Dynamic Interlaminar Fracture Toughness in Polymeric Composites

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SUMMARY: A modified ENF specimens with off mid-plane delamination precrack was used to determine the mixed mode dynamic interlaminar fracture toughness of fiber composites at high crack propagation speeds. A strip of FM-73 adhesive film was placed ahead of the tip of the delamination crack created during laminate lay-up to increase the crack initiation toughness so that after initiation an unstable crack propagation could be produced and high crack propagation speeds achieved. A finite element model was used for the numerical simulation of dynamic crack propagation. Dynamic delamination experiments were performed on modified ENF specimens of unidirectional AS4/3501-6 graphite/epoxy composite under three point bending. The results showed that the dynamic fracture toughness is not affected significantly by crack speed up to 1100 m/s.

KEYWORDS: dynamic crack propagation, interlaminar fracture toughness, unidirectional composites.

INTRODUCTION

Delamination or interlaminar cracking is one of the predominant modes of damage in composite structures. The growth of delamination results in progressive stiffness degradation and eventual failure of composite structures. Thus, the study of the parameters characterizing and influencing delamination fracture is essential in the design and analysis of composite structures.

Delamination in composite structures is often induced by impact loading and delamination cracks often extend dynamically. The question is often asked whether statically measured delamination fracture toughness is valid for dynamic delamination. To answer such a question, dynamic interlaminar fracture toughness of the composite must be measured. Evidently, the essential part of the work requires producing high speed delamination crack propagation.

So far, few experimental investigations on dynamic delamination propagation in composite materials have been reported. Guo and Sun [1] used a modified DCB specimen to produce high speed Mode I crack propagation in polymeric composites. They found that the Mode I dynamic fracture toughness of unidirectional AS4/3501-6 is equal to the static fracture toughness for crack speeds up to 200 m/s. However, the speeds produced in [1] were relatively low compared with the Rayleigh surface wave speed. In using DCB specimens for the Mode I fracture test, high crack speeds cannot be achieved because the part of the specimen ahead of the crack tip is unstressed and the energy needed to sustain crack propagation comes from behind the crack tip. Consequently, crack propagation speed drops quickly after the onset of crack propagation.

In this study, a modified ENF specimen with a tough precrack tip was used to produce high velocity crack propagation in unidirectional composites. The measured crack speed histories were used in conjunction with a finite element simulation model from which the dynamic delamination fracture toughness was obtained.

SPECIMEN DESIGN AND EXPERIMENTAL PROCEDURE

The material tested was Hercules AS4/3501-6 graphite/epoxy composite. The specimen used in the test was similar to the conventional ENF (end-notch flexure) specimen but with the delamination crack placed off the mid-plane to produce mixed mode deformation. As shown in Fig. 1, a piece of FM-73 film adhesive 2.5 mm thick was placed ahead of the crack tip to increase initial fracture toughness. Load was applied quasi-statically at the rate 0.025 mm/s using the three-point-bending setup on an MTS mechine. During the experiment, a small pin of diameter 2.5 mm was inserted into the precrack to increase the initial crack opening.

Twelve conductive lines of pure aluminum were deposited along the path of the propagating crack using the vapor deposition technique. These conductive lines were 0.2 mm thick with a spacing of 4 mm. Because AS4/3501-6 graphite/epoxy is a conductive material, a layer of insulating material must be applied to separate the conductive line circuit from the surface of the specimen. The surface of the specimen on which the conductive lines were applied was sanded first, and then very thin layer of enamel was sprayed on evenly. These conductive lines were broken as the crack passed through yielding the crack tip location as a function of time. All conductive lines were connected to a specially designed circuit [2] which yielded output of square wave-like signals with each rising or falling edge corresponding to the breakage of a conductive line. The output signals were recorded by an oscilloscope at a sample rate of 5 MHz. Continuous records were obtained for the applied load, defection at the loading point, and crack extension history.

NUMERICAL ANALYSIS

In this study, numerical simulations of dynamic crack propagation was performed using the commercial FEA code ABAQUS (Version 5.4). Crack propagation was simulated by using the interface element (INTER2) along the assumed crack path. At the beginning of the analysis, crack surfaces which would be generated was modeled as bonded surfaces connected by the interface elements with zero thickness. When the crack began to propagate, debonding was allowed to occur in the interface elements at a particular point in time, which depended on the position of the crack tip with respect to the reference point. The crack tip position history was provided as ABAQUS input file. Because the interface elements can be used only in conjunction with a 2-D plane element, this simulation can be used only for 2-D deformation. In this study, 2-D plane strain elements were used to model the whole specimen.

