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Evaluation of Carbon/Epoxy Delamination Fracture Toughness

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Abstract: Delamination is one of the most commonly observed failure modes in laminated composites. The existence of a delamination in a structure can significantly reduce the stiffness and strength of the structure. Various types of cracked specimens were designed to quantify the effect of delaminations in composites. The growth of delamination in composite structures starts when the strain energy release rate (G) under service loads exceeds the fracture energy (G_c). The measurement of fracture toughness of a material relies strongly on the method of data interpretation. In the original form, the experimental fracture data normally consists of a load-displacement record for a cracked specimen. Data reduction requires the knowledge of the specimen crack length and dimensions and a suitable method for calculating the fracture parameters. This study presents a simple and reliable procedure for the evaluation of mode I and mode II delamination fracture toughness from the test data of Double Cantilever Beam (DCB) specimens and Cracked-Lap Shear (CLS) specimens made of carbon/epoxy. Critical load estimation of DCB specimens from the measured specific fracture energy (G_{IC}) of the materials is found to be in good agreement with test results.

Key words: Delamination fracture toughness, critical load, carbon/epoxy, glass/epoxy, double cantilever beam, cracked lap shear specimen

Introduction

Delamination or interlaminar cracking in laminated fibre-reinforced composite materials is considered as one of the major failure modes. The delamination or debonds may be as a result of residual stresses due to the curing process, external impact damage, environmental degradation or the fabrication process, or may develop in service, causing structural degradation or failures at stresses well below the strength levels expected for defect free material. The life expectancy for composite structure requires a comprehensive understanding of the materials response to the growth of interlaminar flaws/delaminations. The growth of delamination in composite structures (under opening, shearing, tearing, or a combination thereof) starts when strain energy release rate G under service loads exceeds the fracture energy, G_c.

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Owing to the intrinsic complexities involved such as anisotropy and inhomogeneity, efforts have been made for a quantitative assessment of the effect of realistic delamination on strength and lifetime of a laminate. Zhou and Sun (1990) evaluated interlaminar stresses to predict the onset and growth of delamination. Composite laminates are generally considered as linear elastic materials and it is thus reasonable to apply Linear Elastic Fracture Mechanics (LEFM) to study the interlaminar failure of composite materials. The commonly used test specimens for unidirectional composites are the Double Cantilever Beam (DCB) for mode I fracture, the End-Notched Flexure (ENF) for mode II fracture and the Cracked-Lap Shear (CLS) for mixed mode fracture.

Evaluation of fracture energy or the critical strain energy release rate (G_{IC}) in the opening mode (mode I) for a material lies heavily on the interpretation of fracture data which normally consist of a load-displacement (P-δ) record for specimens with cracks. For direct evaluation of G_{IC} from the recorded fracture data, there are basically two different LEFM methods, viz., the area and compliance methods. Hashemi *et al*. (1989, 1990) evaluated G_{IC} from the test data of DCB specimens and found that the agreement between values from the area and compliance methods is good, but there is poor agreement with those values obtained from the load and displacement methods based on simple beam theory. To account for these discrepancies, they have considered several factors, e.g. errors in the measurement of crack length and displacement, shear correction, large displacement correction and noted that none of these possible errors was significant enough to eliminate the discrepancies and correct the analytical method. Zhou *et al*. (1992) have shown that when using a DCB test to determine the fracture toughness, corrections must be employed. Zhou and He (1994) measured mode II strain energy release rate of composite laminates from the ENF specimens. Kan *et al*. (1987) described an analysis method to predict the static strength of a composite laminate with a delamination, using the resistance curve (R-curve) approach. R-curve being the term used for the fracture behavior when the G_{IC} value increasing with increasing the crack length. Hashemi *et al*. (1989) reported that any differences in the values of G_{IC} or the tendency to show an R-curve must be due to the methods being used to analyze the fracture data.

Rao and Acharya (1995a, b) proposed a realistic procedure for small as well as large deflections considering non-zero slope at the crack-tip of the DCB specimens. Williams (1993) and Charalambides and Williams (1994) have described an analytical method for calculating mode I fracture toughness of composites showing permanent deformation during fracture. Hwu *et al*. (1995) proposed a fracture criterion for delamination and carried out finite element analysis to predict composite laminate as well as in a delaminated composite. Asp (1998) examined the effects of moisture and temperature on the interlaminar delamination toughness of a carbon/epoxy composite. Pagano and Schoeppner (2000) and Tay (2003) have made surveys of the state-of-the-art in research done on delamination in composite materials. Mathews and Swanson (2005) have presented calculations for beam-type geometries that are representative of DCB and ENF specimens, which illustrate the effect of material properties, loading and the compliances of the delaminated sections on the mixed mode.

