Analysis of the initial delamination size on the mode I interlaminar fracture of carbon/epoxy composites

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SUMMARY

This paper describes an experimental study of the initial delamination length effects on the mode I fracture toughness using DCB tests. Delamination failure was also predicted using exponential cohesive model and a quite good agreement with experimental results was obtained. Numerical predictions showed a significant influence of initial delamination length on the force-displacement curves.

Keywords: composites, fracture toughness, finite element analysis, mechanical testing.

INTRODUCTION

Carbon fibre reinforced composite materials are widely used for structural applications in automobiles, ships, aircraft, satellite and sportive goods as a consequence of their beneficial characteristics, such as stability, lightweight and high stiffness. However, the strength, stiffness and global performance of these materials are significantly affected by geometrical and material defects resulting from an imperfect manufacturing process or from external loads during the operational life [1-2].

The impact loading can cause extensive delaminations and matrix cracking within the laminates that may not be visible on the surface [3]. In fact, impact damage is considered the primary cause of in-service delamination in composites giving reductions of the compressive residual strength up to 60% [4-5]. Fracture mechanics approaches have been used to characterize delamination resistance. Various standards have been developed for mode I fracture, in particular the double cantilever beam (DCB) test, involving the measurement of the critical strain energy release rate, G_{Ic}, and several studies can be cited [6-11]. According to Mahdi *et al* [12], several data reduction methods were assessed, like the corrected beam theory (CBT), the experimental compliance (ECM) and the area methods. In the CBT approach the G value can be calculated from the load, the opening displacement of the arms and the measured crack length [12]. For the ECM approach the specimens were not pre-cracked and the initiation and propagation values were determined in one loading/unloading cycle [12]. Finally, the area method involves the measurement of the loading/unloading curves for successive increments of crack length and the G value is calculated from two consecutive loading lines, corrected for zero displacement at zero loads [12]. On the other hand abundant studies are also reported for fracture toughness in mode II, particularly using end-notched flexure (ENF) tests [8, 13-15].

For carbon fibre reinforced epoxies resins, it was found that the typical values of G_{Ic} in stable propagation are around 260 J/m^2 [7]. In order to improve the interlaminar toughness of the composites materials the bibliography suggests the application of thermoplastic resins [7], due their high damage tolerance, or the insertion of ductile resin interleaf between each carbon fibre/epoxy layers [16]. An alternative to the toughened resins is the use of advanced textile technologies with substantially improved delamination resistance [6, 17]. It was demonstrated that G_{IC} values for the knitted composites are about 10 or 20 times higher than for the uniweave composite [6]. However, studies developed by Mahadi *et al* [12] showed that the resistance to crack growth depends on the manufacturing process used.

Others parameters show great influence on the interlaminar fracture toughness. The influence of fibre direction was studied by Miyagawa *et al* [18] and lower values were obtained with samples whose fibre direction was 90º. Chen *et al* [7] observed that the values of G_{Ic} in stable propagation have a dropping tendency with increasing fibre content in the range of 21%-39%. The results show also that the increase of fibre volume content promotes fibre bridging. On the other hand the interfacial properties and weave structure affect the mode I interlaminar fracture toughness as reported by Kotaki and Hamada [9]. The study of these authors showed that the delamination patterns changed from stable to unstable with increasing content of silane coupling agent and with decreasing number of fibre strands transverse to the crack growth direction. Unstable fracture occurs at tougher regions caused by transverse fibre strands and modified resin affected by silane coupling agent. The crack growth was analyzed, via acoustic emission technique, by Kostopoulos *et al* [19], who classified the acoustic emission activity in four different classes. Class 1 is attributed to matrix cracking damage and is the most populated (appears from the beginning of the test until its end) while the class 2 results from the fibre/matrix interfacial debonding/fracture phenomena. Class 3, in parallel with class 2, results from the failure of the bridging fibres and class 4 is considered as mechanical and/or electronic noise.

In this context it is very important for design purposes to understand the interlaminar fracture toughness properties of fibre reinforced composite materials. If the double cantilever beam (DCB) tests present consensus in international community to obtain the mode I fracture, for mode II the most popular tests are the end-notched flexure (ENF), end-loaded split (ELS) and the four-point end-notched flexure (4ENF) [20]. However, Morais and Pereira [20] showed that the ENF specimen combined with the ECM (effective crack method) is the best solution for the characterization of mode II fracture with some advantages like simplicity, negligible friction effects and low tendency for geometric non-linearity.

