

Experimental Verification of the DCB Test Configuration Applicability to Mechanically Coupled Composite Laminates

J Rzeczkowski^{1,*}, S Samborski¹ and J Paśnik¹

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

*Corresponding author: kubarzeczkowski@op.pl

Abstract. This article presents an experimental determination on mode I critical strain energy release rate (c-SERR, G_{IC}). Multidirectional (MD) composite beams were subjected to the double cantilever beam (DCB) test during which the applied load and the load point displacement were registered. The maximum peak force was taken into account in calculation of the G_{IC} . It was computed using three different methods. On the basis of the performed test it was found that the critical strain energy release rate depends on the specimen interface.

1. Introduction

The Fiber-Reinforced Laminate Composites (FRLC) are commonly used in many fields of engineering. For example, these materials are used in contemporary load-carrying structures. Therefore, it demands from the designers thorough recognition of mechanical and strength properties. Delamination is particularly dangerous damage form in laminates. From the engineering and design point of view there is a vital need to assess the risk of a composite structure failure in result of delamination propagation. The fracture toughness (G_{IC}) values can be determined for mode I fracture in the double cantilever beam (DCB) test. This parameter is today counted to basic mechanical characteristics of composite materials beside the Young moduli and the Poisson coefficient [1,2]. The respective ASTM standard [3] covers the measurement of G_{IC} in the form of the critical strain energy release rate (c-SERR) of unidirectional (UD) laminates. In fact, UD specimens are generally used for the DCB test due to the high flexural stiffness and ability to maintain self-similar crack propagation. However, most applications in composite structures involve multidirectional (MD) laminates in which delaminations tend to occur between layers of different orientations [4]. Several studies were conducted of mode I fracture of MD laminates with delamination in α/α , $\alpha/-\alpha$ and $0/90$ interfaces [5-9]. The major problem is the development of interply damage, often associated with extensive fibre bridging and non-linearity. Moreover, MD laminates usually presents elastic couplings. This phenomena can be written in a block-matrix form as a constitutive equations [10] describing all possible couplings in a laminate.

$$\begin{Bmatrix} \mathbf{N} \\ \mathbf{M} \end{Bmatrix} = \begin{bmatrix} \mathbf{A} & \mathbf{B} \\ \mathbf{B} & \mathbf{D} \end{bmatrix} \begin{Bmatrix} \boldsymbol{\varepsilon}^0 \\ \boldsymbol{\kappa}^0 \end{Bmatrix} \quad (1)$$

The key constituents of block matrix in square brackets are respectively; the extensional stiffness matrix (**A**), the coupling stiffness matrix (**B**) and the bending stiffness matrix (**D**). The presence of



coupling can be the source of significant errors in G_{IC} measurements [11-12]. For example, from the practical point of view, in case of the DCB configuration the bending-twisting couplings may cause variability of the initial SERR along delamination front in coupled laminated beam. It is thus important to study mode I fracture of mechanically coupled composite materials. In this article the values of the mode I c-SERR were obtained by using of three calculation methods: the Modified Beam Theory (MBT), Compliance Calibration Method (CCM) and Modified Compliance Calibration (MCC). As expected the experimental test showed that result of calculations for mode I interlaminar fracture toughness in mechanically coupled laminated composites depends on the specimens delamination interface as well as the couplings induced by specific stacking sequences.

2. Experiment

Experimental DCB test were performed on multidirectional composite laminates with delamination interfaces $[0/\alpha]$, $[\alpha/\alpha]$ and $[\alpha/-\alpha]$. Additionally, bending-twisting (BT) coupled laminate with the respective ply sequence: $[\alpha/0\ \alpha/\alpha/0/-\alpha/0/-\alpha/-\alpha/-\alpha/0/-\alpha/\alpha/0/0/\alpha/\alpha]$ and bending extension (BE) coupled laminates $[\alpha/-\alpha/0/-\alpha/0/\alpha/90/\alpha/-\alpha]$ were examined. The fiber orientation angle α set was $\{30^\circ, 45^\circ, 60^\circ, 90^\circ\}$. The specimens dimensions was width $b=20\text{mm}$, total length 150mm and thickness $2h=2,75\text{mm}$.

The tests were carried out in Shimadzu machine at 1 mm/min crosshead speed according to the ASTM D 5528 procedure. All specimens were loaded through piano hinges bonded to the top and bottom legs of a specimen. During the DCB test the applied load P and the load point displacement δ were registered. Also the crack onset and all propagation values along the edges was visually observed and marked on the opposite sides of the specimens. In figure 1 was shown the DCB experimental set-up. In the mode I tests, the fiber bridging phenomena which causes growing resistance during delamination process was observed as illustrated figure 2.