This study presents the carbon/epoxy delamination fracture toughness related to modes I and II from the fracture data. Test data of Double Cantilever Beam (DCB) specimens and Cracked-Lap Shear (CLS) specimens are utilized to measure the delamination fracture toughness. Critical load estimates of DCB specimens from the measured specific fracture energy were compared with test results.

Strain Energy Release Rate

The strain energy release rate, G is a quantity based on energy considerations. A potential H may be defined for a cracked body as

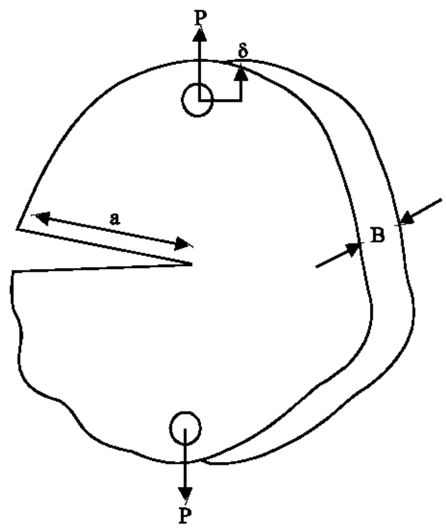

Fig. 1: A cracked plate

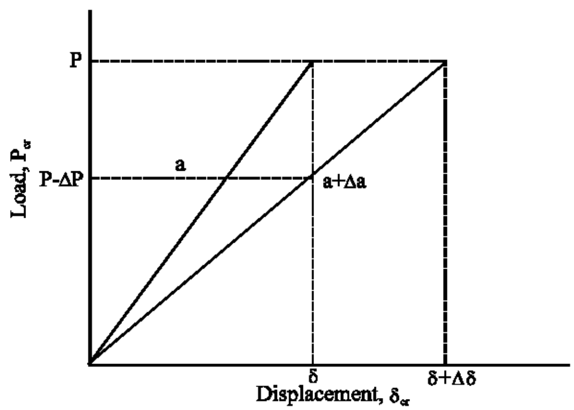

Fig. 2: Illustration of load-displacement relation for crack lengths a and (a+Δa)

$$H = W - U \qquad (1)$$

where, W is the work done by the external forces and U is the elastic strain energy stored in the body. If G_c is the work required to create a unit crack area, it is possible to formulate a criterion for crack growth:

$$\Delta H \geq G_c \Delta A \qquad (2)$$

where, ΔA is the increase in crack area.

Most fracture specimens having constant thickness (B) are employed for interlaminar fracture testing. The amount of new crack surface area ΔA, is then ΔA = B Δa, where Δa is the incremental crack length. The strain energy release rate, G ($\equiv \partial H/\partial A$) can then be expressed as:

$$G = \frac{1}{B}\left(\frac{\partial H}{\partial a}\right) \quad (3)$$

Figure 1 shows a cracked plate of thickness, B under a load P. Figure 2 shows the illustration of load-displacement relation for crack lengths, a and (a+Δa). When there is no crack extension, proportionality exists between displacement and load i.e.,

$$\delta = C\,P \quad (4)$$

where C is the compliance of the cracked body.
The work supplied by the movement of the load P is

$$W = \int_0^{\delta} P d\delta \quad (5)$$

The elastic energy stored in the body is

$$U = \frac{1}{2} P\delta \quad (6)$$

From the Eq. 1-6, the strain energy release rate (G) can be written in the form

$$G = \frac{P^2}{2B} \frac{\partial C}{\partial a} \quad (7)$$

The beam compliance can be expressed as (Fridrich, 1989),

$$C = \frac{\delta}{P} = \frac{a^n}{\alpha} \quad (8)$$

where n and α are parameters to be determined from the test data.
From Eq. 7 and 8 the strain energy release rate, G_I for mode I can be written in the form

$$G_I = \frac{nP^2a^{n-1}}{2B\alpha} = \frac{nP\delta}{2Ba} \quad (9)$$

Double Cantilever Beam (DCB) Specimen

Following the concepts of strength of materials, the potential energy due to bending of a Double Cantilever Beam (DCB) specimen (Fig. 3) having a crack length ‘a’ is

$$H = \int_0^{a} \frac{M^2}{EI} dx = \frac{P^2a^3}{3EI} \quad (10)$$

where M = Px, is the local bending moment, E is the Young’s modulus and I is the area moment. P is the tip-concentrated load and the beam axis x varies from x = 0 (at the tip) to x = a (at the crack tip).

