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EXPERIMENTAL COMPARISON OF INTERLAMINAR TOUGHNESS OF CARBON/PEEK, CARBON/EPOXY AND GLASS/EPOXY COMPOSITES

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Comparative studies of interlaminar toughness G_{Ic} and G_{IIc} of carbon/epoxy, carbon/PEEK and unidirectional glass fabric/epoxy and 2/2 twill fabric/epoxy have been carried out with the use of the Double Cantilever Beam and End Notched Flexure methods. Carbon fiber reinforced composites were made from unidirectional prepregs. The glass reinforced composites were impregnated with the use of wet lay up method. The obtained results suggest that the composites made with prepregs display more consistent mechanical properties than those reinforced with glass fabric impregnated with epoxy resin. On the other hand, the interlaminar toughness of the latter was almost three times higher than those of carbon/epoxy. Unfortunately, due to insufficient number of specimens a meaningful statistical analysis of the results could not be carried out. Application of various data reduction methods have shown that the results they produce are practically the same with the exception of the area method which produces inconsistent numbers.

1. Introduction

Resistance against delamination, (an interlaminar toughness), is one of the most important properties of a laminar composite material. Critical value of the energy release rate, G_c, can be used as its measure. Depending on the loading conditions three basic modes of fracture can be distinguished. They are the opening mode (Mode I), the forward shear mode (Mode II), and the anti-plane shear mode (Mode III). From a practical view point the two first modes are most interesting.

Carbon fiber/epoxy composite structures made with prepregs are in general more brittle and more vulnerable to delamination than those reinforced with glass fiber and made with the use of wet lay up method. To improve performance of the composites reinforced with carbon fiber more tough Poly(ether-ether-ketone) (PEEK) thermoset matrix has been applied to impregnation. To compare interlaminar toughness of the mentioned composites series of tests had been carried out and G_{Ic} and G_{IIc} have been determined with the use of the Double Cantilever Beam, (DCB) and the End Notched Flexure, (ENF), methods respectively. An attempt was made to apply various data reduction schemes and compare the obtained results.

2. Data reduction schemes

Fundamentals for calculation of the energy release rates for cracked laminates are given by Williams (1988). A detailed description of various data reduction procedures was presented, for example, by Martin and Murri (1990). The procedures applied to the test data interpretation can be grouped in two categories, direct methods and methods based on measured compliance.

2.1. Double Cantilever Beam tests

An example of the direct method is the area method. It is based on the following definition of G_{Ic}

$$G_{Ic} = -\frac{1}{B}\frac{dU}{da} \tag{2.1}$$

where

dU – energy change due to crack extension
da – crack extension
B – width of a crack.

This expression can be replaced

$$G_{Ic} = \frac{\Delta S}{B(a_k - a_{k-1})} \tag{2.2}$$

where

ΔS – area enclosed by the loading – unloading trace
B – width of the crack
$a_k - a_{k-1}$ – crack extension.

This expression is valid for the elastic behaviour of material and if the load vs. displacement relationship is linear elastic then simply

$$G_{Ic} = \frac{F_1\delta_2 - F_2\delta_1}{2B(a_2 - a_1)} \tag{2.3}$$

where δ_1 and δ_2 respect consecutive deflections caused by F_2 and F_1, respectively.

The methods based on compliance make use of the following relationship

$$G_{Ic} = \frac{F^2}{2B}\frac{dC}{da} \tag{2.4}$$

where

C – compliance

F – critical force.

A plot of C vs. a must be obtained from an experiment or determined analytically.

- Experimental compliance method

  It is assumed that

  $$C = Ka^n \tag{2.5}$$

  The values of K and n can be find by log-log plot and then G_{Ic} can be expressed as follows

  $$G_{Ic} = \frac{nF\delta}{2Ba} \tag{2.6}$$

- Analytical determination of compliance

  The branches of DCB specimen are considered as two build-in cantilevers and their compliance can be determined analytically and then G_{Ic} can be expressed as follows

  $$G_{Ic} = \frac{3F\delta}{2B(a + \Delta)} \tag{2.7}$$

  The term Δ represents correction for not perfect build-in of the branch ends. Its value can by determined by plotting $\sqrt[3]{C}$ vs. a.

