STUDIES ON MIXED MODE INTERLAMINAR FRACTURE TOUGHNESS OF M55J/M18 CARBON/EPOXY LAMINATES

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(Received 4/00; accepted 8/00)

ABSTRACT

Experimental studies are carried out to determine the interlaminar fracture toughness of unidirectional laminates made of M55J/M18 carbon/epoxy material under different mixed mode ratios (G_I/G_{II}). A mixed mode delamination fracture criterion using mixed mode bending specimens is developed. It is observed that when loading in mode I is predominant, G_{II} has a considerable value but the opposite is not true when mode II is predominant.

1. INTRODUCTION

Delamination continues to be one of the problems limiting the use of composite materials in primary structures. A major step toward predicting delamination is characterising the delamination fracture toughness, i.e. the critical value of strain energy release rate, G_c. Delamination fracture toughness is compared with the predicted value of strain energy release rate, G, corresponding to delamination growth to assess the strength.

Many tests have been used to measure fracture toughness. The double cantilever beam (DCB) test [1] is most often used to measure mode I (opening) delamination fracture toughness, while end notched flexure (ENF) test [2] to measure mode II (sliding shear). However, delamination in structures is usually not a result of pure mode I or pure mode II loading, so it is important that delamination fracture toughness be known for mixed mode loading. The mixed mode bending (MMB) test proposed by Reeder and Crews [3] seems to be a suitable method for determination of mixed mode delamination fracture toughness. The MMB test apparatus was later redesigned to eliminate the non linear effects. The results of the linear analysis of the modified MMB apparatus were similar to those obtained from a non linear analysis of the original MMB apparatus [4].

In the present study, experimental studies are carried out to determine the interlaminar fracture toughness of unidirectional laminates made of M55J/M18 carbon/epoxy material under different mixed mode ratios (G_I/G_{II}) and a mixed mode delamination criterion is developed.

2. EXPERIMENTAL INVESTIGATIONS

The MMB test is used for the mixed mode interlaminar fracture toughness determination. The test method combines the DCB and the ENF loadings into a single test. Schematic diagram of the test apparatus together with the test specimen is shown in Fig. 1. By applying a load P through a loading lever as shown, mode I, mode II or combined conditions may be produced at the crack tip. The position of the loading lever marked as c in the Fig. 1., determines the mixed mode ratio for the test. Pure mode I loading results when the loading lever is removed and an upward load is applied to the hinge. Pure mode

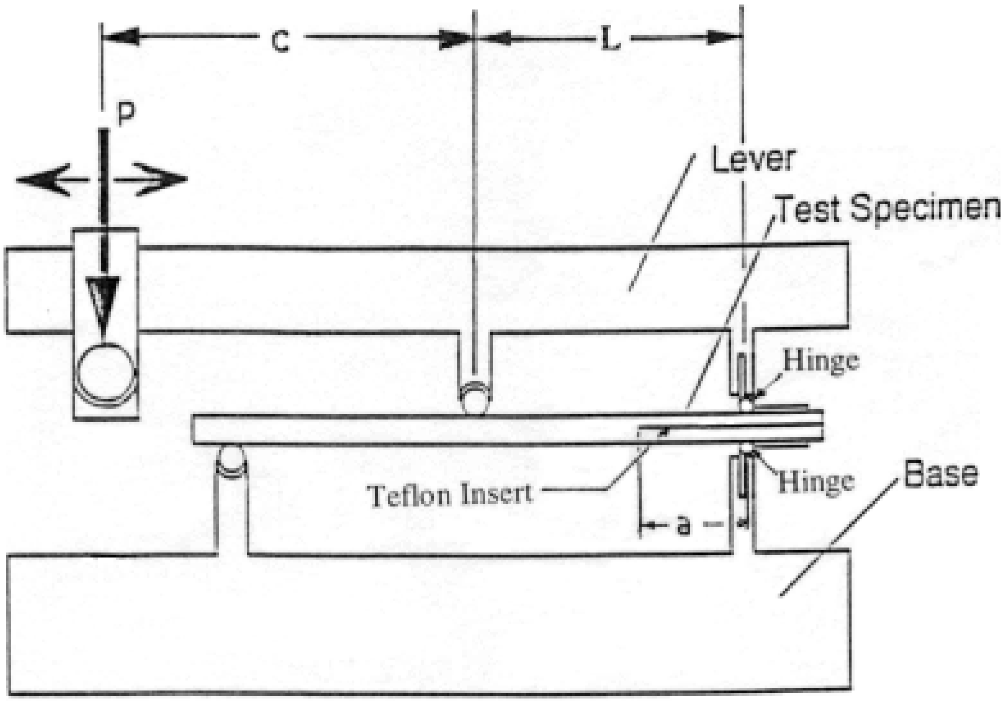

Fig.1. :Schematic Diagram of MMB Specimen and Test Apparatus

II loading results when the load is applied such that $c \leq {}^{L}/_{3}$. Any other position produces mixed mode loading conditions [3]. The modified MMB test fixture proposed by Reeder and Crews [4] is used in the study.

