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INVESTIGATION OF FRACTURE CRITERION FOR COMPOSITE USING CTS SPECIMEN

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ABSTRACT

The interlaminar fracture behavior of a unidirectional carbon fiber reinforced composite under full range of in-plane loading conditions has been investigated. Loading conditions from pure mode I through various mixed mode I/II ratios up to pure mode II have been generated by the aid of the compound version of the compact tension shear (CTS) specimen. From the experimentally measured critical loads the mode I, mode II and the various mixed mode I/II critical energy release rates at crack initiation have been determined by the aid of the finite element method and the modified virtual crack closure integral method. Based on these results the parameters of a fracture criterion for the composite under consideration have been determined. It was shown that for the present carbon/epoxy composite the best approximation is achieved employing in criterion a linear function.

KEYWORDS

Laminated composite, interlaminar fracture, mixed mode fracture, fracture criterion.

INTRODUCTION

The main problem of predicting the failure of laminated composite materials is the evaluation of interlaminar fracture toughness properties under mixed mode loading conditions. Various approaches have been chosen in order to develop test specimens for combined loading conditions, but the main research has been conducted on mode I and mode II interlaminar fracture behavior of composite materials. The double cantilever beam (DCB) and the end notched flexure (ENF) specimens have been employed for mode I and mode II tests, respectively. Also for the mixed mode tests mostly beam type specimens were used in order to obtain mixed mode I/II critical energy release rate. For example, a MMB specimen is widely used to determine the mixed mode critical energy release rates for different composites [1-3].

But still the disadvantage of all beam type specimens is that for pure mode I, pure mode II and for the various mixed mode I/II ratios different beam type specimens have to be used. In order to obtain reliable results for interlaminar fracture toughness under different combined or mixed mode loading conditions starting from pure mode I to pure mode II it is desirable that only one type of specimen would be required. Because this was almost impossible to achieve by using beam type specimens also other types of test specimens have been developed. One other type is the Arcan specimen, which was firstly employed for generating states of plane stress in composite [4], then for fracture tests of isotropic materials [5] and also for mixed mode fracture tests of composites [6,7]. Another type of specimen for studying the interlaminar fracture properties of laminated composites is the Iosipesku specimen [8].

The most recent development [9,10] is a compound version of the compact tension shear (CTS) specimen which covers all in-plane mixed mode loading conditions starting from pure mode I through any mixed mode I/II ratio up to pure mode II loading. The CTS specimen was proposed earlier in [11] for fracture tests of isotropic materials under such general in-plane loading conditions. In the present paper the compound version of the CTS specimen is used for mode I, mixed mode I/II and mode II studies of the interlaminar fracture toughness properties of a carbon/epoxy composite.

EXPERIMENTAL

Material

Unidirectionally reinforced carbon/epoxy laminate was used for interlaminar fracture mixed mode I/II experiments. Volume fracture of the material was 70%. Material is assumed to be transversally isotropic (1 is a fiber direction, 2 and 3 are directions transverse to the fibers). The elastic properties of the material are as follows: E_1=170 GPa, E_2=9.4 GPa, $G_{12}=G_{13}$=4 GPa, ν_{23}=0.35, $\nu_{12}=\nu_{13}$=0.25 and $G_{23}=E_2/2(1+\nu_{23})$=3.5 GPa. These elastic properties were used in the finite element analysis of the CTS specimen. The thickness of the laminate was $2h$=1.3 mm.

CTS specimen

The CTS specimen (see Figure 1) was proposed in [11] for mixed mode fracture experiments. The compound version of the CTS specimen (see Figure 2) was proposed in [9,10]. The CTS (compact tension shear) specimen was made by gluing the composite strip in the glassmat/epoxy-Aluminium blocks.

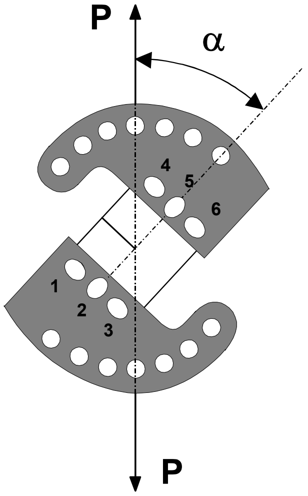

Figure 1: CTS specimen loading device

The load P is applied to the specimen by the loading device under an arbitrary angle α. By this the mixed mode loading of the specimen can be achieved from pure mode I ($\alpha=0^0$) through mixed mode I/II loading ($0^0<\alpha<90^0$) up to pure mode II loading ($\alpha=90^0$). The forces F_i (i=1, 2, ..., 6) acting on the holes of the CTS specimen (see Figure 2) can be calculated by the relations [9]

$$\begin{aligned} F_3 = F_4 &= P\left(\frac{1}{2}\cos\alpha + \frac{c}{b}\sin\alpha\right) \\ F_2 = F_5 &= P\sin\alpha \\ F_1 = F_6 &= P\left(\frac{1}{2}\cos\alpha - \frac{c}{b}\sin\alpha\right) \end{aligned} \tag{1}$$

where α is the loading angle (see Figure 1). In the finite element analysis these forces are applied at the corresponding nodes of the finite element mesh.

