AN EXPERIMENTAL STUDY OF MIXED-MODE FAILURE CRITERIA FOR GLASS/EPOXY COMPOSITES

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Mixed mode delamination tests are performed using MMB specimens. Energy release rate components G_I and G_{II} are calculated using a beam theory. Four mode ratios are chosen to determine a delamination criterion $G_I=f(G_{II})$. This is compared with a second criterion obtained using a second method based on experimentally determined method. Finally, these tests are applied to bonded composite/composite joints.

INTRODUCTION

Delamination of laminate composites has been widely studied using Linear Elastic Fracture Mecanics (LEFM). Interlaminar facture toughness G_c has been measured under pure loading modes, using the DCB (Double Cantilevered Beam) for mode I, and either the ENF (End Load Flexure) or ELS (End Loaded Split) specimens for mode II. However, in practice delaminations are rarely subjected to pure mode loading, but rather combinations of mode I and II. It is therefore essential to determine mixed mode fracture toughness and a specimen allowing this characterisation was presented recently, the MMB (Mixed Mode Bending) specimen, figure 1. This test combines DCB and ENF tests.

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ANALYSIS

Reeder (1) uses beam theory to obtain the well-known expressions of energy release rate components for the MMB test (method 1) :

$$\begin{cases} G_I = \dfrac{12a^2P_I^2}{b^2h^3E} \\ G_{II} = \dfrac{9a^2P_{II}^2}{16b^2h^3E} \end{cases} \tag{1}$$

with
$$\begin{cases} P_I = \left(\dfrac{3c-L}{4L}\right)P \\ P_{II} = \left(\dfrac{c+L}{L}\right)P \end{cases} \tag{2}$$

where a is crack length, P the applied load, L half distance between supports, c length of lever, h half thickness of specimen, b its width and E axial modulus .
The mode ratio is then given by :

$$\frac{G_I}{G_{II}} = \frac{4}{3}\left[\frac{3c-L}{c+L}\right]^2 \tag{3}$$

The partitioning of method 1 is theoretical and has not been fully validates by experiments. This is one of the aims of the present paper. To do this we measure crack opening displacement (δ_I, mode I displacement) and flexural displacement d_c . Thesken et al. (2) express mode II diplacement δ_{II} as $\delta_{II} = d_c + \Delta$ (figure 2), with :

$$\Delta = \frac{\delta_I L}{2\sqrt{(2L)^2 + (\delta_I/2)^2}} \approx \frac{\delta_I}{4} \tag{4}$$

Energy release rate components can be calculated using widely-used pure modes equations. Mode I of the MMB test is analysed like the DCB test, and mode II like the ENF specimen, following Davies (3) and Friedich (4) formulations. Therefore, compliances in mode I $C_I = \dfrac{\delta_I}{P_I}$ and in mode II $C_{II} = \dfrac{\delta_{II}}{P_{II}}$ can be written $C_I = Ka^n$ and $C_{II} = C_0 + ma^3$, where n and m are respectively slopes of curves $\ln(C_I)=f[\ln(a)]$ and $C_{II}=g(a^3)$. So, the second method gives :

for mode I : $$G_I = \frac{nP_I\delta_I}{2ba} \tag{5}$$

and for mode II : $$G_{II} = \frac{3ma^2P_{II}}{2b} \qquad (6)$$

EXPERIMENT - RESULTS

The composite tested here is an unidirectional glass/epoxy laminate, produced by hand lay-up. In order to initiate delamination a 8 μm thick polypropylene film is placed at laminate mid-thickness during moulding. Four theoretical mixed-mode ratios are chosen ; for each one five specimens were tested. The point of crack initiation is controversial so three definitions are used and corresponding values are read on load/displacement curve. The first is the point of deviation from linearity (NL), the second is the point at which slope has decreased by 5% of initial slope (which corresponds to an increase of compliance by 5%). the third definition is based on acoustic emission recording. We present only results using NL definition.

Figure 3 shows that the two methods give similar results. Experimentally determined mixed-mode ratios of method 2 are very close to the first method. Average curves give two criteria and the difference between them is smaller than scatter in results. However, method 2 is less efficient as the proportion of mode II grows, because tests become unstable. Few experimental values are reported, so n and m are determined with less precision. This comparison can be viewed as a verification of the beam theory method.

Then the same procedure was applied to composite/composite bonded joints. We use the same kind of composite as for delamination tests ; the adhesive is an epoxy. The polypropylene delamination starter film is placed in the adhesive joint.

The initiation criterion of figure 4 shows higher energy release rate components and a very different failure behaviour especially with regard to stability.

CONCLUSION

The beam theory method of analysis of the MMB test has been verified by experimental compliance displacement measurements. Then, initiation failure criteria of composite and bonded joint composite/composite assemblies have been compared. The latter give higher energy values than the former, so assembled structures with these components should fail in the composite rather than in the adhesive.