Analytical studies on the test method resulted in several data reduction schemes to obtain G_I and G_{II} from MMB test data. Bhashyan and Davidson [5] presented a review of such schemes and the method proposed by Kinloch *et. al.*[6] evolved as the one producing accurate results in comparison with the respective FE results.

$$G_I = \frac{4P^2(3c-L)^2}{64bL^2E_{11}I}(a+\chi h)^2 \qquad (1)$$

$$G_{II} = \frac{3P^2(c+L)^2}{64bL^2E_{11}I}(a+0.42\chi h)^2 \qquad (2)$$

$$\chi = \sqrt{\frac{E_{11}}{11G_{12}}\left\{3-2\left(\frac{\Gamma}{1+\Gamma}\right)^2\right\}} \qquad (3)$$

$$\Gamma = 1.18\frac{\sqrt{E_{11}E_{22}}}{G_{12}} \qquad (4)$$

Mixed mode ratio defined as the ratio of mode I loading to mode II loading and is given by the expression,

$$\text{Mixed mode ratio} = \frac{4}{3}\left(\frac{3c-L}{c+L}\right)^2 \qquad (5)$$

2.1 Specimen Preparation

Elastic properties of M55J / M18 carbon/epoxy laminates used for the present study are as given in Table 1. MMB specimens of dimensions 150 x 25 mm containing a Teflon insert of 65mm (0.5 mm thick) between the middle layers as detailed in Fig. 1 are cut from a $[0]_{30}$ laminate.

The schematic diagram of the MMB fixture is given in Fig. 1. Brass hinges are used for attaching the specimens to the fixture for loading purpose. Commercially available epoxy based adhesive Araldite with a curing period of 24 hours is used for fixing the hinges to specimen. Care is taken to ensure proper hinge alignment, as

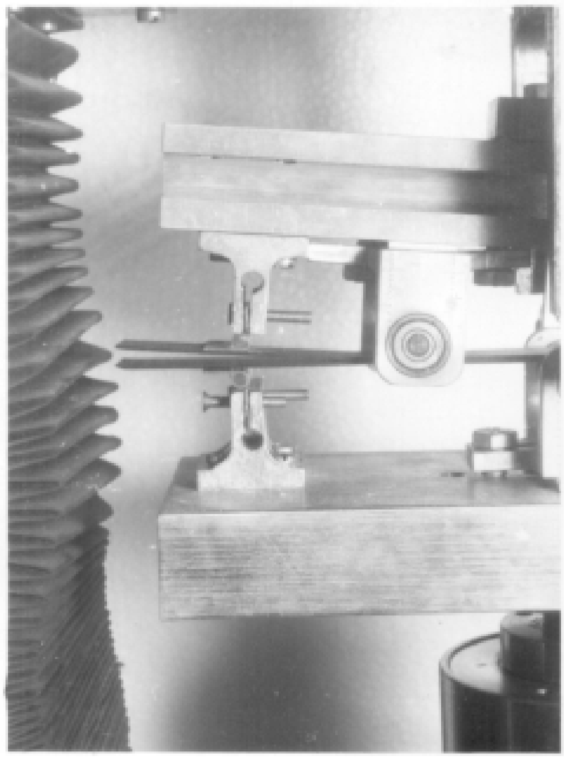

Fig. 2. :MMB Specimen During Testing

improper alignment would cause torsional loading on the specimen. The MMB specimen positioned in the loading fixture is shown in Fig. 2.

2.2. Testing

The specimen is inserted into the fixture and fixed by means of screws. The tests were conducted with a FIE make machine of 5tons capacity. The yoke attached to the lower arm of the machine is lowered till it just rested on the saddle of the MMB fixture. From that point, the yoke is lowered very slowly and force and displacement data are recorded at regular intervals.

The test is conducted for different mixed mode ratios and under pure mode I loading. The test is done under displacement controlled condition with a loading rate of 1.25 mm/min. The pure mode I test is conducted after removing the MMB test fixture and by loading the specimen directly through the hinges by applying tensile load as in a DCB test.

3. RESULTS AND DISCUSSION

Results of the interlaminar fracture toughness tests are presented in Table 2 and through Figures 3 & 4. One can observe that the G_c for pure Mode I and pure Mode II are found to be 66.5 J/m^2 and 223.9 J/m^2 respectively. For the material considered, G_{II} for pure mode II is obtained as 3.4 times higher than the G_c for the pure mode I.