2.2. End Notched Flexure test

To determine G_{IIc} the following compliance methods can be applied

- Compliance method based directly on the beam theory

  In this case a compliance of a cracked beam subjected to the three point bending is determined analytically and then the use is made of Eq (2.4). It results in the following expression

  $$G_{IIc} = \frac{9a^2F\delta}{2B(2L^3+3a^3)} \tag{2.8}$$

  where L is half of the support separation.

  It is possible to correct it for large deflection and shear effects as proposed by Hashemi et al. (1990), however the analysis of the correction factors indicates that for the materials tested and the geometry of specimens applied such effects can be neglected.

- Compliance calibration method

  Compliance is measured for several crack lengths and a least square regression is carried out, of the form

  $$C = C_0 + ma^3 \tag{2.9}$$

  Application of Eq (2.4) results in

  $$G_{IIc} = \frac{3ma^2F^2}{2B} \tag{2.10}$$

3. Materials

Four different materials were tested: unidirectional carbon/epoxy and carbon/PEEK composites made with prepregs from Ciba Geigy and two glass/epoxy composites reinforced with an unidirectional tape and 2/2 twill fabric made with the aid of wet lay up method, supplied by the Institute of Aeronautics and Applied Mechanics. Fiber volume fractions for carbon and glass reinforced composites were around 60% and 40%, respectively.

4. Specimens and experimental procedure

The specimens were cut out from panels 3.2 mm thick in the case of CFRP and 3.6 mm thick in the case of GFRP. Artificial cracks were produced with the help of a starter film $0.025 \div 0.03$ mm thick, included at mid-thickness of the panels during moulding. In addition, for Mode II tests the specimens were precracked under Mode I conditions to eliminate the effect of resin reach zones usually located at the end of a starter film.

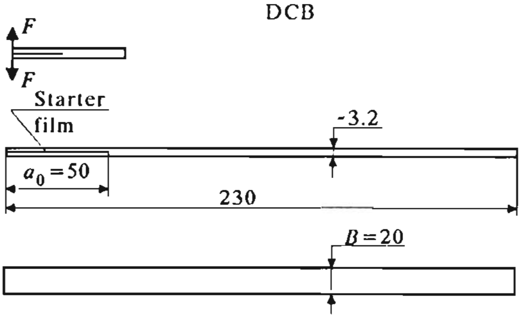

Fig. 1.

To determine G_{Ic} values the double cantilever beam, (DCB), specimens were used, Fig.1. The coupons were 20 mm wide and have 50 mm long initial cracks. Load was applied continuously at crosshead speed 2 mm/min through aluminium hinges glued to the specimen. Crack extension was monitored at one of the sides of each specimen with the help of brittle, white paint.

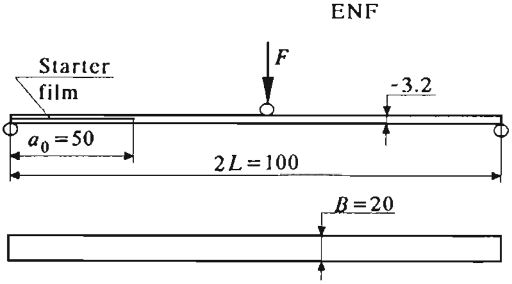

Fig. 2.

For determination of G_{IIc} values the end notched flexure, (ENF), specimens 20 mm wide were used, Fig2. For loading a rig for three point bending with support separation of 100 mm was applied. An initial crack length was 25 mm. The specimens were loaded continuously at crosshead speed 1 mm/min. A crack front motion was monitored with the use of travelling microscope at one of the sides of each specimen, painted with white, brittle paint.

For each specimen a crack extension was recorded on the load-displacement diagram used in a data reduction procedure.