Because the loading rate was very slow compared with the crack speed, in the numerical simulation the displacement of the loading point was assumed constant during crack propagation. The simulation was performed with many steps. In each step, the crack length was increased by the size of one element ahead of the crack tip. At the beginning of each step, the pair of nodes at the current crack tip were released and the nodal forces, which were equal to the reaction forces at the crack tip before nodal release, were applied at these nodes simultaneously. These nodal forces were reduced to zero linearly within a specific time interval. Crack propagation with varying speeds were simulated by using different time intervals in each step. The modified closure method [3] was used to calculate the strain energy release rate. Because this was a simulation based on actual test condition, the calculated total strain energy release rate should be regarded as the dynamic fracture toughness.

RESULTS

For each specimen, the crack tip location history was recorded using the conductive lines. By the least squares method, these discrete data points were fitted into a continuous crack extension curve from which the crack speed history was obtained by taking the derivative. Fig 2 shows a typical crack speed history curve (the solid lone). The crack speed is seen to increase and then drop gradually as it propagates. Noting that there is a short distance between the precrack tip and the first conductive line and that the actual crack speed should start from zero, we modify the crack speed history by adding a transition stage represented by the dashed line shown in Fig. 2. The added portion was obtained by assuming that the crack attained the initial (measured) value at a constant acceleration.

The obtained crack extension history curve was used as input for the numerical simulation. For the quasi-static loading condition, the displacement of the loading point in the specimen was assumed as fixed during crack propagation and the crack propagation was simulated according to the given crack extension history. The numerical procedure described in the last section was used for the numerical simulation. Mode I and mode II dynamic strain energy release rate is shown in Fig. 3 from which it can be seen that mode II fracture dominated during mixed mode crack propagation. It should be noted that the initial portion of the dynamic strain energy release rate should not be considered valid because of the uncertain crack speeds in this region. The calculated dynamic strain energy release rates for four specimens against crack speed are shown in Fig. 4. For comparison, the critical static energy release rate is also presented in dashed line in the same figure. It is evident that the dynamic fracture toughness seems to remain essentially the same as the static fracture toughness for crack speeds up to 1100 m/s.

DICUSSION

The strain energy release rates G and the stress intensity factors K are interchangeable in static linear elastic fracture mechanics. However, the G-K relation in dynamic crack propagation depends on crack speed [4]. It is interesting to note that in dynamic cracking, a constant G_c (with respect to crack speed) does not necessarily imply a constant K_c.

To show the effects of the crack speed on the G-K relation, the problem of a crack propagating in AS4/3501-6 graphite/epoxy under plane strain condition was chosen for numerical calculation. In the calculation, both K_I (Mode I) and K_{II} (Mode II) were assumed to be unity, and G_I and G_{II} were solved as functions of crack speed. The numerical solutions for AS4/3501-6 are shown in Fig. 5. We can see that both G_I and G_{II} are nearly constant in low speed range and increase sharply when the crack speed approaches the Rayleigh surface wave speed. Compared to G_I, G_{II} becomes less sensitive to the crack speed in a larger speed range and increases more sharply when crack speeds reach Rayleigh wave speeds. For AS4/3501-6 at the crack speed of 1100 m/s, which is about 50% of the Rayleigh surface wave speed, G_I increases by about 10% while G_{II} remains basically constant. Thus, for the range of crack speed considered in this study, the relationship between G and K can be considered not affected by crack speed.

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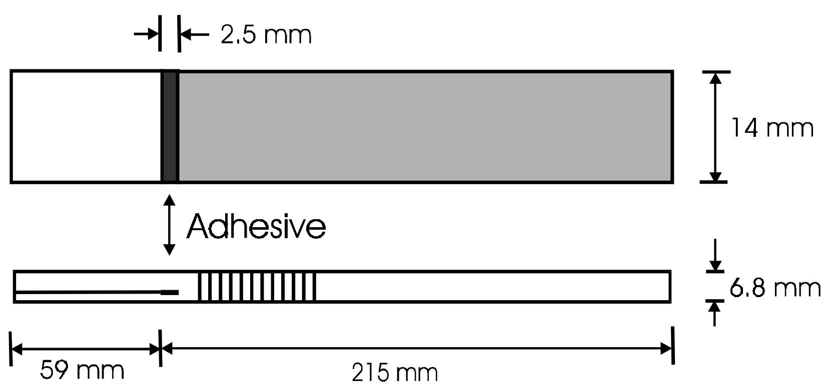