Using Eq. 3 and 10, the strain energy release rate (G_I) for a DCB beam specimen is

$$G_I = \frac{P^2\,a^2}{B\,E\,I} = \frac{3}{2}\frac{P\delta}{Ba}, \quad (11)$$

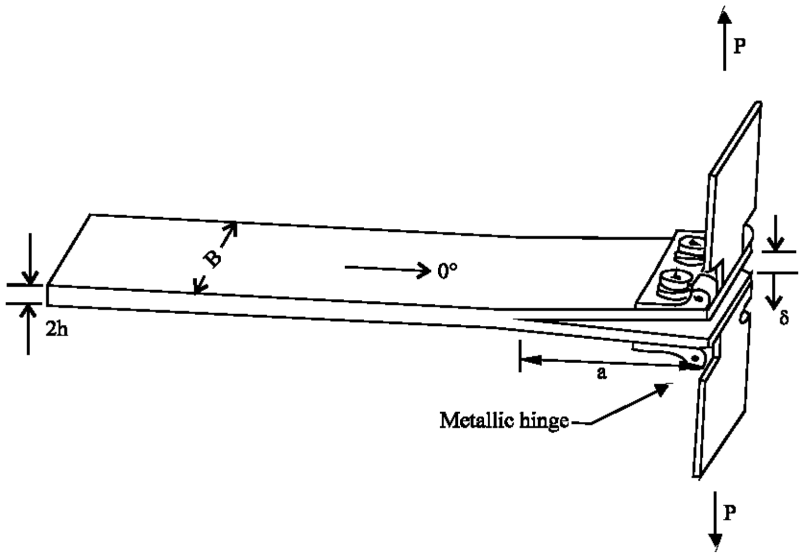

Fig. 3: Double Cantilever Beam (DCB) specimen

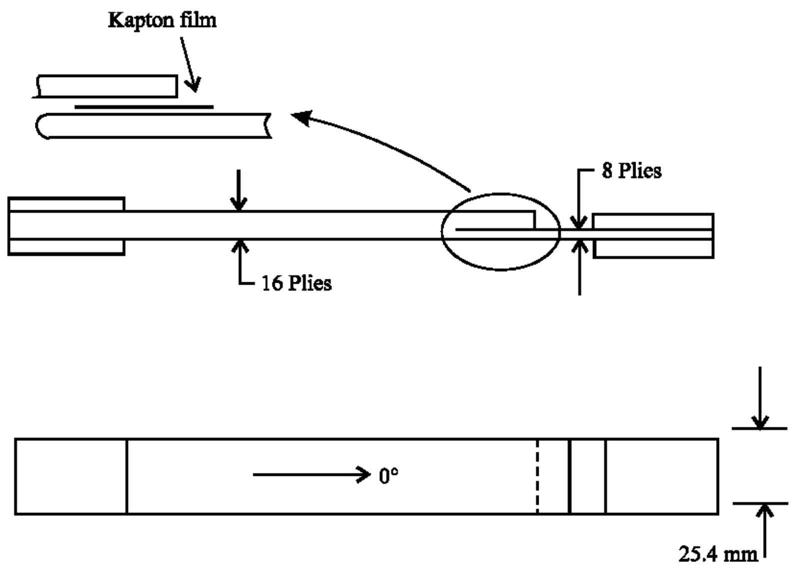

Fig. 4: Cracked-Lap Shear (CLS) specimen

where, $\delta = \frac{2}{3}\frac{Pa^3}{EI}$, is the deflection of the DCB specimen.

It should be noted that Eq. 11 resembles Eq. 9. The deflection and rotation (slope) are assumed to be zero at the crack-tip of the DCB specimen. In actual situation, there is a possibility of non-zero slope at the crack-tip of the DCB specimens. It can be verified from the fracture test data of DCB specimens, through the value of n in Eq. 9. If n = 3, then the slope at the crack-tip of the DCB specimen is zero.