5. Experimental results

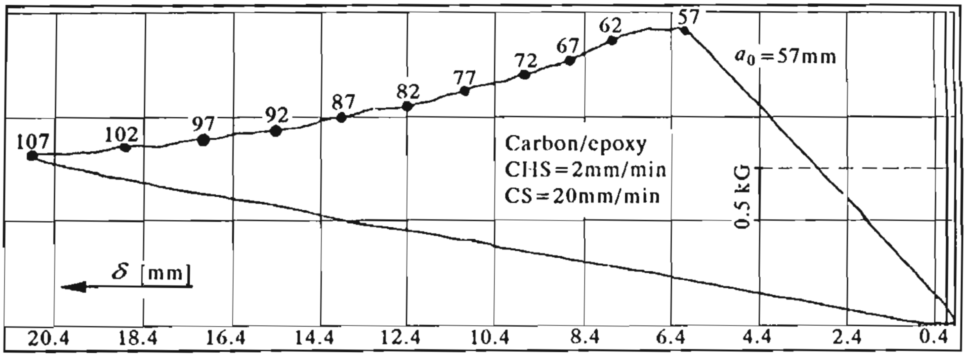

Fig. 3.

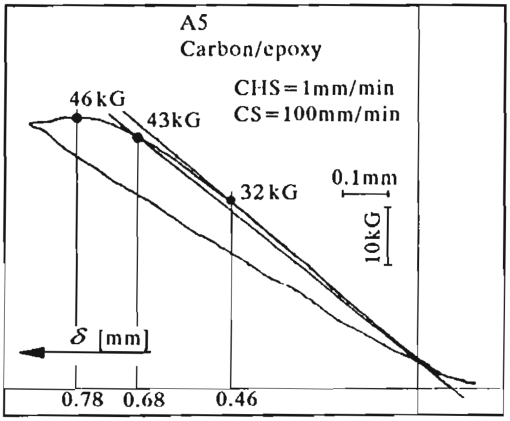

Fig. 4.

Typical load vs. displacement diagrams are presented in Fig.3 and Fig.4 for Mode I and Mode II loadings respectively. Fig.5a presents G_{Ic} values vs. crack length for carbon/PEEK and carbon/epoxy composites. They are the range of 2000 N/m and 200 N/m respectively. Fig.5b depicts the same

