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APPROXIMATE INTERLAMINAR FRACTURE ENVELOPES FOR UNIDIRECTIONAL E-GLASS/POLYESTER COMPOSITE

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Abstract

In this paper an experimental study is performed in order to determine an approximate interlaminar fracture envelope of a unidirectional E-glass polyester composite. First, the pure mode-I fracture toughness is determined by using the standard double-cantilever beam (DCB) specimen. Second, the pure mode-II toughness of the material is evaluated by means of the over-notched flexure (ONF) specimen. Finally, the mixed-mode toughness is determined with the aid of the over-leg bending (OLB) coupon. Both the initiation and propagation fracture toughness are determined within the extended ranges of crack length. The fracture envelopes are determined by using the steady-state values of the fracture toughness at crack initiation and propagation. Two criteria are used to obtain the envelopes: the traditional power expression and the physically more acceptable criterion by Williams. The results are compared with previous envelopes and similarity is established.

Keywords: composite, fracture toughness, delamination, fracture envelope, double-cantilever beam, over-notched flexure, over-leg bending.

1. Introduction

The interlaminar fracture toughness has a great significance in the damage and failure analysis of composite materials. The strain energy release rate (G_C) is an important quantity in the linear elastic fracture mechanics (LEFM). To fully characterize the material behaviour in the case of delamination a complete fracture envelope including the pure mode-I (G_{I}), pure mode-II (G_{II}) and the mixed-mode I/II ($G_{\mathrm{I/II}}$) toughnesses are required [1]. Also, the latter should be evaluated at various mode-mix ($G_{\mathrm{I}}/G_{\mathrm{II}}$) values. Several methods were developed in the literature to perform the required investigations.

To measure the mode-I fracture toughness the standard double-cantilever beam (DCB, ASTM D5528) [2] is an efficient way. For mode-II fracture investigation, at present, six specimens are available: the end-notched flexure (ENF) [3], the stabilized ENF (SENF) [4], the end-loaded split (ELS) [5], the four point bend ENF (4ENF) [6], the over-notched flexure (ONF) [7] and the tapered ENF (TENF) [8] coupons. All of these have advantages and relative drawbacks, as highlighted in [7]. The ENF is the subject in most of the papers, despite of its many drawbacks.

For mixed-mode I/II investigations numerous experimental configurations were developed. The most popular ones are the single-cantilever beam (SCB) [9], the single-leg bending (SLB) [9] and its twin-brother, the mixed-mode flexure (MMF) [10]. These tests are easy to perform, however, they are able to evaluate the mixed-mode I/II toughness only at fixed mode-ratio ($G_I/G_{II} = 1.33$). The cracked-lap shear (CLS) [11] specimen overcomes this problem, although it is not the optimal solution for mixed-mode test. The standard specimen of the mixed-mode I/II loading is the mixed-mode bending (MMB, ASTM D6671-01), which was developed in 1990 by REEDER and CREWS [12]. Although the experimental equipment required for the MMB test is very complex and there is some uncertainty in multidirectional laminate composites, the variable mode-ratio compensates all these disadvantages [13].

In the above-presented configurations the specimens may be considered as slender beams, and consequently the linear beam theories are useful tools for the analysis of the coupons. There are also solutions, which are based on other considerations. YOON and HONG [14] presented an asymmetric test fixture (ATF) for mixed-mode loading in composites. A quite similar fixture, namely the compact tension shear (CTS) specimen, was utilized by RIKARDS et al. [1] and LIN et al. [15]. In both of the mentioned papers the energy release rate components and the mode-ratio are evaluated by the virtual crack-closure technique (VCCT) [1].

In order to obtain a complete fracture envelope at crack initiation and propagation, the possibilities are limited. The mode-I DCB and the mentioned mode-II tests are relatively easy to perform. On the other hand, the MMB test (to the best of our knowledge) is not yet available in Hungary, and apart from that only the initiation toughness can be evaluated. The ATF and CTS tests are suitable again to determine the initiation toughness only. It should also be mentioned that the result of the VCCT is somewhat doubtful because of the singularity nature of the problem.

