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THE EFFECT OF MIXED MODE PRECRACKING ON THE MODE I FRACTURE TOUGHNESS OF COMPOSITE LAMINATES*

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ABSTRACT

We subjected double cantilever beam specimens from four different composite materials to mixed-mode precracking. Three different precracking mode I to mode II ratios were used—1 to 4, 1 to 1, and 4 to 1. Following precracking the specimens were tested for mode I fracture toughness. The mixed-mode precracking often influenced the mode I toughness and its influence persisted for as much as 60 mm of mode I crack growth. We tested composites with untoughened matrices, composites with rubber-toughened matrices, and composites with interlayer toughening. Depending on material type and precracking mode ratio, the precracking could cause either a significant increase or a significant decrease in the mode I fracture toughness.

Key words: composites, interlaminar fracture toughness, fiber bridging, double cantilever beam specimen, end notch flexure specimen, energy release rate, fracture mechanics, delamination, mode I, mode II, mixed mode bending.

INTRODUCTION

Delamination or propagation of an interlaminar crack, is a common mode of failure in composite laminates. The presence of delaminations may cause complete fracture, but even partial delaminations will cause at least a loss of stiffness. The most common method for studying delaminations is to use fracture mechanics where the characterization is via the critical energy per unit crack growth—G_c. Because of the extreme anisotropy of the toughness of composite laminates, delamination crack growth is almost always interlaminar. By varying loading conditions, it is possible to study different modes of propagation. Some of the propagation modes observed in composites are not commonly observed in isotropic materials. The most obvious failure mode is mode I, the opening mode, which gives G_{Ic}. In certain bending geometries, the crack may propagate by sliding or shear motion, which is characterized by G_{IIc}. A combination of opening and shear loadings can give mixed mode crack propagation which is characterized by a failure envelope of G_{II} *vs.* G_I.

In this paper we looked at the effect of crack history on the mode I toughness or G_{Ic}. We subjected various specimens to mixed-mode precracking prior to a standard mode I test. We tested four different material types and found that crack history can have a significant effect on mode I toughness. The implication is that delamination is a complex process that not only depends on the current loading conditions, but also depends on the delamination formation history.

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NOMENCLATURE

a	delamination length
B	specimen width
c	position of the applied load on the lever
C	compliance
χ_h	crack length correction factor
δ	load point displacement
G_I	mode I strain energy release rate
G_{II}	mode II strain energy release rate
G_{Ic}	delamination fracture toughness for mode I loading
G_{IIc}	delamination fracture toughness for mode II loading
h	specimen half thickness
L	specimen half span
P	applied load

MATERIALS AND METHODS

The experiments were conducted on four different carbon fiber composite materials—AS4/3501-6, IM7/8552, IM7/XLASC, and IM7/2600. AS4/3501-6 and IM7/2600 are characterized as having homogeneous, untoughened epoxy matrices. IM7/8552 has a rubber toughened epoxy matrix. IM7/XLASC has a bismaleimide matrix with toughening interlayers between the plies. AS4/3501-6, IM7/8552, and IM7/XLASC were all made by autoclave processing according to the manufacturer's instructions. IM7/2600 was made in a hot press. All tested laminates were unidirectional laminates. The AS4/3501-6, IM7/8552, and IM7/XLASC laminates were 32 ply laminates. The IM7/2600 laminates were 24 ply laminates. All specimens were six inches long and one inch wide. An aluminium foil was inserted as a crack starter in the prepreg lay-up before autoclave curing. Hinges were glued to the ends of the specimens over the insert for mounting in the fixture described below.

There are various mixed mode testing methods available. In this study, the fixture developed by Reeder and Crews [1, 2] was used. Their mixed-mode bending (MMB) fixture combines a mode I double cantilever beam (DCB) test with a mode II end notch flexure (ENF) test. This combination is achieved by adding an opening mode load to a mid-span loaded ENF specimen as shown in Fig. 1. The additional load separates the arms of the unidirectional laminate as in a DCB test. A single applied load produces two reactionary forces, tensile and bending, at the hinge and at the lever. The loading position, c, determines the relative magnitude of the two resulting loads on the specimen and, therefore, determines the mixed-mode delamination ratio. Pure mode II loading occurs when the applied load is directly above the beam mid-span ($c = 0$). Pure mode I loading can be achieved by removing the loading beam and pulling up on the hinge. Mixed mode loading is achieved by varying c.