Table 1. :Elastic properties of M55J / M18 carbon/epoxy composite

Longitudinal Young's modulus, E_{xx} / GPa	329
Transverse Young's modulus, E_{yy} / GPa	6.0
Poisson's Ratio, ν_{xy}	0.346
Shear Modulus, G_{xy} / GPa	4.4
Longitudinal tensile strength, X / MPa	1327
Transverse tensile strength, Y / MPa	22
Shear strength, S / MPa	74.9

Table 2. :Results of Interlaminar Fracture Toughness tests with Mixed Mode Bending Specimens of M55J/M18 Carbon/epoxy Composite Laminate

Mixed mode ratio		**Fracture Toughness** / J/m^2		
G_I/G_{II}	No. of Specimens	G_I	G_{II}	G_c
Pure Mode I		66.5	0.0	66.5
4.8	1	83.58	17.05	100.63
	2	72.85	15.31	88.16
3.0	1	68.09	21.93	90.02
	2	88.89	29.27	118.16
	3	58.49	19.65	78.11
1.8	1	147.36	74.3	221.66
	2	147.3	74.6	221.96
	3	121.3	75.04	196.34
	4	83.78	52.78	136.56
1.3	1	115.07	77.13	192.2
	2	108.23	72.88	181.11
	3	101.45	88.61	190.06
0.8	1	63.18	77.22	140.38
0.4	1	37.01	95.17	132.185
0.0 Pure Mode II	1	0.0	211.7	211.7
	2	0.0	220.0	220.0
	3	0.0	240.	240.0

It was established in literature that the material critical energy release rate, G_c obtained in a mixed mode crack condition might be several times larger than G_I obtained under pure mode I condition. Wilkins [7] reported that G_c is found to be more than 3.5 times larger than G_{Ic} for AS 3501-06 graphite/epoxy system. From the present experimental results it is seen that the above argument is also found to be true for the M55J/M18 carbon/epoxy system.

Fig. 3 shows the variation of G_I and G_{II} as mode mixture G_{II}/G_c changes from 0 to 1.0. It can be noticed from Fig. 3 that even as the mixed mode ratio (ratio of mode I loading to mode II loading, Table-2) is reduced (means mode II loading is increased) both G_I and G_{II} increases till G_{II}/G_c.=0.4. Then G_I decreases and tends to zero while G_{II} continues to increase almost linearly till it becomes pure mode II.

When mode mixture G_{II}/G_c=0.5 (that corresponds to a mixed mode ratio (G_I/G_{II})equal to unity, as G_I=G_{II}) which physically means equal loading in both mode I and mode II, the value of G_I and G_{II} should be equal. It is interesting to note from Fig 3 that for the mixed mode ratio of 1, G_I obtained from the test is found to be nearly equal to G_{II} as anticipated$_{II}$ In other words, based on the present study G_I is 50% G_c so also G_{II} 50% of G_c when G_{II}/G_c.=0.54 instead of 0.5 (Fig.3). But for any other mode mixture such proportionality in fracture toughness does not found to exist.

For the range of G_{II}/G_c less than 0.5 which means loading in mode I is higher than mode II, the rate

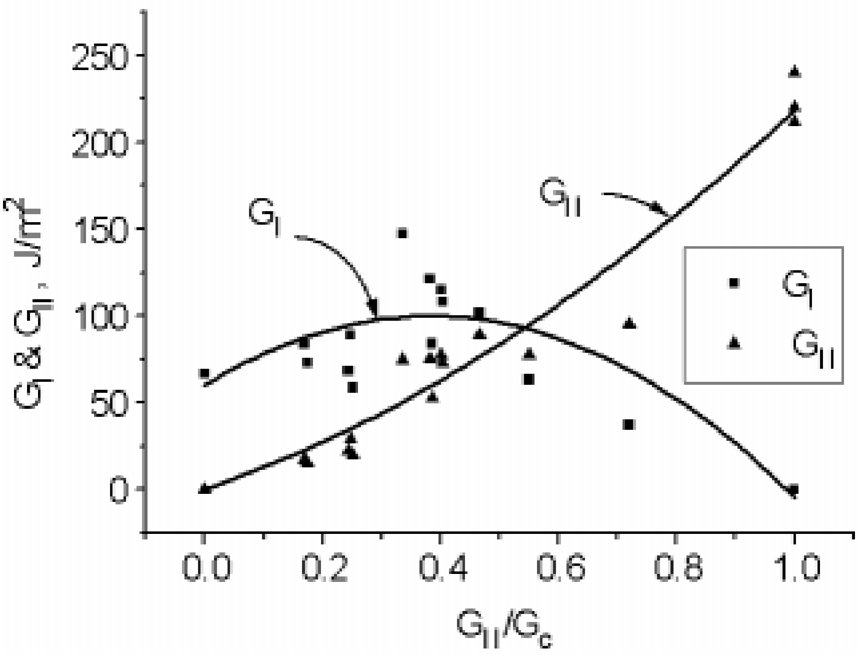

Fig. 3 :G_I and G_{II} values compared with G_{II}/G_c

at which G_{II} increases is considerable and G_I is found to be almost constant. For the range of G_{II} / G_c > 0.5 (which means loading in mode II is higher than mode I), one would expect G_{IIc} should remain almost constant. But it is seen that G_{IIc} increases rapidly. Thus it can be concluded that when loading in mode I is predominant, G_{II} is having a considerable value but when mode II is predominant, G_I is not having much significance. Probably this may be the reason why in a composite structure where interlaminar shear stresses are very high, (Mode II predominant), the conventional design is based on only the interlaminar shear strength.

