Composite Structures 89 (2009) 303–314

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Effects of Mode-I and Mode-II interlaminar fracture toughness on the energy absorption of CFRP twill/weave composite box sections

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ARTICLE INFO

Article history:
Available online 20 August 2008

Keywords:
Interlaminar fracture toughness
Specific energy absorption
Laminate design
Crush box
LS-DYNA

ABSTRACT

Mode-I and Mode-II interlaminar crack growth affect the failure modes of the progressive crushing of composite box structures. These failure modes which are known as lamina bending, brittle fracture, transverse shearing and local buckling contribute to specific energy absorption (SEA) of composite box. In this regard, the effect of laminate lay-up of the composite crush box was sought by studying their effects on Mode-I and Mode-II interlaminar fracture toughness. The double cantilever beam (DCB), three-point-end-notched flexure (3ENF) and axial crush box specimens were fabricated from carbon/epoxy twill–weave fabrics of $[0]_4$, $[45]_4$ and $[0/45]_2$ and they were tested under quasi-static condition to determine the interlaminar fracture toughness in Mode-I (G_{IC}), Mode-II (G_{IIC}) and SEA of each lay-up. It was shown that interlaminar crack propagation in Mode-I and Mode-II contributes significantly on the type of the progressive crushing mode and SEA. The interfaces of 0/45 and 0/0 have higher Mode-I and Mode-II interlaminar fracture toughness and as a result the crushed box with these lay-ups showed a higher energy absorption capability in comparison with crush box lay-up of $[45]_4$. An analytical solution was proposed to predict the mean crushing force for each failure mode. The crushing process of composite boxes was also simulated by finite element software LS-DYNA and the results were verified with the relevant experimental results.

1. Introduction

The brittle nature of most fibre reinforced polymer (FRP) composites accompanying other forms of energy absorption mechanisms such as fibre breakage, lamina bending, and buckling, matrix cracking and crushing, debonding at the fibre–matrix interface and especially plies delamination which occurs due to shear and tensile separation between fronds, play important roles on progressive failure mode and energy absorption capability of composite boxes.

In design of energy absorbers structures from FRP materials, the main source of energy absorption is due to four crushing modes and their combinations during progressive failure of composite crush box [1]. The first mode is *transverse shearing* (fragmentation) which is characterised by a wedge-shaped laminate cross section with one or multiple short interlaminar and longitudinal cracks. In this mechanism interlaminar crack propagation and bundle fracture control the energy absorption. The second mode is *lamina bending* which is developed from long interlaminar, intralaminar, and parallel to fibre cracks. This mechanism causes the formation of continuous fronds which spread inwards and outwards. Friction and inter/intra laminar fracture controls the energy absorption of lamina bending mode. The third mode is *brittle fracturing* mode which is a combination of transverse shearing and lamina bending crushing modes. In this mode the length of the interlaminar cracks are between 1 and 10 laminate thickness. In this case the main energy absorption mechanism is fracturing of lamina bundles. The highest energy absorption of composite tubes has been observed in brittle fracture and lamina bending crushing modes [2]. The fourth mode is *local buckling* which occurs in brittle FRP composites when (i) the interlaminar stresses are small relative to the strength of the matrix, (ii) the matrix has a higher failure strain than the fibre, and (iii) the matrix exhibits plastic deformation under high stress.

During progressive collapse, frond bending following the growth of a main central interwall crack due to delamination in the side wall causes a significant amount of energy absorption. The main central interwall cracks are Mode-I interlaminar crack propagation. Sliding occurs between lamina bundles during frond bending, and they dissipate the energy in Mode-II crack propagation.

The effects of delamination fracture toughness on the energy absorption of composite materials and structures have been investigated by other researchers [3–8]. Savona et al. [3] studied the relation between specific sustained crushing stress (SSCS) of GFRP composite plates with their Mode-I and Mode-II fracture

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doi:10.1016/j.compstruct.2008.08.004

