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Experimental Investigation of Mechanically Coupled Composite Specimens in the ENF Test Configuration

J Rzeczkowski[1], S Samborski[1] and J Paśnik[1]

[1]Lublin University of Technology, Department of Applied Mechanics, Nadbystrzycka 36 St., Lublin 20-618, Poland

E-mail: kubarzeczkowski@op.pl

Abstract. This paper reports an experimental study on the mode II interlaminar fracture of carbon/epoxy multidirectional (MD) laminates as well as on composite laminates with specific stacking sequence exhibited mechanical couplings. The aim of the analysis was to determine the mode II critical strain energy release rate (c-SERR, G_{IIC}) and an applicability of the data reduction schemes. Specimens were subjected to the end notched flexure (ENF) test. During the experiment the applied load and the load point displacement were registered. Additionally, the crack onset and all propagation values were observed and marked on the specimens edges. Moreover, the acoustic emission (AE) data were registered. The values of the mode II c-SERR were obtained with assumptions of the Direct Beam Theory (DBT) and Corrected Beam Theory (CBT). The experiment proved that the fracture toughness depends on the specimen delamination interface. For the asymmetric laminates, the mode II c-SERR reached significantly greater values for those specimens where the bending-extension coupling (BE) occurred.

1. Introduction

Fiber-Reinforced Laminated Composites (FRLC) are widely used for responsible parts for example in the aircraft. Their physical and mechanical properties have made them a superior candidate in many applications. Meanwhile, some sorts of defects and damage modes frequently appear in structures made of these materials [1]. Delamination is one of the most dangerous forms of damage modes in laminated composites therefore characterization of delamination resistance is thus of great relevance in design of composite parts. The basic modes of delamination include mode I (tensile opening), mode II (in-plane shear) and mode III (transverse shear). Among them the end-notched flexure (ENF) test is currently standardized for the measurement of the mode II interlaminar critical strain energy release rate of unidirectional (UD) laminates [2]. Most of the present design approaches are based on macromechanics, and many structures are subjected to bending loads, which naturally give rise to significant mode II in $[0°]_n$ composites. Owing to their high stiffness and ability to sustain self-similar crack growth conditions, UD specimens are particularly convenient for interlaminar fracture tests. However, most applications involve multidirectional (MD) laminates and it is observed that delamination generally occur between plies with different fiber directions, and the interface angles (defined as the ply angles of the two layers that forming the interface) are thought to be main factor among various factors that may influence the delamination in multidirectional laminates. It is, therefore, essential to study the interlaminar fracture of multidirectional specimens if critical strain energy release rates are to be applied in design. Delamination has a high tendency for intra-ply cracking between off-axis plies, which induces crack branching and/or delamination migration from the orginal interface [3,4]. Various studies were already reported on the mode II fracture of MD laminates [5-9]. For the mode II critical strain energy release rate (mode II c-SERR) its calculation formulae come from the beam theory [10]. During the test, the applied load and traverse displacement are recorded. The crack propagation is also observed and registered. To determine the maximum load point and propagation onset at the load-displacement plot, the Acoustic Emission (AE) signal can be registered as additional data [11]. It allows to increase the accuracy of determining the crack initiation moment. The results of the ENF tests showed that mode II critical strain energy release rate distribution was changing with the delamination interface ply angle and the type of mechanical coupling [12].

2. Experiment

The ENF test specimens beam were subjected to three-point bending in accordance with ASTM D7509 Standard [2]. The samples consisted of multidirectional composite laminates containing a PTFE insert at the mid-plane that served as delamination initiator. During the test samples with delamination interfaces [0/ α], [α/ α] and [α/- α] were used. Additionally, bending-twisting (BT) coupled laminate with the respective ply sequence: [α/0/ α/ α/0/- α/0/- α/- α/- α/- α/0/- α/ α/0/0/ α/ α] and bending extension (BE) coupled laminate [α/- α/0/- α/0/ α/90/ α/- α] were examined. The fiber orientation angle α took the following values {30°, 45°, 60°, 90°}. The specimens dimensions were width *b*=20 mm, total length *2L*=150 mm and thickness *2h*=5.5mm.

All test were carried out with the Shimadzu universal testing machine at 1 mm/min crosshead speed according to the ASTM D 7905 indications. All specimens were loaded through loading roller acting in half-length of samples. During the ENF test the applied load and the load point displacement were registered. Also the crack propagation along the edges of the specimen was observed and recorded. Figure 1 shows the deformed ENF specimen with the test parameters, including the applied load *P,* the load point displacement *δ* and the crack length *a*.

