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**INVESTIGATION OF FIBER
BRIDGING IN DOUBLE
CANTILEVER BEAM SPECIMENS**

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INTRODUCTION

Much attention has recently been focused on the understanding of the delamination behavior of composite materials. Composite delamination is a potential failure mode at ply drop-offs, edges, holes, and in the area of impact damage. Therefore, the delamination problem must be well understood before safe and efficient composite structures can be designed. One approach to understanding this problem is to characterize the interlaminar fracture toughness of the composite's matrix material. Because delamination is a cracking problem, it is natural to describe the phenomenon in terms of fracture mechanics. The double cantilever beam (DCB) specimen is a popular specimen for the determination of the opening mode interlaminar fracture toughness. However many tests using the DCB specimen are plagued by " fiber bridging." Fiber bridging occurs when fibers are pulled from one side of the delamination plane to the other. (This will be discussed later in more detail.) Bridging results in the observed fracture toughness being higher than for delamination through the matrix material alone. The increase in fracture energy is required to debond the larger surface area of the bridged fibers and to eventually fracture the bridged fibers.

The fiber bridging effect on the interlaminar fracture toughness may be looked upon in two ways. The first viewpoint is that the high toughness values that result from bridging may be representative of the actual structure if bridging is likely to occur in the structure. In application higher toughness is

desirable even if it is achieved by fiber bridging. However, these toughness values may be unconservative if the expected bridging in the structure fails to occur. The second viewpoint is that bridging is undesirable when one is trying to determine the in situ fracture toughness of a composite matrix material. In order to understand the relationship between matrix toughness and composite toughness, the fiber bridging needs to be suppressed.

The purpose of this study is to (1) investigate ways of eliminating fiber bridging, or at least reducing its effect and (2) look for alternative ways to determine in situ mode I toughness values of matrix materials used in composite laminates subject to fiber bridging.

APPROACH

Usually fiber bridging has been attributed to "nesting" of the fibers and to weak fiber/matrix interfaces. Nesting, as shown schematically in Fig. 1, is common in unidirectional lay-ups where fibers migrate during the pressure/temperature cure cycle. Where nesting occurs there is no clear line (or plane) for delamination. Therefore, bridging as illustrated in Fig. 2 is the result of the delamination wandering among the fibers.

This investigation will focus on T6C/Hx205* composite material. The Hx205 base resin is a standard bisphenol A diglycidyl ether modified with an epoxy novolac and chain extended with additional bisphenols. The Hx205 was chosen for this study because it has relatively high toughness and its toughness has been well characterized [1].

In this paper the extent of fiber bridging and the resulting effect on toughness will be compared for specimen lay-ups conducive to fiber nesting and those that will not result in fiber nesting. The effect (or extent) of fiber bridging will be inferred from the measured G_{IC} (mode I critical strain-energy-release-rate) versus delamination length data. Any increase in G_{IC} with delamination length will be attributed to bridging effects.

Chai [2] has shown that for BP907 matrix material, the interlaminar fracture toughness (G_{IC}) of the composite is approximately equal to the toughness of a BP907 adhesive bondline of thickness less than 0.04 mm (0.0015 in.). This same approach will be used herein to evaluate the toughness of Hx205 used as an adhesive.

* T6C/Hx205 prepreg was supplied by Hexcel Corp., Dublin, CA.

The fibers are Celion 6000.

SPECIMENS

Three groups of DCB specimens were fabricated and tested to evaluate the mode I interlaminar toughness and fiber bridging of T6C/Hx205 composites. The composite panels had a fiber volume fraction of 0.65. All specimens were 300 mm long and 25.4 mm wide. Each specimen was 12 plies thick with a 50.8 mm length of folded 0.0127 mm thick teflon at the midplane on one end as shown in Fig. 3. The 0.0254-mm thickness of the folded teflon is sufficiently thin to serve as a good crack starter. The 6 plies on either side of the midplane were unidirectional; however, the top laminate plate and the bottom plate were laid at small angles to each other. Three angles were chosen for testing: 0, 1.5, and 3 degrees. The angles of 1.5 and 3 degrees were intended to avoid nesting of fibers along the mid-plane but still be small enough to avoid twisting of the adherends upon loading.

