AN EXPERIMENTAL STUDY TO DETERMINE THE MIXED-MODE II/III DELAMINATION FRACTURE CRITERION OF COMPOSITE MATERIALS

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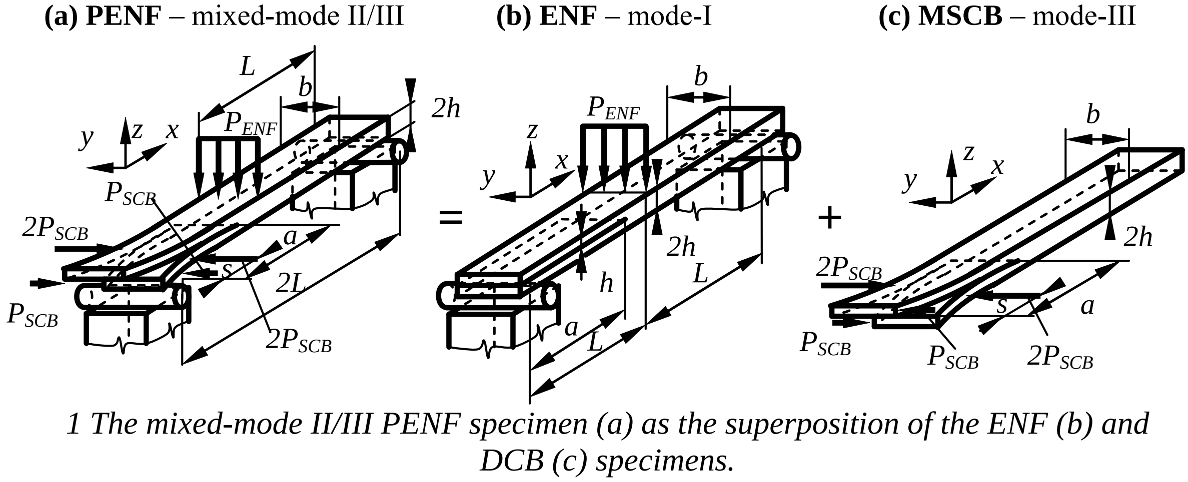
ABSTRACT

In this work the prestressed end-notched flexure system is developed for mixed-mode II/III delamination characterization of composites. The mode-III part of the strain energy release rate is fixed by a special grip, while the mode-II energy release rate is provided by the external load using a three-point bending setup. The pure mode-II and mode-III fractures are investigated by the end-notched flexure and the modified single-cantilever beam. Finally, the fracture criterion including the mixed-mode II/III delamination is calculated using traditional methods.

KEYWORDS
interlaminar fracture, composite, experiment

1 INTRODUCTION

In the last decade more and more attention was focused on the mode-III delamination resistance of laminated composite materials. A number of excellent test methods have been published including the single-cantilever beam (SCB) [1] and its modified versions [1,2]. The main problem of these setups was the significant mode-II component of the total strain energy release rate. Later this problem was eliminated using a special grip by Sharif et al. [2]. Nowadays the edge-crack torsion (ECT) is very close to be the subject of an ASTM standard for mode-III delamination characterization [3]. However, this system requires a long specimen with a central crack in the longitudinal direction, which is in contrast with the traditional specimen geometry, where the central crack is located along the specimen width. Finally, the mode-III version of the four-point end-notched flexure (4ENF) coupon [4] should be mentioned, although it was developed mainly for the testing of wood.