The Reeder and Crews [1, 2] MMB fixture was used to precrack the unidirectional delamination specimens. The initial crack length created by the aluminium foil crack starter was 20–35 mm. We precracked each specimen at a selected constant mixed-mode ratios until the delamination length was about 50 mm (15–30 mm of precrack growth). The precracking was done using three different ratios of mode I to mode II loading—4 to 1, 1 to 1, and 1 to 4. After precracking, each specimen

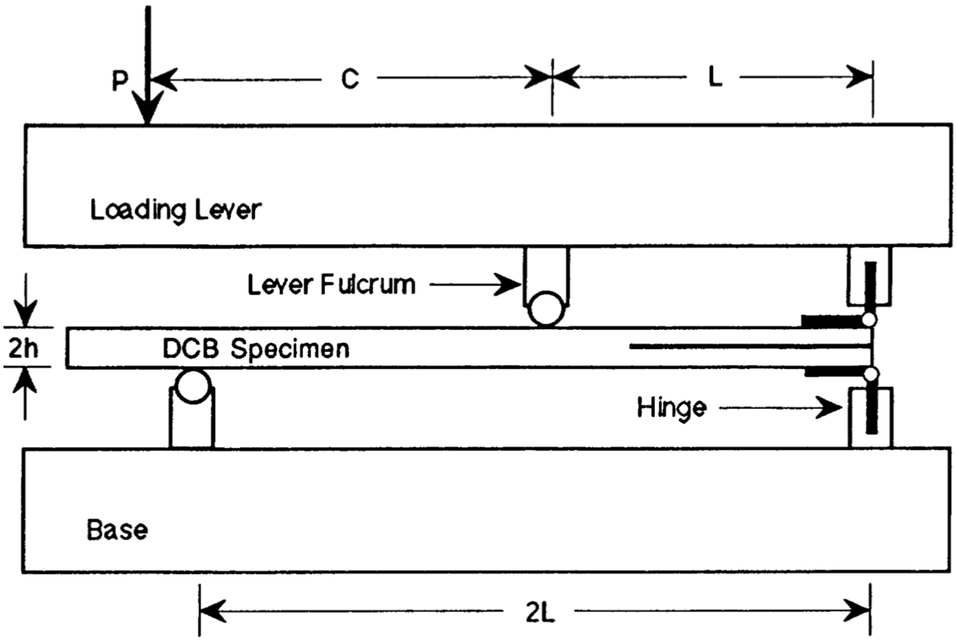

Figure 1: The mixed-mode bending fixture from Ref. [1] used to precrack DCB specimens at various mode I to mode II ratios. The mode I to mode II ratio was changed by varying c.

was subjected to a pure mode I delamination test. During the mode I delamination test, the load and displacement were noted after each 5 mm of delamination crack propagation. This data was used, as described below, to calculate fracture toughness as a function of delamination length. Both the mixed-mode precracking and the mode I test were done in a 25 kN servohydraulic Minnesota Testing Systems (MTS) testing frame under displacement control. The displacement rate was always 0.03 inches/min.

As described above, the mixed-mode precracking was followed by a mode I delamination test. According to the area method, the fracture toughness, or critical strain energy release rate in a mode I test is

$$G_{Ic} = \frac{P_1\delta_2 - P_2\delta_1}{2B(a_2 - a_1)} \tag{1}$$

where subscripts 1 and 2 refer to load, displacement, or crack length before and after a small amount of crack growth. This is an exact definition of G_{Ic} but it is imprecise because, what is in effect a derivative must be determined numerically from two experimental measurements. Area methods suffer from other disadvantages. They determine only an average value of G_{Ic} over some change in delamination length. They are influenced by hysteretic energy losses and zero offset effects as discussed by Hashemi, Kinloch, and Williams [3].