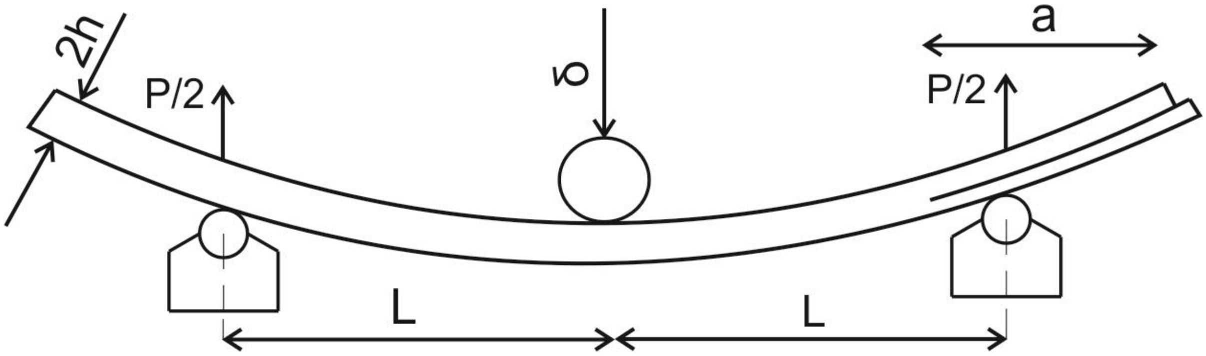

Figure 1. Deformed ENF Specimen

To determine mode II critical strain energy release rate two calculation methods were used: the Direct Beam Theory (DBT) and Corrected Beam Theory (CBT).

For the first method, G_{IIC} was determined from the following formula:

$$G_{IIC} = \frac{9a^2 P\delta}{2b(2L^3 + 3a^3)} \qquad (1)$$

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For corrected beam theory CBT, G_{IIC} is determined as follows:

$$G_{IIC} = \frac{9a^2P^2}{16b^2h^3E_f} \tag{2}$$

Here E_f is the axial modulus and is calculated according to equation (3) and C_0 is the initial compliance at $a=a_0$ as determined from the experimental compliance procedure.

$$E_f = \frac{L^3}{4bh^3C_0} \tag{3}$$

In order to increase of the accuracy of detect initiation of the peak force values related to the fracture process initiation, the acoustic emission (AE) recordings were made. The delamination onset point was indicated by the first AE phenomenon. Figure 2 shows load-displacement curves and the energy of the acoustic emission signal. The two initiation failure envelopes P_{max} and AE are very close to each other. This results suggests that the peak force of the load displacement curve and the first acoustic signal both correspond to the failure initiation.

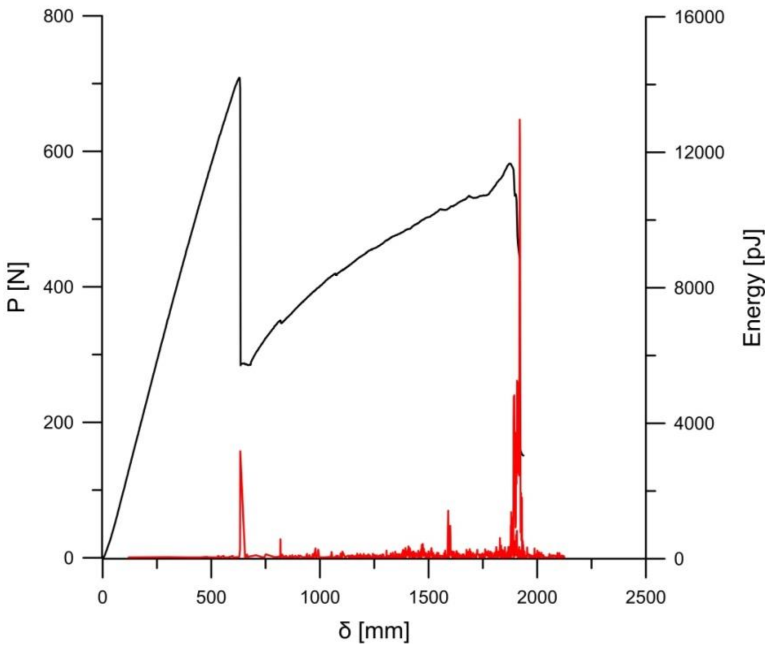

Figure 2. Load/displacement curves and energy of acoustic signal

3. Results and discussion

Figure 3 shows the experimental values of the initial G_{IIC} for specimens with the interface α/α. The greatest value of mode II c-SERR was equal 1.5 N/mm for samples with the interface 0°/0°. In configuration 90°/90° this value was on average level of 1.1 N/mm. Specimens with the interface 30°/30°, 45°/45° and 60°/60° exhibited lower values of the G_{IIC}. This effect can be induced by the couplings, as explained in [9,12,13]. For these interfaces it could be observed, that along with ply angle growth, the value of critical strain energy release rate also increased.

