Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 10 (2011) 1865–1870

Engineering Procedia

ICM11

Tensile behaviour of anti-symmetric CFRP composite

K. J. Wong[a,b,*], X. J. Gong[a], S. Aivazzadeh[a], M. N. Tamin[b]

[a] *Département de Recherche en Ingénierie des Véhicules pour l'Environnement, Université de Bourgogne, 58000 Nevers, France*
[b] *Centre for Composites, Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, 81310 Johor, Malaysia*

Elsevier use only: Received date here; revised date here; accepted date here

Abstract

This paper addresses the response of a 17-ply anti-symmetric carbon/epoxy composite subjected to uniaxial tensile loading. Hashin ply damage model is adopted to describe the damage behaviour of the plies, whereas damage initiation and progression of the interfaces are characterised by mixed-mode cohesive damage model. Force-displacement curves obtained numerically and experimentally show good agreement. Results show that all laminae and interfaces experience the damage except laminae with 0^o fibre. In addition, damage is concentrated at the tab and central regions of the tensile specimen. Edge delamination is observed in all interfaces.

Keywords: CFRP composite; Tensile behaviour; Lamina damage; Interface failure; Finite Element Method (FEM)

1. Introduction

Carbon fibre reinforced polymer (CFRP) composites are widely employed in advanced structural applications. In order to be used safely as structural materials, thorough understanding on the response of the composites under different loading conditions is inevitable.

Studies on glass fibre reinforced polymer (GFRP) composites with central cut-out were reported by Rakesh and his coworkers [1]. Hashin model [2,3] was adopted to predict the damage initiation of the lamina. Besides, Lapczyk and Hurtado studied blunt notch fibre metal laminate (FML) behaviour numerically by considering both lamina and interface failure [4]. Through both experimental and numerical works, it was reported that matrix cracking and delamination are the two dominant failure modes in quasi-isotropic (QI) carbon/epoxy composite laminates [5]. From the works mentioned above, it

* Corresponding author. Tel.: +33 3 86 71 50 36; fax: +33 3 86 71 50 18.
E-mail address: jye1189@gmail.com.

1877-7058 © 2011 Published by Elsevier Ltd. Open access under CC BY-NC-ND license.
Selection and peer-review under responsibility of ICM11 doi:10.1016/j.proeng.2011.04.310

is recommended that both lamina and interface failures should be modelled in order to accurately characterise the damage behaviour of the composites.

In this study, the response of a 17-layer anti-symmetric CFRP composite arranged in the ply sequence of [$-60_2/0/60_5/0/-60_5/0/60_2$] subjected to tensile load is examined. This particular layup could eliminate coupling stiffness matrix **[B]** and the entries A_{16}, A_{26}, D_{16} and D_{26} in extensional **[A]** and bending **[D]** stiffness matrices respectively. Besides, for other entries, A_{ij} is proportional to D_{ij}.

Nomenclature

Lamina

$G_{ft,C}$, $G_{fc,C}$	fibre critical fracture energy, *t* and *c* refer to tensile and compressive respectively
$G_{mt,C}$, $G_{mc,C}$	matrix critical fracture energy, *t* and *c* refer to tensile and compressive respectively
S^L, X^T, Y^T	longitudinal shear, longitudinal and transverse strength
α	coefficient of shear stress contribution
$\hat{\sigma}_{ij}$	effective stress components on *ij*th-plane

Interface

D	damage parameter
G_C	effective strain energy release rate
G_j, G_{jC}	mode *j* strain energy release rate, *C* refers to critical strain energy release rate
t_n, t_s, t_t	nominal traction stress vector in normal, shear and tangent directions
$t_{u,n}$, $t_{u,s}$, $t_{u,t}$	interface strength in normal, shear and tangent directions
δ_o, δ_m, δ_f	interface relative displacement at damage initiation, intermediate and total failure
η	material parameter

2. Numerical models

2.1. Lamina damage model

The different failure modes of Hashin damage failure criterion [2,3] are treated separately and the tensile failure conditions are described by equations (1)-(2) as follow:

$$\text{Fibre tension, } F_{ft} = \left(\frac{\hat{\sigma}_{11}}{X^T}\right)^2 + \alpha\left(\frac{\hat{\sigma}_{12}}{S^L}\right)^2 = 1 \quad (1)$$

$$\text{Matrix tension, } F_{mt} = \left(\frac{\hat{\sigma}_{22}}{Y^T}\right)^2 + \left(\frac{\hat{\sigma}_{12}}{S^L}\right)^2 = 1 \quad (2)$$

Damage is initiated for any of the failure modes whenever the criterion given by the equations is satisfied. Damage evolution is described by linear softening law, which is to be discussed in the next section.