1 The mixed-mode II/III PENF specimen (a) as the superposition of the ENF (b) and DCB (c) specimens.

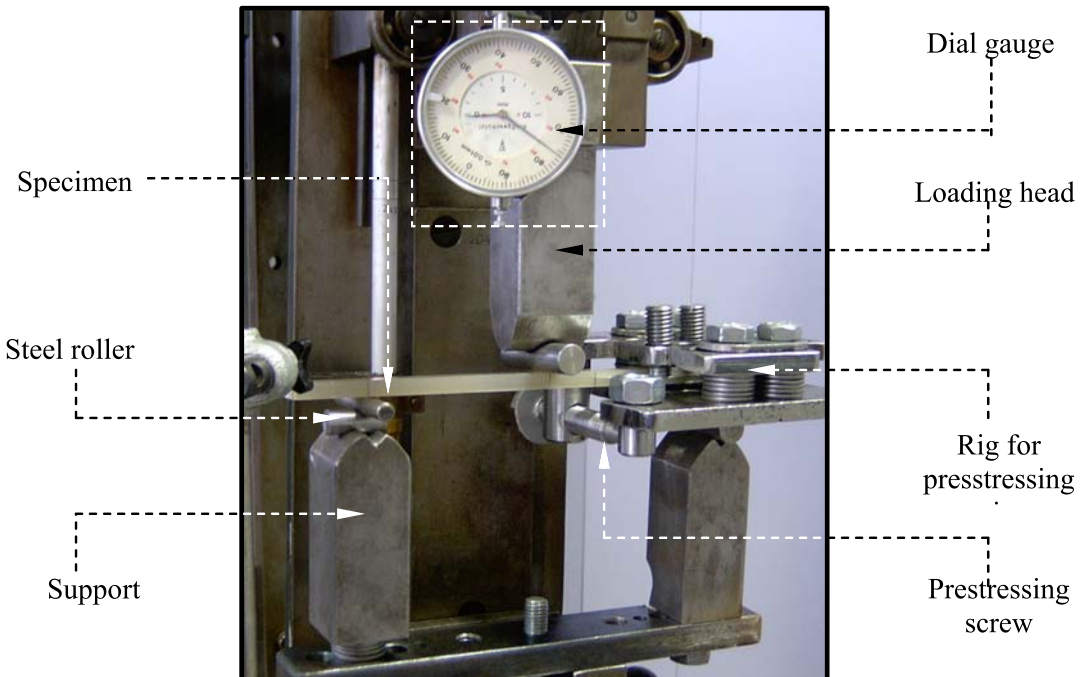
To the best of the author’s knowledge a configuration, which combines the mode-II and mode-III fracture of composites using the prestressing method has not yet exist. This motivated the author to construct the mixed-mode II/III version of the prestressed end-notched flexure ($PENF_{II/III}$) specimen and calculate the fracture criterion of a glass/polyester composite in the G_{II}-G_{III} plane.

2 THE CONCEPT OF THE $PENF_{II/III}$ SYSTEM

The $PENF_{II/III}$ specimen (Figure 1a) simply combines the mode-II end-notched flexure (ENF) (Figure 1b) and the modified single-cantilever beam (MSCB) specimens. Using a special grip, depicted in Figure 2 the mode-III energy release rate of the system can be controlled by using a screw. If the critical crack tearing displacement (CTD) of the MSCB specimen is known then the grip can be used to prestress the specimen and to fix the mode-III strain energy release rate (SERR). Then, the prestressed specimen is put into a three-point bending fixture and the mode-II component of the energy release rate is provided by the external load. This way it is possible to provide any combination of the mode-II and mode-III delamination fracture at crack propagation onset (initiation).

3 EXPERIMENTS

For the experiments unidirectional $[0°]_{14}$ glass/polyester composite specimens were manufactured. The elastic properties of the specimens are: E_{11}=33 GPa, G_{13}=3 GPa, ν_{13}=0.27. Three types of tests were performed: the ENF test for pure mode-II, the MSCB for mode-III and the mixed-mode II/III PENF test. In each case the crack initiation was identified visually.