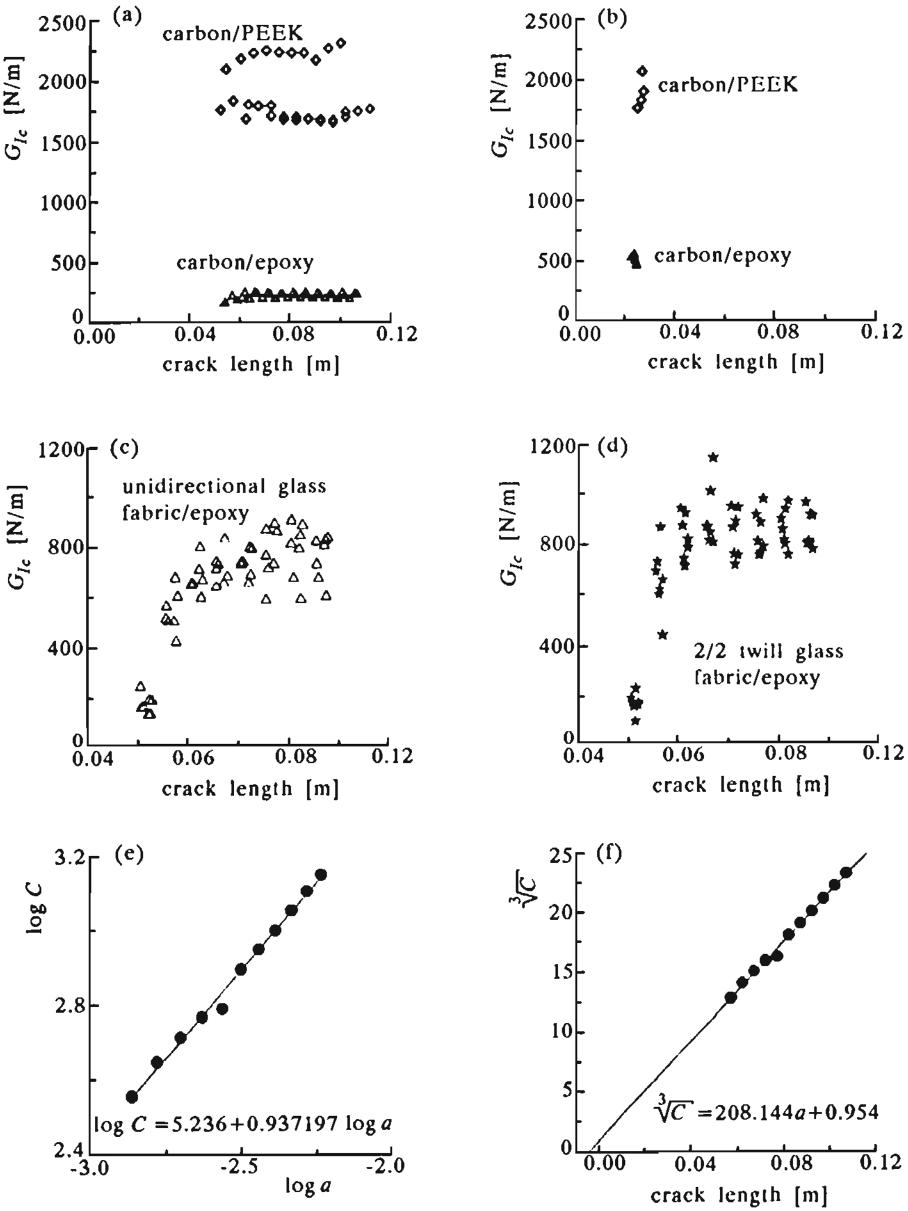
(a)
carbon/PEEK
carbon/epoxy
G_{Ic} [N/m]
2500
2000
1500
1000
500
0
0.00
0.04
0.08
0.12
crack length [m]
(b)
carbon/PEEK
carbon/epoxy
G_{Ic} [N/m]
2500
2000
1500
1000
500
0
0.00
0.04
0.08
0.12
crack length [m]
(c)
unidirectional glass fabric/epoxy
G_{Ic} [N/m]
1200
800
400
0
0.04
0.06
0.08
0.12
crack length [m]
(d)
2/2 twill glass fabric/epoxy
G_{Ic} [N/m]
1200
800
400
0
0.04
0.06
0.08
0.12
crack length [m]
(e)
log C
3.2
2.8
2.4
-3.0
-2.5
-2.0
log a
$\log C = 5.236 + 0.937197 \log a$
(f)
$\sqrt[3]{C}$
25
20
15
10
5
0
0.00
0.04
0.08
0.12
crack length [m]
$\sqrt[3]{C} = 208.144a + 0.954$

Fig. 5.

relationship for the specimens loaded in Mode II. For carbon/epoxy system G_{IIc} is in the range of 500 N/m, for carbon/PEEK composite values of G_{IIc} are in the same range as G_{Ic}. Fig.5c,d show G_{Ic} vs. crack length for the specimens reinforced with unidirectional and 2/2 twill glass fabrics, respectively. The composites display pronounced R-curve. The plateau of G_{ic} values for the both composites lies within the range of 1000 N/m. The examples of diagrams used for application of the compliance methods are shown in Fig.5e,f. Compliance vs. crack length relationship presented in Fig.5e was used for determination of the n value present in Eq (2.6). Fig.5f shows a typical diagram used for calculation of the end correction factor Δ, Eq (2.7). Fig.6 presents discrepancies between G_{Ic} values resulting from the application of different data reduction procedures based on the area method, the beam method, the corrected beam method and the experimental compliance method, respectively.

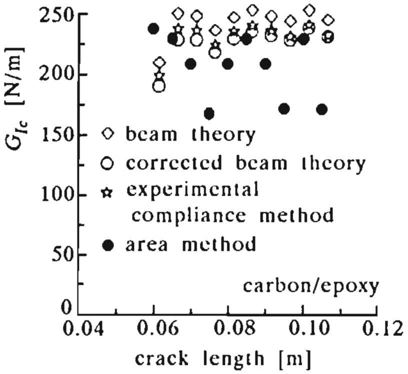

Fig. 6.