Figure 1. DCB experimental setups

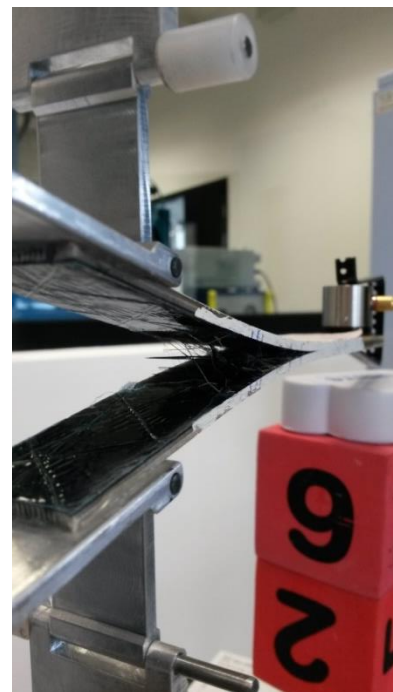


Figure 2. Deformed DCB specimens

To determine mode I critical strain energy release rate three different calculation methods were used: the MBT, the CCM and the MCC methods, respectively.

MBT method uses correction parameter Δ which may be determined experimentally by generating a least squares plot of the cube root of compliance $C^{1/3}$ as a function of delamination length a . The load and displacements corresponding to the visually observed delamination onset on the edge and all the propagation values were used to generate this plot. Mode I interlaminar fracture toughness is expressed following equation:

$$G_{IC} = \frac{3P\delta}{2b(a + |\Delta|)} \quad (2)$$

The CCM method determines additional parameter n which is the slope of $\ln(C)$ versus $\ln(a)$ curve. Therefore, the critical SERR is calculating as follows:

$$G_{IC} = \frac{nP\delta}{2ab} \quad (3)$$

In the MCC method, the first critical SERR can be expressed the following equation:

$$G_{IC} = \frac{3P^2C^{2/3}}{2A_1bh} \quad (4)$$

where A_1 is the slope of a least squares plot of delamination length normalized by specimen thickness a/h , as a function of the cubic root of compliance $C^{1/3}$.

3. Results and discussion

Table 1 collects the results of calculation mode I critical strain energy release rate calculated using the three different methods.

Table 1. Values of mode I critical strain energy release rate for different delamination interfaces and calculation methods

Specimens Interface	G_{IC} [N/mm]		
	MBT	CMM	MCC
0°/30°	0.327	0.319	0.374
0°/45°	0.807	0.830	0.872
0°/60°	0.957	0.894	0.947
0°/90°	0.867	0.874	0.847
30°/30°	0.746	0.749	0.686
30°/-30°	0.892	0.865	0.730
45°/45°	0.719	0.757	0.738
45°/-45°	0.527	0.516	0.546
60°/60°	1.113	1.039	1.039
60°/-60°	0.821	0.816	0.712
90°/90°	1.095	1.040	1.029

The results show influence of delamination interface on G_{IC} both for samples with interface $0/\alpha$, α/α as well $\alpha/-\alpha$. In case of the $0/\alpha$ interface differences can be observed between mode I c-SERR value. For the interface $0^\circ/60^\circ$, G_{IC} increases significantly above the one determined for the $0^\circ/30^\circ$ configuration. Its value was 0.957 N/mm, while for the interface $0^\circ/30^\circ$ only 0.327 N/mm. For the angle α {45°, 60° 90°} the c-SERR values are on similar level. Also close results

of the critical strain energy release rate calculation were both for the interface $30^\circ/30^\circ$ and $45^\circ/45^\circ$ as well as $60^\circ/60^\circ$ and $90^\circ/90^\circ$ but along with angle growth also a growth of G_{IC} values was observed. For $\alpha \{30^\circ, 45^\circ\}$ this value was on average level of 0.732 N/mm and for $\alpha \{60^\circ, 90^\circ\}$ reached about 1.104 N/mm. Comparing $45^\circ/45^\circ$ and $45^\circ/-45^\circ$ configuration the difference between the critical strain energy release rate is about 0.250 N/mm. Similar situation was observed in case of the $60^\circ/60^\circ$ and $60^\circ/-60^\circ$ interface. The smallest difference of G_{IC} occurred for the $30^\circ/30^\circ$ and $30^\circ/-30^\circ$ layups. The biggest value of mode I critical strain energy release rate was for the $60^\circ/60^\circ$ interface and reached 1.113 N/mm. Also the $90^\circ/90^\circ$ interface characterized itself with a high level of the G_{IC} value i.e. 1.095 N/mm. At most, the rest of specimen reached c-SERR value on the level of 0.800 N/mm except $45^\circ/-45^\circ$ interface (0.527 N/mm) and the $0^\circ/30^\circ$ (3.327 N/mm), which is the smallest value in the whole experiment.

