Composites Science and Technology 126 (2016) 52–59

Contents lists available at ScienceDirect

Composites Science and Technology

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

Large scale fiber bridging in mode I intralaminar fracture. An embedded cell approach☆

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ARTICLE INFO

Article history:
Received 7 December 2015
Received in revised form
29 January 2016
Accepted 31 January 2016
Available online 10 February 2016

Keywords:
Polymer-matrix composites (PMCs)
Fracture
Fiber bridging
Multiscale modeling
Finite element analysis

ABSTRACT

Fiber reinforced composites can develop large scale bridging upon mode I fracture. This toughening mechanism depends on the constituents and the geometry of the specimen, and is especially important in unidirectional laminates when fracture is parallel to the fibers. The mode I intralaminar fracture behavior of unidirectional carbon-epoxy laminates was investigated by means of a three-dimensional multiscale model based on an embedded-cell approach. A double cantilever beam specimen was represented by an anisotropic homogeneous solid, while the bridging bundles ahead of the crack tip were included as beam elements. The failure micro-mechanisms controlling the crack propagation (namely, decohesion and subsequent failure of the bridging bundles) were included in the behavior of the different constituents. Numerical simulations were able to predict the macroscopic response, as well as the development of bridging and the growth of the crack. These results demonstrated the ability of the virtual testing approach to study complex fracture processes in composite materials. Finally, the developed model was employed to study the thickness effect and ascertain the influence of the constituents' properties on the energy released during fracture.

1. Introduction

The study of fracture of Fiber Reinforced Polymers (FRP) is a challenging problem due to the variety of failure mechanisms interacting at different scales. At the micro-scale, the fiber/matrix interface plays a critical role in the onset of transverse ply failure [1]. The polymeric matrix can exhibit plastic deformation [2], while fibers display brittleness under tensile loads and fail due to fiber kinking under compression [3]. The laminate, made by stacking unidirectional plies, inherits all of these damage micro-mechanisms and exhibits delamination due to the mismatch of properties between the different lamina orientations. The evolution of a crack in a composite structure is usually followed by the development of bridging ligaments that slow down crack propagation and increase the fracture energy of the material.

Fracture in a Double Cantilever Beam (DCB) composite specimen in mode I along the direction of the fibers, develops an extensive fiber bridging zone with dimensions comparable to the specimen's size. This phenomenon is called Large Scale Bridging (LSB) and is one of the most studied toughening mechanisms in FRPs [4,5]. The resistance curve (R-curve) in these materials indicates that the fracture energy increases during crack propagation due to the development of bridging ligaments until reaching the plateau at steady-state, where the bridging zone is fully developed. As a direct consequence of LSB, the R-curve in these materials, using the DCB test, is dependent on the specimen's geometry and should not be seen as a material property [6,7]. Numerous experimental efforts have been carried out to study bridging mechanisms in FRPs. Sorensen et al. [8] incorporated fiber Bragg grating sensors to measure the strains developed in the specimen during mode I delamination and calculated the bridging tractions through an inverse-numerical approach. The same technique was adapted by Manshadi et al. [9,10] and Farmand-Ashtiani et al. [11] to study the thickness effect on the interlaminar failure. These experiments demonstrated that the length of the bridging zone was linearly proportional to the thickness of the specimen, while the maximum bridging traction and the crack opening at the end of the bridging remained constant. A recent investigation on mode I intralaminar fracture of unidirectional laminates was also able to reproduce the thickness effect [12]. The inverse-numerical approach based on the strain data of fiber Bragg sensors was employed to identify the bridging tractions. This study confirmed the linear dependency of the bridging length

☆ Fully documented templates are available in the elsarticle package on CTAN.
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http://dx.doi.org/10.1016/j.compscitech.2016.01.025
0266-3538/

with the thickness of the specimen and a thickness independent maximum bridging traction.

The progressive failure of FRP is usually modeled through cohesive models, which are able to capture the initiation and development of damage [13–15]. However, these models usually rely on experimental data to find an adequate cohesive law, and they are not able to reproduce the experimentally observed geometry dependence. Analytical models have been developed to represent fiber bridging and identify the material parameters controlling the toughening mechanisms. Spearing and Evans [16] proposed an energy balance between the bending and the decohesion of the ligaments to obtain the bridging tractions. Kaute et al. [17] considered that pull-out and subsequent peel-off of bridging fibers were the main mechanisms controlling the bridging angle and transferred tractions. This model was able to quantitatively reproduce the mode I fracture resistance experimentally measured in ceramic matrix composites. Sørensen et al. [18] extend the work of Spearing and Evans to the mixed mode crack growth. These analytical micromechanical models provide useful closed-form solutions that can be easily implemented in a cohesive element to describe the bridging traction in the steady state. However, none of these models is able to capture the onset of the failure and the thickness dependent crack growth.