This paper describes an experimental study developed to characterize mode I fracture toughness using DCB in carbon/epoxy woven composites. Numerical studies based on the finite element method were also developed to obtain the strain energy release rate and to characterize interlaminar crack growth using a cohesive energy method. Good agreement was observed with the experimental results. Finally, the effect of initial crack length was simulated on order to obtain its effect on the interlaminar fracture toughness.

EXPERIMENTAL PROCEDURE

Composite laminate sheets were manufactured using twelve woven, balanced, bi-directional, layers of carbon fibres (with 196 g/m^2) all of them with the same orientation 0/90º, and an epoxy resin matrix. Fibres and resin were hand placed in a mould and subjected to low compression. The mould was then put into a vacuum bag during 8 hours for room temperature curing. The fibre volume fraction (V_f) was 0.66 and the average plate thickness was 3 mm. Details about the manufacture process of the composites laminates can be found in previous work of the authors [21]. A 40 µm PTFE film was used to generate the starter crack, introduced into the plates during moulding of the laminates.

Figure 1 shows the fibre distribution along the longitudinal direction, and misalignment is evident. This misalignment presented some variation along longitudinal axle. The angle misalignment of fibre was determined using the Designer 6.0 software applied on lateral view photos. An average angle of 5.2º was obtained with a standard deviation of 1.7.

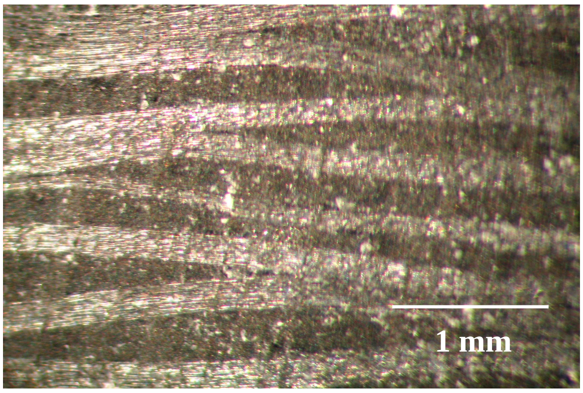

Figure 1: Lateral view showing the fibre distribution along of the longitudinal direction of the specimen.

The experimental work involved double cantilever beam (DCB) tests. The specimens of composite material were cut with a diamond table saw from the original plates, which were 300 mm long and 100 mm wide, aligned with one fibre direction. The geometry and dimensions of the specimens are shown in Figure 2. DCB specimens were used with 180 mm length, 25 mm width and initial crack (a_o) of 30 mm. Two piano hinges were bonded to both surfaces of the specimen at the cracked end for load transmission. The piano hinges and the specimens were grit-blasted with sandpaper before bonding and then cleaned with alcohol impregnated soft paper. The adhesive used for bonding was an Araldite 420 A/B bi-component. The DCB tests were performed in tension, according to ASTM D 5528-01 [22], using an electromechanical machine, Shimadzu model AG-X, equipped with a 1kN load cell. The load level, the displacement and the crack length were recorded during the tests. Figure 3 shows the test apparatus.

For each condition five samples was tested and the experiments carried out with the crosshead velocity of 0.5 mm/min [18]. In all samples one of the edges was painted with nail varnish and then several marks were made to facilitate the determination of the crack length

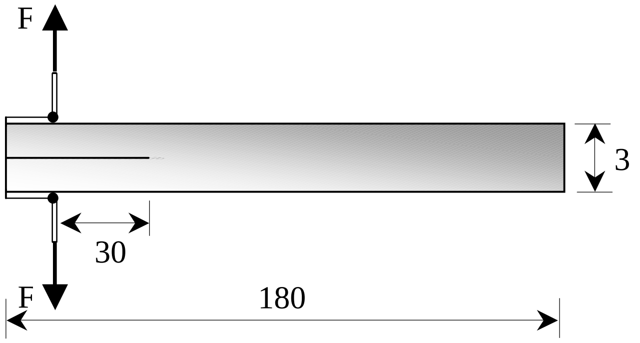

Figure 2: DCB specimen (Mode I), dimensions in mm.

