ACCURATE CHARACTERIZATION OF MODE II INTRALAMINAR DELAMINATION FRACTURE TOUGHNESS IN INTERLAYER-TOUGHENED CFRP

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Abstract

The crack growth behavior of intralaminar delamination is different from that of interlaminar delamination and longitudinal intralaminar matrix crack owing to the difference in the level of fiber misorientation. Intralaminar and interlaminar delamination fracture toughness behaviors under mode II loading were investigated with non-toughened and interlayer-toughened unidirectional CFRP laminates by four point end notched flexure tests. The intralaminar fracture toughness of interlayer toughened CFRP was less than half of the interlaminar fracture toughness of the same laminates, and the intralaminar fracture toughness of interlayer-toughened CFRP laminates was almost identical to the interlaminar and intralaminar fracture toughness of non-toughened CFRP laminates. Thus, the intralaminar fracture toughness was not influenced by interlayer-toughening. It is also interesting to note that there was little difference between intralaminar and interlaminar fracture toughness from the initial values to propagation values for non-toughened CFRP. This behavior is quite different from that under mode I loading in which the fiber bridging effect was much higher for intralaminar fracture. The difference in the fracture mechanisms between intralaminar and interlaminar fracture was investigated from the viewpoints of microscopic fracture mechanisms using high resolution X-ray computed tomography at the damaged zone near the crack tip.

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1. Introduction

Fracture modes parallel to fiber direction in carbon fiber reinforced plastic (CFRP) laminates are categorized as (a) interlaminar delamination, (b) intralaminar delamination, (c) longitudinal intralaminar matrix crack, and (d) transverse intralaminar matrix crack as shown in Fig. 1 [1]. When the crack growth direction is parallel to fiber direction, the crack growth behavior of (b) intralaminar delamination is different from that of (a) interlaminar delamination and (d) longitudinal intralaminar matrix crack. Firstly, the local fiber volume fraction of the interlaminar resin-rich region is typically lower than that of intralaminar fiber-rich region. Secondly, the level of fiber misorientation in X-Y plane is often higher than that in X-Z plane. Though the fracture properties for intralaminar delamination are similar to those for longitudinal intralaminar matrix crack, the fracture toughness of longitudinal intralaminar matrix crack possibly gives non conservative values owing to higher contribution of fiber bridging.

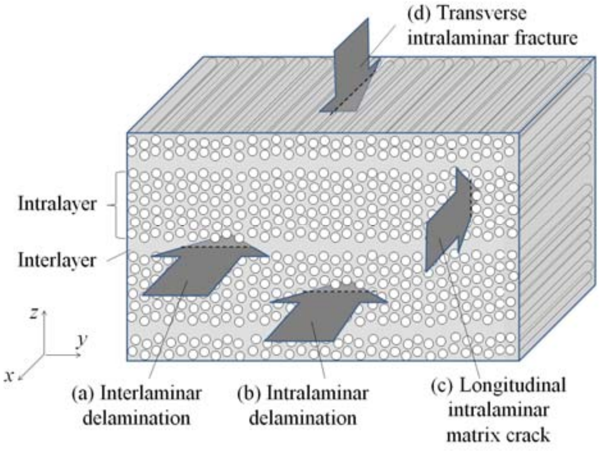

Figure 1. Schematic drawings of intralaminar and interlaminar delamination.

In our previous study, a new initial crack insertion method, "intralaminar film insertion method" was developed to evaluate the mode I intralaminar delamination crack growth properties [2]. Here, a release film was inserted inside a single lamina prepreg. In the present study, intralaminar and interlaminar delamination fracture toughness behaviors under mode II loading were investigated with non-toughened and interlayer-toughened unidirectional CFRP laminates by four point end notched flexure (4ENF) tests.