Therefore, in the present work we construct a fracture envelope for unidirectional glass-polyester composite using beam-like specimens, such as the mode-I DCB, the mode-II ONF [7] and the mixed-mode I/II over-leg bending (OLB) [16] coupons. The latter is suitable to obtain the fracture toughness at a mode-mix of $G_I/G_{II} = 1.33$, however, this way we may determine the fracture envelope including toughness values at crack initiation and propagation. The specimens are demonstrated in *Fig. 1*.

2. Experiments

The unidirectional $[0°]_{14}$ glass/polyester composite specimens were manufactured by using a special pressure tool. The specimens with nominal thickness of $2h =$

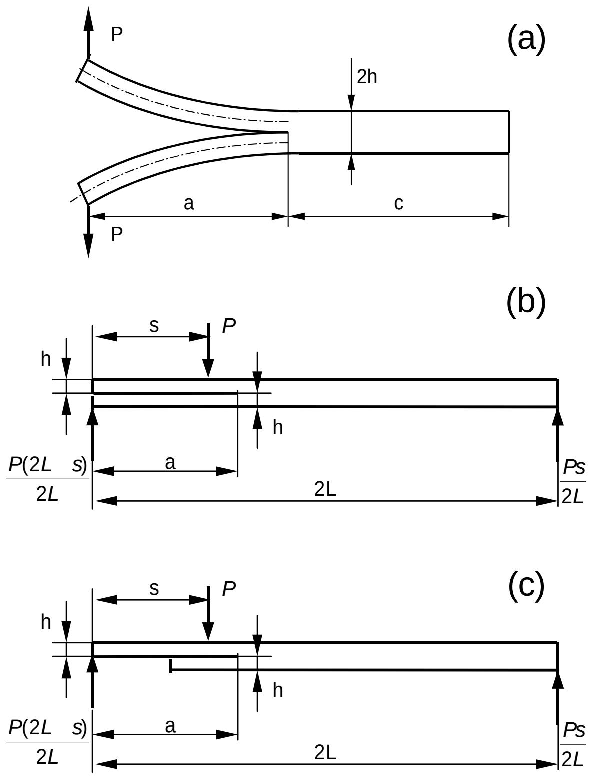

Fig. 1. The mode-I DCB (a), the mode-II ONF (b) and the mixed-mode I/II OLB (c) specimens

6.1 mm, width of $b = 20$ mm, total length of 180 mm and with fiber-volume fraction of $V_f = 43\%$ were manufactured. A nylon insert with thickness of 0.03 mm was placed at the midplane of the specimens to make an artificial starting defect. The specimens were slightly transparent, what facilitated the observation of the crack front. The specimens were precracked in opening mode of about 3–5 mm. Three types of interlaminar fracture tests were performed: the DCB, ONF and OLB ones. For all the three coupons, two kinds of measurements were carried out using a displacement controlled Amsler testing machine. At the first stage, the specimens were loaded up to fracture initiation. In this case only the load and displacement were recorded. At the second stage, propagation tests within reasonable ranges of the crack length were conducted. Apart from the load and displacement values, the crack length was also measured. The load was recorded by using the scale of the machine, while the displacement was measured by using mechanical dial gages. A millimeter scale was traced on the lateral sides of the specimens, the position of the crack tip was marked and the crack length was read visually.