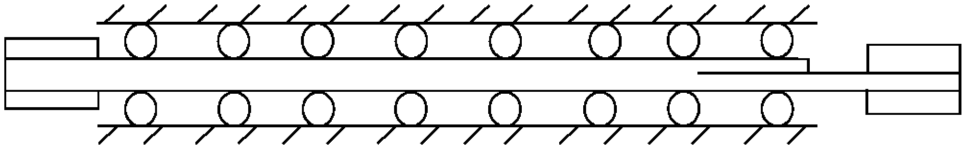

Fig. 5: Constrained Cracked-Lap Shear (CCLS) specimen

Cracked-Lap Shear (CLS) Specimen

Due to the presence of weak planes between the layers of a composite laminate, delaminations often grow under the influence of a mixed-mode stress field. In a mixed-mode, both normal and shear stresses act across the interface ahead of the crack-tip. And both opening and sliding displacements occur on the crack faces behind the crack-tip. Cracked-lap Shear (CLS) specimen shown in Fig. 4 (unconstrained CLS specimens) can be used to examine the delamination growth in a mixed-mode (mode I and mode II). The mode I contribution arises from the eccentricity in the remote loads which causes out-of-plane loading on the delaminated plies. Test data on constrained CLS specimens (Fig. 5) will be useful to examine the delamination fracture toughness without having out-of-plane loading on the delaminated plies. The strain energy release rate (G) is evaluated from the test data of CLS specimens utilizing Eq. 7 and 8.

Results and Discussion

It is essential to gain the knowledge of the crack growth behavior for material development and selection and for design and life-prediction studies. A popular approach to the characterization of the propagation of interlaminar cracks has been through the application of LEFM which enables the critical energy release rate or fracture energy (G_c) to be deduced. Kan *et al*. (1987) presented test results of Double Cantilever Beam (DCB) specimens, Cracked-lap Shear (CLS) specimens and Constrained Cracked-lap Shear (CCLS) specimens (Fig. 3-5) for two material systems of carbon/epoxy (AS4/3501-6 and IM6/5245C). Delamination fracture toughness (G_c) values are evaluated from the fracture data utilizing Eq. 7 and 8. Table 1 gives delamination fracture toughness values for carbon/epoxy. The mixed mode strain energy release rate of unconstrained CLS specimens is found to be lower than that of the constrained CLS specimens. This is mainly due to the contribution of opening mode-I. This arises from the eccentricity in the remote loads, which causes out-of-plane loading on the delaminated plies.

The following expressions are utilized while estimating the critical load for the DCB specimens from the evaluated delamination fracture toughness (G_{IC}):

$$P_c = \sqrt{\frac{2B\alpha G_{Ic}}{na^{n-1}}} \quad (12)$$

$$\delta_c = \frac{2BaG_{Ic}}{nP_c} \quad (13)$$

The relative error and Standard Error (SE) are computed from

Table 1: Delamination fracture toughness (G_C) of carbon/epoxy from the fracture data (Kan *et al*., 1987) of DCB, CLS and CCLS specimens

	DCB specimen (Fig. 3)		CLS specimen (Fig. 4)		CCLS specimen (Fig. 5)	
Material	n	$G_c(Nm^{-1})$	n	$G_c(Nm^{-1})$	n	$G_c(Nm^{-1})$
Carbon/epoxy AS4/3501-6	2.75	172	0.281	359	0.329	627
Graphite/Bismaleimide IM6/5254-C	2.70	369.5	0.327	359	0.318	620

Table 2: Critical load and displacement estimates of DCB specimen made of carbon fibre T300/epoxy Width, B = 25 mm, Thickness 2 h = 4.18 mm, G_{Ic}= 261 N m^{-1} Material Constant in Eq. 8: α = 1201.2 and n = 2.8