2. Experimental procedure

2.1. Materials and specimens

Unidirectional laminates with a nominal thickness of 3.6 mm (for intralaminar tests: $(0)_{19}$) and 3.8 mm (for interlaminar tests: $(0)_{20}$) were fabricated from carbon fiber/epoxy prepregs of Toray T800S/model epoxy/(PA12 particles). Both non-toughened laminates and interlayer-toughened laminates with heterogeneous interlayer of PA12 particles and neat resin were prepared. Starter slits were introduced into the laminates by inserting single 13 μm thick PTFE film at midplane. For intralaminar delamination, "intralaminar film insertion method" was used [2]. Here, a PTFE release film was inserted inside a single lamina during the resin impregnation process of prepreg manufacturing. Four types of laminates were prepared for the tests. These are intralaminar and interlaminar delamination for non-toughened laminates, and intralaminar and interlaminar delamination for interlayer-toughened laminates.

End notched flexure (ENF) specimens were used for tests under mode II loading. Four-point ENF (4ENF) tests were carried out for static fracture toughness tests in order to stabilize crack growth [3,4]. Specimens of width, B = 12.8 mm, length between the supports, 2L= 100 mm, length between the loading noses = 60 mm were used for 4ENF tests. To avoid the friction between fracture surfaces, a PTFE film of thickness of 50 μm was inserted in the initial crack at the position above the left support. Mode I precracks of 2-4 mm in length were introduced in all specimens.

2.2. Fracture toughness test

The energy release rate under mode II was calculated using experimentally obtained compliance curves for each specimen. Here, the equations were designated to avoid the effect of the specimen thickness [5]. The tests were carried out in a computer-controlled servohydraulic testing system (Shimadzu 4830, 49 kN). A load cell of 2.45 kN in capacity were attached for tests. The cross head

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speed was 0.2 mm/min. Initial values of the fracture toughness, G_{IIC}, were determined from the onset of nonlinearity in the initial load-loadline displacement curves (NL point) [6].

Microscopic damage near the crack tip was observed using high resolution X-ray computed tomography (Xradia XRM-410 Versa). The area of the diameter =1.9 mm and length = 1.9 mm in fiber direction was observed.

3. Results and discussion

Fig. 2 shows the relationship between the mode II fracture toughness and the crack extension for intralaminar and interlaminar delamination in non-toughened and interlayer toughened laminates. The intralaminar fracture toughness of interlayer toughened CFRP was less than half of the interlaminar fracture toughness of the same laminates, and the intralaminar fracture toughness of interlayer-toughened CFRP laminates was almost identical to the interlaminar and intralaminar fracture toughness of non-toughened CFRP laminates. Thus, the mode II fracture toughness of the interlayer-toughened CFRP much depends on the crack growth paths, and the intralaminar fracture toughness was not influenced by interlayer-toughening. It is also interesting to note that there was little difference between intralaminar and interlaminar fracture toughness from the initial values to propagation values in non-toughened laminates. This behavior is quite different from that under mode I loading in which the fiber bridging effect was much higher for intralaminar fracture [2].

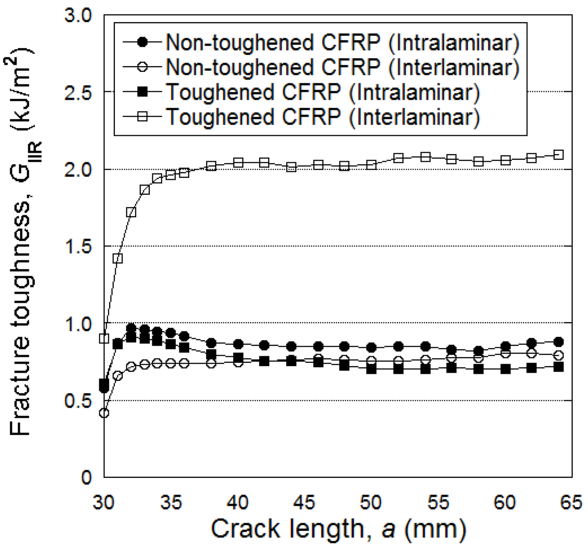

Figure 2. Relationship between fracture toughness and crack length for intralaminar and interlaminar delamination in non-toughened and interlayer toughened CFRP.

