Composites Science and Technology 111 (2015) 32–39

Contents lists available at ScienceDirect

Composites Science and Technology

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

A numerical investigation into size effects in centre-notched quasi-isotropic carbon/epoxy laminates

Xiaodong Xu *, Michael R. Wisnom, Xiangqian Li, Stephen R. Hallett

Advanced Composites Centre for Innovation & Science (ACCIS), University of Bristol, University Walk, Bristol BS8 1TR, UK

ARTICLE INFO

Article history:
Received 1 July 2014
Received in revised form 23 January 2015
Accepted 1 March 2015
Available online 6 March 2015

Keywords:
A. Laminate
B. Strength
C. Finite element analysis (FEA)
C. Notch
Size effect

ABSTRACT

Numerical modelling of scaled centre-notched $[45/90/-45/0]_{4s}$ carbon/epoxy laminates was carried out. The in-plane dimensions of the models were scaled up by a factor of up to 16. A Finite Element (FE) method using the explicit code LS-Dyna was applied to study the progressive damage development at the notch tips. Cohesive interface elements were used to simulate splits within plies and delaminations between plies. A failure criterion based on Weibull statistics was used to account for fibre failure. There is a good correlation between the numerical and experimental results, and the scaling trend can be explained in terms of the growth of the notch tip damage zone. The modelling gives new insights into the damage development in the quasi-isotropic laminates with sharp cracks, specifically, the growth of splits, delaminations and local fibre breakage.

1. Introduction

Notched tensile strength of composites is a critical design driver. For example, notched tensile tests are important to determine the damage tolerance of composite fuselage structures. The sizes of laboratory notched coupons are usually at the scale of centimetres. In contrast, large composite structures are normally sized in metres. There is an obvious dimension gap, so it is important to understand the relationship between the notched tensile strength of the small coupons and that of the large structures.

A few numerical methods were used to investigate the size effects in notched composite laminates [1–4]. These approaches did not simulate the detailed damage development at the notches. As a result, they need additional fracture parameters (e.g. translaminar fracture toughness) in order to capture the scaling of strength. In contrast, this paper adopts a virtual test technique which simulates the detailed notch-tip damage development at different load levels and in different specimen sizes.

Discrete transverse crack and delamination were found to be crucial mechanisms in the failure of composite laminates [5]. For example, splitting and delamination can significantly affect the stress gradient at the notch tip. Different numerical approaches have been developed to study fracture and damage in composites, such as continuum modelling [6–8], embedded crack modelling, e.g. eXtended Finite Element Method (X-FEM) [9] and discrete modelling, e.g. cohesive interface methods [5,10,11]. Among the above modelling techniques, numerical methods have been developed to simulate matrix cracking and delamination initiating from free edges [12–14], and those initiating from notches [9,15,16]. Compared with continuum damage modelling, cohesive interface methods can better represent the physical mechanisms at the discontinuities that arise at the discrete failures. There may be scope to apply the X-FEM approach in the future, but that would require further development to combine with the Weibull statistics based criterion for fibre breakage which is crucial in the current study.

A numerical technique using the explicit FE code LS-Dyna and cohesive interface elements was developed to simulate the subcritical damage in composite laminates with open holes [17] and sharp cracks [18]. Such detailed modelling technique can successfully predict the tensile strength of open-hole specimens and blocked-ply over-height compact tension specimens. In those cases, the final failure follows immediately from the first fibre failure. However, the dispersed-ply laminates with sharp cracks were not well simulated, in which the first fibre failure does not lead to the final failure straight away. Instead, a damage zone which consists of stable fibre breakage, multiple splits and delaminations is observed at the crack tips [19]. Simulating the first fibre failure alone is not enough, and simulation of the development of the damage zone and its influence on progressive fibre failure is necessary for accurate predictions.

An experimental investigation into the size effects in in-plane scaled centre-notched $[45/90/-45/0]_{4s}$ laminates has recently been conducted [19]. The damage zone was shown to play an important

* Corresponding author. Tel.: +44 (0)117 33 15775.
E-mail address: xiaodong.xu@bristol.ac.uk (X. Xu).

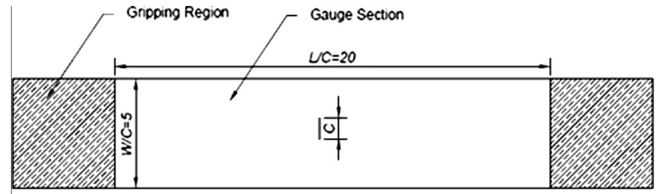
http://dx.doi.org/10.1016/j.compscitech.2015.03.001
0266-3538/

role in the scaling of centre-notched tensile strength. The centre-notched strength decreases towards a Linear Elastic Fracture Mechanics (LEFM) asymptote as the notch length increases, with the size of the damage zone approaching an approximately constant value. In the present paper, the damage development in in-plane scaled centre-notched $[45/90/-45/0]_{4s}$ laminates was studied through an FE approach based on that of Li et al. [18]. The sizes of the simulated damage zones in the scaled models were compared with those in the CT images from interrupted tests [19], which has not hitherto been done. Because the scaled FE models simulate closely the damage zone behaviour, the size effects can be well represented and explained in terms of the growth of the damage zone, which can be observed in much greater detail than is usually possible experimentally. Using this information to provide understanding of the mechanisms giving rise to the size effects in sharp notched specimens is the main novelty of this paper.