These tests have also been applied to fracture of composite/steel and steel/steel bonded joints, and composites with non-central defects, and results will be presented later.

SYMBOLS USED

a = crack length (m)
b = width of MMB specimen (m)
c = length of the lever (m)
δ_I =displacement in mode I (m)
δ_{II} =displacement in mode II (m)
d_c =flexural displacement (m)
E = axial modulus (N/m^2)
G_c = energy release rate (J/m^2)
G_I = energy release rate component in mode I (J/m^2)
G_{II} = energy release rate component in mode II (J/m^2)
h =thickness of MMB specimen (m)
L =length of MMB specimen (m)
P =applied load (N)
P_I = component in mode I of the load (N)
P_{II} = component in mode II of the load (N)

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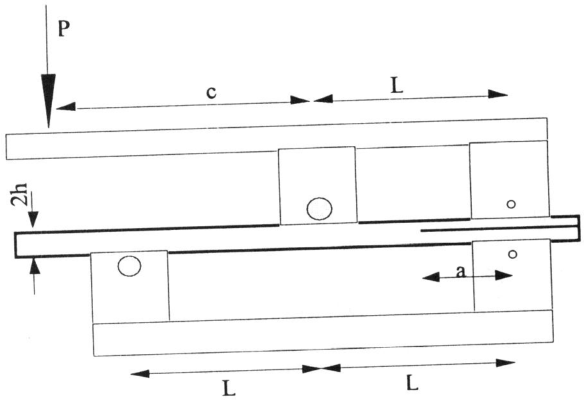

Figure 1. MMB specimen

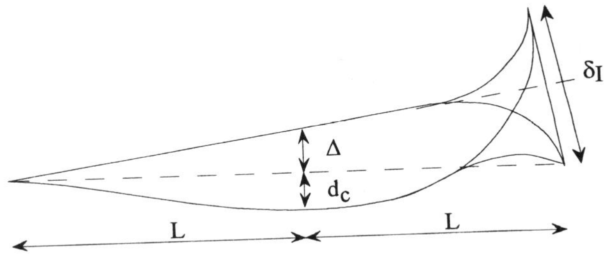

Figure 2. MMB specimen
Determination of δ_{II}

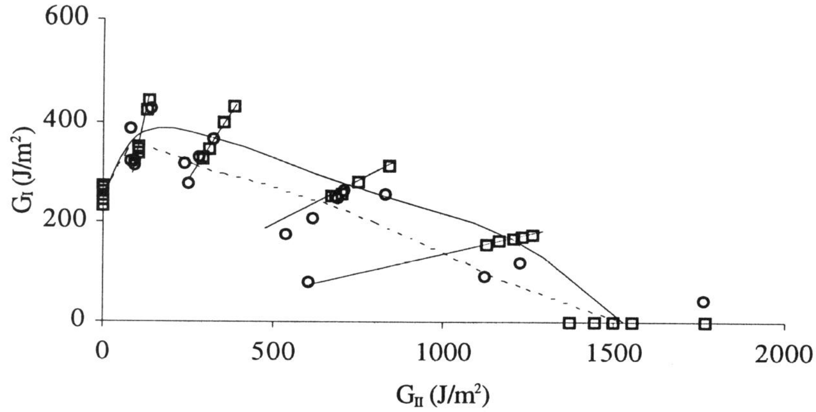

Figure 3. Initiation Failure Criterion (NL definition)
Methods 1 (□ ———) and 2 (○ - - - - -).

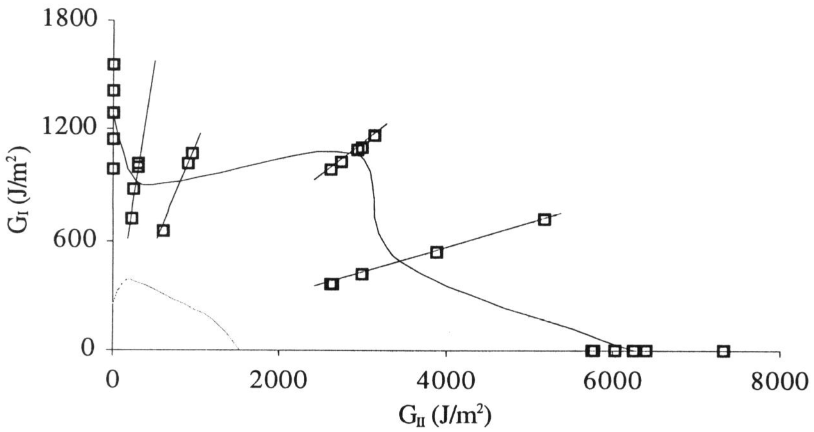

Figure 4. Initiation failure criteria of bonded (NL definition)
composite/composite joint (□ ———) and composite (·········) (method 1).