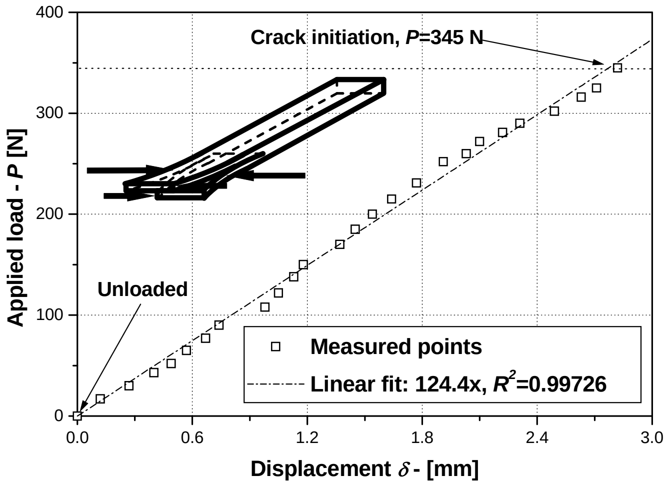


2 The mixed-mode II/III Prestressed End-Notched Flexure ($PENF_{II/III}$) specimen.

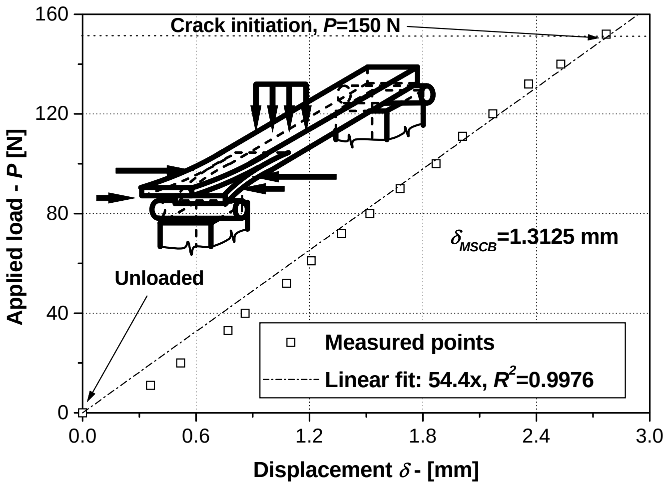
For the ENF test four coupons were tested at the crack length of a=55 mm. The width of the specimens was b=9 mm, the thickness was $2h$=6.1 mm. The coupons were placed in a three-point bending setup with span length of $2L$=150 mm and were loaded until fracture initiation in an Amsler testing machine. The values of the load at crack initiation were recorded and averaged.

In the case of the MSCB test also four specimens were tested until crack initiation. The crack length of interest was a=55 mm with the same geometrical properties as that mentioned before. A test rig similar to that used by Sharif et al. [2] was constructed and

(a)



(b)



3. Load-displacement curve of the MSCB specimen (a) and the $PENF_{II/III}$ specimen (b).

applied for delamination testing. The values of the load at crack initiation were determined and the results by four coupons were averaged. The relationship between the crack tearing displacement (CTD) and the applied load was fit with a linear function of the form:

$$P_{MSCB} = 122.78 \cdot \delta_{MSCB} \tag{1}$$

The experimental equipment for the $PENF_{II/III}$ specimen is demonstrated in Figure 2. The tests were carried out in the same Amsler machine. The span length was 2L=150 mm. The CTD of the specimen was set using the screw of the prestressing rig (see Figure 2) including the following values: 1.3125, 1.75, 2.1875 and 2.625 mm. At each value four coupons were used and the critical values of the load (P_{ENF}) were averaged.

The measured load-displacement curves for the MSCB specimen and the $PENF_{II/III}$ at δ_{MSCB}=1.3125 (G_{III}/G_{II}=3.02) specimen are shown in Figure 3. Each curve is essentially linear, which confirm the application of the linear elastic fracture mechanics (LEFM).

4 DATA REDUCTION

Due to the complex loading of the specimen (see Figure 1) it is necessary to perform finite element calculations for the reduction of the experimental data. The load related to the mode-III component (P_{SCB}) was determined using Eq. (1) at each value of the CTD. Then a 3D finite element model was constructed using the COSMOS/M 2.0 package and the specimen was loaded in the way depicted in Figure 1a. After the analysis had been performed the mode-II and mode-III SERRs of the system were calculated adopting the virtual crack-closure technique [5]:

$$G_{II} = \frac{1}{2\Delta z\Delta y} F_{x1}(u_1 - u_2), \tag{2}$$

$$G_{III} = \frac{1}{2\Delta z\Delta y} F_{z1}(w_1 - w_2), \tag{3}$$

where Δz and Δx are the sizes of the finite elements around the crack tip, F_x and F_z are the nodal forces in the x and z directions (refer to Figure 1), respectively, u_1, u_2, w_1 and w_2 are the nodal displacements in the delamination front.