An adhesively bonded joint using Hx205 as the adhesive was also fabricated and tested. Aluminum adherends 6.35 mm thick were used. The aluminum surfaces were treated by a chromic acid etch and then bonded immediately. Teflon film (0.0127 mm thick) was doubled and placed between the adherends to serve as a debond starter on one end and for thickness control on both ends, thus assuring a 0.0254 (0.001 inch) thick bondline as shown in Fig. 4.

Both the composite and the aluminum specimen types used adhesively bonded steel hinges to transmit load into the specimens as shown in Figs. 3 and 4. For the aluminum specimens two small bolts were used on each hinged tab to provide additional peel strength.

TESTING PROCEDURES

The DCB specimens were tested under displacement control in a servo-electric-hydraulic testing machine. The displacement rate was approximately 2 mm per minute. The applied displacements and loads were recorded on an x-y plotter. The applied displacement was increased until a noticeable drop in load occurred (usually between 5 to 25 percent of the maximum load), indicating crack growth. The displacement was then returned to zero.

Both edges of the specimens were painted with a brittle white coating to aid in locating the delamination or debond crack front. A low cyclic level of displacement was used to cause the crack front to open and close at approximately 2 Hz to help locate the crack tip. The crack front was marked and measured on both sides of the specimen before and after each static crack advance.

ANALYSIS

Load-displacement records were obtained for each static load fracture test. The loading and unloading compliance of the specimen was calculated for each crack extension test and the crack length was recorded. The total mode I strain-energy-release-rate, G_{IC} , was calculated from

$$G_{IC} = P_{cr}^2/2B \quad dC/da$$

where

P_{cr} = critical load for crack extension

B = specimen width

C = compliance

a = crack length.

Further details about analysis of DCB data are presented in ref. [3].

RESULTS AND DISCUSSION

The results from the three T6C/Hx205 delamination specimen types (0, 1.5, and 3.0 degrees) and the aluminum adherend specimen are plotted on Fig. 5. The initial toughness values for the delamination tests, for the most part, are between 350 and 450 J/m². (Hunston [5] reported average interlaminar toughness values of 380 J/m² for Hx205.) The values of G_{IC} rapidly increase with crack length for the 0 degree specimens up to values of 1000 J/m² and above. The lines shown in Fig. 5 are the average response for two replicate delamination tests. The toughness of the 1.5 and 3.0 degree specimens also show G_{IC} increases with crack length. However, their values level off at approximately 650 J/m², which is significantly less than that of the 0 degree specimens.

The increase in G_{IC} with increasing crack length is attributed to fiber bridging. A typical view of fiber bridging in the 0 degree specimen is shown in Fig. 6. Although fiber bridging was still evident in the 1.5 and 3 degree specimens, the density (number of fibers bridged per unit area) was noticeably less than in the 0 degree case. Less bridging of the 1.5 and 3.0 degree specimens resulted in the lower toughness plateaus shown in Fig. 5. Interestingly, fiber bridging and toughness increases with crack length were found even in those layups where fiber nesting was probably not a factor. In so far as trying to surpress the effects of fiber bridging, reducing the plateau toughness level by a factor of three is encouraging. However, the plateau toughness is still 50 percent higher than the matrix value prior to fiber bridging.

The observed decrease in the toughness plateau between the 0 degree and the 1.5 and 3.0 degree specimens can probably be attributed to the decrease in fiber bridging due to nesting. However, some other mechanism may be causing the smaller amount of bridging associated with the 1.5 and 3.0 degree specimens. Either weak fiber/matrix interfaces or large crack tip yield zones could cause fiber bridging.

Microscopic examination of the delamination failure surfaces revealed that the failures were in the matrix material and not at the fiber/matrix interfaces. Therefore it seems unlikely that fiber bridging resulted from weak interfaces in this case.