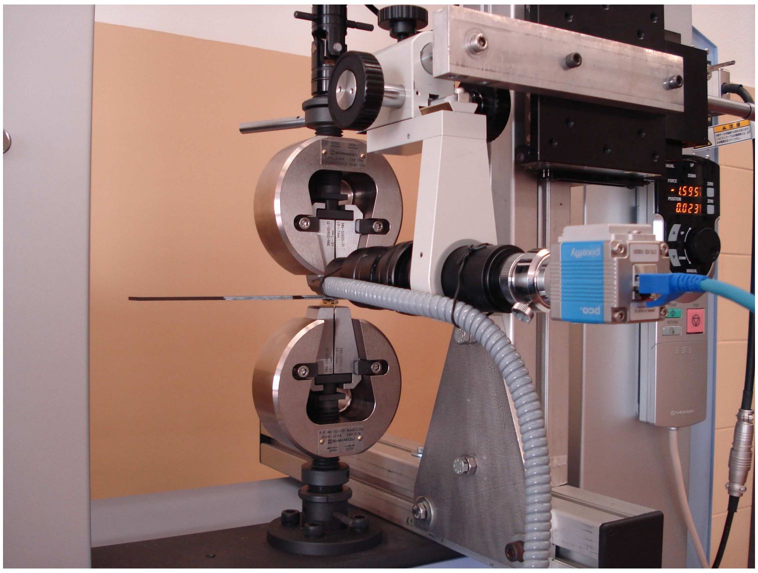

Figure 3: DCB test apparatus with video image.

EXPERIMENTAL RESULTS

Figure 4 shows typical experimental load-displacement curves from the DCB tests. These curves were reproducible and similar to other reposted literature results. However load drops are evident indicating large instantaneous delaminations. According to the study developed by Kotaki and Hamada [9] the unstable fracture occurs at tougher regions caused by transverse fibre strands. In fact it is possible to observe in figure 1 regions with reduced amounts of resin, where the fibres practically contact, while other regions are rich in resin. Therefore there are regions with different toughness and consequently unstable propagation occurs. As a consequence of this phenomenon the crack length measurement was found to be difficult, therefore a large scatter was observed. Figure 5 shows the energy release rate for mode I. The formulation used to obtain G can be found in the work of Morais and Pereira [20]. For the DCB specimen the peak of G_{Ic} was obtained at a crack length of 35 mm and the maximum value obtained was 500 J/m^2.

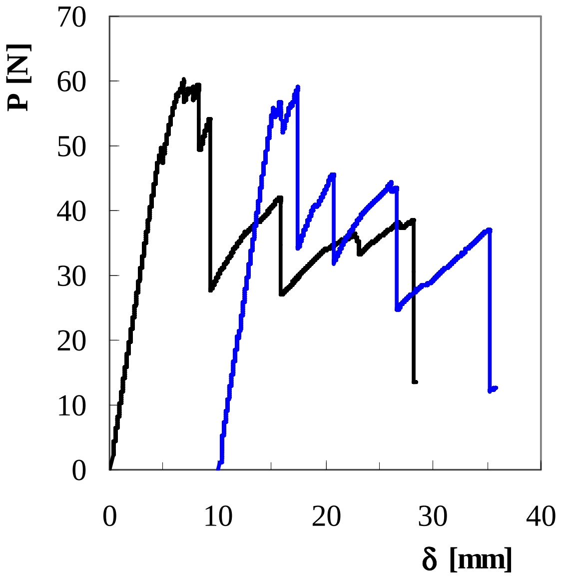

Figure 4: Typical load-displacement curves for the DCB tests.

