

3. Mode I and Mode II interlaminar fracture toughness

Two values of Mode I interlaminar fracture toughness were defined, namely $G_{IC}(VIS)$, which is G_{IC} relative to the point when the crack was observed visually to move from the pre-crack tip, and $G_{IC}(PROP)$, which corresponds to the plateau value of the R-cures. Two delamination initiating states were adopted to evaluate Mode II interlaminar fracture toughness, i.e. by film-induced crack and propagated pre-crack produced by ENF tests with the insert film. Mode I and Mode II interlaminar fracture toughness for three composite systems are presented in Fig. 6 and Fig. 7 respectively.

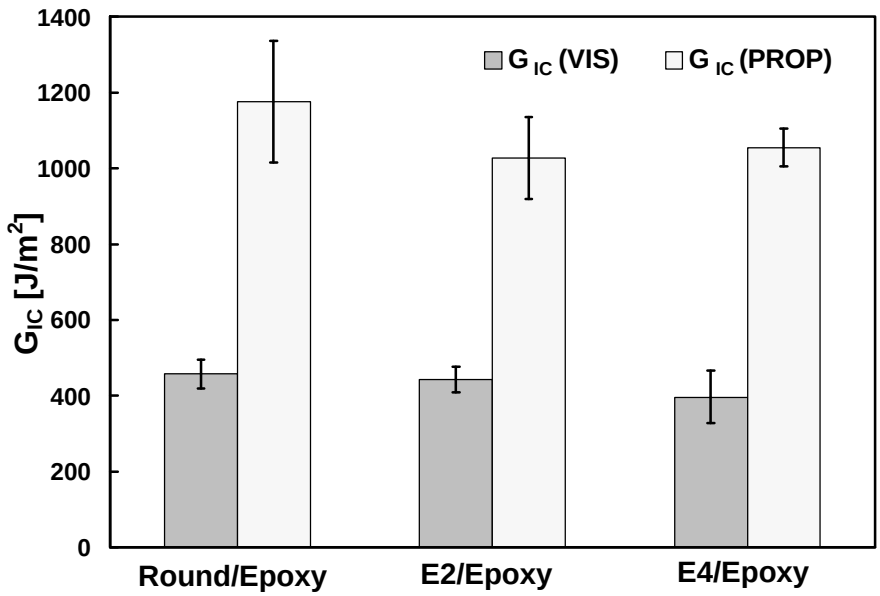


Fig. 6 Mode I interlaminar fracture toughness

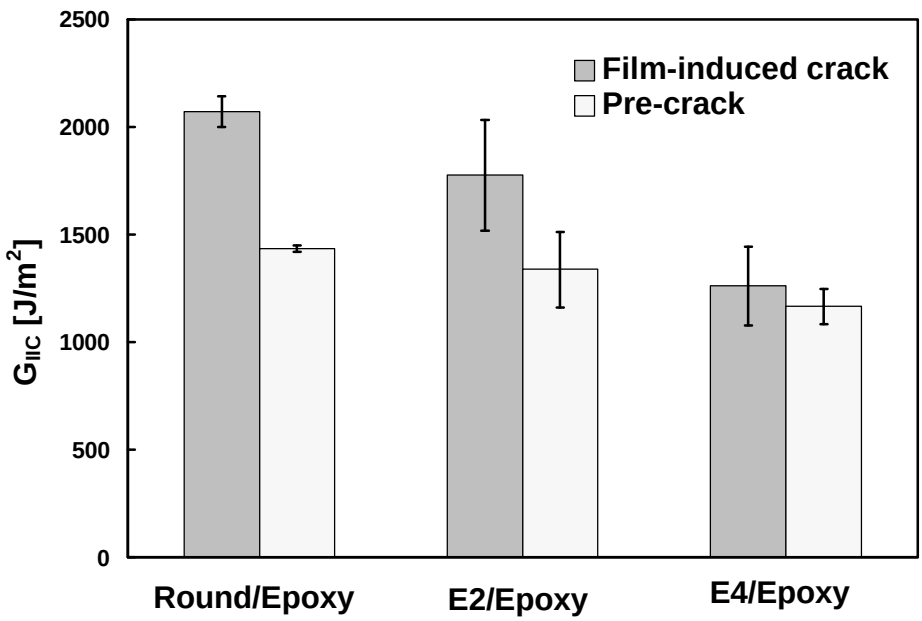
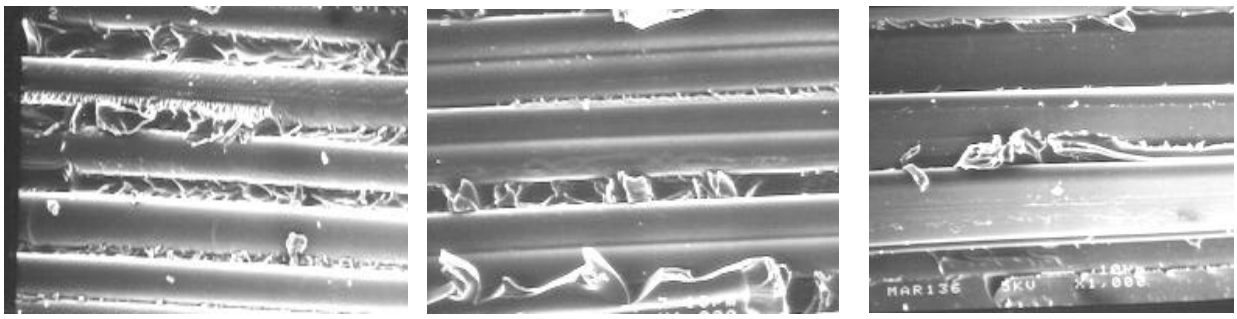