6. Discussion of results

Inspection of Fig.6 shows that the application of various data reduction procedures resulted in almost the same values of G_{Ic} with exception of the data produced by the procedure based on the area method. This procedure provided less consistent results and, furthermore, the critical values of the energy release rates needed to initiate crack propagation calculated with the help of this method were always higher than those necessary for a stable crack propagation which is in contradiction with the results obtained with the help other methods. It could be due to integration over a finite crack increment and to the agreed convention that the initiation of a crack propagation corresponds to the maximum load. Fractography of DCB specimens and a numerical analysis of G_I distribution over a crack front done by the author (1992) and (1994) show that a crack starts to propagate in a central section of its front line. Therefore the initiation of crack propagation can not be detected by an optical inspection of specimen sides. In the case of ENF specimens a loading closes crack faces and its initiation is, in practice, unnoticeable. For those reasons various conventions defining the onset of crack propagation can be accepted. It can be agreed that the initiation corresponds to the first deviation from linearity of a load-displacement diagram, or 5% drop of compliance, or the maximum load. In the present research one assumed that a crack starts to propagate when the load reaches its maximum value. From an engineering viewpoint such an assumption seems to be the most reasonable however this problem is not solved yet and must be investigated in the future, for example, with the help of the Accustic Emission.

For determination of G_{IIc} values for CFRP the compliance method based on the beam theory was used. Due to insufficient length of the available specimens it was not possible to generate data for establishing C vs. a relationship and for this reason the data reduction procedure based on the compliance calibration method was not applied. In the case of glass fabric/epoxy composites values of G_{IIc} were underestimated. The thickness to length ratio of the specimens was such that under three point bending condition the shearing force was to low to cause Mode II fracture and the failure of the specimens was controlled by normal stresses.

Comparison of Fig.5a,c,d shows that under Mode I conditions carbon/PEEK composite displays the highest resistance against delamination. It can be explained by the comparison of morphology of the crack faces presented for example by Xian (1995) for epoxy matrix and by Hashemi (1990) for PEEK matrix. The latter displays better adhesion to carbon fibers and undergoes much larger plastic deformation which results in larger energy consumption. An unexpected high value of G_{Ic} displayed by the glass fabric/epoxy composites is not well understood and a further studies of this phenomenon are needed.

All the tested materials display the R-curve. Their shapes depend on crack lengths and are not unique. It is believed that the presence of R-curves is due to fiber bridging occurring behind the crack fronts and contributing to fracture energy. The phenomenon is described in detail by Davis (1989) and Hashemi (1990).

A statistical analysis of the results was not carried out because of insufficient number of the available specimens, nevertheless the comparison of diagrams in Fig.5a,c,d suggests that the composite materials manufactured with prepregs display more consistent mechanical properties than those produced by wet lay up method.

7. Conclusions

1. The best resistance against delamination is displayed by carbon/PEEK system.
2. All the tested composites display the R-curve.
3. The glass fabric/epoxy composites made with the aid of wet lay up method display unexpected high resistance against delamination in comparison with carbon/epoxy composites made with prepregs. The phenomenon is not well understood and should be subjected to further studies with the help of fractography.
4. Results produced by the methods based on compliance are very similar and more consistent than those produced by the area method.

8. References

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Porównawcze badania odporności na rozwarstwienia kompozytów zbrojonych włóknem węglowym w osnowie epoksydowej i PEEK oraz kompozytów szklano-epoksydowych zbrojonych tkaninami

Streszczenie

Wyniki porównawczych badań G_{Ic} i G_{IIc} wskazują, że kompozyty węglowe w osnowie PEEK, wykonane z preimpregnatów charakteryzują się stosunkowo najlepszą odpornością na rozwarstwienia. Nadspodziewanie wysoką odporność na tego rodzaju uszkodzenia wykazały kompozyty zbrojone tkaninami szklanymi. Powód nie jest jasny i konieczne są dalsze badania fraktograficzne. Zastosowanie różnych metod analizy wyników pomiarów wykazało, że metody wyznacznia G_{Ic} posilkujące się podatnością dają bardzo zbliżone wyniki i o stosunkowo najmniejszym rozrzucie.

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