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Experimental studies on fracture characterisation and energy absorption of GFRP composite box structures

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ABSTRACT

Interlaminar fracture toughness of composite materials plays an important role in the specific energy absorption (SEA) characteristics of crushing composite materials. In this regard the effect of fibre orientation and stacking sequence on the composite crash box design is sought by studying their effects on the interlaminar fracture toughness. In order to achieve this, glass fibre/epoxy orientations of $[\pm 60]_{10}$, $[0_2/\pm 45]_5$, $[0/90]_{10}$ and $[0/90]_{5S}$ were studied experimentally. Tensile, shear, double cantilever beam (DCB) and axial crush box specimens from different lay-ups were made and tested under quasi-static conditions to determine the mechanical properties, interlaminar fracture toughness (G_{IC}) and SEA. It was shown that the interlaminar fracture toughness of glass fibre/epoxy affects the frond bending resistance due to the main central interwall crack in a progressive crushing failure and consequently SEA. A higher interlaminar fracture toughness between laminates will enhance the SEA in the axial crushing of the composite box.

1. Introduction

The high energy absorbing capabilities of fibre reinforced polymer composite (FRP) materials is one of the main factors in their application in automotive and aerospace structures. They also provide other functional and economic benefits such as enhanced strength, durability, weight reduction and hence lower fuel consumption. For structural vehicle crashworthiness, FRP composites are able to collapse in a progressive, controlled manner which results in high specific energy absorption in the event of crash. Unlike metals and polymers, the progressive energy absorption of composite structures is dominated by extensive micro-fracture instead of plastic deformation [1–4]. The highest energy absorption of composite tubes occurs in two progressive crushing mechanisms which are brittle fracture and lamina bending [4,5]. These two crushing mechanisms absorb energy due to interlaminar and intralaminar crack growth and fracturing of lamina bundles. During progressive collapse, the sources of energy absorption are mainly from [5,6]:

- Frictional resistance between wedge and fronds and between fronds and platen: about 45% of total energy.
- Frond bending due to delamination between plies: about 40%.
- Interwall crack propagation: about 12%.
- Axial splitting between fronds: about 3%.

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Various fracture mechanisms such as fibre breakage and buckling, matrix cracking and crushing, debonding at the fibre–matrix interface and especially plies delamination play important roles on progressive failure mode and energy absorption of composite tubes. Warrior et al. [7] studied the influence of toughened resins, thermoplastic resin additives, through-thickness stitching and thermoplastic interleaving on the interlaminar fracture toughness (G_{IC}) and the SEA for continuous filament random mat (CoFRM) and 0/90 non-crimp fabric (NCF) E-glass reinforced polyester composite tubes. They reported that all above mentioned factors increase G_{IC}, but only toughened resin and through-thickness stitching can increase SEA. In general a tougher matrix gives a higher G_{IC}, for the composite and this is a benefit in crashworthiness design [8]. Farley [9] concluded that matrix stiffness has only a small effect on energy absorption of materials which crush by a brittle fracture and transverse shearing mechanism, and more effect of matrix stiffness is considered by lamina bending mechanism. Cauchi Savona and Hogg [10] studied the relation between sustained crushing stress of glass fibre reinforced plastic composite plates with their Mode-I and Mode-II fracture toughness properties. According to their results, materials which show low Mode-I and Mode-II fracture toughness, yield low crushing energies. Solaimurugan and Velmurugan [11,12] recently have studied the effect of stitching, fibre orientation and stacking sequence on G_{IC}, SEA, and of progressively crushing of glass/polyester composite cylindrical shells under axial compression. They reported that axial fibres placed close to the outer surface of tube led to more petal

Nomenclature

a	crack length	V_f	volume fraction
b	side of box	X_t	longitudinal tensile strength
C	compliance	X_c	longitudinal compressive strength
CFE	crush force efficiency	Y_t	transverse tensile strength
DCB	double cantilever beam	Y_c	transverse compressive strength
E	Young's modulus	ν	Poisson's ratio
F	force	σ_1	longitudinal stress
F_{max}	initial maximum force	σ_2	transverse stress
F_m	mean force	σ_{12}	transverse shear stress
G_{12}	shear modulus	β	weight factor
G_{IC}	Mode-I interlaminar fracture toughness	δ	displacement
GFRP	glass fibre reinforced plastic	σ_u	ultimate tensile stress
SEA	specific energy absorption	θ	fibre orientation
S	shear strength	Δ	extension correction factor for DCB sample
t	thickness	α	trigger angle