Test (Williams, 1984)			Present analysis			
a (mm)	P_c (N)	δ_c (mm)	P_c (N) Eq. 12	Relative error (%)	δ_c (mm) Eq. 13	Relative error (%)
40	88.6	2.26	85.54	-3.5	2.18	-3.6
50	71.5	3.33	69.98	-2.1	3.33	0.0
55	67.5	4.01	64.23	-4.9	3.99	-0.5
60	62.0	4.74	59.39	-4.2	4.71	-0.7
65	56.9	5.37	55.26	-2.9	5.48	2.1
70	52.9	6.18	51.69	-2.3	6.31	2.1
75	50.7	7.14	48.58	-4.2	7.20	0.8
80	47.3	7.85	45.84	-3.1	8.13	3.6
85	45.4	8.97	43.41	-4.4	9.13	1.7
90	42.3	9.82	41.23	-2.5	10.17	3.6
95	39.0	10.76	39.27	0.7	11.27	4.8
100	38.1	12.03	37.50	-1.6	12.43	3.3
105	36.0	13.38	35.89	-0.3	13.64	1.9
110	34.7	14.47	34.42	-0.8	14.90	2.9
115	33.4	15.74	33.07	-1.0	16.21	3.0
120	32.0	17.02	31.83	-0.5	17.57	3.3
125	30.6	18.55	30.68	0.3	18.99	2.4
130	29.5	19.96	29.61	0.4	20.46	2.5
135	28.4	21.51	28.62	0.8	21.98	2.2
			SE	0.03	SE	0.03

$$\text{Relative error}(\%) = 100\left(1-\frac{\text{Analysis result}}{\text{Test result}}\right) \tag{14}$$

$$\text{Standard error(SE)} = \sqrt{\sum_{i=1}^{N}\left(1-\frac{\text{Analysis result}}{\text{Test result}}\right)_i^2} \tag{15}$$

where, N is the number of test specimens.

Figure 6 and 7 show the comparison of critical load and displacements with the test data of Kan *et al*. (1987) for different values of the crack length (a). It should be noted that the critical displacement (δ_c) derived in Eq. 13 is inversely proportional to the critical load (P_c) of the DCB specimen. If the critical load (P_c) for the crack length (a) evaluated from the delamination fracture toughness (G_{IC}) of the DCB specimen is lower (or higher) than the measured value, then the critical displacement (δ_c) estimates will be higher (or lower) than its measured value. This is the reason why one quantity is higher than the other when analytical estimates are compared with test results in Fig. 6 and 7. In addition, there may be a possibility of scatter in the experimental results.

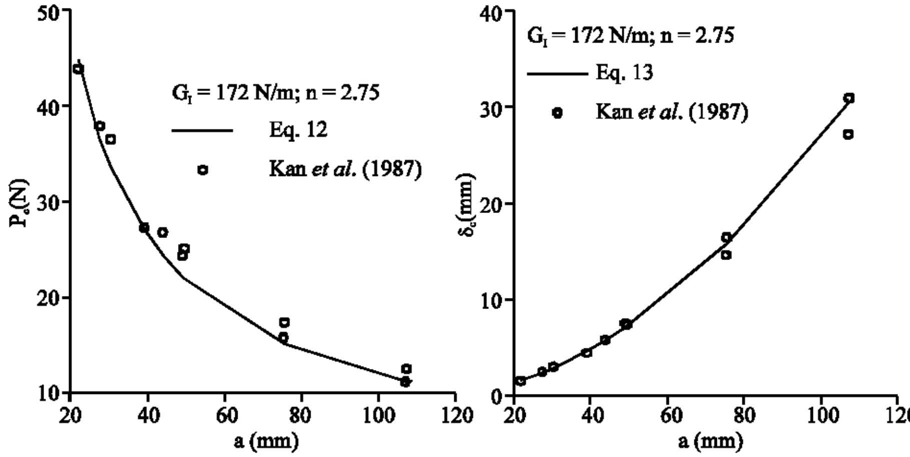

Fig. 6: Comparison of critical load (P_c) and displacement (δ_c) with test data of DCB specimen made of carbon/epoxy (AS4/3501-6). (B = 254.5 mm; 2 h = 2.24 mm)