Bradley and Cohen [4] suggested that a tougher resin matrix may have a plastic zone at the crack tip that extends into several plies on either side of the delamination plane. This zone represents an area of high, nearly uniform stress in the matrix. Therefore if an area of weakness (e.g., void, defect, poor fiber/matrix bond) occurs within this zone in a ply above or below the original delamination plane, the weak area may delaminate and grow. (Reference 4 contains a number of micrographs illustrating this behavior.) Thus a parallel delamination may develop in a plane above or below the initial one. This new delamination may actually grow ahead of the original and become the dominant crack, thus causing the fibers to bridge as shown in Fig. 7. The tougher the matrix the larger this plastic (or deformation) zone. Therefore, this mechanism for fiber bridging is more likely to occur for tougher resin matrices.

As shown in Fig. 5, the Hx205 adhesive specimen with the aluminum adherends gave rather constant toughness values with increasing crack length. The average toughness value was 432 J/m^2 for the 0.0254 mm thick Hx205 adhesive bondline. The failures within the adhesive were uniformly cohesive. The toughness values obtained from the thin bondline specimen are assumed to represent the in situ toughness of the composite matrix. Further, these toughness values are nearly equal to the first toughness values found in each composite specimen before fiber bridging. The matrix toughness values found in the composite specimens prior to fiber bridging are also considered to be the in situ matrix toughness.

These test results are significant because they indicate that a thin bondline of a resin can be used to measure what the in situ fracture toughness of that resin would be when used as a composite matrix material. This technique requires only a small amount of resin and does not require the actual fabrication of a composite laminate. This technique could be extremely useful when screening a number of new resins for potential composite applications.

Hunston [5] has reported toughness values of 230 J/m^2 for neat resin specimens of Hx205. The thicknesses of the compact specimens used by Hunston were such that plane strain conditions existed. The reason why the neat resin toughness is about half the in situ value is not clear at this time. The difference in toughness may, for example, be due to differences in molecular structure or in stress states at the crack tip.

The presented test results suggest two possible approaches for determining the mode I interlaminar fracture toughness of a composite matrix material used in a composite system prone to fiber bridging: (1) In a composite specimen, use only the first few values of toughness obtained ahead of a very thin starter strip (i.e., 0.0254 mm thick teflon) prior to fiber bridging effects; or (2) In a bonded joint specimen, use the matrix material as a very thin adhesive bondline (i.e., $t < 0.03$ mm) and test for fracture toughness. The latter approach seems reasonable for the presented results and for those of Chai [2].

CONCLUSIONS

The purpose of this study was to (1) investigate ways of eliminating fiber bridging or at least reducing its effect and (2) look for alternative ways to determine the in situ mode I fracture toughness values of composite matrix materials. Toward this end double cantilever beam specimens were made using unidirectional lay-ups of T6C/Hx205 composite materials in which the delaminating halves were placed at angles of 0, 1.5, and 3 degrees to each other. The small non-zero angles between the delaminating plies were used to avoid fiber nesting without significantly affecting the mode I behavior. A starter delamination was introduced by using a thin teflon insert. Double cantilever beam specimens were also fabricated with a 0.0254 mm thick bondline of Hx205 resin between aluminum adherends and tested. This study resulted in the following conclusions:

- o The extent to which fiber bridging and interlaminar toughness increase with crack length can be reduced by slight cross plying at the delamination plane to reduce fiber nesting.
- o Some fiber bridging may occur even in the absence of fiber nesting.
- o The first values of toughness measured ahead of the thin teflon insert were about the same for each of the three delamination specimen types (0, 1.5, and 3 degrees) tested. These values (350-450 J/m²) appear to represent a characteristic in situ toughness for the matrix material. However, these toughness values are higher than those from neat resin specimens (230 J/m²).
- o The thin (0.0254 mm) adhesive bondline of matrix material appears to give toughness values equal to the interlaminar toughness of the composite matrix without fiber bridging. Therefore the thin adhesive bondline specimen is a very attractive alternative for determining the interlaminar fracture toughness of a matrix material.