Recent advances in multiscale simulation strategies have demonstrated their ability to perform "virtual test" of engineering materials [19,20]. In particular, these simulation strategies are useful in FRP due to the complexity of failure mechanisms in these materials. In this work, a multiscale simulation approach was used to study bridging toughening and its thickness dependency on of unidirectionally reinforced carbon/epoxy composites in mode I intralaminar fracture. The actual bridging mechanisms were ascertained by microscopic observations, which were subsequently used to develop an embedded cell model capable of reproducing the evolution of the crack, the development of bridging, and the size effect in the R-curves. Finally, a parametric study was carried out to investigate the influence of the constituents' properties in the toughening of FRP.

2. Materials and experimental background

The computational model developed in this paper relies on the experimental results obtained on mode I fracture of unidirectional composite laminates. Some of these results are summarized here to support the computational model (see Ref. [12] for further details).

Unidirectional panels of carbon/epoxy laminate $[0]_{50}$ were prepared by stacking pre-impregnated layers of SE-70 (Gurit) that were then consolidated in the autoclave at 78 °C and 3 bar for 12 h. After manufacturing, panels were visually inspected to ensure that they were free of delaminations and other defects. The final dimensions of the panels were $360 \times 200 \times 10$ mm^3. Beams with a rectangular cross-section of 340 mm long were machined from the panels with the fibers parallel to the longitudinal axis. The beams had a constant width of 10 mm, given by the thickness of the composite panel, while three different thicknesses (H = 6, 10 and 14 mm) were considered to study their effect in fracture of the DCB specimens. A 60 mm intralaminar pre-crack notch was machined with a diamond 130 μm diameter wire. Finally, cubic loading blocks with sides of 10 mm were bonded to each specimen using an epoxy adhesive (Fig. 1).

The DCB tests followed the ASTM Standard D5528-13 [21] and were conducted in an Instron 5848 electromechanical testing machine under stroke control at a constant cross-head speed of 3 mm/min. The applied load (P) was measured with a 2 kN load-cell while the applied displacement (Δ) was determined from the position of the actuator. Additionally, propagation of the crack tip was monitored with a high resolution CCD camera. At least four specimens of each thickness were tested. Three representative load–displacement curves of the specimens with three studied thicknesses are plotted in Fig. 2a. The initial elastic stiffness and maximum load showed a clear increase with specimen thickness. After the maximum load, crack propagation continued along the mid-plane of the specimen with a subsequent decrease in the load. The Energy Release Rate (ERR) was computed with the crack advancement data and the load–displacement curves using the modified compliance calibration method. The averaged R-curves for the tested specimens are plotted in Fig. 2b. The data in Fig. 2b show that the ERR for the crack initiation was ≈260 J/m^2, independent of the specimen's thickness, while the ERR increased with crack advancement upon continued loading. Note that the initial slope of the R-curve indicated a dependency on the geometry of the specimens. Thus, the thinner the specimen the steeper the R-curve, in agreement with previous experimental observations [6,4]. The R-curves reached a plateau at the steady state, when the bridging region was completely developed, with corresponding values for the different thicknesses ≈2.05 kJ/m^2 (H = 6 mm), ≈2.50 kJ/m^2 (H = 10 mm) and ≈3.05 kJ/m^2 (H = 14 mm).

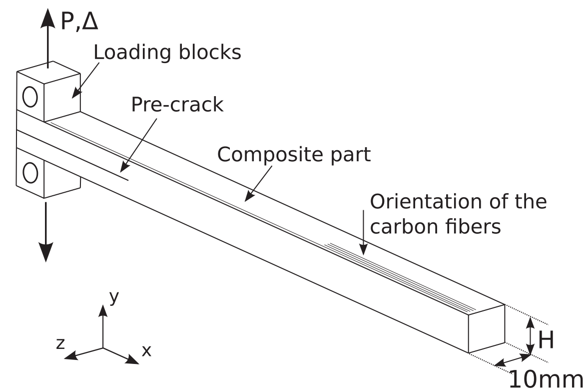

Fig. 1. Schematic of double cantilever beam specimens for the determination of the mode I fracture toughness on unidirectional carbon/epoxy laminates.

Two tested specimens of H = 6 and 14 mm were sectioned at different positions along the bridging region and prepared for inspection in the optical microscope to observe the toughening micro-mechanisms and determine the size and the distribution of the bridging fiber bundles. The cross-sectional area of the bundles was automatically measured using the particle analyzer feature available in Image J [22]. The histograms of the bundle size for a section at a crack opening of ≈0.3 mm are plotted in Fig. 3. Bridging ligaments smaller than 0.001 mm^2 were removed from the plot to improve observation of the thick bundles, which carry most of the tractions.

3. Computational model

The mode I intralaminar fracture of the carbon/epoxy composite was simulated by a multiscale virtual test of the DCB experiments. Only half of the specimen was represented in the model, taking advantage of the symmetry with respect to the xy plane (Fig. 1). The microstructure of the bridging region was included by implementing an embedded cell, following the strategy employed in Refs. [23,24,1]. The geometric model to simulate the DCB specimen comprised two three-dimensional parts, symmetric with respect to the xz plane, where the homogeneous material was assumed to be a unidirectional laminate with the carbon fibers oriented along the length of the specimen and behaving as a linear and elastic