In figure 3 was presented the values of the mode I critical strain energy release rate for specimens with specific ply sequences induces the bending-extension (BE) coupling and having the superior meaning in the case of mode I experimental test - the bending-twisting (BT) coupling. For the BT samples the value of mode I c-SERR was on the level of 0.800 N/mm and for the BE specimens it reached about 0.450 N/mm.

For the mechanically coupled specimens, three different data reduction schemes were used as it was mentioned before. The values of the mode I critical strain energy release rate were on similar level for all methods.

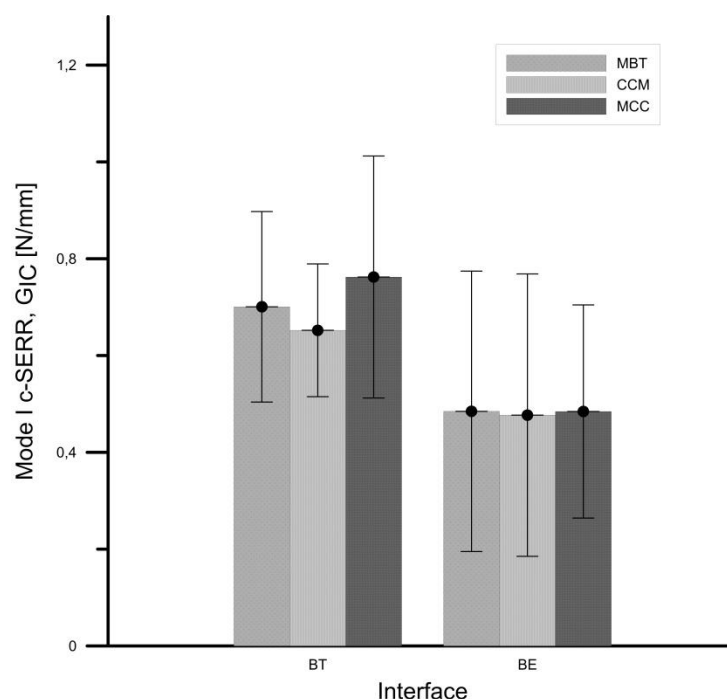


Figure 3. Mode I critical strain energy release rate for specimens with bending-twisting and bending-extension couplings

4. Conclusions

The experimental analysis of the DCB test configuration according to the ASTM 5528 Standard in case of the mechanically coupled laminated composite beams was performed. In particular, the effect of different interfaces of plies neighboring the delamination plane was discussed. The critical strain energy release rate (G_{IC}) was obtained using different calculation methods. The results shows that mode I c-SERR depends on specimens interface. Also, as it was expected, the bending-twisting

coupling had strongest effect on the c-SERR values in the DCB configuration applicability to mechanically coupled specimens.

5. References

- [1] Samborski S 2016 *Comp. Struct.* **152** 477-487
- [2] Samborski S and Rzeczkowski J 2018 *AIP Conference Proceedings* **1922** 080010
- [3] ASTM D 5528-01. Standard test method for mode I interlaminar fracture toughness of unidirectional fiber-reinforced polymer matrix composites 2001
- [4] Pereira A B, de Moraes A B, de Moura M F S F and Magalhaes A G 2005 *Elsevier*. **36** 1119-27
- [5] Chai H 1984 *Composites*. **15** 277-90
- [6] Laksimi A, Benzeggagh M L, Jing G, Hecini M and Roelandt J M 1991 *Compos Sci. Technol.* **41** 147-64
- [7] Robinson P and Song D Q 1992 *Compos. Mater.* **33** 73-100
- [8] Polaha J J, Davidson B D, Hudson R C and Pieracci A J 1996 *Reinf. Plast. Compos.* **15** 141-73
- [9] Choi N S, Kinloch A J and Williams J G 1999 *J. Compos Mater.* **33** 73-100
- [10] York C B 2013 *Compos A* **44** 140-8
- [11] de Moraes A B, de Moura M F, Marques A T and de Castro P T 2002 *Compos. Sci. Technol* **62** 679-86
- [12] Davidson B D, Kruger R and Konig M 1996 *Eng. Fract. Mech.* **55** 557-69

Acknowledgments: The paper was financially supported by the Ministerial Research Project No. DEC-2016/21/B/ST8/03160 financed by the Polish National Science Centre.