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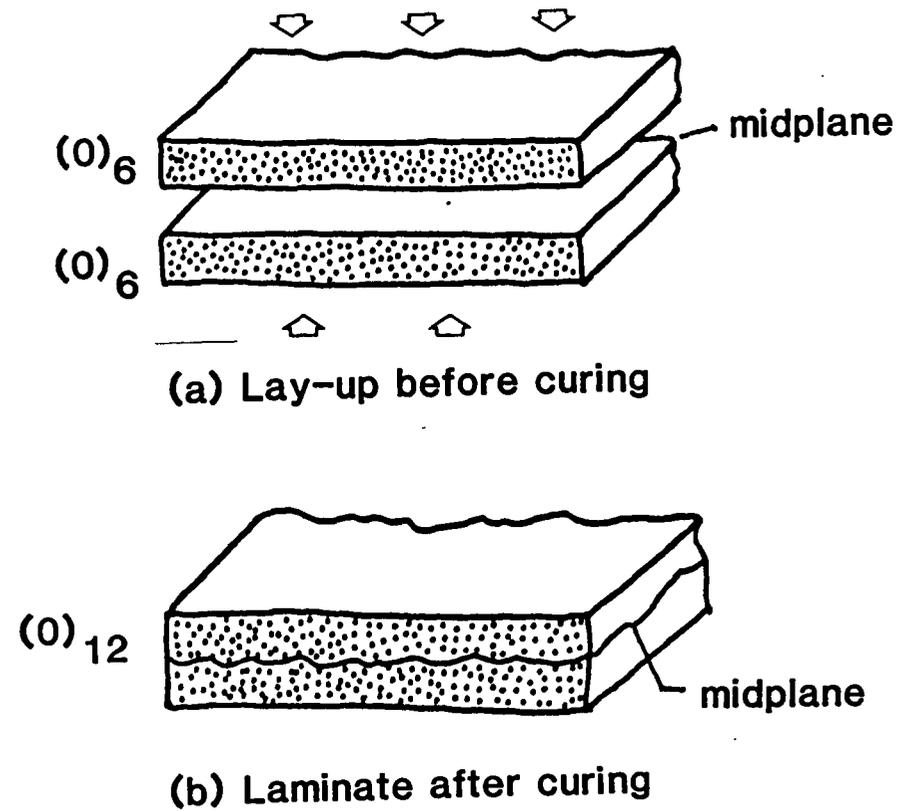


Figure 1 - Schematic of fiber nesting at the midplane of an all unidirectional laminate.

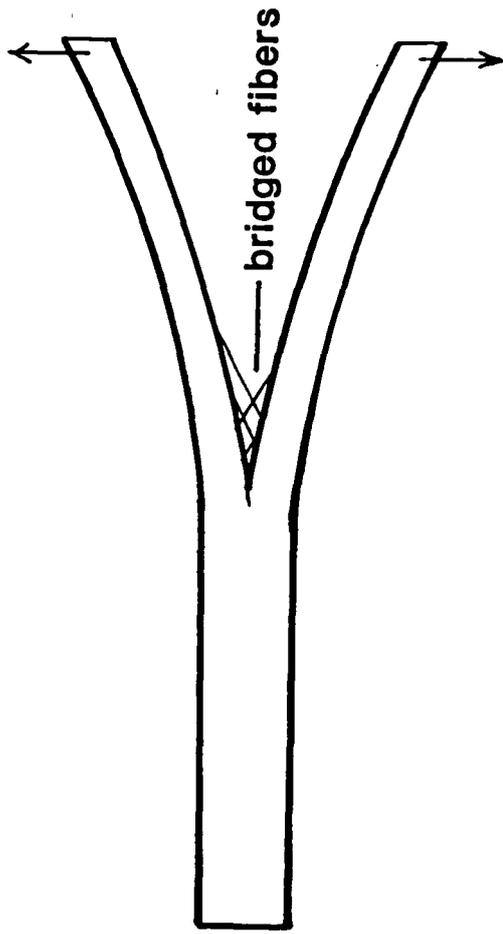


Figure 2 - Schematic of fiber bridging.