The difference in the fracture mechanisms between intralaminar and interlaminar fracture, and mode II and I fracture was investigated from the viewpoints of microscopic fracture mechanisms using high resolution X-ray computed tomography at the damaged zone near the crack tip. Fig. 3 indicates the number of density of fiber bridging in non-toughened laminates. The total number of fiber bridging (= unbroken fiber bridging + broken fiber bridging) is almost constant without respect to the distance from the crack tip. The number of density of fiber bridging for intralaminar delamination (= 58 mm^{-2}) is much larger than that for interlaminar delamination (= 34 mm^{-2}).

Figure 4 shows the comparison of the number of bridging fibers between mode I and II. It is clear that the contribution of bridging fiber under mode I is much more than that under mode II. This figure also indicates the clear difference between the intralaminar and interlaminar delamination under mode I. This is responsible for the different R-curves between intralaminar and intralaminar delamination [2].

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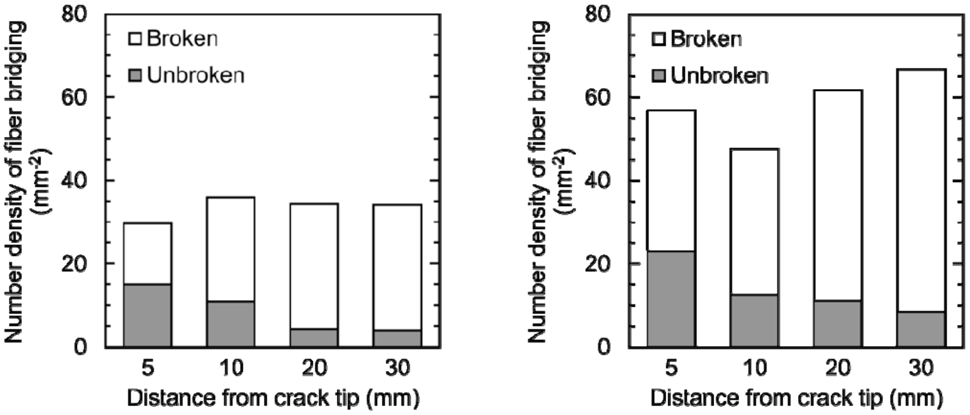
A model was proposed to investigate the contribution of fiber birding to the increase in toughness from the initial value for R-curves. Here, contribution of each fiber bridging are summarized by counting debond of fiber from matrix and fracture of fiber bridging. The results showed that the contribution of fiber bridging is minimal, suggesting that the contribution of micro damage at the crack tip is much larger. Further investigation is urgently required.



(a) Interlaminar delamination (b) Intralaminar delamination

Figure 3. Density of fiber bridging near the crack tip in non-toughened laminates.

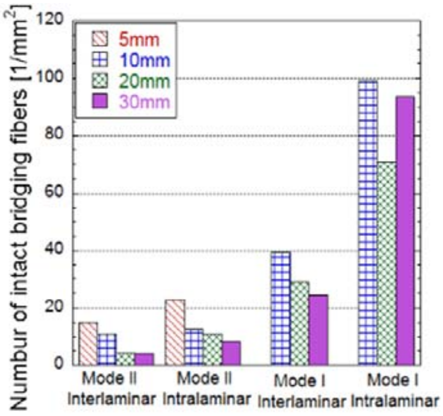


Figure 4. Comparison of number of intact bridging fibers between mode I and II in non-toughened laminates.

4. Summary

Intralaminar delamination fracture toughness under mode II loading was firstly investigated in CFRP laminates. Both non-toughened and interlayer-toughened laminates were investigated. The intralaminar fracture toughness of interlayer toughened CFRP was less than half of the interlaminar fracture toughness of the same laminates, and the intralaminar fracture toughness of interlayer-toughened CFRP laminates was almost identical to the interlaminar and intralaminar fracture toughness of non-toughened CFRP laminates. Then, the intralaminar fracture toughness was not influenced by interlayer-toughening. It is also interesting to note that there was little difference between intralaminar and interlaminar fracture toughness from the initial values to propagation values in non-toughened laminates.

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