formation and stable crushing process, while axial fibres close to inner surface tube cause higher energy absorption. Furthermore, the energy absorption in the form of circumferential delamination increases for higher values of Mode-I fracture toughness. They also reported that stitching increases the Mode-I interlaminar fracture toughness which causes higher energy absorption of cylindrical tube. Farley [13] studied the static crushing process of graphite/epoxy and Kevlar/epoxy square cross section tubes to investigate the effect of geometry on energy absorption of composite materials. He reported that energy absorption of graphite/epoxy and Kevlar/epoxy tubes is a non-linear function of (b/t) where b is the side of the box and t is the wall thickness. It was reported that the energy absorption increased with decreasing b/t ratio. Generally, the highest energy absorption occurs when the thickness of all types of tubes is in the range of 2–3 mm [8]. Farley and Jones [14] also reported that in quasi-static crushing of glass/epoxy tube with fibre orientation of $[0/\pm\theta]_S$, by increasing θ the energy absorption capability of tube increases non-linearly however, as θ increases, the energy absorption capability of the carbon/epoxy tube decreases non-linearly. Generally, they reported that fibre orientation of [0/±45] is preferred for glass fibre epoxy tubes. Schmueser and Wickliffe [15] showed that SEA of carbon–epoxy, glass–epoxy and aramid–epoxy $[0_2/\pm\theta]$ specimens all generally increase with increasing θ. Jimenez et al. [16] have concluded that the bevel trigger mechanism with angle of 60 shows the highest energy absorption in composite profiles.

The present work is mainly focused on the effect of fibre orientation and stacking sequence on G_{IC} and SEA. The DCB and crash box specimens were made and tested with different lay-ups but with the same geometry and material. The experimental results were compared together to find the relationship between G_{IC} and SEA.

2. Experimental studies

Five different types of test were conducted to characterize the mechanical characteristic of a GFRP material. These were tensile, shear, double cantilever beam (DCB), fibre volume fraction determination and quasi-static crush box tests. All tensile, shear, DCB and fibre volume fraction tests were carried out in accordance with the relevant standards [17–20]. All specimens were manufactured from glass fibre material of density 2.1 g/cm^3 with epoxy resin.

2.1. Mechanical properties

A separate panel was made for each type of test and specimens were cut from the panel for testing. The dimensions of each panel were determined by the size and quantity of specimen required for each test. As three types of test specimen had the same dimensions, this simplified the manufacturing process as they could all be prepared in the same way, using the same templates and equipment. Five specimens were made for each test which meant the panels from which they were to be cut would need to be 125 mm wide by the required length, 250 mm. With allowances for machining and possible defects around the edge these numbers were rounded up to 300 × 200 mm. The thickness of each specimen was 2 mm with 250 mm length and 25 mm width. All specimens were cured first in a curing cycle of 30 min at 60 °C with a heating rate of 3–5 °C/min and the temperature was held at 125 °C for 60 min. Tensile tests were carried out on specimens with [0] and [90] lay up with the aim of finding Young's modulus, E_1 and E_2, Poisson's ratio ν_{12} and ν_{21}, and the ultimate tensile strengths according to BS ISO 2747 standard [17]. There are several test methods for measuring the shear modulus of composite materials. The $[\pm 45°]_S$ tensile shear test was chosen for the shear testing as this type of test can be carried out using a conventional tensile testing machine. The state of stress in each laminate was not pure shear but a combination of normal stresses, in addition to desired shear stress. Firstly, the shear stress–strain responses of many composite materials are non-linear, and may exhibit strain softening characteristics, due to rearrangement of dislocations. So, although the biaxial stress in the specimen is likely to cause the measured value of shear strength to be lower than the true value, the reduction may be small because of the non-linear softening response. Secondly, the magnitudes of the interlaminar stresses for laminates containing lamina with high orthotropic ratios are a maximum at ply angles of 15–25°, and the interlaminar stresses for 45° ply angles are considerably smaller. These tests were conducted in accordance with BS ISO 14129 standard [18]. The tests were carried out on a Denison–Mayes 100 kN universal testing machine with crosshead speed of 2 mm/min. For measuring Young's modulus in the axial and transverse direction a biaxial rosette strain gauge Showa N22-FA-8 with a resistance of 120 Ω and gauge length of 8 mm was placed at the central part of the specimen and for measuring the shear modulus a 0/45/90 rosette strain gauge was used.

The fibre volume fraction of the GFRP was determined by the resin burn-off method. It is particularly suitable for GFRP composite because glass is resistant to oxidation at elevated temperatures. This test followed ASTM D 3171 standard [19]. Three small specimens of composite, approximately 15 × 15 × 2 mm, were cut from a larger panel. The width, thickness and length were measured in three places using a micrometer, a mean average taken and the volume of the specimen calculated. Three ceramic crucibles were