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SOME STUDIES ON INTERLAMINAR AND INTRALAMINAR FRACTURE TOUGHNESS OF MULTILAYERED COMPOSITE STRUCTURES

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SUMMARY: Closely stiffened carbon/epoxy composite panel is tested under compression and interlaminar fracture load is obtained with a delamination mode of failure between the base panel and the stringer. Strain energy release rate (G) of the panel is evaluated based on well-known MCCI approach introducing regressive delamination lengths between the skin and the stiffener. A good agreement is observed between the test and analytical prediction. Intralaminar mode I fracture toughness values of M55J/M18 carbon/epoxy composite for cross ply laminate $[0°/90°]_{15}$ (alternate 0° and 90° layers) and its constituents, namely the $[0°]_{30}$ and $[90°]_{30}$ laminates are also theoretically evaluated corresponding to the fracture loads obtained by testing C(T) specimens. Comparison of analytically determined K_{Ic} of the cross ply C(T) specimen based on a new relationship using the respective values of K_{Ic} of its constituent C(T) specimens shows a good agreement with both test data as well as MCCI approach. For M55J / M18 composite the interlaminar fracture toughenss is found to be 2.5 times lesser than intralaminar toughness value.

INTRODUCTION

The fracture of fibre reinforced laminated composite materials can be broadly classified into interlaminar and intralaminar fracture. The interlaminar fracture is commonly encountered in the form of a delamination between layers and intralaminar fracture by a crack apparently running parallel to fibres through the thickness. It has been reported in literature that intralaminar fracture toughness is more than interlaminar fracture toughness for different types carbon-epoxy laminates [1]. This is one of the reasons why the most of the studies on evaluation of the fracture toughness are confined to interlaminar fracture toughness. For the evaluation of mode I, mode II and mixed mode interlaminar fracture toughness, double cantilever beam test [2], end notched flexure test [3] and mixed mode bending tests [4,5] are the accepted test methods while for the intralaminar fracture toughness the compact tension specimen, usually referred as C(T) specimen is used. Theoretically, the well known modified crack closure integral (MCCI) method is used to evaluate the both types of fracture toughness corresponding to the fracture load.

Stringer stiffened composite panels are fabricated by co-curing the stiffeners with the skin to avoid mechanical fasteners. Under compressive loading it may fail either by compression or delamination of the stringer from the base panel once its critical compression failure strength is much higher than critical buckling strength. The most common failure mode reported in such cases is the stiffener delamination[6] . Accurate assessment of the failure load should be possible by comparing G with its critical value of interlaminar fracture toughness G_c. In the case of a through the thickness crack, it is compared with the intralaminar fracture toughness.

Theoretical evaluation of fracture load using MCCI approach is quite involved mainly due to its mode of failure. Though the failure surface observed is, say parallel to the fibre direction as in the case of an angle ply laminate with a through the thickness crack, evaluation of G should be based on the cracking angle along which the strain energy possesses the minimum value[7]. For the stringer stiffened panel, if the compressive failure strength is higher than the critical buckling strength then there will not be any interlaminar fracture failure. On the other hand, when there is a delamination failure then it is necessary to evaluate the mixed mode delamination fracture toughness. Fibre splitting in a multilayered composite adds further complication for the accurate evaluation of the intralaminar G. More over, for a given laminate with a crack, onset of fracture or progressive failure can take place depending up on the type of resin system used.

In the present study, initially, interlaminar fracture load of stringer stiffened composite panel is obtained through test and evaluated the same based on MCCI approach introducing regressive delamination lengths between the skin and the stiffener. Then intralaminar fracture load of cross ply and constituent laminate are obtained through test using C(T) specimen and compared using MCCI method. A new relationship is presented to predict analytically the fracture toughness of the cross ply laminate specimen using its constituent toughness values.

DESCRIPTION OF THE MODEL

Composite panel of size 400 mm X 750 mm with four hat type stringer stiffeners co-cured with the skin (panel) on one side of the panel is shown in Fig 1.The structure is made up of M55J/M18 carbon-Epoxy prepreg. The material properties of unidirectional laminate are given in Fig 1. The details of the lay-up sequence of the skin and stiffeners are also given in Fig 1. Each layer in the

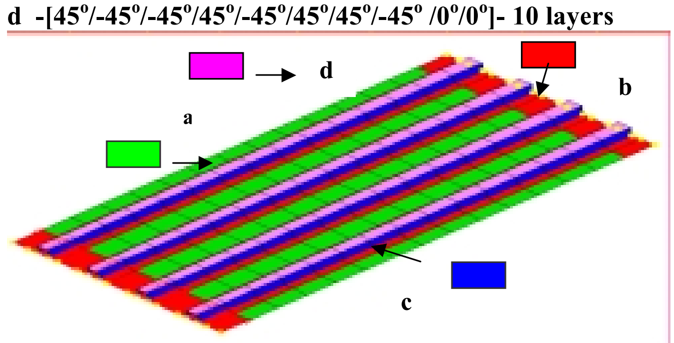
a - [30°/-30°/30°/-30°/60°/-60°/60°/-60°/-30°/30°/-30°/30°]
12 layers