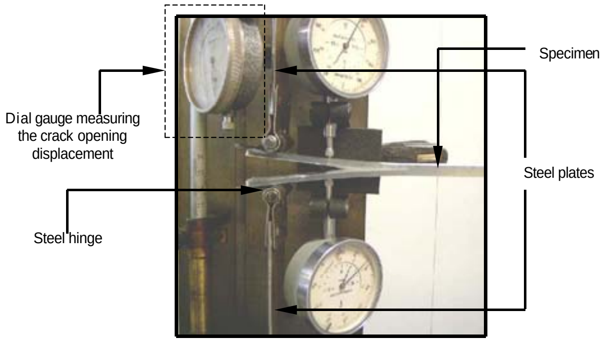

Fig. 2. Experimental setup for DCB testing

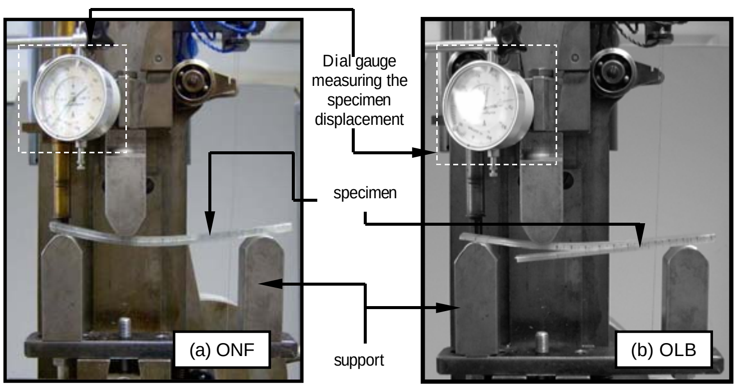

Fig. 3. Over-notched flexure (a) and Over-leg bending (OLB) tests for interlaminar fracture

2.1. Mode-I DCB Test

The measuring instrument of the mode-I DCB test is demonstrated in *Fig.* 2. Steel hinges were bonded to the upper and lower specimen arms. For the initiation tests 18 specimens with $a = 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 90, 100, 110, 120,$ 130 and 140 mm were prepared. In the case of the propagation tests the range of $a = 30 - 150$ mm was investigated by using six specimens.

2.2. Mode-II ONF Test

The fixture for the ONF geometry is illustrated in *Fig. 3a*. The ONF test was performed in a three-point bending setup by introducing eccentrically the load between the two supports. For the initiation tests the range of $a = 50$ to 105 mm with 5 mm increment was investigated. The propagation tests were performed with the help of six specimens in the range of $a = 50$ to 90 mm.

2.3. Mixed-mode I/II OLB Test

The OLB system can be seen in *Fig. 3b*. The test was carried out in the same three-point bending setup as it was shown in the ONF test (*Fig.3a*). The investigated crack length range for the initiation tests is: $a = 55$ to 115 mm with 5 mm increment, while for the propagation tests the range of $a = 50$ to 100 mm was used.

2.4. Data Reduction

The simplest way to reduce the experimental data is the application of the direct beam theory [17]. The energy release rate of the DCB specimen is given by [17, 18]:

$$G_{\rm I}^{\rm DCB} = \frac{3P\delta}{2ba}, \tag{1}$$

where P is the applied load, δ is the measured specimen displacement, b is the width and a is the crack length. For the ONF test the result of the direct beam theory is slightly more complicated [7]:

$$G_{\rm II}^{\rm ONF} = \frac{9P\delta}{2b(2L-a)}\frac{1}{\theta}, \tag{2}$$

where:

$$\theta = 1 + \frac{4a}{2L-a} + \frac{8aL}{(2L-a)^2} + \frac{16L^2a}{(2L-a)^3} + \frac{8Ls(s-4L)}{(2L-a)^3}, \tag{3}$$

where P is the applied load, δ is the experimentally determined specimen displacement, a is the crack length, s is the position of the applied load from the left support and L is half of the span length, respectively. Finally, for the OLB test the mixed-mode I/II strain energy release rate is [16]:

$$G_{\rm I/II}^{\rm OLB} = \frac{21P\delta}{2b(2L-a)}\frac{1}{\lambda}, \tag{4}$$

where:

$$\lambda = 1 + \frac{8a}{2L - a} + \frac{16aL}{(2L - a)^2} + \frac{32L^2 a}{(2L - a)^3} + \frac{16Ls(s - 4L)}{(2L - a)^3}, \tag{5}$$

where the parameters are identical to those mentioned in the ONF specimen.

