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On the determination of interlaminar fracture toughness of carbon/epoxy cross-ply composites

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Abstract
Delamination between layers is a dangerous failure mode in fiber reinforced composite laminates. Pure mode I tests were conducted to determine the interlaminar fracture toughness, using 16-ply DCB specimens prepared from carbon/epoxy unidirectional fabric, under quasi-static condition. Analysis of the test specimens in terms of mode I interlaminar critical strain energy release rate, G_{Ic} showed good agreement between data reduction methods based on modified beam theory, compliance calibration, and modified compliance calibration. The results showed that the measured G_{Ic} values at initiation for $[0/90]_{4s}$ specimens are higher than that of unidirectional $[0^0]_{16}$ specimens.
Keywords**:** delamination, interlaminar fracture toughness, mode I fracture, carbon/epoxy, quasi-static condition

1. Introduction

Delamination is a common major failure mode in high performance composite structures. This damage may significantly results in the loss of structural stiffness and strength, which leads to catastrophic failure. So, preventing failure of composite material systems has become a great importance in engineering design. This delamination establishes restrictions in achieving the full weight saving potential of composite materials [1,2]. The characterization of the delamination resistance in mode I fracture based on fracture mechanics has become a generally accepted practice to measure the critical strain energy release rate, G_{Ic}, of unidirectional (UD) laminates [3-6]. It is very quite convenient for such specimens to test under DCB but most engineering applications uses multidirectional (MD) laminates, where delamination occurs between layers of different fiber orientations. The standard DCB specimen has been used to assess the mode I delamination resistance of carbon/epoxy cross-ply laminates [7,8].

Several studies have assessed that the measured values of G_{Ic} were practically independent of the interface fiber orientation at the delamination [8], while other studies concluded that the values of G_{Ic} were increases with the change of fiber orientation of the adjacent plies and also with the change of orientation of the sub-adjacent plies [9-11]. As a result, it is of a great interest for this study to get more understanding on the effects of different fiber orientations of the adjacent plies on the mode I crack propagation.

This work is mainly focused on the effect of cross-ply on G_{IC} of a carbon/epoxy composite laminate. The double cantilever beam (DCB) specimens were prepared from carbon fabric of 300 gsm with epoxy resin. Two different 16-ply specimens were made with ply sequence of $[0]_{16}$ and $[0/90]_{4s}$ and they were tested under quasi-static condition. The experimental interlaminar fracture toughness in Mode-I were measured.

2. Experimental Techniques

2.1. Preparation of Dcb Specimen

Mode I interlaminar fracture tests were conducted on DCB specimens. For this purpose, DCB specimens were made from unidirectional carbon fabric of 300 gsm with epoxy resin by hand layup method. Two different 16-ply specimens were prepared with ply sequence of $[0]_{16}$ and $[0/90]_{4s}$ to form a 150 by 150 mm panel. Initially, grease is used as a releasing agent for easy removal of the composite from the mould. A mixture of resin and hardener was rolled over on each layer till all the 16 layers were over and allowed to dry. A Teflon film of 0.1 mm thickness was embedded at mid-thickness to produce a pre-crack. The panels were cured at 25^0 C and a weight of 30 kg was applied for 24 h. The recommended specimen dimensions are 125 mm long and 20 mm width with an initial crack length of 50 mm measured from the load line to the end of the insert as shown in Fig.1. Test specimens were cut from each panel by using a rotary diamond cutter.

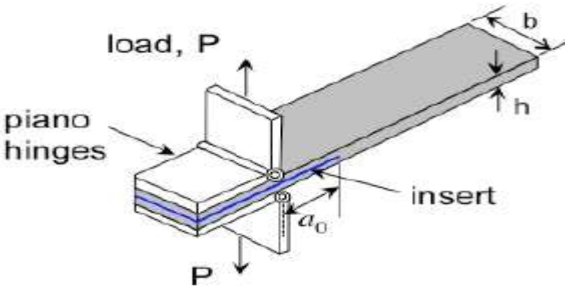


Fig.1. Double Cantilever Beam Specimen

2.2. Mechanical Tests

DCB Specimens with Aluminum clamps were firmly fixed in the Jaws of a Universal Testing Machine as shown in Fig.2. Three specimens per each layup were tested in a displacement mode with a constant displacement rate of 0.5 mm/min. The machine is connected to a computer where the load and its corresponding displacement data is recorded and displayed. Test specimen edges were white painted and marks were made at every 5 mm on the both specimen edges from the tip of the delamination to monitor the crack propagation. The crack propagation was observed and the values of crack opening displacement corresponding to every 5mm extension were recorded. The failure load for each case was selected as the highest load to determine the mode I critical energy release rate G_{Ic}.