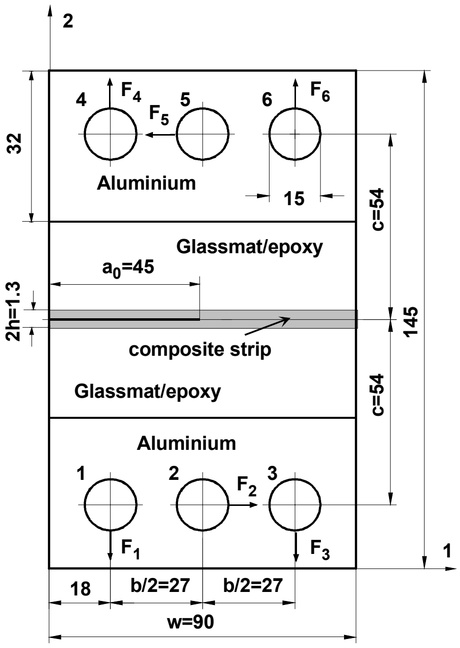

Figure 2: Compound version of the CTS specimen (dimensions are given in mm)

The advantage of the compound version of the CTS specimen is that with the same test specimen all in-plane loading conditions can be generated, starting from pure mode I through all combinations of plane mixed mode I/II ratios and also including pure mode II. In the present investigation experiments have been carried out for pure mode I (α=0^0), pure mode II (α=90^0) and for the mixed mode loading conditions with α=45^0, 60^0, 75^0, 81^0, 84^0 and 87^0.

Testing procedure

The CTS specimens were tested on MTS testing machine. The specimens were loaded with a constant displacement rate 0.5 mm/min and the critical loads P_c at crack initiation were measured. At all 29 samples were tested under various mixed mode ratios.

FINITE ELEMENT ANALYSIS

The finite element model of the specimen consists of quadrilateral plane strain elements with 4 nodal points. The plain strain conditions was used in the finite element analysis. The loads on the specimen were applied according to Figure 2 and were calculated by the expressions (1). The finite element analysis was performed by the program ANSYS [12]. For the calculation of the energy release rates G_I and G_{II} the Modified Virtual Crack Closure Integral (MVCCI) method is utilized so that the separated strain energy release rates are obtained by only one calculation (MVCCI or 1C method) for the actual crack length a as proposed in [13]

$$\begin{aligned} G_I^{1C}(a) &= \frac{1}{t\,\Delta a}\cdot\frac{1}{2}\left[F_y^i(a)\Delta u_y^{i-1}(a)\right]; \\ G_{II}^{1C}(a) &= \frac{1}{t\,\Delta a}\cdot\frac{1}{2}\left[F_x^i(a)\Delta u_x^{i-1}(a)\right], \end{aligned} \tag{2}$$

where $F_x^i(a)$ and $F_y^i(a)$ are the nodal point forces at the crack tip node i in x and y directions, respectively, while $\Delta u_x^{i-1}(a)$ and $\Delta u_y^{i-1}(a)$ are the relative nodal point displacements of the opposite crack faces at node i-

1 in x and y directions, respectively. Therefore $\Delta u_x^{i-1}(a)$ is the relative crack sliding displacement, while $\Delta u_y^{i-1}(a)$ is the relative crack opening displacement at a distance Δa behind the crack tip and t=10 *mm* is the width of the specimen. In the finite element model a crack increment of Δa=0.5 *mm* was used.

The finite element analysis for the CTS specimen with the initial crack a=45 *mm* was carried out. The energy release rates have been calculated by expressions (2). The calculated values by loading of the compound version of the CTS specimen under the applied load P=1000 N are presented in Table 1.

TABLE 1

ENERGY RELEASE RATES AT DIFFERENT LOADING ANGLES

Loading angle α	G_I, kJ/m^2	G_{II}, kJ/m^2
0	0.179799	0
15	0.170867	0.001103
30	0.140009	0.004062
45	0.095687	0.008083
60	0.049916	0.012089
75	0.014946	0.015009
78	0.010161	0.015385
81	0.006249	0.015679
84	0.003261	0.015891
87	0.001224	0.016019
90	0	0.016055

From the values of the separated energy release rates G_I and G_{II} calculated under load P=1000 N easily can be obtained the experimental values of the critical energy release rates. In the experiment for each specimen the critical loads P_c at crack initiation were measured. Since the energy release rate is quadratic function of the applied external load $G=kP^2$ from the Table 1 the corresponding critical energy release rates can be calculated.

