INTERLAMINAR FRACTURE TOUGHNESS OF A CARBON-FIBER REINFORCED COMPOSITE UNDER MIXED-MODE CONDITIONS

G. Steinmetz[1], F.J. Arendts[1]

The interlaminar fracture toughness of a carbon fiber reinforced epoxy for the crack opening mode I, mode II and mixed-mode (I/II) has been determined. The mixed-mode ratio G_I/G_{II} was varied from 0 to ∞ by changing the test setup. The experiments showed that the fracture toughness was strongly influenced by the ratio of G_I/G_{II}. For short crack lengths a failure criterion is proposed.

INTRODUCTION

The delamination is the most critical defect in fiber reinforced materials, since it may lead to a considerable loss of flexural stiffness and in-plane compressive strength. If such a defect is located in a loaded angle ply laminate, crack opening will be in general of a mixed-mode type. Therefore it is of particular interest to know the delamination fracture toughness for mode I, mode II and the whole range of mixed-mode ratios.

Test Methods

For the evaluation of the interlaminar fracture toughness different test methods have been established. The setups used in this investigation will be described in the following.

Mode I. In the case of the pure opening mode the DCB (= Double Cantilever Beam) test is used to determine G_{Ic}. The crack is centrally located

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[1] Institute for Aircraft Design, University of Stuttgart

and the arms of the specimen are loaded by equal forces, which act symmetrically to the crack plane as shown in figure 1.

Mode II. In the case of the pure sliding mode the ELS (= End Loaded Split) test is performed. The specimen is clamped at one end while at the other end both arms are equally bent in the same direction as shown in figure 1.

Mixed-Mode (I/II). The mixed-mode crack opening is achieved by two different test setups. One of them was proposed by Hashemi et al in [1]. Here it will be called MMELS (= Mixed Mode End Loaded Split) test. A schematic sketch of the loaded specimen is given in figure 2. The setup is similar to the ELS test except that the load is applied to the specimen's upper beam only. By varying the thickness h_1 and h_2 of the two arms the mixed-mode ratio can be influenced.

The other setup was suggested by Reeder and Crews [2], who called it the MMB (= Mixed Mode Bending) test, which is just a combination of a DCB and a ENF test as shown in figure 3. By varying the distance c the desired mixed-mode ratio can be adjusted. Here G_I/G_{II} was varied from 0.5 to 6.

MODE SEPARATION

Based on the elementary beam theory the mixed-mode ratio can be determined for the MMELS test as

$$\frac{G_I}{G_{II}} = \frac{(1-\xi)^2}{3\xi^4} \qquad \text{with} \qquad \xi = \frac{h_1}{h_1+h_2} \tag{1}$$

and for the MMB test as

$$\frac{G_I}{G_{II}} = \frac{4}{3}\left(\frac{6c-L}{2c+L}\right)^2 \qquad \text{with} \qquad c \geq \frac{L}{6}. \tag{2}$$

Because of various effects, which are not accounted for in the linear beam theory, such as large displacements, shear deformation and stiffening of the arms caused by the end blocks, the mixed-mode ratio was also determined by the finite element method. The specimens were modeled using eight-noded, quadrilateral and six-noded, triangular, isoparametric plane-strain elements. Geometrically non-linear effects have been considered. The energy release rates have been evaluated by the crack closure method developed by Raju [3]. The results from the finite element calculations showed that G_I/G_{II} is generally not independent of crack length and loading. In figure 5 G_I/G_{II} is plotted versus the total energy release rate $G_{tot} = G_I + G_{II}$ for a MMELS specimen, which contains a crack in its midplane. In this case G_I/G_{II} from linear beam theory equals 1.33. At least for short crack lengths (< 50 mm) the deviation from that value is negligible compared to the experimental scatter of fracture toughness measurements.

EXPERIMENTAL

Material and Specimen Fabrication

The investigated material was the modified epoxy "Rigidite 5208" reinforced with the high-tensile carbon fibers "G30-500" from CELION. The composite material has been delivered as preimpregnated tapes from BASF.

The specimens have been produced by manual lay-up of 24 unidirectional prepreg tapes and subsequent curing in an autoclave. To produce a starter crack a folded, 0.025 mm thick KAPTON-film was inserted between two plies at the desired position.

The specimens had a length of 250 mm, a width of 25 mm and a thickness of 3 mm. The loading was applied by aluminum end blocks, which were bonded at the cracked end of each specimen.

Test Procedure

Before testing the starter crack was extended by a few millimeters to avoid crack tip blunting at the resin rich zone ahead of the KAPTON-film. This precracking was always done in the same crack opening mode as the following measurement. Then the specimen was loaded until the crack length was increased by a certain increment. After the crack tip was marked on each side of the specimen the load was returned to zero. This procedure was repeated several times until the available test length of the specimen was reached. During testing the load P and the crack opening displacement (COD) were continuously registered.

Data Reduction

To evaluate the critical strain energy release rate G_c the registered data i.e. load, crack opening displacement and crack length have been treated according to various data reduction schemes. Because of the non-linear load-deflection behaviour especially in the case of MMELS and MMB tests the area method seemed to be most suitable. This method is based on the determination of the area enclosed within the loading and unloading P-COD curves. Permanent crack opening displacements have been treated according to Keary [4].

RESULTS

From the DCB and the ELS tests the interlaminar fracture toughness has been determined to $G_{Ic} = 0.167$ kJ/m^2 and $G_{IIc} = 0.51$ kJ/m^2. Both values do not depend on the crack length. However in the mixed-mode test the same material showed a considerable increase of the interlaminar fracture toughness with crack length. The measured R-curve reached a plateau at a crack length of about 60 mm. At this point the fracture process seemed to have reached a steady state.