<u>Stiffener</u>

b- [45°/-45°/-45°/45°/-45°/45°/45°/-45°/30°/-30°/30°/ -30°/60°/-60°/60°/-60°/-30°/30°/-30°/30°]- 20 layers

c - [45°/-45°/-45°/45°/-45°/45°/45°/-45°] - 8 layers

d -[45°/-45°/-45°/45°/-45°/45°/45°/-45° /0°/0°]- 10 layers



Longitudinal Young's Modulus, E_L-329 GPa
Transverse Young's Modulus, E_T - 6 GPa
Shear Modulus, G_{LT} – 4.4 GPa, ν_{LT}-0.346
More details in Refs 5-7.

Fig.1 STRINGER STIFFENED PANEL AND FINITE ELEMENT MODEL laminate is 0.1 mm thick.

TESTING

The testing is done in INSTRON machine. For the composite panel the compressive load is applied at the rate of 500 kg/min. The load at which delamination occurs is also noted. For the intralaminar fracture toughness evaluation testing, the loading rate is from 3kg/min to 25kg/min, depending on the lay up sequence. For instance, the loading rate for $[0°]_{30}$ specimen was 3kg/min while the same for $[0°/90°]_{15}$ was taken as 25kg/min. Fracture load P_s obtained from tests are used to determine K_{Ic} values as a measure of the fracture toughness using the following data reduction scheme[8].

$$K_{Ic} = P_s \; f(a/w) \, / \, B \, w^{1/2} \quad . \qquad (1)$$

where, P_s is the fracture load obtained from the test, B is the thickness of the C(T) specimen (3 mm in the present study), ‘a’ is crack length from loading point, a/w is the aspect ratio of the plate and f(a/w) a factor associated with the aspect ratio[ ].

FINITE ELEMENT MODEL

Finite element analysis for the composite panel is carried out using a four node plate/shell element available in NISA(Fig.1). Beam elements are considered to idealise the aluminium sections used on both ends of the panel. The model for delamination analysis differs slightly from the model used for static compression and buckling in which the flanges of the stiffener and the panel are modelled as two separate plates in the region of delamination. The strain energy release rate was evaluated using the well-known formulae based on virtual crack closure technique [6,7]. Now by comparing the obtained G values with the delamination fracture toughness value, the load at which the structure fails due to debonding is calculated. For the intralaminar fracture toughness evaluation, relation between mode I and stress intensity factors, and associated strain energy release rates are used [7] .

For the FE modeling of the C(T) specimen, an eight node quadrilateral plate/shell element with six degrees of freedom (three translations and three rotations) available in MSC\NASTRAN is used. Analysis is carried out with average value fracture load P_s (load at which crack initiates or on set of fracture takes place) obtained from the test.

A simply supported boundary condition was given at the top and bottom of the panel except the corresponding degrees of freedom along the direction of the load at the bottom. Compressive loads were applied along the stringer direction (along 750 mm height) at the bottom nodes as point loads (Fig.1). In the case of the finite element model of C(T) specimen, corresponding to the bottom loading point of the specimen all the degrees of freedom are constrained and point load is applied at the top loading point [7].

RESULTS AND DISCUSSIONS OF INTERLAMINAR FRACTURE

Based on Tsai-Wu criterion the compressive load is evaluated as 58.720 kN while the critical buckling load is found to be 51 kN. The test showed a delamination of stringers from the panel at 46.75 kN. It may be noted that as the compressive failure load is marginally higher than the critical buckling load by 15 % and the mode of failure may be either buckling or delamination. Since the critical buckling load is found to be less than the compressive failure load delamination analysis is carried out using the MCCI method. The value of G_I and G_{II} are obtained for different delamination lengths which is varied from 22.5 mm to 7.5 mm . These values are calculated for all the plate elements forming the delamination at the four regions idealised by eight elements(Fig.1) and the average value is computed for the analysis. FE model is refined and convergence is established. Hence in the present study the medium size mesh shown in Fig.1 is used. For a semi crack length of 7.5 mm, G_I and G_{II} values are obtained as 1.16 J/m^2 and 41.12 J/m^2 respectively at 20 kN and as the crack length increases to 22.5mm these values are found to be 1.43 and 46.27 J/m^2.