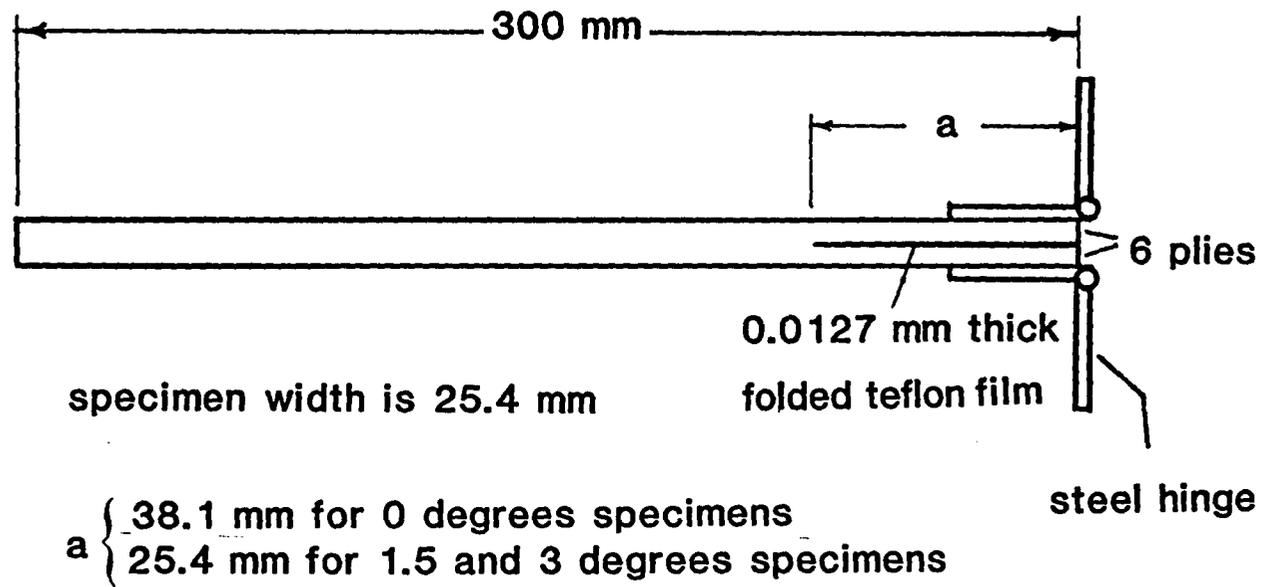


Figure 3 - Double cantilever beam specimen made of T6C/Hx205 composite material.