2.2. Interface damage model

A quadratic nominal stress criterion is used to indicate the initiation of interface damage, as shown in equation (3).

$$\left\{\frac{\langle t_n \rangle}{t_{u,n}}\right\}^2 + \left\{\frac{t_s}{t_{u,s}}\right\}^2 + \left\{\frac{t_t}{t_{u,t}}\right\}^2 = 1 \tag{3}$$

Following interface damage initiation event, subsequent damage propagation upon further loading is predicted using a mixed-mode energy-based criterion given by equation (4) [6,7].

$$G_{IC} + (G_{IIC} - G_{IC})\left\{\frac{G_{II} + G_{III}}{G_I + G_{II} + G_{III}}\right\}^{\eta} = G_C \tag{4}$$

In the current work, linear softening law is used and the damage variable is described as follows:

$$D = \frac{\delta_f(\delta_m - \delta_o)}{\delta_m(\delta_f - \delta_o)} \tag{5}$$

In the lamina damage model, *D* refers to fibre and matrix damage variables respectively.

2.3. Finite element model

The finite element model of the composite specimen consists of seventeen laminae and six interfaces, as shown in Fig. 1. Besides, four cross-ply GFRP tabs are modelled. Both laminae and tabs are modelled using continuum shell elements and the interfaces are modelled using cohesive elements. Fig. 2 shows the finite element model used in this study along with the loading and boundary conditions used.

Fig. 1. Layup and designation of the composite used in this study

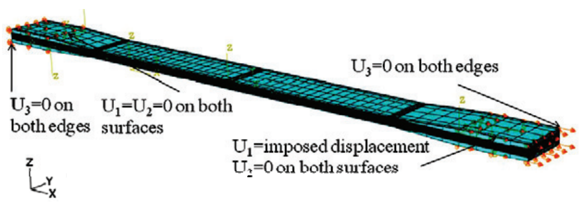

Fig. 2. The finite element model used in this study

The properties of the lamina, interface and GFRP tab are shown in Tables 1 thru 6 below. The parameter, α is chosen to be unity, as proposed by Hashin [3].

Table 1. Material properties of the lamina

E_1 (GPa)	E_2 (GPa)	E_3 (GPa)	G_{12} (GPa)	G_{13} (GPa)	G_{23} (GPa)	v_{12}	v_{13}	v_{23}
131.9	9.51	9.43	5.27	7.03	3.39	0.326	0.341	0.485

Table 2. Strengths of the lamina

X^T (MPa)	X^C (MPa)	Y^T (MPa)	X^C (MPa)	S^L (MPa)	S^T (MPa)
1328	1064	70.9	221	71.2	94.5

Table 3. Fracture energies of the lamina

$G_{mt,c}$ (N/mm)	$G_{mc,c}$ (N/mm)	$G_{ft,c}$ (N/mm)	$G_{fc,c}$ (N/mm)
0.33	0.33	2	2

Table 4. Material properties of the interface

K_{nn} (MPa)	K_{ss} (MPa)	K_{tt} (MPa)
4000	1400	1400

Table 5. Damage properties of the interface

$t_{u,n}$ (MPa)	$t_{u,s}$ (MPa)	$t_{u,t}$ (MPa)	G_{IC} (N/mm)	$G_{IIC} = G_{IIIC}$ (N/mm)	η
25	13.5	13.5	0.33	0.79	1.45

Table 6. Material properties of the tab

E_1 (GPa)	E_2 (GPa)	$G_{12} = G_{13}$ (GPa)	G_{23} (GPa)	ν_{12}
55	9.5	5.5	3	0.33

3. Results and discussion

3.1. Load-displacement curves

The measured and predicted load-displacement responses of the composite specimen under tensile loading are compared in Fig. 3. The strain gauges readout is used to compute the relative displacement over the gauge length of 3 mm. The linear plot suggests that no apparent damage is observed during loading until the final catastrophic fracture occurs. The deviation in the measured and predicted stiffness could be attributed to imperfect composite plate fabrication. The peak load at fracture is compared well to predicted load magnitude. The difference could be due to inability of the numerical computation to account for the load carrying ability of the fibre after complete failure of the matrix.