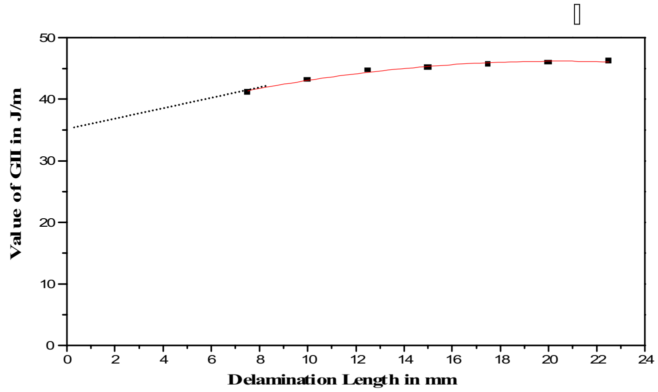


FIG. 2 VARIATION OF G_{II} WITH DELAMINATION LENGTHS

The variation of G_{II} with respect to delamination lengths is shown in Fig 2. From this graph, the value of G_{II} corresponding to the zero delamination length is estimated by extrapolating the curve to meet the Y-axis . This value of G_{II} (34.5 J/m^2) corresponding to zero delamination length at 20 kN is used to estimate the fracture load for the mixed mode ratio, G_{II}/G . G_{Ic} and G_{IIc} values for M55J/M18 carbon/epoxy laminate indicates the critical value of strain energy release rate as 66.5 J/m^2 and 240 J/m^2 respectively[5]. As G_I is smaller when compared to $G_{II,}$ the mixed mode ratio G_{II}/G is obtained as 0.96. Thus fracture load is evaluated as 52.37 kN as against the test data of 46.75 kN.

It is found from the analysis that in the mixed modes of G_I and G_{II}, the contribution of G_{II} is very much greater than G_I which indicates the failure is mainly due to shear. In the present method the delamination fracture toughness of M55J/M18 unidirectional mixed mode bending specimen is used[5] to compare G obtained from the analysis where at the common delaminated interface, fibre angle of the base panel is +30^0 and +45^0 of the stringer. This is one of the reasons for deviation between the test and prediction.

From the results discussed so far one can see that the evaluation of failure load based on delamination is necessary to assess the margin of safety of the structure accurately. It may be noted that since the mode of failure is delamination, evaluation of failure load based on critical buckling load is not acceptable even though the structure may sometimes be safe.

RESULTS AND DISCUSSIONS OF INTRALAMINAR FRACTURE

It is observed from the fractured specimens that there are matrix cracking for $[0°]_{30}$ and $[90°]_{30}$ laminates while for the cross ply laminate there is a fibre breakage as anticipated.

Test results obtained for mode I intralaminar fracture toughness K_{Ic} for all the three types of specimens considered are presented in Table.1 with specimen details, which show that the scatter in the test data is minimum for the cross ply laminate and maximum for the $[90°]_{30}$ laminate. Typically, the deviation with respect to the average value for the cross ply laminate is 5.3% whereas for $[0°]_{30}$ and $[90°]_{30}$ laminates, it is 8.5% and 17%, respectively.

The average fracture toughness values of $[0°]_{30}$, $[90°]_{30}$ and $[0°/90°]_{15}$ laminates obtained from the test are 36.42 $N/mm\sqrt{mm}$, 137.82 $N/mm\sqrt{mm}$ and 808.59 $N/mm\sqrt{mm}$ respectively. Similar values determined by MCCI approach corresponding to the fracture loads are 39.33 $N/mm\sqrt{mm}$ 117.67 $N/mm\sqrt{mm}$ and 870.84 $N/mm\sqrt{mm}$. The theoretical prediction of K_{Ic} value of $[0°]_{30}$ laminate is found to be 8% higher than the test. Similar comparison for $[90°]_{30}$ and cross ply laminates are 14.6 % and 7.7% respectively. Marginal higher estimation in the theoretical prediction (except $[90°]_{30}$ laminate) is due to the linear FE analysis and in $[90°]_{30}$ laminate, it is due to the scatter in the fracture load of the two specimens. Thus it can be concluded that K_{Ic} evaluated based on the linear analysis is quite close to the actual value of K_{Ic} obtained from the test. In other words, crack initiation load assumed in the analysis is quite close to the fracture load obtained from the test. It may be noted that the intralaminar G_I for $[0°]_{30}$ is 168 J/m^2.