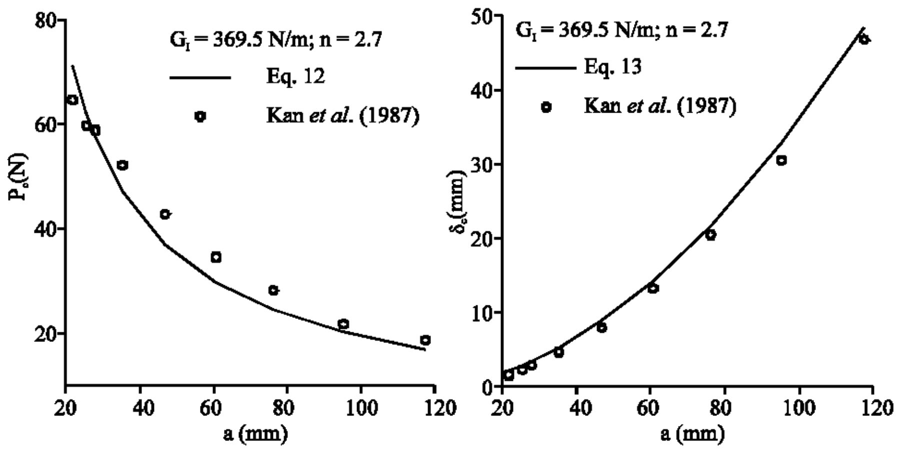

Fig. 7: Comparison of critical load (P_c) and displacement (δ_c) with test data of DCB specimen made of carbon/epoxy (IM6/5254C). (B = 25.4 mm; 2 h = 2.24 mm)

Figure 8 shows a good comparison of the critical load (P_c) and the critical displacement (δ_c) for different values of the crack length (a) of the DCB specimens made of glass/epoxy with test results of Devitt *et al*. (1980). Rao and Acharya (1995b) have carried out large deflection analysis considering non-zero slope at the crack-tip of the DCB specimen made of glass/epoxy composites. G_{IC} values are found to vary between 869.3 and 1008.2 N m^{-1}. They reported the average value of G_{IC} as 969.4 N m^{-1} with 3.9% coefficient of variation. The minimum value of G_{IC} at 99.7% confidence level is worked out to be 856 N m^{-1}, which is close to the present analysis value of 848 N m^{-1}.

Williams (1984) generated fracture data from DCB specimens made of carbon fiber T300/epoxy, AS4/PEEK and AS4/PES composites. Material constants in Eq. 8 for these materials are

Table 3: Critical load and displacement estimates of DCB specimen made of carbon fibre AS4/PEEK Width, B = 20 mm, Thickness 2 h = 4.37 mm, G_{Ic} = 1974 N m^{-1} Material Constant in Eq. 8: α = 1112 and n = 2.8

Test (Williams, 1984)			Present analysis			
a (mm)	P_c (N)	δ_c (mm)	P_c (N) Eq. 12	Relative error (%)	δ_c(mm) Eq. 13	Relative error (%)
35	224.8	4.3	228.31	1.6	4.32	0.5
40	204.7	5.4	202.45	-1.1	5.57	3.2
45	186.3	6.64	182.09	-2.3	6.97	5.0
50	172.3	8.17	165.62	-3.9	8.51	4.2
55	156.9	9.81	152.00	-3.1	10.20	4.0
60	147.5	11.86	140.55	-4.7	12.04	1.5
65	136.0	13.63	130.78	-3.8	14.02	2.8
70	125.8	15.76	122.35	-2.7	16.13	2.4
75	118.0	17.83	114.98	-2.6	18.39	3.2
80	113.1	20.19	108.49	-4.1	20.79	3.0
85	107.9	22.9	102.73	-4.8	23.33	1.9
90	103.1	25.28	97.58	-5.4	26.01	2.9
95	95.8	28.37	92.94	-3.0	28.82	1.6
100	93.7	31.53	88.75	-5.3	31.77	0.8
105	88.1	33.99	84.94	-3.6	34.86	2.6
110	86.6	37.76	81.46	-5.9	38.08	0.9
			SE	0.04	SE	0.03

Table 4: Critical load and displacement estimates of DCB specimen made of carbon fibre AS4/PES Width, B = 20 mm, Thickness 2 h = 4.05 mm, G_{Ic} = 2049 N m^{-1} Material Constant in Eq. 8: α = 864.5 and n = 2.8