5 RESULTS AND DISCUSSION

The distribution of the SERR along the specimen width is demonstrated in Figure 4 including the mode-III MSCB specimen (Figure 4a) and the $PENF_{II/III}$ (Figure 4b) at G_{III}/G_{II}=0.53. It is conspicuous that while the mode-III component has a uniform distribution, the mode-II component is asymmetric along the width (Figure 4b). However, it may be assumed that applying an experimental or analytical reduction technique the results may reflect a width-wise average of the SERR by FE method. It can be seen that in the case of the MSCB specimen the mode-III part of total energy release rate is 98.3%, hence it is considered as a pure mode-III test. It is also noteworthy that the ECT [3] test provides 92% mode-III, while the $4ENF_{III}$ test[4] gives 90% mode-III., so from this point of view the MSCB specimen seems to be a good choice.

The main purpose of the work is to determine the delamination fracture criterion of the material in the G_{II}-G_{III} plane. In accordance with the traditional power criterion the following relation may be established between the mode-II and mode-III strain energy release rates [6]:

$$\left(\frac{G_{III}}{G_{IIIC}}\right)^{p_1} + \left(\frac{G_{II}}{G_{IIC}}\right)^{p_2} = 1, \tag{4}$$

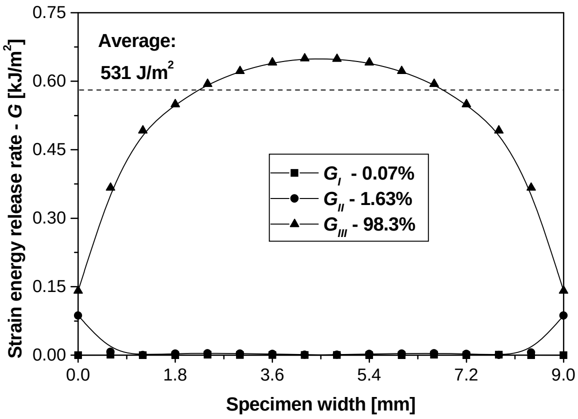
On the other hand Williams' criterion [6] recommends the following expression:

$$\left(\frac{G_{III}}{G_{IIIC}} - 1\right)\left(\frac{G_{II}}{G_{IIC}} - 1\right) - I_i\left(\frac{G_{III}}{G_{IIIC}}\right)\left(\frac{G_{II}}{G_{IIC}}\right) = 0, \tag{5}$$

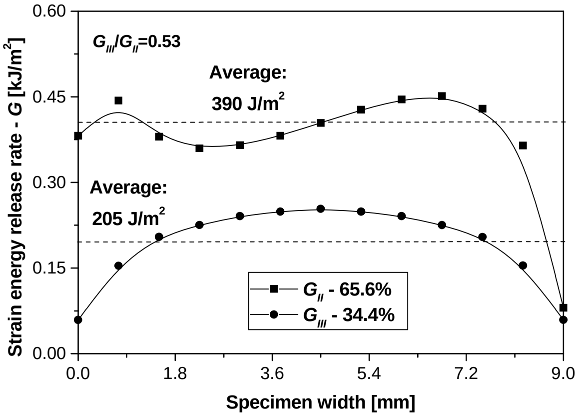
where I_i is the interaction parameter between the mode-I and mode-II SERRs. If I_i=0 then there is no interaction. Furthermore, if I_i=1 then Eq. (5) states a simple addition. In Eqs. (4)-(5) G_{IIIC} is the critical strain energy release rate under pure mode-I (calculated from the data of the MSCB specimen), G_{IIC} is the mode-II critical strain energy release rate (calculated from the data of the ENF specimen). The results of the $PENF_{II/III}$ test were used to provide four additional points in the G_{II}-G_{III} plane. In each case the widthwise average of the SERR was used. The power parameters (p_1, p_2) in Eq. (4) and the interaction parameter (I_i) in Eq. (5) were determined by a curve-fit technique.