RELATIONSHIP FOR K_{IC} OF CROSS PLY C(T) SPECIMEN BASED ON K_{IC} OF ITS CONSTITUENT SUB LAMINATES

It has been mentioned in the above section that crack initiation load assumed in the analysis is quite close to the fracture load obtained from the test. Thus under static equilbrium, the fracture load acting on $[0°/90°]_{15}$ laminate is assumed as a sum of loads shared by $[0°]_{30}$ and $[90°]_{30}$ layers in the cross ply laminate. Thus mode I fracture toughness of cross play C(T) specimen can be expressed in terms of mode I fracture toughness of $[0°]_{30}$ C(T) specimen and $[90°]_{30}$ C(T) specimen as given below.

$$K_{\mathrm{Ic}}^{[0°/90°]_n} = \frac{n}{B}\left[K_{\mathrm{Ic}}^{0^{\circ}} + K_{\mathrm{Ic}}^{90^{\circ}}\right] \qquad \text{....(2)}$$

where n is the number of pairs of alternate 0° and 90° layers and B is the thickness of laminate .

PREDICTION OF K_{IC} FOR CROSS PLY LAMINATE USING EQN. (2) BASED ON TEST DATA

Initially using eqn. (2) with n=15 and B=3mm, K_{Ic} of $[0°/90°]_{15}$ laminate is analytically determined based on the tested values of K_{Ic} of $[0°]_{30}$ and $[90°]_{30}$ C(T) specimens as 871.20 $N/mm\sqrt{mm}$ (Table-2). The actual average test value of K_{Ic} of the cross ply laminate is 808.59 $N/mm\sqrt{mm}$ (Table-1). This shows a good agreement in K_{Ic} determined using eqn. (2).

PREDICTION OF K_{IC} FOR CROSS PLY LAMINATE USING EQN. (2) BASED ON MCCI METHOD

K_{Ic} of $[0°/90°]_{15}$ laminate is analytically determined based on K_{Ic} of $[0°]_{30}$ and $[90°]_{30}$ C(T) specimens obtained by FE analysis as 785.00 $N/mm\sqrt{mm}$ (Table-4) as against the actual average test value of K_{Ic} of the cross ply laminate of 808.59 $N/mm\sqrt{mm}$ (Table-2 & 4). This also shows a good agreement in K_{Ic} determined using eqn. (2).

In general the predicted value based on the K_{Ic} values from test shows good agreement within 8% of the actual tested value of K_{Ic} for the cross ply laminate while a similar correlation based on K_{Ic} values from the finite element analysis is within 10%, thus validating the equation (2).

CONCLUSIONS

Stringer stiffened M55J/M18 carbon/epoxy composite panel has been tested and the delamination fracture load evaluated using MCCI approach has shown good agreement with the test data. The delamination analysis also shows the separation of the stringer from the panel like that observed in the test. This occurs mainly due to the shear as G_{II} is found much higher than G_I. Intralaminar mode I fracture toughness values of M55J/M18 carbon/epoxy composite for the cross ply laminate $[0°/90°]_{15}$ and its constituent laminates $[0°]_{30}$ and $[90°]_{30}$ have been theoretically evaluated based on the modified crack closure integral method corresponding to the failure loads obtained by testing C(T) specimens. An analytical relationship for the evaluation of mode I intra laminar fracture toughness of the cross ply laminate based on its constituent sub laminates of the C(T) specimens is presented and validated for M55J/M18 carbon/epoxy composite.

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TABLE 1. SPECIMEN DETAILS WITH TEST RESULTS

Lay – up →	**$[0°]_{30}$**				**$[90°]_{30}$**		**$[0°/90°]_{15}$**			
Specimen No	1	2	3	4	1	2	1	2	3	4
w mm	51.3	50.5	51.13	50.62	50.8	50.81	50.8	50.6	50.44	50.76
a mm	25.9	24.0	25.93	25.02	22.9	24.77	25.1	25.5	25.0	24.12
a/w	0.504	0.475	0.507	0.494	0.451	0.488	0.494	0.504	0.496	0.475
$f(a/w)$	9.78	8.96	9.871	9.426	8.363	9.313	9.483	9.779	9.541	8.960
Ps (N)	74.56	82.40	74.75	96.14	292.3	370.3	1844.3	1795.2	1849.2	1826.6
K_{Ic} from Test $N/mm\sqrt{mm}$	33.93	34.63	34.39	42.46	114.3	161.2	817.94	822.66	828.07	765.73

TABLE 2. PREDICTION OF K_{Ic} $[0°/90°]_{15}$ CROSS PLY LAMINATE BASED ON CONSTITUENT LAMINAE

K_{Ic} $[0°/90°]_{15}$ $N/mm\sqrt{mm}$	PRESENT ANALYTICAL PREDICTION (eq.(5)) K_{Ic} $[0°/90°]_{15}$ $N/mm\sqrt{mm}$
ACTUAL TEST DATA **808.59**	BASED ON TEST DATA OF 0° & 90° LAMINATES **871.20**
	BASED ON FE ANALYSIS OF 0° & 90° LAMINATES **785.00**