2. Experimental specimen configuration modelled

A schematic of the in-plane scaled centre-notched specimens and their dimensions are illustrated in Fig. 1. Detailed ply-by-ply 3D FE models with 8-node constant stress solid elements are constructed in LS-Dyna. All nodes at its one end are fixed, with uniform displacements applied to the nodes at the other end. Half thickness of each specimen is modelled, with symmetric boundary conditions applied to the nodes at the mid-plane. The in-plane dimensions of the quasi-isotropic specimens were scaled up by a factor of up to 8. In addition, a larger specimen with only the width and notch length doubled from the one-size-smaller specimens (named as the "short variant") was also modelled as a further comparison. FE analysis demonstrated that in the short variant specimens the closer boundaries in the length direction do not affect the stress distribution near the notches.

The material used in the tests was Hexcel HexPly® IM7/8552 carbon–epoxy pre-preg with a nominal ply thickness of 0.125 mm. All specimens were of the same $[45/90/-45/0]_{4s}$ layup. The nominal thickness was 4 mm, which is very close to the actual specimen thickness of 4 mm (C.V. 1.4%).



Specimens	Notch length C	Gauge width W	Gauge length L
Baseline	3.2	15.9	63.5
Scale 2	6.4	31.8	127.0
Scale 4	12.7	63.5	254.0
Scale 8	25.4	127.0	508.0
Scale 16	50.8	254.0	508.0

Fig. 1. Schematic of the in-plane scaled centre-notched specimens and dimensions (mm).

3. FE model setup

3.1. Typical FE mesh

Fig. 2 illustrates a typical FE mesh. A triangular shaped sharp notch tip was modelled. In the experiments, a 0.25 mm-wide notch tip was cut with a piercing saw blade, which was proved to be sharp enough not to affect the measured fracture toughness in Ref. [19]. The CT images from the experimental study show that fibre breakage is usually constrained within ±45° lines starting from the notch tips. So in the FE analysis, a refined mesh was arranged near the notch tips within the ±45° lines to be able to simulate the progressive damage development. A coarser mesh was used outside this region.

The models were set up with a nominal ply thickness of 0.125 mm, so have a thickness of 4 mm, similar to the measured value of 4 mm (C.V. 1.4%). The model of the baseline specimens with one element through the thickness of each ply was compared with a model with two elements through the thickness of each ply. The results were within 1.2%, so only one element through each ply thickness was used in all of the subsequent FE models.

3.2. Cohesive interface elements

In the FE analysis, cohesive interface elements were used to simulate the splits within plies and the delaminations between plies. Specifically, to simulate the damage zone at the notch tips, multiple potential split paths in the 0° plies were pre-defined. For example, there are 9 pre-defined potential 0° split paths (marked in red[1]) in the typical FE mesh in Fig. 2(a). In contrast, there is only a single pre-defined potential split path, starting from each notch tip, in the plies with other orientations (±45° and 90°). This is because the models showed that there is no fibre breakage in the other plies before final failure, and no further potential split paths are needed to blunt the stress concentrations after initial fibre fracture. Additional potential split paths could have been included in these plies. However they would not affect the results and would increase computation time. Fig. 2(b) illustrates how the potential split paths are arranged. The properties of the cohesive interface elements are shown in Table 1 [17]. The mixed-mode traction displacement relationship for cohesive interface elements is shown in Fig. 3 [20].

3.3. Fibre failure criterion

A criterion based on Weibull statistics has been used to predict fibre failure. The theory supposes that the strength of a brittle-like material is controlled by defects which follow a Weibull distribution, and the strength is related to the stressed volume [21]. When the volume adjusted stress reaches the unnotched unidirectional strength, fibre failure will occur. Using the assumption of equal probability of survival between the model and unit volume of material, we have Eq. (1) [18]:

$$\int_V \left(\frac{\sigma}{\sigma_{\text{unit}}}\right)^m dV = \sum_{i=1}^{\text{Total No. of Solid Elements}} \left(\frac{\sigma_i}{\sigma_{\text{unit}}}\right)^m V_i = 1 \tag{1}$$

where σ_i is the elemental stress, V_i is the elemental volume, $\sigma_{\text{unit}} = 3131$ MPa is the tensile strength of a unit volume of material, $m = 41$ is the Weibull modulus from scaled unnotched unidirectional tensile tests of the same material [22]. Other lamina properties are shown in Table 1 [17].

Eq. (1) is checked at each time step. When this fibre failure criterion is satisfied, the element with the maximum fibre direction stress loses its load carrying capability and its contribution is removed. After this, the load is automatically redistributed to the

[1] For interpretation of color in Fig. 2, the reader is referred to the web version of this article.