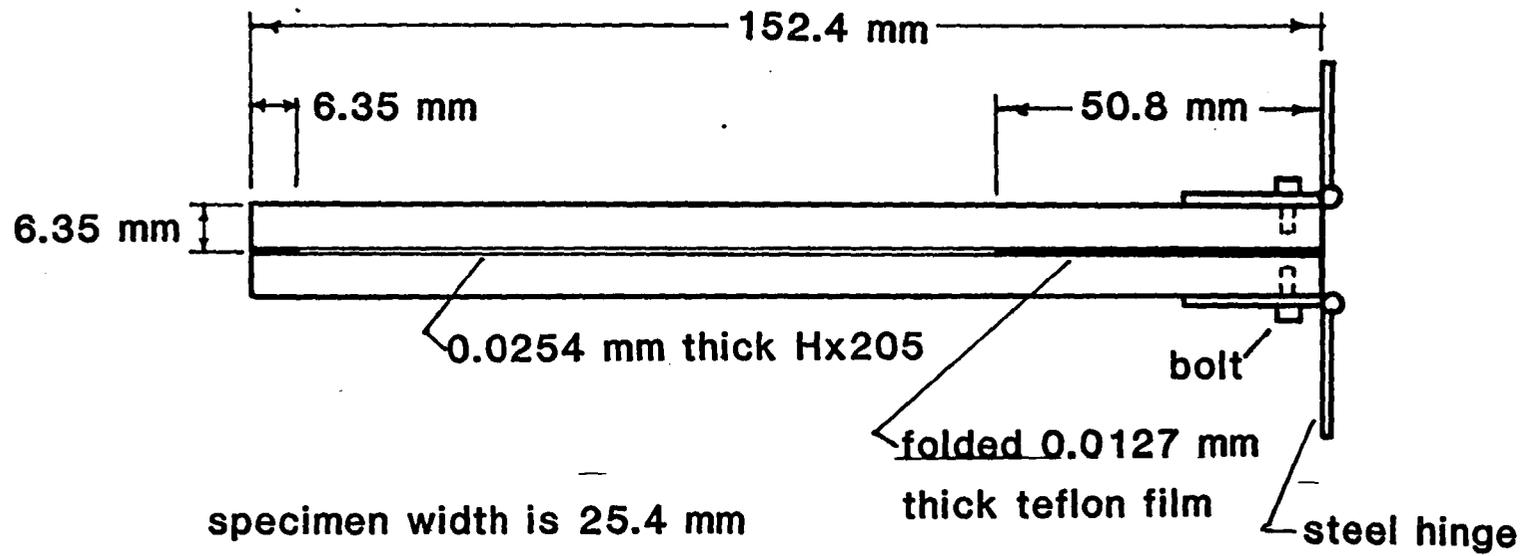


Figure 4 - Double cantilever beam specimen with Hx205 resin used as an adhesive between aluminum adherends.