Fig.2. DCB test specimen in Universal Testing Machine

3. Data reduction methods

For DCB mode I tests as suggested in ASTM standard D 5528-13 [4], the interlaminar fracture toughness in terms of the critical strain energy release rate can be measured by three data reduction models such as a modified beam theory(MBT), a compliance calibration method(CC), and a modified compliance calibration method(MCC) are, respectively, as follows:

$$G_{Ic} = \frac{3P\delta}{2b(a+|\Delta|)} \quad (1)$$

where $|\Delta|$ translates the effect of testing conditions as well as the rotation at the crack front.

$$G_{Ic} = \frac{nP\delta}{2ba} \quad \text{with Berry's compliance calibration : } C = \alpha a^{n} \quad (2)$$

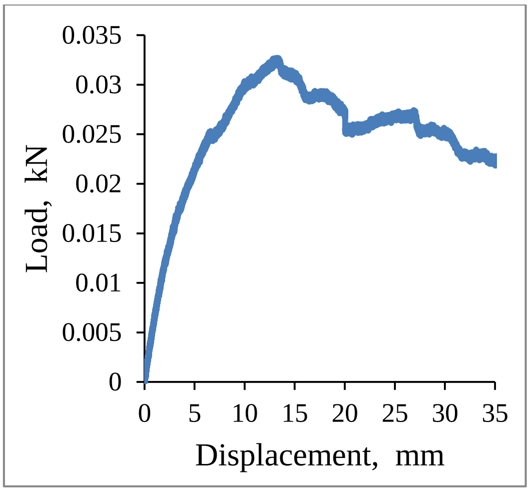
$$G_{Ic} = \frac{3P^2C^{2/3}}{2A_1bh} \quad \text{here } A_1 \text{ has to be determined by } (a/h) = A_1 C^{1/3} \quad (3)$$

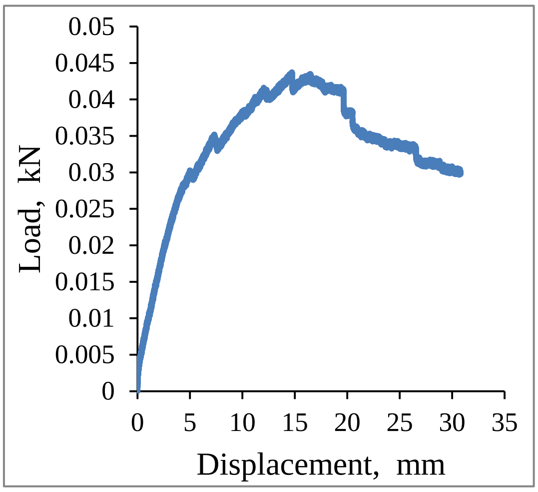
All of the above methods have calculated curve fit parameters by experimental compliance calibration.

4. Results and Discussions

The typical load- displacement response of two different 16-ply DCB specimens was displayed in Fig.3 (a) & (b). It is seen from both the plots of Fig.3 that the loads increase linearly and stay steady as the delamination propagates which means a stable crack growth under mode I fracture. The failure loads for the DCB specimens were estimated from the experimental results and used to determine the critical energy release rate. The G_{Ic} values in terms of critical strain energy release rate were assessed using the three data reduction methods consists of the modified beam theory, the compliance calibration method and the modified compliance calibration method for different ply sequences are listed in Table 1and Table 2 and are in good agreement with each other.

The R-curves for both $[0]_{16}$ and $[(0/90)]_{4s}$ specimens are presented in Fig.4 (a) & (b) based on MBT and MCC data reduction methods. It is seen from the plots shown in Fig.4 that the G_{Ic} values increases continuously with considerable variation in crack extension of curve with $[0]_{16}$ layup is due to the stable crack growth that occurred at crack initiation and propagation. But in the case of curve with $[(0/90)]_{4s}$ layup, it is observed that the sudden increase in G_{Ic} values accompanied by a small variation in its crack extension at the beginning of curve and becomes stable as the delamination propagates. It is also observed that the measured G_{Ic} values for $[(0/90)]_{4s}$ layup were slightly higher than the G_{Ic} values for $[0]_{16}$ layup at the initiation due to the development of transverse intralaminar and unstable crack propagation when the test progresses. Regarding the results and recommendations of other works on DCB-tests on multidirectional laminates [12,13], G_{Ic} values of initiation are reported as interlaminar fracture toughness. The experimental results show that cross-ply layers at the crack interface affects the G_{Ic} as indicated in Table 3. However to fully understand this, more ply orientation combinations need to be tested to characterize mode I crack behavior.





(a) $[0]_{16}$ (b) $[(0/90)]_{4s}$

Fig.3. The load displacement behavior of a DCB specimens with (a) $[0]_{16}$ and (b) $[(0/90)]_{4s}$ lay-ups.

Table 1: Interlaminar fracture toughness obtained from DCB test for $[0]_{16}$ lay-up.