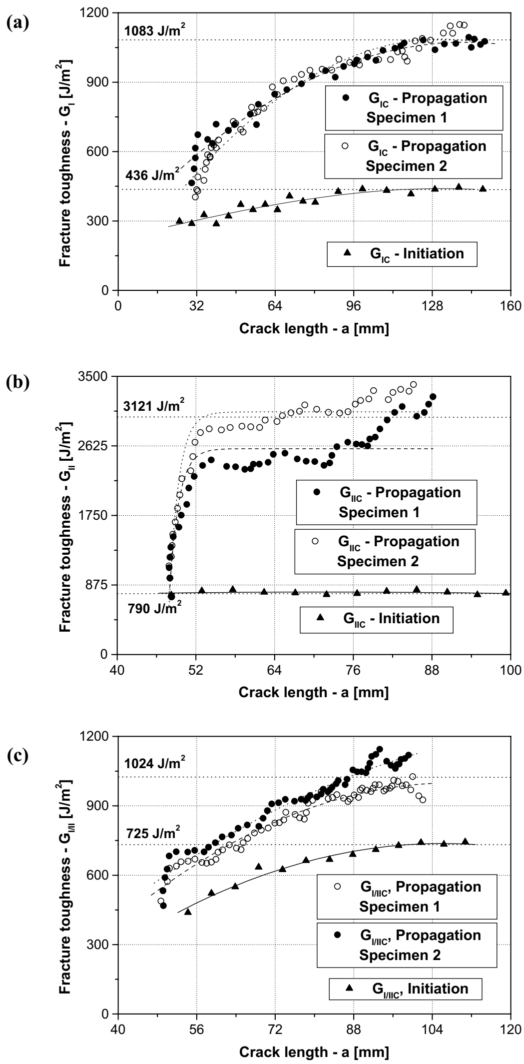

Fig. 4. Initiation and propagation fracture toughness of glass/polyester composite under mode-I (a), mode-II (b) and mixed-mode I/II (c) condition

3. Test Results

The strain energy release rate obtained from the three tests against the crack length is illustrated in *Fig. 4*. In *Fig. 4a* the results obtained from the DCB test are plotted. The steady-state value of the mode-I fracture toughness is about 436 J/m^2 in the case of crack initiation, while it is about 1083 J/m^2 if crack propagation is considered. It should be mentioned that in *Fig. 4a* only the results of two specimens are displayed, however, the steady-state values were obtained by averaging the results of six DCB coupons.

The mode-II fracture toughness at crack initiation and propagation is demonstrated in *Fig. 4b*. The relevant steady-state values are highlighted in *Fig. 4b* (790 and 3121 J/m^2). A remarkable feature is that the mode-II propagation toughness is about three times higher in comparison with the mode-I toughness (1083 against 3121 J/m^2). However, this was proved also by other researchers [17, 18]. The mode-II initiation toughness (790 J/m^2) is almost two times higher compared to the mode-I toughness (436 J/m^2).

Fig. 4c presents the fracture resistance values under mixed-mode condition. An immediate observation is that the mixed-mode I/II propagation toughness is almost equal to that by the DCB test for mode-I condition. The steady-state values obtained by the help of six specimens are also marked in *Fig. 4c*. The value of the steady-state initiation toughness is between the corresponding mode-I and mode-II values.

It should be kept in mind that during the propagation tests fiber-bridging was observed. In this respect especially the DCB and the OLB specimens should be mentioned. The extent of the fiber-bridging was relatively high, however, the present data reduction technique neglects this feature. In the case of the ONF specimen the fiber-bridging may also be assumed to arise, however, this is more complicated to observe than in the DCB and OLB specimens since there is not a crack opening during testing. Thus, the present results should be considered in the light of these limitations. During the initiation tests the fiber-bridging effect is eliminated, since the crack was only initiated.

4. Fracture Envelope

The fracture envelope for the present composite material was composed by using two criteria. In accordance with the traditional criterion the following relation may be established between the mode-I and mode-II strain energy release rates [1, 18]:

$$\left(\frac{G_{\mathrm{I}}}{G_{\mathrm{IC}}}\right)^{\alpha} + \left(\frac{G_{\mathrm{II}}}{G_{\mathrm{IIC}}}\right)^{\beta} = 1, \tag{6}$$

where G_{IC} is the critical strain energy release rate under pure mode-I and can be equated to the steady-state values in *Fig. 4a*. Furthermore, G_{IIC} is the mode-II critical strain energy release rate and may be considered as the steady-state values in *Fig. 4b*. To construct the fracture envelope we need at least three points. The pure mode-I and mode-II toughnesses are known. The mixed-mode toughness (*Fig. 4c*) should be decomposed into mode-I and mode-II parts. An analytical mode decomposition technique [16] revealed that the mode-ratio ($G_{\rm I}/G_{\rm II}$) is equal to 1.33 in the case of the OLB specimen, so a third point is known for *Eq.* (6). WILLIAMS' criterion [17, 18] recommends the following expression:

