DELAMINATION RESISTANCE IN RANDOM AND ALIGNED CNF-GFRP MULTISCALE STRUCTURAL COMPOSITES

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Abstract

The improvement in mode-I interlaminar fracture toughness of glass fiber reinforced polymer (GFRP) laminates was explored in detail while carbon nanofibers are used as reinforcements with the epoxy matrix. Fracture tests with double cantilever beam (DCB) laminates were used to characterize the mode-I interlaminar fracture toughness and traction separation parameters. The mode-I traction separation parameters for delamination were identified for control laminates as well as for the CNF-GFRP DCB laminates. The effect of through thickness CNF alignment on interlaminar fracture toughness as well as on the traction separation parameters was also investigated. FE simulation was performed using the experimentally obtained TSLs to predict the load-displacement responses of control GFRP, random and aligned CNF-GFRP DCB laminates.

1. Introduction

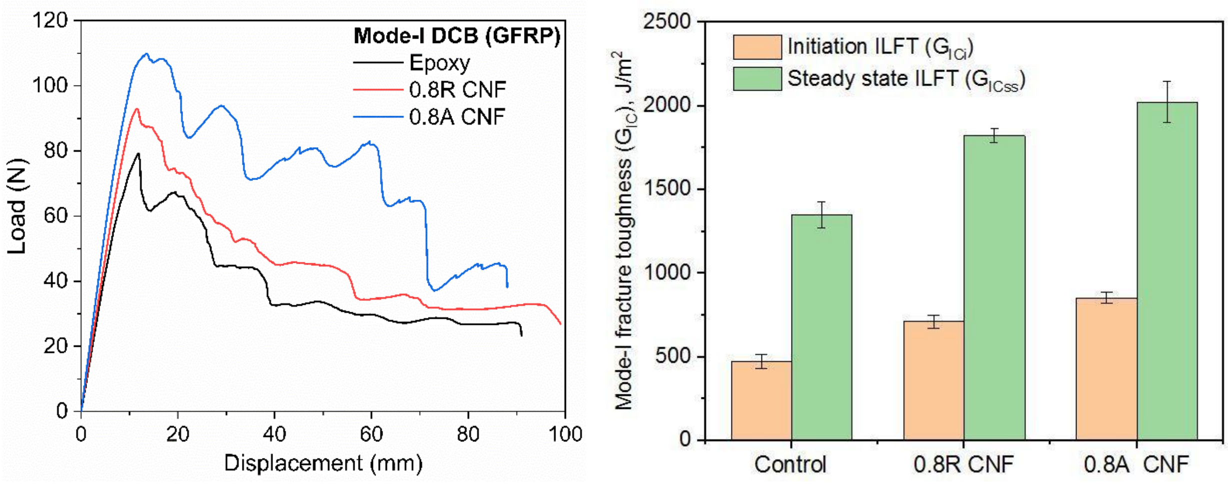
The use of fiber reinforced polymer composites (FRPs) is becoming prominent in aerospace, automotive, marine, and renewable energy applications owing to their high specific strength and stiffness. Those FRPs possess excellent in-plane properties, however, they lack out-of-plane mechanical properties. The poor out-of-plane mechanical properties induce delamination that can cause catastrophic failure of those composite structures. Though there are different modes of delamination, study on mode-I received maximum attention as the mode-I interlaminar fracture toughness is the lowest compared to all the three pure modes of fracture. One of the ways to increase the mode-I delamination resistance/interlaminar fracture toughness (ILFT) is to use through-thickness reinforcement (especially carbon-based nanofillers) between the laminas. Carbon-based nanofillers (specially carbon nanotube, CNT and carbon nanofiber, CNF) have superior physical properties and their addition confers multi-functionalities to the composites. The usual dispersion of carbon nanofillers in matrix is random and does not provide significant enhancement in properties. However, it was already proven experimentally and numerically that the arrangement of carbon nanofillers in a particular orientation can better contribute to mechanical load bearing or resistance to crack propagation.

A fracture mechanics approach was proposed in this study to characterize and to propose design methodologies for the mode-I delamination resistance of multiscale composite structures. Double cantilever beam (DCB) specimens of E-glass fiber/epoxy (control GFRP) and CNF doped GFRP were fabricated by hand layup and vacuum bagging method. DCB specimens with aligned CNF (in the through thickness direction) were also fabricated by applying an AC electric field during the curing of the laminate. The delamination resistance or ILFT of control GFRP, random and aligned CNF-GFRP was measured by conducting mode-I fracture test. Digital image correlation of crack tip images were conducted to extract corresponding traction separation law (TSL) of those laminates. Comparing the extracted TSL parameters and ILFT obtained were analyzed to understand the effect of CNF addition and alignment. Experimentally obtained TSL parameters were also used for the numerical prediction of load-displacement responses.

2. Results

The mode-I fracture tests of all DCB specimens were conducted at a displacement rate of 1 mm/min and the typical load-displacement responses of control GFRP, random, and aligned CNF-GFRP specimens are shown in Fig. 1a. The crack initiation during the loading was observed with a travelling microscope and the initiation interlaminar fracture toughness was determined using the observed load and displacement values at visual crack initiation. Obtained R-curve (through compliance based beam method) showed the initial increasing trend in the interlaminar fracture toughness followed by a steady state propagation zone.

As can be seen from Fig. 1a, the peak load values were increased with the addition and alignment of CNF. The mode-I initiation ILFT (G_{ICi}) was increased by ~50% and ~80% in the case of 0.8 wt% random and aligned CNF-GFRP DCB, respectively, compared to the control GFRP DCB. The improvement in the steady state fracture toughness (G_{ICss}) was also found to be enhanced by ~35% and 50%, in the case of random and aligned CNF-GFRPs (see Fig. 1b). The enhancement in the interlaminar fracture toughness could be because of crack-bridging, void growth of the matrix, and crack deflection due to the presence of CNF. The through thickness alignment of CNF could contribute better in the crack bridging thereby resulted in more improvement. A detailed scanning electron microscopy was also conducted to reveal the toughening mechanisms.



(a) **(b)**

Fig. 1 – (a) Experimental load-displacement responses and (b) interlaminar fracture toughness of control GFRP, 0.8 wt% random and 0.8 wt% aligned DCB specimens,

The crack tip images were recorded during the crack initiation period and later analyzed using digital image correlation (DIC) software to obtain the fracture toughness vs. crack tip opening displacement (G vs CTOD) profile. The G vs CTOD response was fitted using 6th degree polynomial and then differentiated to obtain the traction separation plot. The traction separation parameters for control GFRP, random and aligned CNF-GFRP were analyzed to find out the effect of CNF addition and alignment and also used for the numerical prediction of load-displacement responses of all DCB specimens.

3. Conclusions

The effect of CNF addition and their through thickness alignment on the mode-I interlaminar fracture toughness of GFRP laminates was conducted in this study. Both random and aligned specimens showed higher fracture toughness compared to control GFRP, however, the alignment resulted in comparatively higher initiation and steady state fracture toughness. The experimentally obtained traction separation parameters for all specimens also revealed the failure mechanisms in a better way and could be used successfully for the prediction of load-displacement responses.