Fig. 1 : Dynamic fracture toughness v.s. crack speed for AS4/3501-6

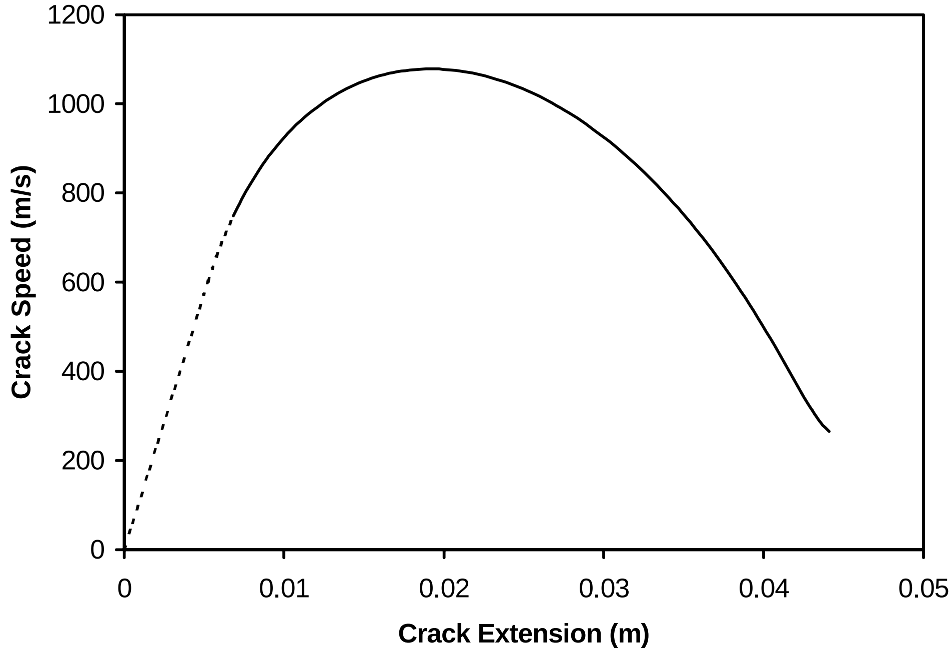

Fig. 2 : Strain energy release rate of specimen ZT17

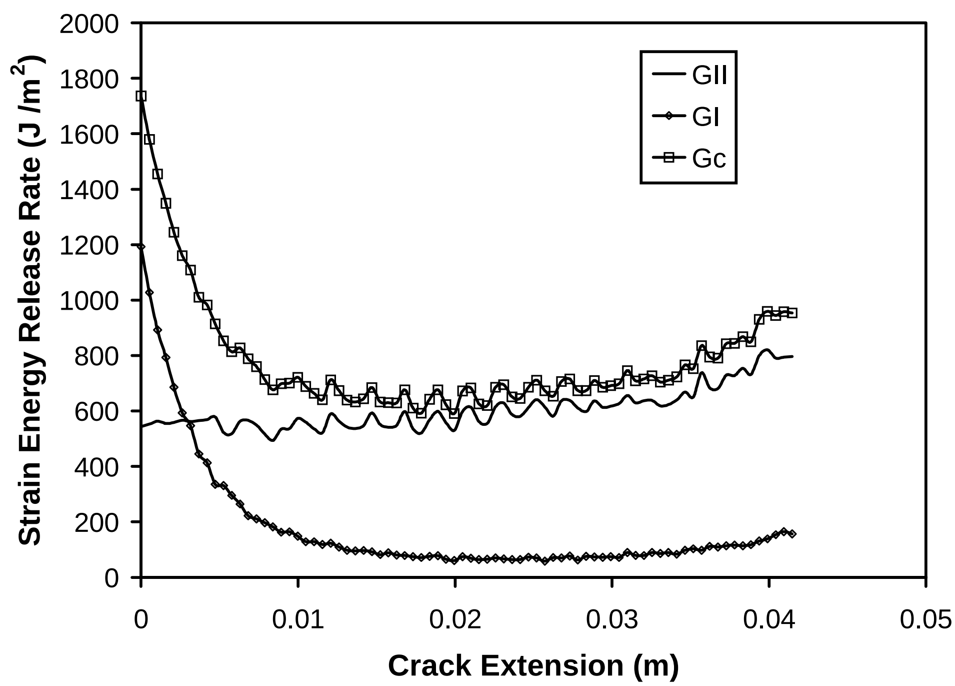

Fig. 3 : Mode I and Mode II strain energy release rate of specimen ZT17