It is often desirable to use beam theory, instead of the above area method, to analyze fracture results. According to beam theory of a DCB specimen, the mode I toughness is:

$$G_{Ic} = \frac{3P\delta}{2Ba} \tag{2}$$

This equation assumes that the compliance at the crack root is zero, but in realty there is some deflection and rotation at the crack tip. It has been shown experimentally by Hashemi, Kinloch,

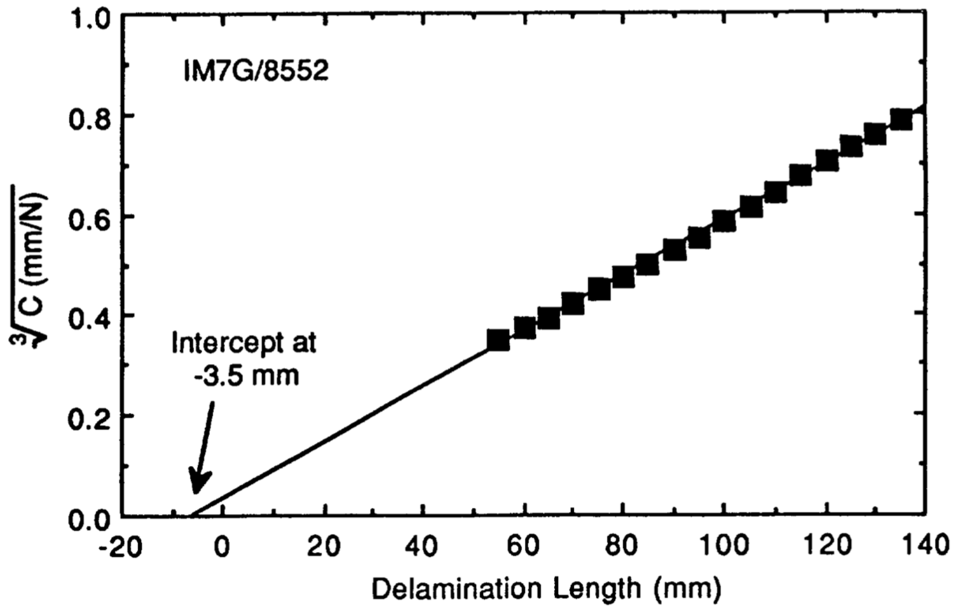

Figure 2: A plot of $C^{1/3}$ as a function of delamination length for a IM7/8552 laminate. The intercept on the x axis defines the crack length correction factor for this material.

and Williams [3] that this effect can be modelled by adding a length χ_h to the real crack length where χ_h is a constant which depends on the elastic properties of the material. It can be found experimentally from the intercept of a plot of $\sqrt[3]{C}$ *vs.* the measured delamination length, a. The corrected value of G_{Ic} becomes,

$$G_{Ic} = \frac{3P\delta}{2B(a + \chi_h)} \tag{3}$$

We used Eq. (3) to measure mode I fracture toughness as function of delamination length. For each material and each precracking condition we determined χ_h by plotting $\sqrt[3]{C}$ *vs.* a. A typical result for IM7/8552 is given in Fig. 2. The intercept when $C = 0$ gives $\chi_h = 3.5$ mm. For all specimens, the measured values of χ_h ranged from 0 mm to 12 mm.

EXPERIMENTAL RESULTS

For each material and for each precracking mode ratio, we measured the mode I fracture toughness as a function of delamination growth length. Some typical results at a mode I to mode II precracking ratio of 4 to 1 are given in Fig. 3. All results follow a similar pattern. They begin with some mode I toughness, which may be high or low, and eventually level off at some steady state value. The steady state value occurs after there has been enough crack growth to insure that the mode I crack *forgets* about the precracking mode ratio. Surprisingly it can take as much as 60 mm of mode I crack growth to reach the steady state value. The steady state toughnesses of the four materials were as follows:

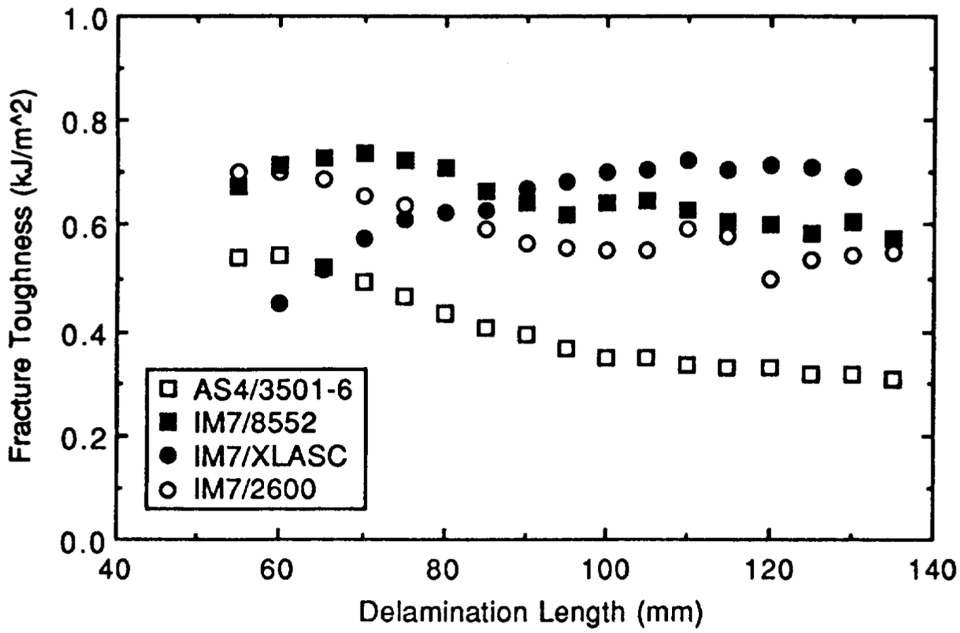

Figure 3: Mode I fracture toughness as a function a delamination length for all materials following mixed-mode precracking using a mode I to mode II ratio of 4:1

$$\begin{array}{ll} \text{AS4/3501}-6 & G_{Ic} = 0.28 \pm 0.02 \text{ kJ/m}^2 \\ \text{IM7/2600} & G_{Ic} = 0.50 \pm 0.02 \text{ kJ/m}^2 \\ \text{IM7/8552} & G_{Ic} = 0.60 \pm 0.10 \text{ kJ/m}^2 \\ \text{IM7/XLASC} & G_{Ic} = 0.66 \pm 0.04 \text{ kJ/m}^2 \end{array}$$

The steady state toughnesses were independent of the precracking mode ratio. The steady state results were reproducible with the most variable results coming from the IM7/8552 laminates. For the first 60 mm of crack growth, the mode I toughnesses of each material may differ significantly from its steady state toughness. The remainder of this section discusses the effect of precracking on the early mode I crack growth.

Figure 3 shows the mode I toughness of each material following a precracking mode I to mode II ratio of 4 to 1. Of the ratios we used, this ratio had the highest amount of mode I loading and should therefore be expected to produce the smallest effects. All materials, except IM7/XLASC, showed a slight increase in mode I toughness during early crack growth. For these materials the initial mode I toughnesses were 10% to 40% higher than the steady state toughnesses. As crack growth increased the mode I toughnesses decreased towards the steady state toughnesses. For IM7/XLASC, the initial mode I toughness was about 35% lower than the steady state toughness. The IM7/XLASC was unique in using toughening interlayers. These results suggest that materials with toughening interlayers are susceptible to decreases in mode I toughness when they experience mixed-mode precracking.

Figure 4 shows the mode I toughness of each material following a precracking mode I to mode II ratio of 1 to 1. The two toughened materials (solid symbols in Fig. 4) showed a slight decrease (10% to 35%) in mode I toughness at early stages in crack growth. The two untoughened systems (open symbols in Fig. 4) showed a slight increase (15% to 50%) in mode I toughness at early stages in