$$\left(\frac{G_{\rm I}}{G_{\rm IC}}-1\right)\left(\frac{G_{\rm II}}{G_{\rm IIC}}-1\right)-I_i\left(\frac{G_{\rm I}}{G_{\rm IC}}\right)\left(\frac{G_{\rm II}}{G_{\rm IIC}}\right)=0, \tag{7}$$

where I_i is the interaction parameter between the mode-I and mode-II strain energy release rates. If $I_i = 0$ then there is no interaction. Also, if $I_i = 1$ then *Eq.* (7) states a simple addition. The power parameters (α, β) in *Eq.* (6) and the interaction parameter (I_i) in *Eq.* (7) may be determined by a curve fitting technique.

The fracture envelopes at crack initiation and crack propagation are depicted in *Fig. 5*. In fact, the difference between the traditional and Williams' criterion is negligible, both criteria describe the same failure locus. Overall, the fit curves report that there is a notable interaction between the mode-I and mode-II loading.

For comparison, several works may be referred to, quite similar fracture envelope was determined by RIKARDS et al. [1] for glass/epoxy composite using the CTS type specimen, only initiation toughness values were measured. HASHEMI et al. determined fracture envelopes for crack initiation and propagation by using the DCB, ELS and SCB specimens for carbon/PEEK [17] and polyether sulphone-fiber [18] composites. The determined envelopes followed the same trend as it was found by us in *Figs. 5a* and *5b*.

Since the strain energy release rate is an interface property, the presented envelopes may also be used to predict failure locus in practical composite structures, which are manufactured by using the same constituents and exhibit the same fiber-volume fraction as the present glass/polyester material. However, to evaluate the mode-I and mode-II SERRs and the mode-ratio in a real structure, which can not be considered as a slender beam, a numerical (finite element) model is required.

5. Conclusions

Approximate fracture envelopes were determined for a unidirectional $[0°]_{14}$ glass/polyester composite including crack initiation and propagation in the material. The DCB specimen was used to obtain the pure mode-I toughness, while the pure mode-II critical energy release rate was determined by using the ONF test. The OLB coupon was utilized to obtain the critical strain energy release rate under mixed-mode I/II condition including a mode-ratio of 4/3. The approximate steady-state values of the fracture toughness were established and the fracture envelopes were constructed by means of the traditional criterion and the one, physically more justified by Williams. At both crack initiation and propagation the two criteria predicted similar failure loci. A strong interaction was established between the

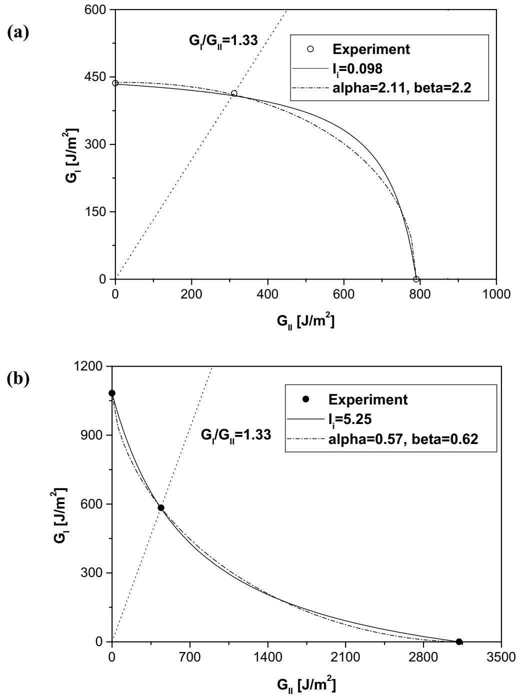

Fig. 5. Interlaminal fracture envelopes for crack initiation (a) and propagation (b) in glass/polyester composite

mode-I and mode-II toughnesses. The obtained envelopes were compared to those that were obtained by other researchers and similarity was established. Being the critical strain energy release rate an interface property, the fracture envelopes may be utilized also in the practice.

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