Based on the present experimental results on

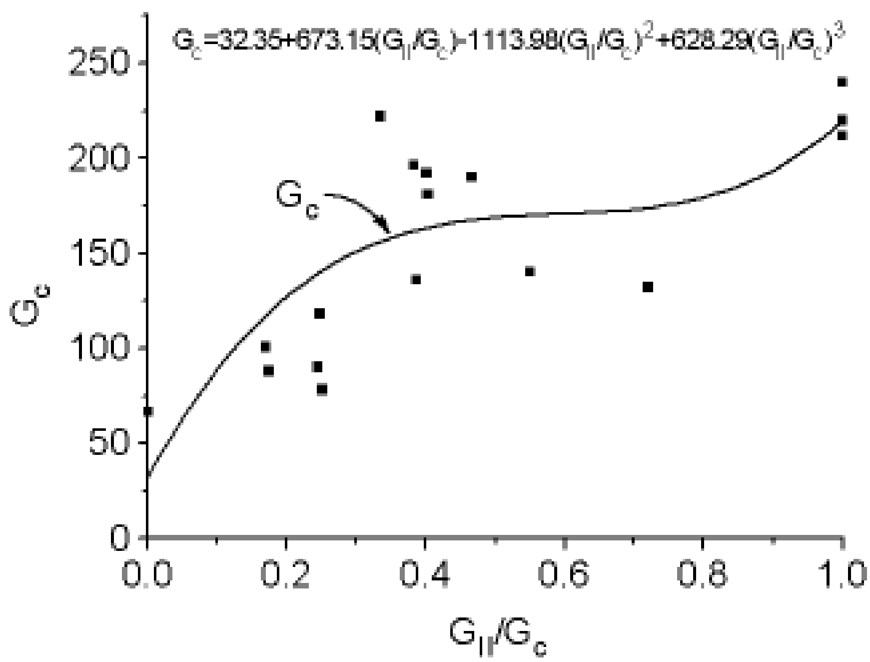

Fig. 4 :Mixed Mode Delamination Criterion for M55J/M18 Carbon-Epoxy Uniderectional Laminates.

M55J/M18 laminates the mixed mode delamination criterion is arrived at as shown in Fig. 4. In this figure G_c for delamination is plotted as a function of the ratio of G_{II} to G_c. At G_{II}/G_c = 0, which corresponds to a pure opening mode I, the value of G_I (pure mode I)is obtained as 66.5 J/m^2. For G_{II}/G_c = 1 (pure mode II), value of G_{II} is found to be 3.4 times the former one.

In Ref. 8 a semi-empirical relation for mixed mode delamination is presented for M10 epoxy resin (Vicotex) reinforced with 52 % by volume of E-glass fibres, 5% of which are woven perpendicularly. As the variation of the G_c with respect to G_{II}/G_c in Ref. 8 is found to be different for the present material used (probably due to an order of increase in modulus value in the fibre direction) in the present study a new criterion is aimed at. The mixed mode delamination criterion for M55J/M18 unidirectional laminates is obtained based on a polynomial regression as:

$$\mathbf{G_c} = 32.\mathbf{35} + 673.15\left(\mathbf{G_{II}}/\mathbf{G_c}\right) - 111\mathbf{3.98}\left(\mathbf{G_{II}}/\mathbf{G_c}\right)^2 + \mathbf{628.3}\left(\mathbf{G_{II}}/\mathbf{G_c}\right)^3 \qquad (6)$$

4. CONCLUSIONS

Interlaminar fracture toughness of M55J/M18 carbon/epoxy laminate for pure mode I, mixed mode ratios and pure mode II have been experimentally evaluated using MMB specimen standards. The mixed mode delamination criterion for M55J/M18 unidirectional laminates is obtained by test and presented in a form suitable for a designer. It is interesting to note from the present study that for the mixed mode ratio of 1, G_I obtained from the test is found to be nearly equal to G_{II} as anticipated. It has been concluded that when loading in mode I is predominant, G_{II} is having a considerable value but when mode II is predominant, G_I is found to be insignificant. Probably this may be the reason why in a composite structure where interlaminar shear stresses are very high, (Mode II predominant), the conventional design is based on only the interlaminar shear strength.

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