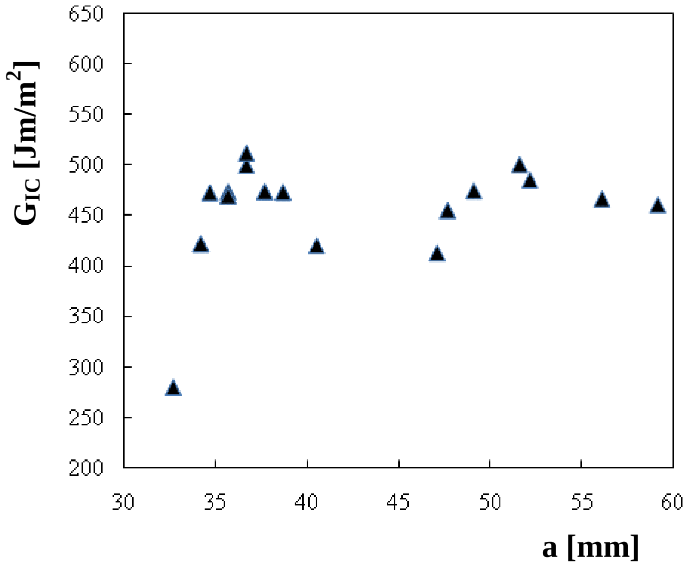

Figure 5: G_{Ic} versus crack length.

NUMERICAL SIMULATION OF DELAMINATION

Interface elements were considered at the interface to simulate the crack propagation by delamination. The strain measures at the interface elements were the relative displacements between the top and bottom edges. The relative displacements are combined in an equivalent value and the constitutive behavior of the interface elements is defined in terms of an equivalent traction versus the equivalent relative displacement. The area below the traction-displacement curve is called the cohesive energy, or critical energy release rate (G_{Ic}). The displacement corresponding to the initiation of damage is called critical displacement, v_c, as illustrated in Figure 6. Figure 6b shows the deformed shape of DCF specimen and the final crack length resulting from damage progression.

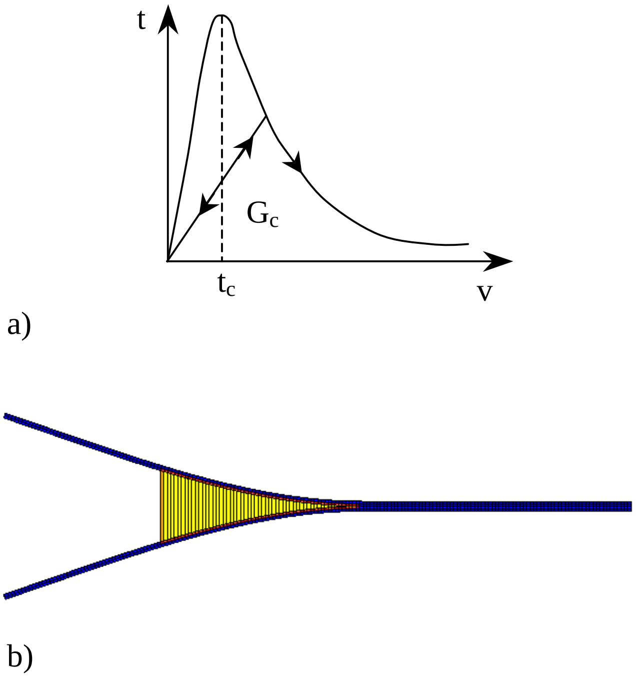

Figure 6: a) Exponential damage model. b) Deformed shape of DCB specimen.

Figure 7 presents the numerical predictions obtained for the DCB specimen considering different parameters. The global shape of the numerical load versus displacement curve agrees with the experimental curve (figure 4). This indicates that the delamination elements are adequate to model damage propagation in the carbon-epoxy laminate. At the beginning of loading there is a linear region without delamination, corresponding to the elastic deformation of material. The decreasing region of the force-displacement curve corresponds to the progression of the damage. Variations of 10% were introduced in G_{Ic} and v_c. The cohesive energy (G_c) and the critical displacement (v_c) have a major influence on the descending region of the load versus displacement curve, corresponding to damage progression, as figures 7b and 7c illustrate. Finally, the initial crack length has a major influence on the linear region of the curve, i.e., affects the initial rigidity of the specimen, but has no influence on damage progression (figure 7d).