Fig. 7 Mode II interlaminar fracture toughness

In the specimens for DCB and ENF tests, there is a small “resin-pocket” ahead of the film-induced crack, being a resin-rich area. The initiation of delamination needs to break this barrier, producing a fracture energy, $G_{IC}(VIS)$. Since the same matrix resin and insert film were used for all the DCB and ENF specimens following the same procedures, the resin-rich areas for all the specimens should be roughly the same, and thus the differences in the $G_{IC}(VIS)$ values are expected to be marginal. However, the values of $G_{IC}(PROP)$ are dependent on the mechanisms of delamination growth, determined by several factors including the level of fibre-matrix adhesion, the interlaminar bonding strength, and the degree of fibre bridging caused by fibre “nesting” or “peel-off”. In DCB and ENF tests, as soon as the delamination starts, it propagates along a path where the resistance is lowest. For the DCB and ENF specimens of E2/Epoxy and E4/Epoxy, crack propagation will advance through the fibre contact areas where the bonding is weak. However, in the specimens of Round/Epoxy, higher resistance exists at the fibre-matrix interface because of the relative stronger fibre-matrix adhesion, compared to the fibre contact areas in E2/Epoxy and E4/Epoxy. Therefore, if on other mechanism plays an overriding role, the lower interlaminar fracture toughness values are expected for such composite systems reinforced by fibres of large cross-sectional aspect ratios because of extensive fibre overlapping formed during fabrication. The SEM micrographs of fracture surfaces for DCB and ENF specimens from the three composites showed the different failure mechanisms. As shown in Fig. 8 for the fracture surfaces of ENF specimens, some matrix materials were stuck on the surface of fibres of Round/Epoxy, designating the extensive matrix deformation and failure, while for E2/Epoxy and E4/Epoxy some fairly clean fibre surface can be seen, indicating delamination along the contact areas between fibres. Since there is more serious fibre “nesting” or “peel-off” in E2/Epoxy and E4/Epoxy specimens induced by the weak contact areas between the overlapping fibres, it could increase the resistance to delamination. Therefore, the decrease of $G_{IC}(PROP)$ for E2/Epoxy and E4/Epoxy is not so significant, compared to that for Round/Epoxy.



Round/Epoxy E2/Epoxy E4/Epoxy

Fig. 8 SEM micrographs of fracture surfaces for ENF specimens from three composites

CONCLUSION

In the composite systems reinforced by the glass fibres with large fibre cross-sectional aspect ratios fabricated by a filament winding process for making the prepregs, followed by autoclaving, a preferred fibre alignment formed in the composites with the long axis of the fibre cross section being perpendicular to the direction of the applied pressure. As a result, there are many fibres overlapped with each other with large contact areas where the matrix resin is too thin to play the role for stress transfer. The large fibre contact areas caused by

fibre overlapping are weak places and can act as a path for crack propagation. A process of cumulative damage progression occurred during longitudinal tensile and flexural tests with the increased strain-to-failure, compared to that of the composites reinforced by the conventional round glass fibres.

The tensile modulus and strength in the longitudinal direction were nearly the same for the three composite systems. The transverse tensile strength showed the similar case (within the experimental scatter). However, the high strain-to-failure and the low transverse tensile modulus were obtained for the composites reinforced by the glass fibres of large fibre cross-sectional aspect ratios. Meanwhile, a low delamination resistance was found for such composite systems reinforced by fibres of large cross-sectional aspect ratios because of the extensive fibre overlapping, compared with the conventional round fibre composite system. Test results from DCB and ENF showed the same trend that the resistance to delamination decreases with the increase of fibre cross-sectional aspect ratios.

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