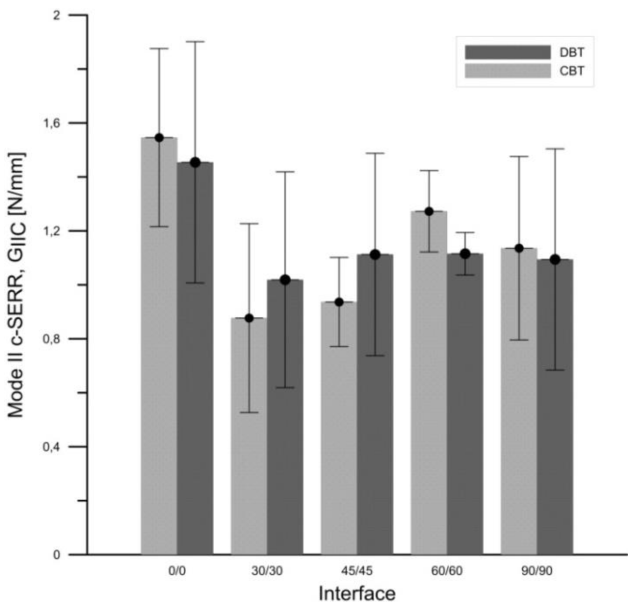

Figure 3. Mode II critical strain energy release rate G_{IIC} calculated using the DBT and the CBT method for the α/α interface

For the interface 30°/-30° the mode II c-SERR was on average level 1.3 N/mm and in comparison to the interface 30°/30° this value was about 0.3 N/mm greater. The G_{IIC} both for the interface 45°/-45° and 60°/-60° reached similar average values as in the interfaces 45°/45° and 60°/60°. The experimentally obtained results of the c-SERR for specimens with the interface α/-α were shown in Figure 4.

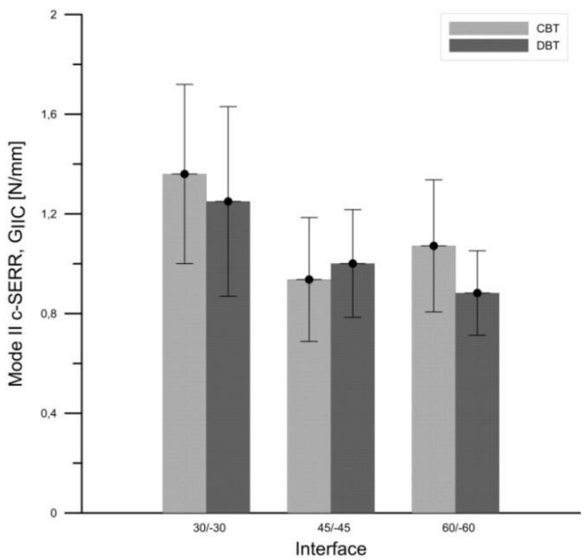

Figure 4. Mode II critical strain energy release rate G_{IIC} calculated using the DBT and the CBT method for the α/-α interface

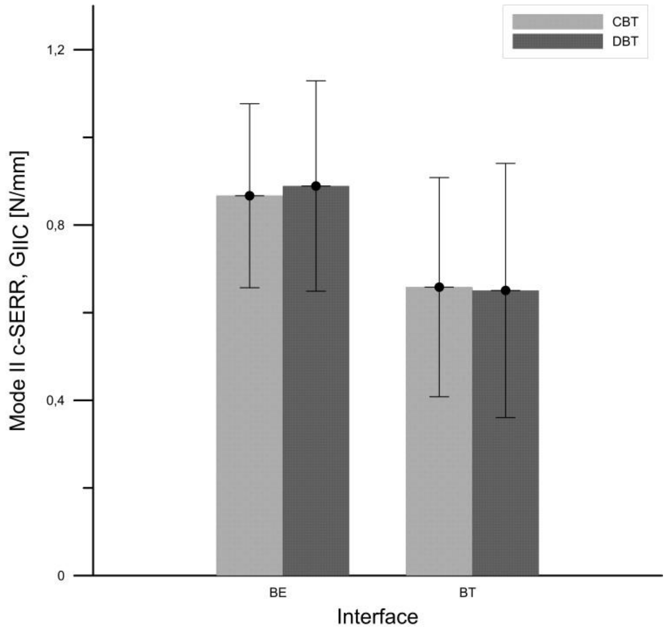

Figure 5. Mode II critical strain energy release rate G_{IIC} calculated using the DBT and the CBT method for specimens with mechanical couplings

Mechanical coupling laminates exhibited similar results of calculation of the mode II critical strain energy release for the corrected beam theory and the direct beam theory. For specimens with the bending-extension (BE) coupling the G_{IIC} was about 0.87 N/mm and for the bending-twisting (BT) couplings was equal 0.65 N/mm (Figure 5).

For the CBT and DBT methods the differences between the results of calculations of the mode II c-SERR for all specimens were minimal.

4. Conclusions

The experimental analysis of the standard ENF test for the multidirectional and coupled laminate beam specimens was performed with respect to the ASTM D7905 Standard. The critical strain energy release rate (GIIC) was obtained using different calculation methods. Acoustic emission signal was used as a additional data in order to recognize maximum load point. The results show that mode II c-SERR depends on specimens interface and mechanical coupling.

5. References

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