Why the R-curve is just present in the case of mixed-mode loading is not yet fully understood. Therefore only initial values from the first measurement after precracking will be presented. They are shown in figure 4, where G_{Ic} is plotted versus G_{IIc}.

Since the presented fracture toughness values were measured at crack lengths smaller than 30 mm the G_I/G_{II}-ratio from linear beam theory was considered to be precise enough.

It can be seen that the results from the mixed-mode experiments show a considerable scatter. The reason could be the slightly different precrack length of each specimen. Another inaccuracy was caused by the determination of the incremental crack length, which was done by optical methods.

For short crack lengths the failure criterion suggested by Jurf and Pipes [5]

$$\frac{G_I}{G_{Ic}} + \frac{G_{II}}{G_{IIc}} = 1 \tag{3}$$

is proposed. It is presented as a solid line in figure 4 connecting G_{Ic} and G_{IIc}.

CONCLUSIONS

A further improvement of the test procedure is necessary to minimize the scatter of the evaluated fracture toughness. This could be done by a more precise method to determine the crack length. Furthermore reproducible precracking seems to be important for the evaluation of the initial fracture toughness.

To reduce the nonlinearity of the load-displacement curves in the MMB test the apparatus will be redesigned according to Reeder and Crews [6].

REFERENCES

[1] Hashemi, S., Kinloch, A.J. and Williams, J.G., ICCM(VI), Vol. 3, 1987, pp. 3.254-3.264

[2] Reeder, J.R. and Crews Jr., J.H., AIAA-Journal, Vol. 28, No. 7, 1990, pp. 1270-1276

[3] Raju, I.S., Engineering Fracture Mechanics, Vol. 28, No. 3, 1987, pp. 251-274

[4] Keary, P.E. et al., J. Comp. Mat., Vol. 19, 1985, pp. 154-177

[5] Jurf, R.A. and Pipes, R.B., J. Comp. Mat., Vol. 16, 1982, pp. 386-394

[6] Reeder, J.R., Crews Jr., J.H., ICCM(VIII), 36 B, 1991

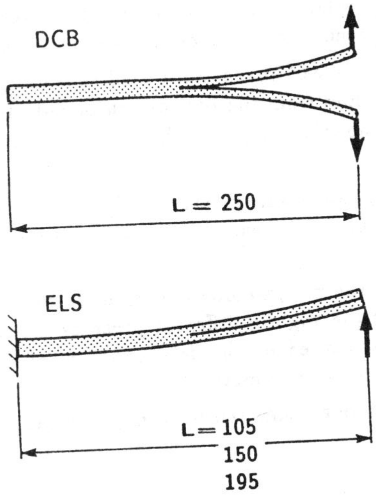

Figure 1: DCB and ELS test

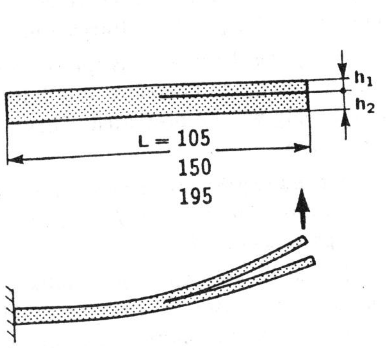

Figure 2: MMELS test

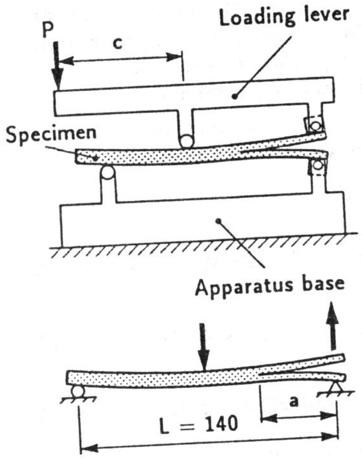

Figure 3: Mixed Mode Bending test

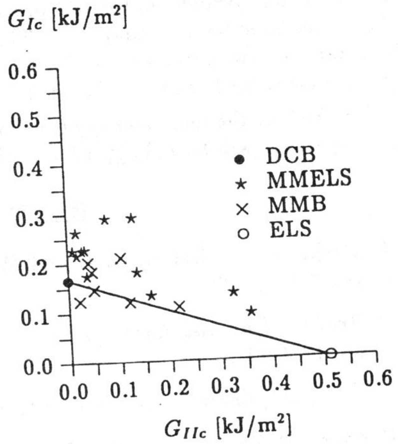

Figure 4: G_{Ic} versus G_{IIc} from MMELS tests

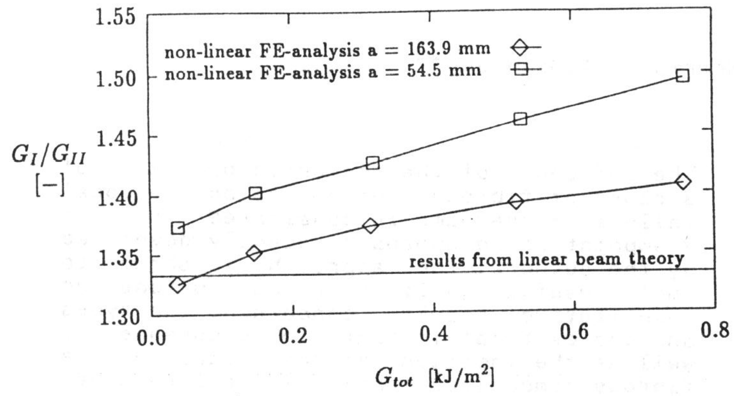

Figure 5: G_I/G_{II} versus the total energy release rate G_{tot} for two different crack lengths