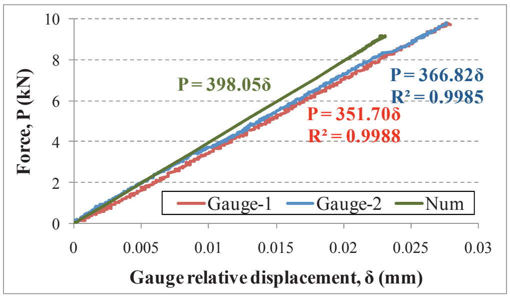

Fig. 3. Experimental and predicted load-displacement curves

3.2 Damage behaviour of laminae and interfaces

Evolution of internal states and damage in the laminae and interfaces throughout the loading, as predicted by the finite element model is now presented and discussed. Fig. 4 describes the corresponding time at damage initiation of each lamina and interface. Damage is initiated in all laminae and interfaces except laminae with 0° fibre. It is predicted that only tensile matrix failure occurs in the lamina during the tension test. This matrix damage occurs due to the combined effect of σ_{22} and σ_{12}, that leads to $F_{mt} = 1$ (see equation (2)). Interlaminar failure is a result of combined stresses in 33 and 13-direction.

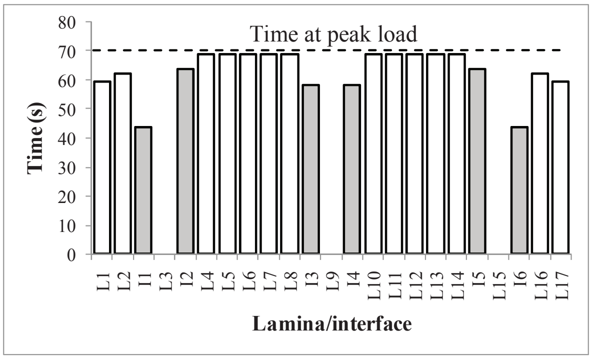

Fig. 4. Damage initiation time of damaged laminae and interfaces

Next, the progression of damage in L1 is described. Fig. 5 illustrates the sequence of matrix damage propagation with continuously increasing tensile loading of the specimen. Results show damage is initiated at near tab region (Fig. 5(a)). Then, the stresses and thus matrix damage variable are increased uniformly across the whole lamina (Fig. 5. (b)). This is followed by matrix damage initiation at isolated region nearby (Fig. 5. (c)), that propagated to the edges (Fig. 5. (d)). Fig. 5. (e) illustrates the damage contour at peak load, where matrix cracking at the central region is observed. Besides, anti-symmetric feature of the lamina is obvious as reflected in anti-symmetric distribution of matrix cracking damage.