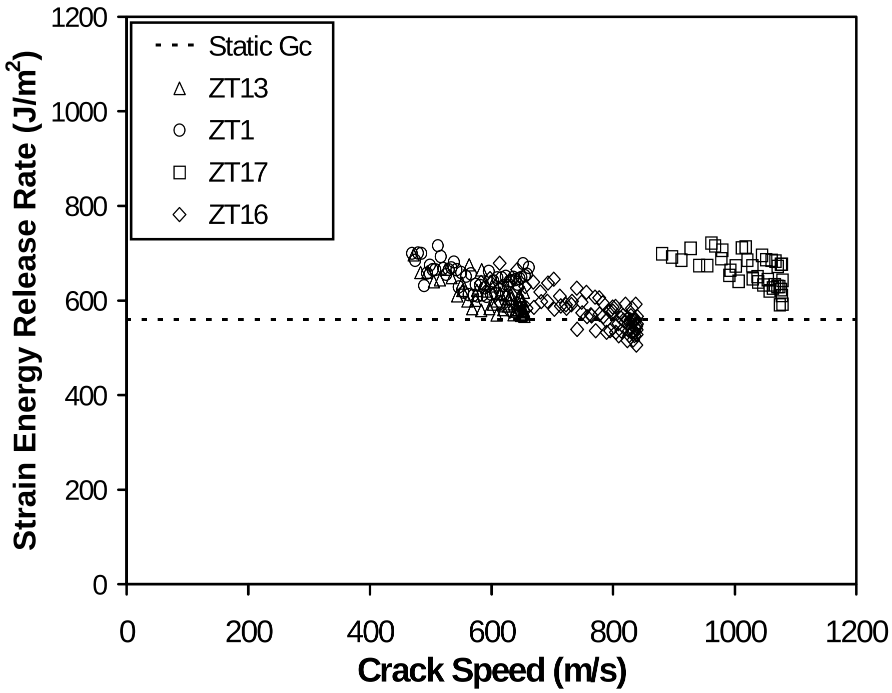

Fig. 4: Dynamic fracture toughness vs crack speed for AS4/3501-6

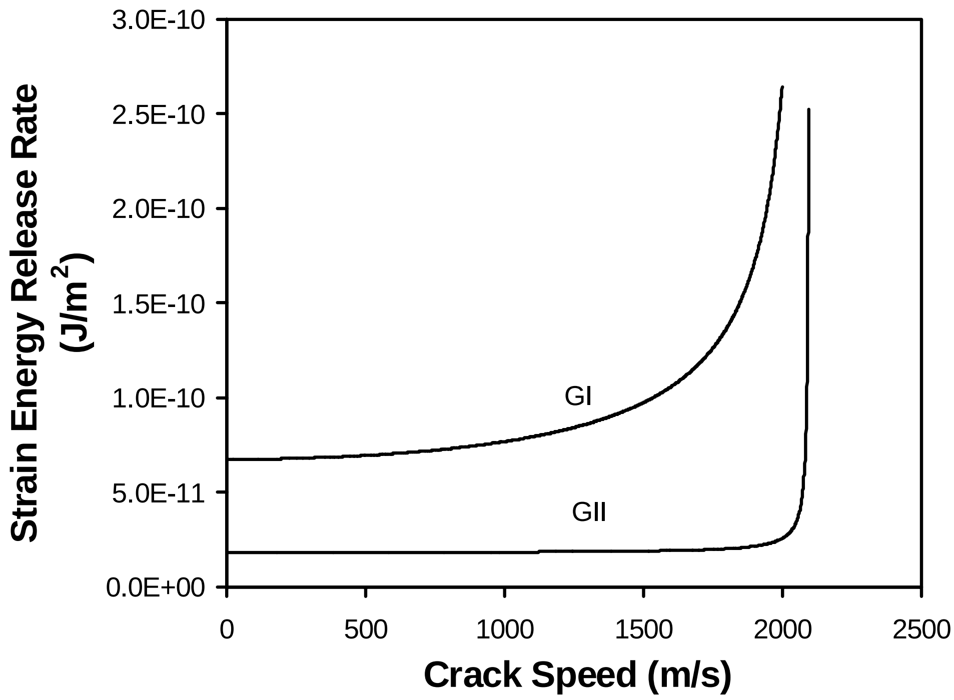

Fig. 5: Speed effect on the relationship between energy release rates and stress intensity factors of unidirectional AS4/3501-6