Test (Williams, 1984)			Present analysis			
a (mm)	P_c (N)	δ_c (mm)	P_c (N) Eq. 12	Relative error (%)	δ_c(mm) Eq. 13	Relative error (%)
30	215.8	3.51	235.61	9.2	3.73	6.2
35	191.6	4.77	205.09	7.0	5.00	4.7
40	177.5	6.29	181.87	2.5	6.44	2.4
45	165.3	7.97	163.57	-1.0	8.05	1.0
50	151.9	9.43	148.78	-2.1	9.84	4.3
55	143.2	11.47	136.55	-4.6	11.79	2.8
60	129.8	13.51	126.26	-2.7	13.91	3.0
65	122.7	15.31	117.49	-4.3	16.19	5.8
70	117.2	17.44	109.90	-6.2	18.64	6.9
75	108.5	19.87	103.29	-4.8	21.25	7.0
80	100.5	22.34	97.46	-3.0	24.03	7.6
85	95.9	25.33	92.28	-3.8	26.96	6.4
90	92.1	29.4	87.66	-4.8	30.05	2.2
95	89.0	32.51	83.49	-6.2	33.31	2.4
100	86.9	37.39	79.73	-8.3	36.71	-1.8
105	85.1	41.63	76.30	-10.3	40.28	-3.2
110	82.4	46.34	73.17	-11.2	44.00	-5.0
115	81.0	50.26	70.30	-13.2	47.88	-4.7
120	77.0	54.8	67.66	-12.1	51.91	-5.3
			SE	0.07	SE	0.05

determined from the fracture data. The delamination fracture toughness (G_{IC}) of these materials is evaluated for critical load evaluation of DCB specimens. Table 2 to 4 show the comparison of the critical load (P_c) and the critical displacement (δ_c) for different values of the crack length (a) of the DCB specimens. Critical load estimates are found to be reasonably in good agreement with test results of Williams (1984). From the large deflection analysis, Rao and Acharya (1995b) reported the average value of G_{IC} for carbon fiber/epoxy composites as 263.3 N m^{-1} with 1.9% coefficient of variation. The minimum value of G_{IC} at 99.7% confidence level is worked out to be 248.3 N m^{-1}, which is 5% lower

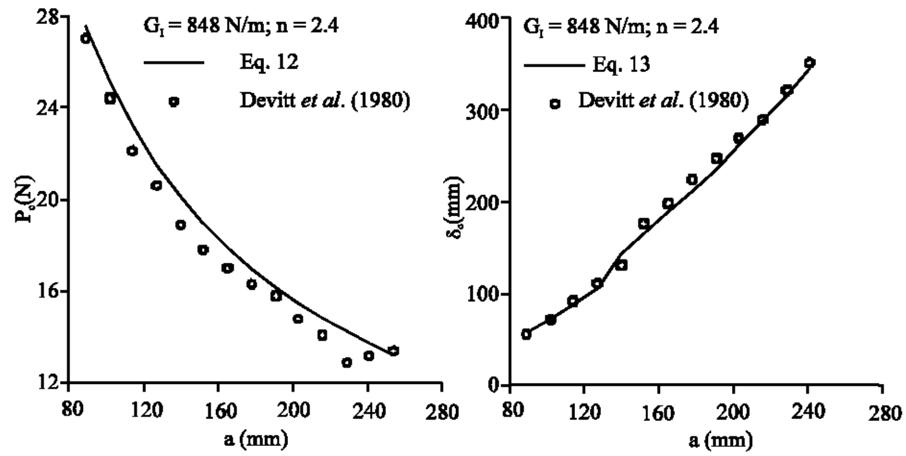

Fig. 8: Comparison of critical load (P_c) and displacement (δ_c) with test data of DCB specimen made of glass/epoxy. (B = 25.4 mm; 2 h = 2.59 mm)

than the value of 261 N m^{-1} in Table 2. Rao and Acharya (1995b) reported the average value of G_{IC} for carbon fiber/PEEK composites is 1984 N m^{-1}, which is close to the present analysis value of 1974 N m^{-1} in Table 3.

The compliance method followed in the present study will be useful for direct evaluation of the critical strain energy release rate (G_{IC}) from the fracture data of cracked specimens. The accuracy of the evaluated G_{IC} is demonstrated through comparison of analytical and experimental critical load (P_c) and displacement (δ_c) for different crack sizes of DCB specimens made of carbon/epoxy composites.

Conclusions

One of the simplest and reliable LEFM methods, viz., the compliance method, is adopted here for direct evaluation of the critical strain energy release rate from the fracture data of carbon/epoxy composites. The test data of Double Cantilever Beam (DCB) specimens and Cracked-lap Shear (CLS) specimens were utilized to evaluate mode I and mode II delamination fracture toughness of the materials. Critical load (P_c) and the critical displacement (δ_c) for different values of the crack length (a) of the DCB specimens from the determined fracture energy (G_{IC}) are found to be reasonably in good agreement with test results.

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