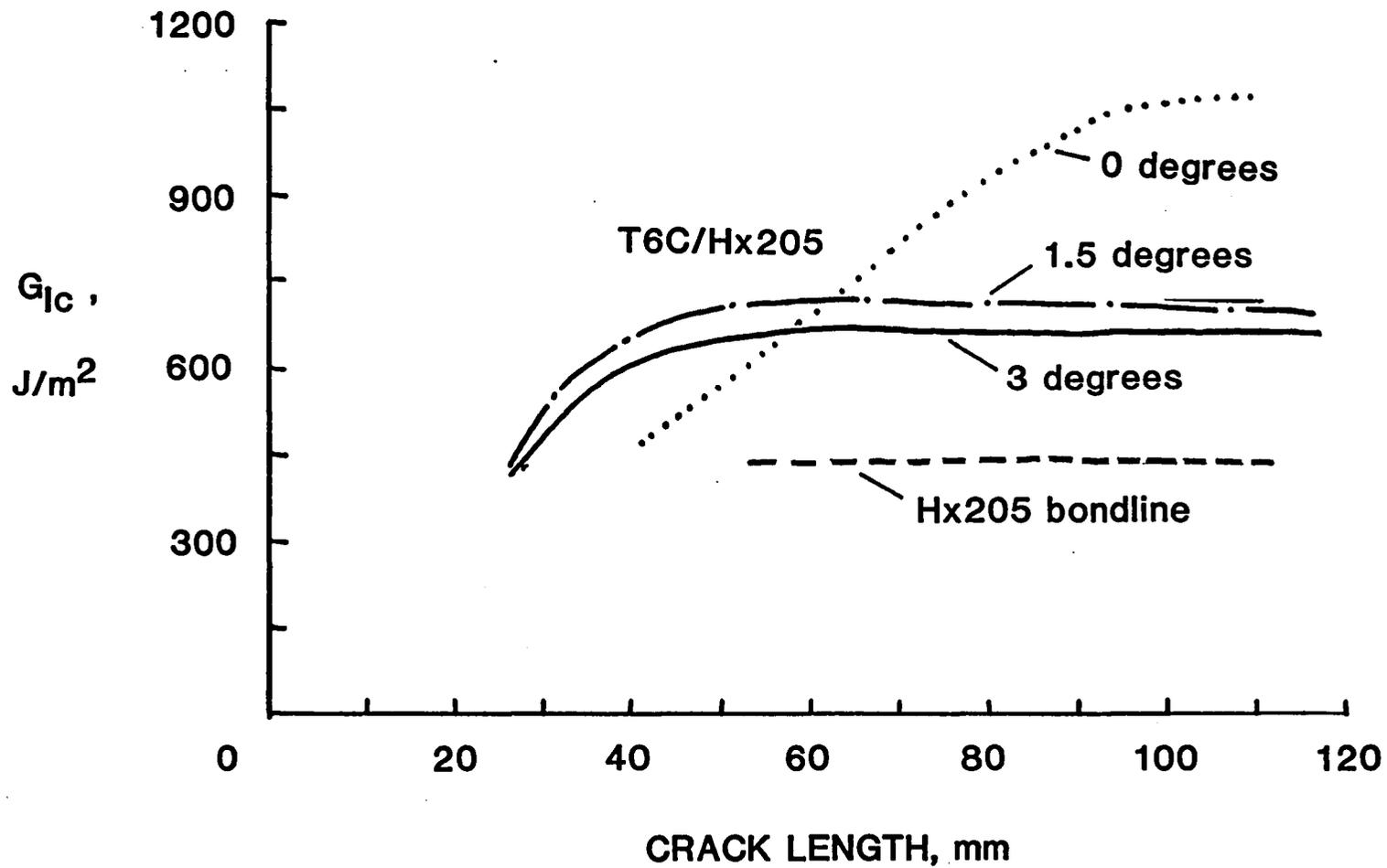


Figure 5 - Mode I fracture toughness versus crack length for double cantilever beam specimens.

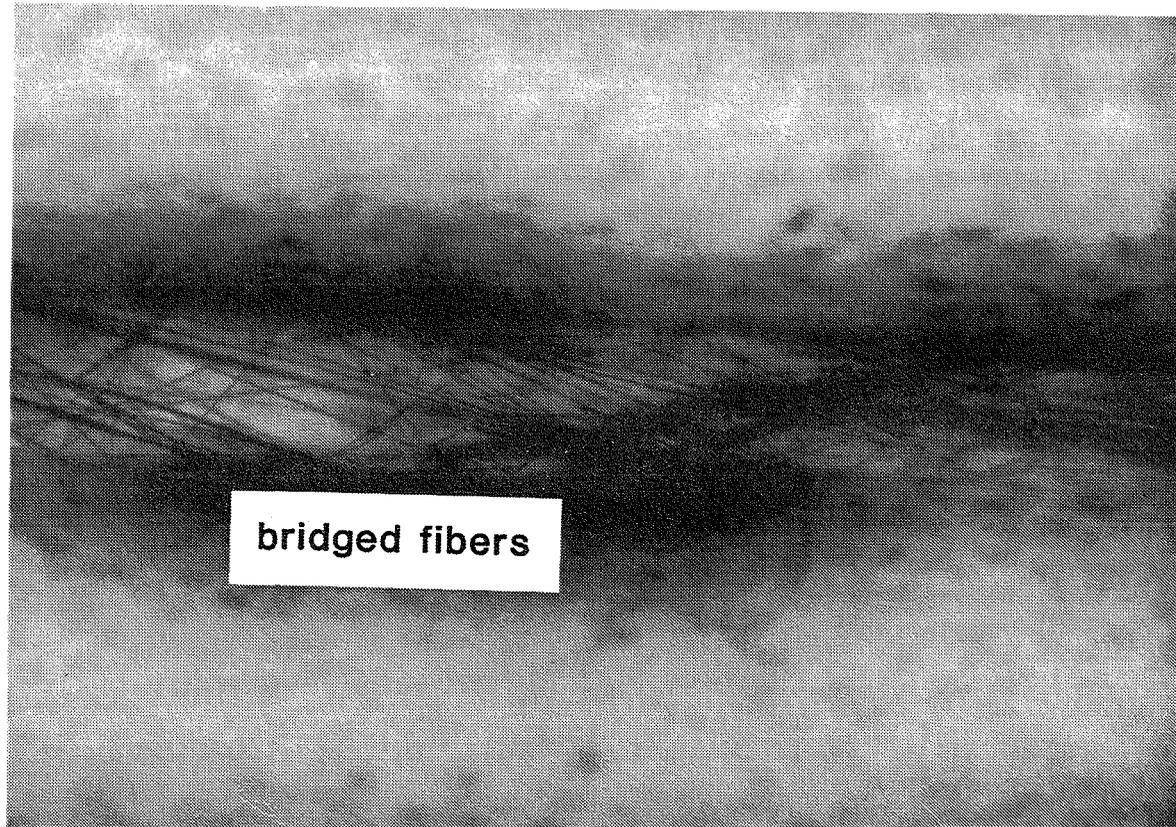


Figure 6 - Fiber bridging in the 0° layup T6C/Hx205 double cantilever beam specimen. Notice that fibers are bridging from top to bottom and bottom to top.