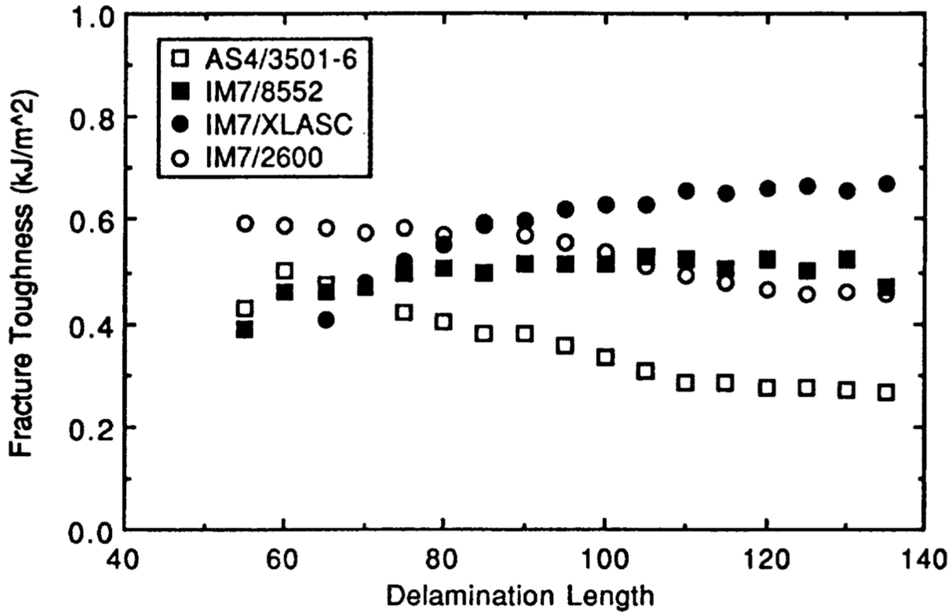

Figure 4: Mode I fracture toughness as a function a delamination length for all materials following mixed-mode precracking using a mode I to mode II ratio of 1:1

crack growth. An interesting observation is that both of the untoughened composite material systems have a higher mode I toughness during early stages of crack growth than either of the toughened systems. These results suggests that toughening methods that enhance pure mode I toughness may be ineffective or less effective following mixed-mode crack growth histories.

Figure 5 shows the mode I toughness of each material following a precracking mode I to mode II ratio of 1 to 4. Of the ratios we used, this ratio had the highest amount of mode II loading. The two toughened materials (solid symbols in Fig. 5) showed a significant decrease (40% to 70%) in mode I toughness at early stages in crack growth. The two untoughened systems (open symbols in Fig. 5) showed little or no effect from this predominantly mode II precracking.

It is interesting to cross-plot the results and give plots for a single material at the three different mode ratios. The results for AS4/3501-6 and for IM7/XLASC at the three different precracking mode ratios are in Figs. 6 and 7, respectively. The untoughened AS4/3501-6 laminates showed no effect of precracking or a slight increase in mode I toughness. The increase in mode I toughness got larger as the amount of mode I loading in the precracking increased. The IM7/XLASC laminates, which were toughened with an interlayer, showed only a decrease in mode I toughness with precracking. The decrease in mode I toughness got larger as the amount of mode II loading in the precracking increased. After the most extreme mode II precracking (mode I to mode II ratio of 1 to 4), the initial mode I toughness of IM7/XLASC was 70% lower than its steady state toughness. The results for the second untoughened material, IM7/2600, were similar to those of AS4/3501-6. Likewise, the results for the second toughened material, IM7/8552, were similar to those of IM7/XLASC.

To gain some insight into mechanisms, we observed the fracture surfaces of the precrack and of the mode I crack. There was a distinct contrast between the two regions showing that the delaminations grew by different growth mechanisms. As might be expected, the contrast was largest when using the mode I to mode II ratio of 1 to 4. As the amount of mode I loading in the