Nomenclature

a	crack length
a_e	effective crack length
b	side of box
C	compliance
CFE	crush force efficiency
CFRP	carbon fibre reinforced plastic
DCB	double-cantilever beam
3ENF	three-point-end-notched flexure
E	Young's modulus
F	load
F_{max}	initial maximum load
F_m	mean load
G_{12}	shear modulus
G_{IC}	Mode-I interlaminar fracture toughness
G_{IIC}	Mode-II interlaminar fracture toughness
h	ENF specimen half-thickness
L	half span of ENF specimen
SEA	specific energy absorption
t	crush box wall thickness
V_f	fibre volume fraction
U_e	external work
U_f	energy dissipated by friction
U_b	energy dissipated in bending
U_{bu}	energy dissipated in local buckling
U_{bf}	energy dissipated by bundle fracture
U_c	energy dissipated in axial splitting
U_d	energy dissipated by delamination
U_s	energy dissipated in shear deformation
$U_{LB/BF}$	energy dissipated for lamina bending/brittle fracture crushing modes
$U_{BU/TS}$	energy dissipated for local buckling/transverse shearing crushing modes
x	sliding distance on the platen
Y	geometry factor
z	crushing distance
ν	Poisson's ratio
λ	crush length of a single stroke
β	weight factor
μ	coefficient of friction
δ	displacement
σ_u	ultimate tensile stress
σ_b	flexural strength
τ_s	shear strength
θ	fibre orientation
φ	semi-angle of the wedge
Δ	crack length correction factor in DCB test

toughness properties. According to their results, materials which show Mode-I and Mode-II interlaminar fracture toughness absorb low crushing energy. They also showed that the G_{IC} and G_{IIC} of initiation are more influential than theG_{IC} and G_{IIC} of propagation on the energy absorption mechanism. Solaimurugan and Velmurugan [4] had studied the effect of stitching, fibre orientation and stacking sequence on G_{IC}, SEA, and progressively crushing of glass/polyester composite cylindrical shells under axial compression. They reported that axial fibres placed close to the outer surface of the tube led to more petals formation and stable crushing process, while axial fibres close to inner surface of the tube cause higher energy absorption. Furthermore, the energy absorption during delamination increases when Mode-I fracture toughness is higher. They also reported that through-thickness stitching increases the Mode-I interlaminar fracture toughness which increases energy absorption of cylindrical tube. Warrior et al. [5] 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. A comprehensive review of the effect of fibre type, matrix type, fibre architecture, specimen geometry, process conditions, fibre volume fraction and testing speed on energy absorbing capabilities of composite crash elements are reported in [6]. It was shown that in general, a tougher matrix gives a higher G_{IC} for the composite and this has a positive effect on their crash performance. Farley [7] concluded that matrix stiffness has a minor effect on energy absorption of materials which crushed by a brittle fracture and transverse shearing mechanism, but the effect of matrix stiffness is more important in lamina bending mechanism. Ghasemnejad et. al. [8] recently studied the effect of Mode-I interlaminar fracture toughness on the energy absorption of laminated GFRP composite box made from various fibre orientations. They concluded that using suitable laminate design for composite box improves interlaminar fracture toughness and consequently energy absorption capability. They also showed that the variation of specific energy absorption (SEA) with interlaminar fracture toughness (G_{IC}) is non-linear for various box lay-ups.

Jimenez et al. [9] experimentally studied the energy absorption capability of a unidirectional box section, and an I-section made of alternating layers of mat and fabric. For each one of the two profiles, six different trigger geometries were analysed. They showed that the I-section is a good candidate for being considered for energy absorption applications. They also concluded that when studying a trigger geometry, slight modifications (as the bevel angle of a bevel trigger) can result in important variations of the results. Elgalai et al. [10] examined the crushing behaviour of axially crushed composite corrugated carbon fibre/epoxy and glass fibre/epoxy tubes. A series of experiments was conducted for tubes with corrugation angle ranging from 10° to 40°. Their results showed that the crushing behaviour of composite corrugated tube is sensitive to the change in corrugation angle and fibre type. Alkateb et al. [11] experimentally examined the behaviour of composite elliptical thin walled cones with the same ellipticity ratio and different vertex angles subjected to quasi-static axial crushing. They showed that the catastrophic failure mode is avoided by deviating from the elliptical tubular shape to the elliptical conical one. A significant enhancement in load carrying capacity and energy absorption capability were seen in the case of elliptical conical shells. Melo et al. [12] looked at the effect of the processing conditions (with or without vacuum) on the specific energy absorption capacity of composite tubes under quasi-static compression load. Their test results showed that, among the conditions considered, tubes of circular cross section fabricated under applied vacuum display the highest level of specific energy absorbed. Mahdi and Kadi [13] implemented artificial neural networks (ANN) technique in the prediction of the crushing behaviour and energy absorption characteristics of laterally loaded glass fibre/epoxy composite elliptical tubes.

Zarei et al. [14] performed dynamic crash tests in order to determine the crash behavior of woven fiberglass/polyamide thermoplastic composite crash boxes. The LS-DYNA explicit finite element code was used for modelling. They compared the crash performance of the optimum composite crash box with an optimum aluminium tube. Lee et al. [15] performed the tensile and