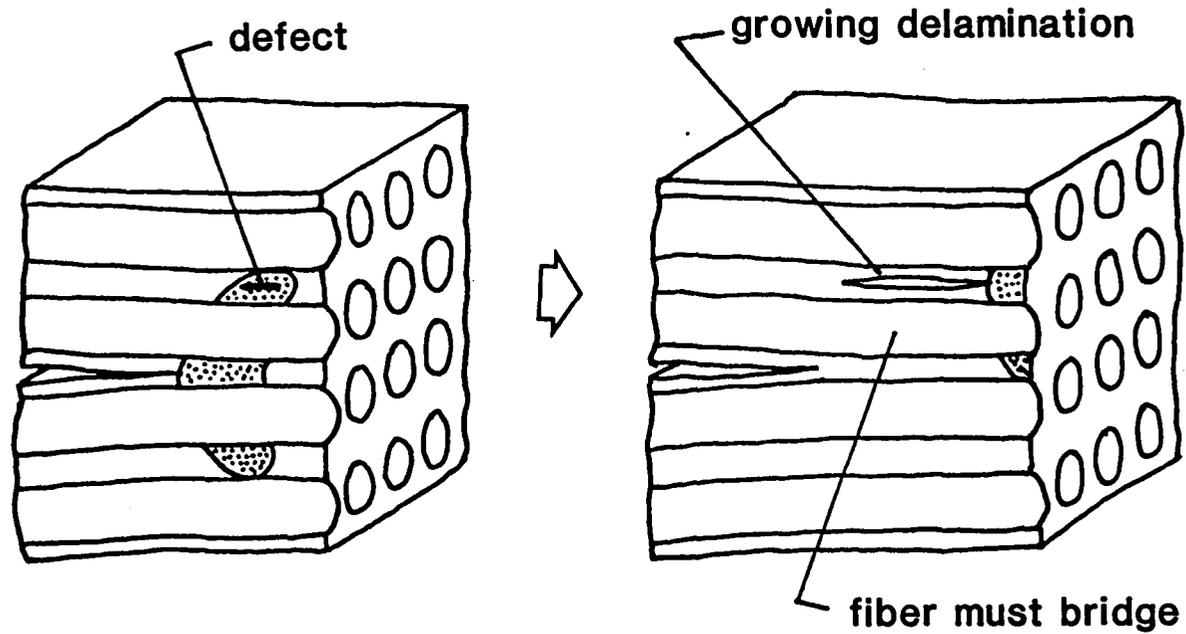


Figure 7 - Schematic of a deformation zone ahead of a delamination. A delamination initiates within the deformation zone in the ply above the original delamination and grows. The new delamination becomes the primary crack and causes a fiber to bridge.

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16. Abstract An investigation was conducted to (1) see if fiber bridging could be eliminated or at least reduced, and (2) evaluate an alternative approach for determination of in situ mode I fracture toughness values of composite matrix materials. Toward this end double cantilever beam (DCB) specimens were made using unidirectional lay-ups of T6C/Hx205 composite material in which the delaminating halves were placed at angles of 0, 1.5, and 3 degrees to each other. The small angles between the delaminating plies were used to avoid fiber nesting without significantly affecting mode I teflon insert. DCB specimens were also fabricated and tested with a study resulted in the following conclusions: The extent which fiber bridging and interlaminar toughness increase with crack length can be reduced by slight cross ply at the delamination plane to reduce fiber nesting; Some fiber bridging may occur even in the absence of fiber nesting; The first values of toughness measured ahead of the thin teflon insert were observed to be very close to the toughness of the matrix material with no fiber bridging; Thin (0.0254 mm) adhesive bondline of matrix material appears to give toughness values equal to the interlaminar toughness of the composite matrix without fiber bridging.					
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