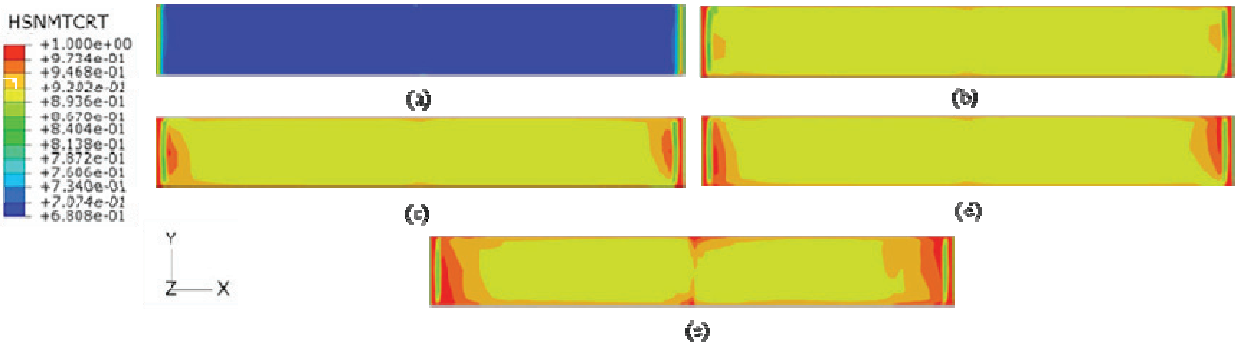

Fig. 5. Progression of damage initiation in L1

Fig. 6 describes the initiation and progression of delamination damage in I1. Since damage is initiated at the edges near the tabs (circled in red in Fig. 6. (a)), delamination propagates across the width and connects after that (Fig. 6. (b)). It is accompanied by edge delamination along the edges. Then, delamination is predicted to propagate slightly further from the tabs (Fig. 6. (c)). When peak load is attained, delamination is found at the central edges of the specimen (Fig. 6. (d)).

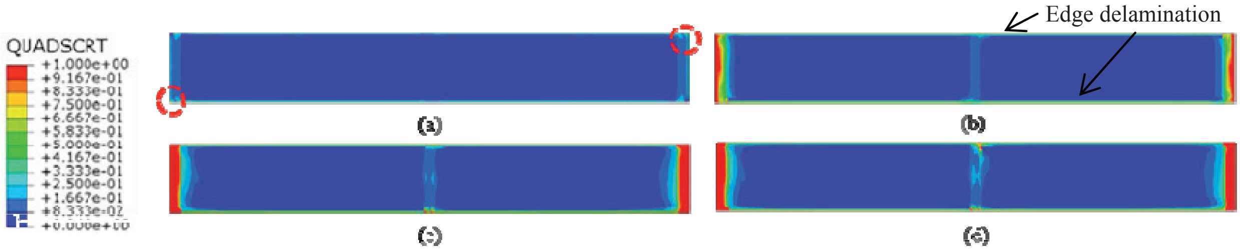

Fig. 6. Interface damage initiation and propagation in I1

4. Conclusions

Failure process of anti-symmetric CFRP composite laminate specimen under tensile loading has been examined both experimentally and using finite element method. Both lamina damage and interface delamination were modelled. Results show that:

1. Numerical prediction and experimental measurement of load-displacement curves are in good agreement.
2. Damage occurs in two forms, which are matrix cracking (in laminae) and delamination (in interfaces).
3. For both lamina and interface, damage is first initiated at the tab region, which eventually propagated slightly and accompanied by damage at the central region. As for interfaces, delamination occurs along the edges as well.

References

[1] Rakesh PK, Singh I, Kumar D. Failure prediction in glass fiber reinforced plastics laminates with drilled hole under uni-axial loading *Mater Des* 2010;**31**(6):3002-7.

[2] Hashin Z, Rotem A. A fatigue failure criterion for fiber reinforced materials. *J Compos Mater* 1973;**7**:448–64.

[3] Hashin Z. Failure criteria for unidirectional fiber composites. *J Appl Mech* 1980:**47**(2):329-34.

[4] Lapczyk I, Hurtado JA. Progressive damage modeling in fiber-reinforced materials. *Compos Part A-Appl S* 2007;**38**(11):2333-41.

[5] Hallett SR, Jiang WG, Khan B, Wisnom MR. Modelling the interaction between matrix cracks and delamination damage in scaled quasi-isotropic specimens. *Compos Sci Technol* 2008;**68**(1):80-9.

[6] Gong XJ, Benzeggagh ML. Mixed mode interlaminar fracture toughness of unidirectional glass/epoxy composite. In: Martin RH, editor. *Composite materials: Fatigue and Fracture - Fifth Volume, ASTM STP 1230*, Philadelphia: American Society for Testing and Materials; 1995, p. 100-23.

[7] Benzeggagh ML, Kenane M. Measurement of mixed-mode delamination fracture toughness of unidirectional glass/epoxy composites with mixed-mode bending apparatus. *Compos Sci Technol* 1996;**66**:1479-96.