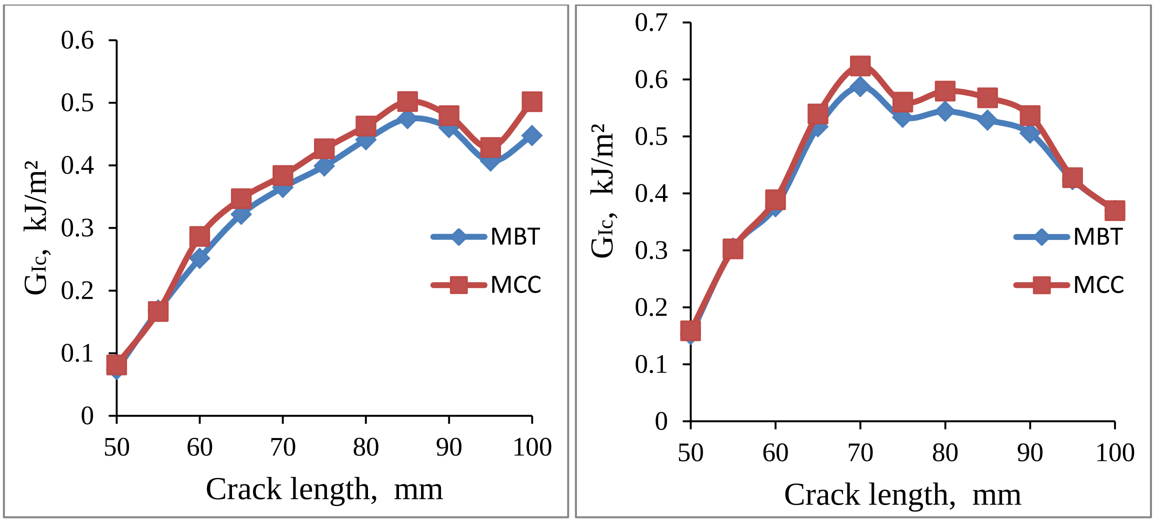
S.No	Displacement δ (mm)	Load P (kN)	Compliance δ/P	Delamination *a* (mm)	Width b (mm)	G_{Ic} (kJ/m^2) MBT	G_{Ic} (kJ/m^2) CC	G_{Ic} (kJ/m^2) MCC
1	3.3916	0.0178	190.539	50	20.76	0.08393	0.08334	0.08188
2	7.0813	0.0311	227.695	55	20.76	0.16869	0.18752	0.16956
3	8.1132	0.0296	274.095	60	20.76	0.29148	0.27628	0.28853
4	12.9968	0.0348	373.471	65	20.76	0.34162	0.48030	0.34016
5	13.8362	0.0304	455.138	70	20.76	0.39470	0.41477	0.38676
6	15.6234	0.0267	585.146	75	20.76	0.42882	0.38392	0.42923
7	17.5698	0.0274	641.234	80	20.76	0.45083	0.41538	0.46570
8	23.1176	0.0267	865.828	85	20.76	0.49445	0.50124	0.50541
9	25.8456	0.0244	1059.246	90	20.76	0.48026	0.48367	0.48282
10	26.3798	0.0222	1188.279	95	20.76	0.44687	0.42551	0.43151
11	27.6649	0.0244	1133.807	100	20.76	0.49746	0.46594	0.50522

Table 2: Interlaminar fracture toughness obtained from DCB test for $[(0/90)]_{4S}$ lay-up.

S.No	Displacement δ (mm)	Load P (kN)	Compliance δ/P	Delamination *a* (mm)	Width b (mm)	G_{Ic} (kJ/m^2) MBT	G_{Ic} (kJ/m^2) CC	G_{Ic} (kJ/m^2) MCC
1	4.375	0.028	156.250	50	20.78	0.15246	0.15938	0.16276
2	7.796	0.034	229.294	55	20.78	0.30371	0.31350	0.30991
3	9.591	0.037	259.216	60	20.78	0.37671	0.38474	0.39828
4	12.751	0.041	311.000	65	20.78	0.51695	0.52320	0.55219
5	15.114	0.042	359.857	70	20.78	0.58746	0.58991	0.63865
6	16.579	0.037	448.081	75	20.78	0.53349	0.53205	0.57366
7	18.432	0.036	512.000	80	20.78	0.54430	0.53956	0.59356
8	20.029	0.034	589.088	85	20.78	0.52857	0.52116	0.58133
9	22.145	0.031	714.355	90	20.78	0.50566	0.49619	0.54955
10	24.213	0.025	968.520	95	20.78	0.42423	0.41449	0.43782
11	25.146	0.022	1188.455	100	20.78	0.36976	0.35987	0.38861

Table 3: Interlaminar fracture toughness obtained from DCB test for various fiber lay-ups.

	Fiber lay-up	Modified Beam Theory(MBT)	Compliance Calibration(CC)	Modified Compliance Calibration(MCC)
G_I (kJ/m^2) (Mean values)	$[0]_{16}$	0.35083	0.37435	0.37880
	$[0/90]_{4s}$	0.44030	0.43946	0.47148



(a) $[0]_{16}$ (b) $[(0/90)]_{4s}$

Fig.4. Resistance curve (R-curve) in DCB specimens with (a) $[0]_{16}$ and (b) $[(0/90)]_{4s}$` lay-ups.

5. Conclusions

Experimental study of the delamination fracture toughness of carbon/epoxy cross-ply composite laminates was presented. A double cantilever beam specimens with two different 16-ply sequences were used to determine mode I interlaminar fracture toughness. Analysis of the specimens based on compliance measurements agreed with each other. The results showed that the measured G_{Ic} values were higher than those of unidirectional $[0^0]_{16}$ specimens.

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