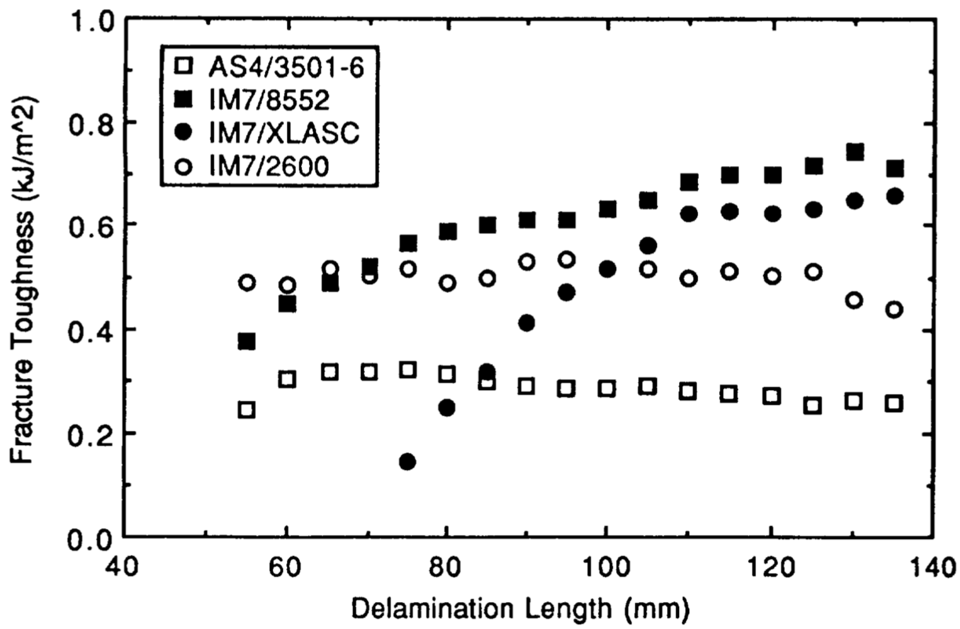

Figure 5: Mode I fracture toughness as a function a delamination length for all materials following mixed-mode precracking using a mode I to mode II ratio of 1:4

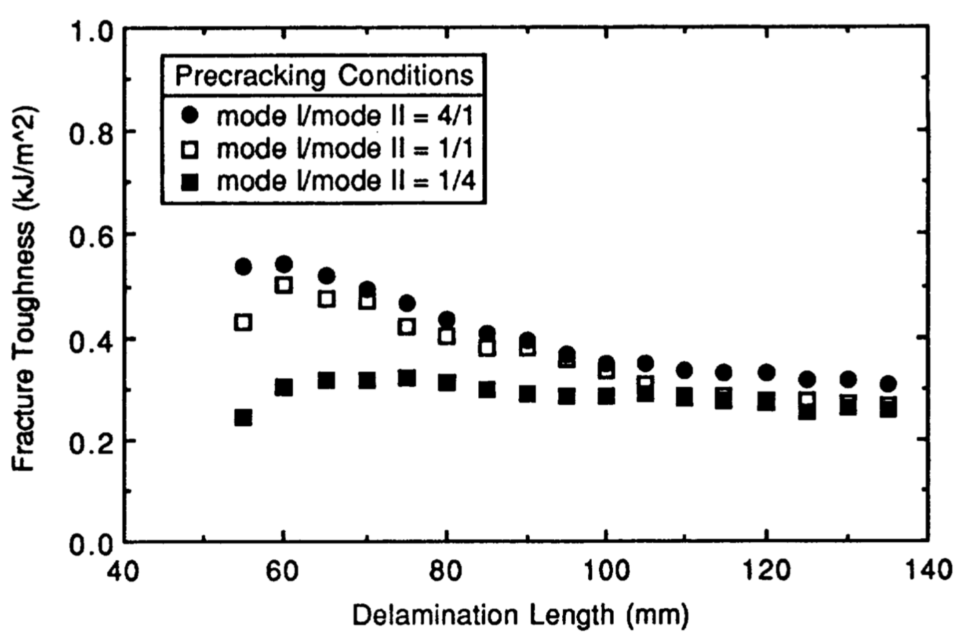

Figure 6: Mode I fracture toughness as a function of delamination length for AS4/3501-6 laminates following different mixed-mode precracking using different mode I to mode II ratios.