RESULTS OF EXPERIMENT

Specimens have been loading under different angles α. The loading angles were chosen in order to obtain different mixed mode ratios giving maximum information about interlaminar fracture behavior of the laminate. In Table 1 it is seen that in the range of loading angles from 0^0 up to 60^{0-} the mode I loading conditions at the crack tip are dominant. At the loading angle 75^0 the mixed mode ratio is G_I/G_{II}=1. For the loading angles from 78^0 to 90^{0-} the mode II loading conditions at the crack tip are dominant. By using the experimental values and the finite element results from Table 1 the critical energy release rates at crack initiation are calculated. The results are presented in Figure 3. Rather large scatter of the results can be observed. Similarly large scatter of the results were obtained in the CTS experiments performed on glass/epoxy laminates [9,10]. One reason of such a large scatter is that width of the specimen is only 10 mm and therefore the influence of edge effects is significant. The loading device was designed for the CTS specimen width 10 mm. It should be noted that for the DCB (double cantilever beam) and ENF (end notched flexure) beam specimens it is recommended the width from 20 to 25 mm. However, as it was investigated in [9] there was no statistically significant difference between the mode II results obtained by the ENF and CTS tests. For some composites the scatter of the results obtained by the DCB tests also is rather large.

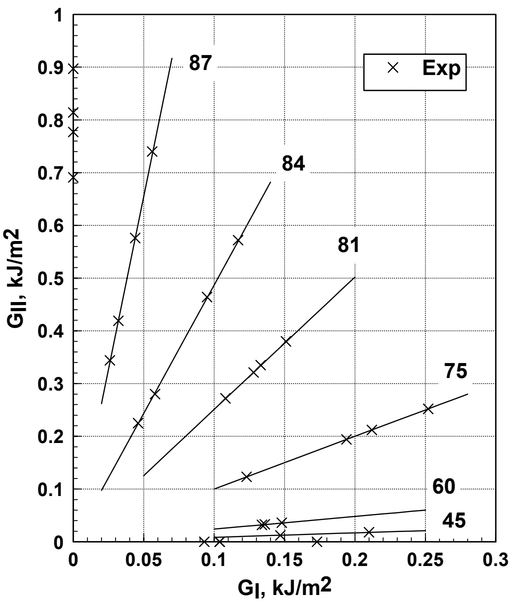

Figure 3: Mixed mode critical energy release rates obtained in the experiment under different loading angles

FRACTURE CRITERION

In the literature a number of mixed mode fracture criteria have been proposed for describing the interlaminar fracture of composites. These criteria are similar to those used for isotropic materials. Fracture criteria can be formulated on the basis of different fracture parameters like stress intensity factor (SIF) or energy release rate for which the critical fracture parameters (K_C or G_C) can be determined experimentally. Previously the stress intensity factors were used preferably as fracture parameters but for composites the energy release rates, which also are used in the present investigation, proved to be more useful and common.

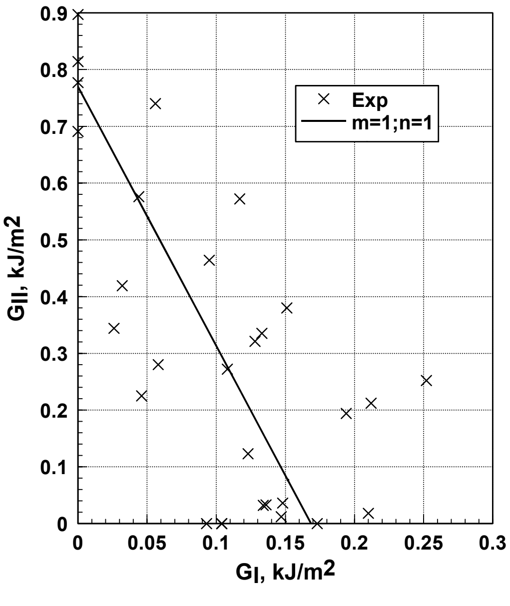

Figure 4: Criterion (3) for the exponents *m*=1 and *n*=1

The mixed mode fracture criterion can be written in a general form [14]

$$\left(\frac{G_I}{G_{IC}}\right)^m + \left(\frac{G_{II}}{G_{IIC}}\right)^n = 1 \qquad (3)$$

Here the exponents m, n and parameters G_{IC} and G_{IIC} can be determined by the least squares fit of the experimental data. Employing all combinations of a linear and quadratic terms it was found that the best fit criterion is with the exponents m=1 and n=1, i.e. for the linear criterion

$$\frac{G_I}{G_{IC}} + \frac{G_{II}}{G_{IIC}} = 1 \tag{4}$$

It was found that the best fit for the present material (see Figure 4) is for the parameters G_{IC}=0.168 kJ/m^2 and G_{IIC}=0.770 kJ/m^2.

It should be noted that for the glass/epoxy laminate investigated in [9] the best fit criterion was found with the exponents m=1 and n=2. For the present carbon/epoxy laminate better approximation was obtained employing the linear criterion. Therefore, the criterion (4) can be used to evaluate the interlaminar fracture behavior of the present carbon/epoxy laminate.

CONCLUSIONS

The mixed mode I/II experiments of carbon/epoxy laminate have been performed by using CTS tests. At all 29 samples were tested under different mixed mode ratios starting from pure mode I up to pure mode II loading conditions. By using the experimental results the fracture criterion has been developed. It was found that the best fit criterion is the linear criterion.

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