The calculated fracture envelopes are displayed in Figure 5. The difference between

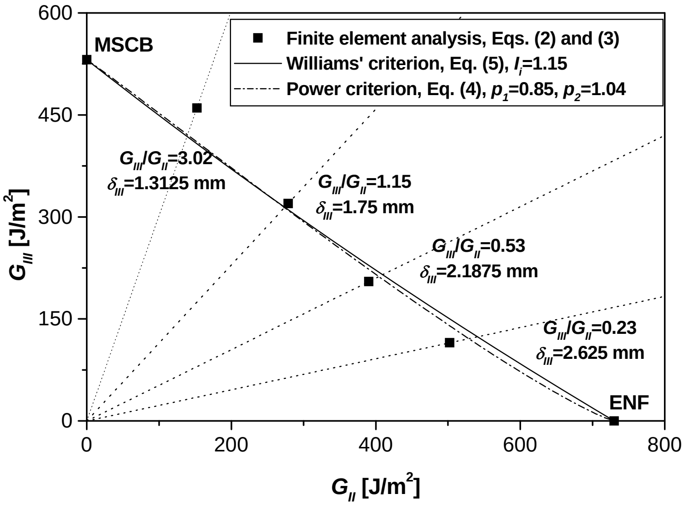
(a)



(b)



4 Distribution of the strain energy release rate along the delamination front. MSCB specimen (a), $PENF_{II/III}$ specimen (b).



5 Interlaminar fracture envelope in the G_{II}-G_{III} plane for glass/polyester composite calculated by using the finite element method.

the power and Williams' criteria is negligible, both describes the same failure locus. However, the application of Williams' method is simpler. The curves of the envelope are very close to a linear regression. The presented results are only approximate ones, and they should be verified by other analytical and experimental reduction techniques.

6 CONCLUSIONS

This work proposes the prestressed end-notched flexure specimen for the mixed-mode II/III delamination fracture characterization of composite materials. Three types of test were performed: the traditional ENF test for pure mode-II, the MSCB for mode-III and the newly designed $PENF_{II/III}$ for mixed-mode II/III. The experimental data was reduced by using numerical models and the delamination fracture criterion was determined using two methods. Both described the same failure locus.

The main advantage of the $PENF_{II/III}$ specimen is that the material can be tested at any mode ratio. The relative drawbacks of the test are the complex loading system and the dependence of the mode ratio on the crack length. The latter fact indicates that at the present stage the test is recommended mainly for the testing of transparent composite materials.

The next steps are developing a useful analytical model in order to reduce the large computational effort involved by the finite element model and comparing it to a reliable experimental reduction technique. Finally, the recommendation of an accurate reduction scheme is also necessary. All these issues will be published in subsequent papers.

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REFERENCES

1. Hwang S.-F., Hu C-L. (2001), “Tearing mode interlaminar fracture toughness of composite materials”, Polymer Composites Vol. 22, 57-64.
2. Sharif F., Kortschot M.T., Martin R.H. (1996) “Mode III Delamination Using a Split Cantilever Beam”, *Composite Materials: Fatigue and Fracture – Fifth Volume* ASTM STP 1230, Ed.: Martin R.H., ASTM, Philadelphia, 1995, 85-99.
3. Suemasu H. (1999), “An experimental method to measure the mode-III interlaminar fracture toughness of composite materials”, *Composites Science and Technology*, Vol. 59, 1015-1021.
4. Yoshihara H., (2006) “Examination of the 4-ENF test for measuring the mode III R-curve of wood” Engineering Fracture Mechanics Vol. 73, 42-63.
5. Rybicki E.F., Kanninen M.F. (1977), “A finite element calculation of stress intensity factors by a modified crack closure integral”, Engineering Fracture Mechanics Vol. 9, 931-938.
6. Hashemi S., Kinloch J., Williams J.G. (1990), “Mechanics and mechanisms of delamination in a poly(ether sulphone)-fibre composite”, Composites Science and Technology Vol. 37, 429-462.

AFFILIATION

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