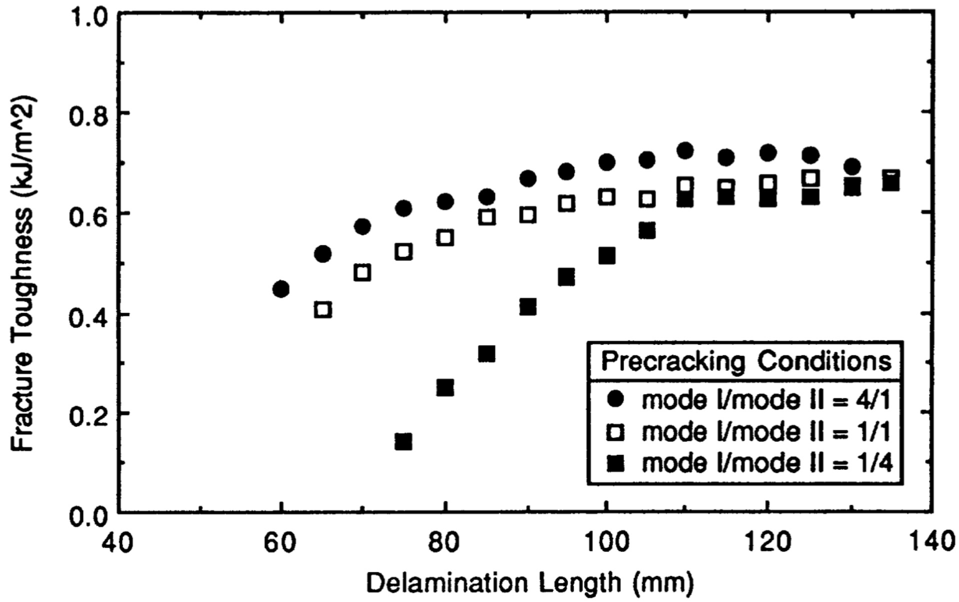

Figure 7: Mode I fracture toughness as a function of delamination length for IM7/XLASC laminates following different mixed-mode precracking using different mode I to mode II ratios.

precracking stage increased, the fracture surface contrast decreased. We attempted to assess the extent of fiber bridging. There appeared to be significantly more fiber bridging in the mode I fracture surface than in the precracking fracture surface.

DISCUSSION AND CONCLUSIONS

Our experimental results show that the mixed-mode precracking can have a profound effect on the initial mode I fracture toughness of subsequent mode I crack growth. The precracking can cause mode I toughness increases as high as 40% as well as mode I toughness decreases as high as 70%. Surprisingly, we found that the effect of the precrack persists for a macroscopic distance of about 60 mm. After 60 mm of crack growth all specimens approached a steady state mode I fracture toughness.

The two toughened materials, IM7/8552 and IM7/XLASC, tended to show decreases in mode I toughness following mixed-mode precracking. The amount of decrease increased as the mode II component of the precracking increased. We can arrive at a speculation on the effect of mode II precracking on mode I toughness by considering mode II stress states around crack tips in isotropic, homogeneous materials. When a material can yield easily, the singular stresses near the crack tip are more realistically imagined as being limited by the yielding process. If one assumes a yield criterion (*e.g.* Von Mises or Tresca), it is possible to estimate the yield zone size for any loading condition. For delamination specimens, the most relevant dimension of the yield zone is the one directly ahead of the crack tip. For plane-strain conditions in isotropic, homogeneous materials, the extent of yielding ahead of the crack tip is profoundly affected by stress state. It is at a minimum for pure mode I loading and increases dramatically as the amount of mode II loading increases.

To interpret the results in this paper, we suggest that the rubber toughened matrix in IM7/8552 and the toughening interlayer in IM7/XLASC are prone to yielding or have a low yield strength.

During the precracking stage, any mode II loading will therefore lead to a yielded damage zone ahead of the crack tip. We suggest that the mode I toughness of the damage zone is low and thus precracking causes an initial reduction in mode I toughness. This model predicts that the larger the amount of mode II loading, the larger would be the reduction in mode I toughness. This prediction agrees with the observations in Fig. 7. The AS4/3501-6 and IM7/2600 laminates are different because their untoughened matrices have higher yield strengths. The observation that mode II precracking does not decrease their subsequent mode I toughness suggests that the higher yield strength matrices did not become damaged by the mode II loading present during precracking.

When the precracking mode I to mode II ratio was 4 to 1 we observed an increased initial mode I toughness (see Fig. 3). It is difficult to imagine a precracking mechanism that would enhance the subsequent mode I toughness. The increase could possible be related to fibers bridging from the precrack zone into the mode I crack growth. However, we have no evidence to prove or disprove this claim. For now, the apparent increase in mode I toughness remains unresolved.

In conclusion, the closer we look, the more we realize that the characterization of delamination toughness is a complex problem. It is clearly insufficient to study only mode I, mode II, or mixed-mode crack growth emanating from a crack starter. The delamination process is now seen to have *memory*. In other words the delamination toughness is not only a function of the loading conditions but also a function of the loading conditions that gave the initial crack. A good example from this paper concerns the development of tougher composites. The IM7/8552 and IM7/XLASC composites are tougher materials by standard mode I testing. When subjected to precracking with a high component of mode II loading, however, these materials become less tough than untoughened composite systems. The design implication is that *so-called* toughened materials will not always produce tougher structures than their untoughened counterparts. We suggest there is something deficient, or rather specific, about the toughening mechanisms taking place in today's toughened composites. Their toughening mechanisms work for mode I loading but can be rendered ineffective by various precracking conditions

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