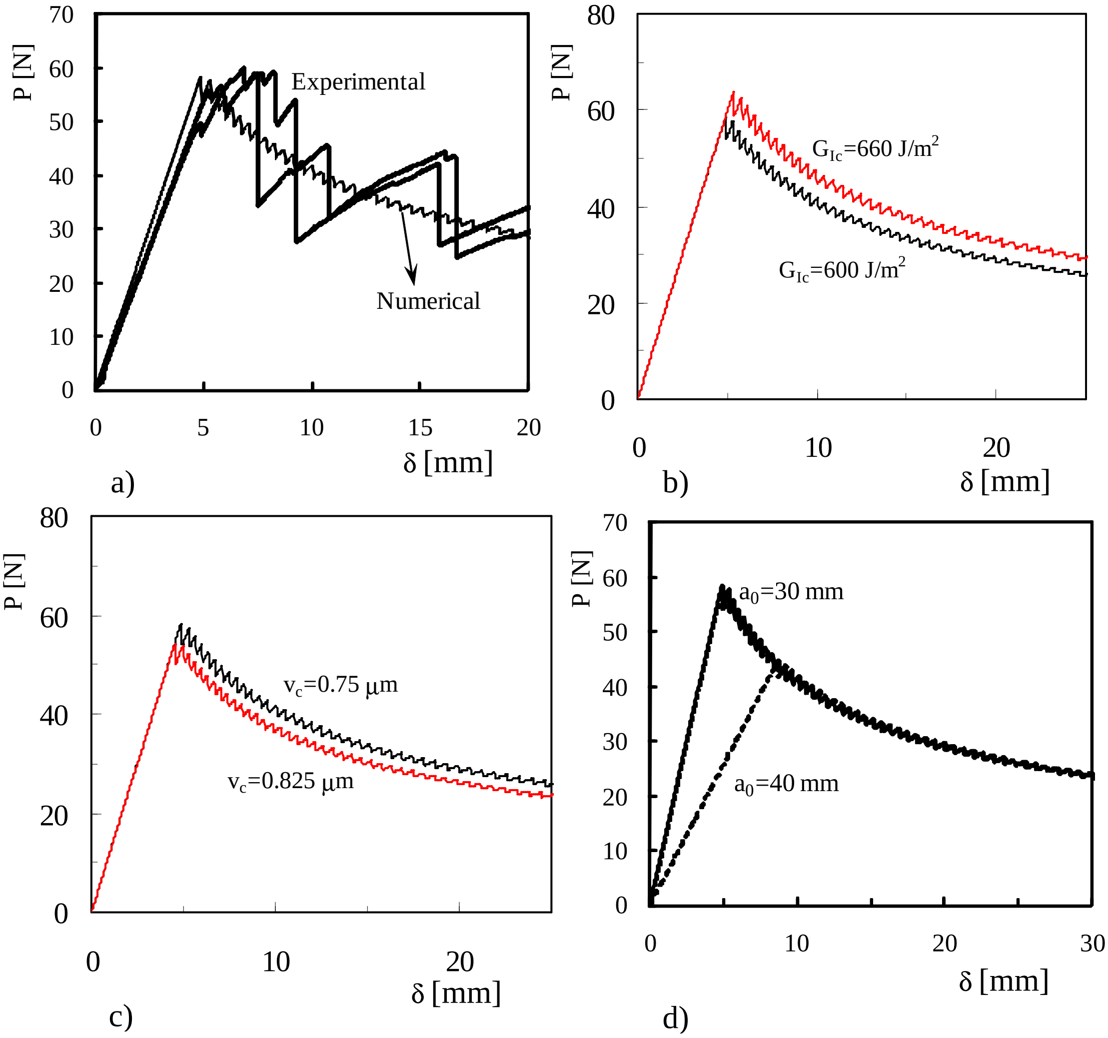

Figure 6: a) Experimental results versus numerical predictions. b) Influence of cohesive energy (G_c); Influence of critical displacement (v_c). d) Effect of initial delamination length. (E= 40.89e^{9}Pa; G_c=600 N/m; v_c=7.5E-07 m; t=2.8 mm; ν= 0.26; a_0= 30mm).

CONCLUSIONS

The delamination of woven carbon-epoxy laminated composites was studied using mode I DCB specimen. The main conclusions are listed below.

- Notched specimens were prepared, and tested under quasi-static loading, in order to obtain the load-displacement curves and energy release rate versus crack length. Significant instantaneous delaminations were observed for all DCB specimens. The mode I critical energy release rate showed oscillatory behaviour, explained by the instantaneous delaminations. The maximum value obtained for G_{Ic} was 500 J/m^2.

- Delamination was modeled using interface elements together with a cohesive energy method and good agreement was found between the load versus displacement curves obtained numerically and experimentally. A relatively high sensitivity was found relatively to the numerical parameters of the damage model (G_{Ic} and v_c). The increase of initial crack length was found to produce a decrease of rigidity, but the damage progression was not affected.

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