Determination of the mode I strain energy release rate in carbon fibre reinforced composites by means of digital image correlation technique

A. Khudiakova[1], M. Wolfahrt[2], D.Godec[3], G. Pinter[4]

[1]Polymer Competence Center Leoben GmbH, Roseggerstraße 12, 8700 Leoben, Austria
anastasiia.khudiakova@pccl.at www.pccl.at
[2]Polymer Competence Center Leoben GmbH, Roseggerstraße 12, 8700 Leoben, Austria
markus.wolfahrt@pccl.at www.pccl.at
[3]Faculty of Mechanical Engineering and Naval Architecture (University of Zagreb),
Ul. Ivana Lučića 5, 10000, Zagreb, Croatia
dgodec@fsb.hr www.unizg.hr
[4]Chair of Material Science and Testing of Polymers (Montanuniversitaet Leoben),
Otto Glöckel-Straße 2, 8700 Leoben, Austria
Gerald.Pinter@unileoben.ac.at www.kunststofftechnik.at

Keywords: fracture mechanics, double cantilever beam test, digital image correlation

Abstract

The present research proposes a methodology to localize the crack tip in the double cantilever beam (DCB) testing by applying the digital image correlation (DIC) method. The challenging task of the DCB test is to determine the applied load and displacement as well as the developing delamination length simultaneously, for both, continues and uncontrolled crack increments. Therefore, the DCB testing can be a time and effort consuming process, which results rely on a well-practiced machine operator ensuring the accuracy of the experimental data. In the suggested method the high strain concentrations are tracked by DIC to detect the corresponded position of the crack tip and to measure the crack length. Data reduction techniques for the energy release rate (ERR) calculations are presented for carbon fibre reinforced thermoplastic specimens. The obtained results are in good agreement with the experimental data measured in a conventional manner using a magnification glass.

1. Introduction

Delamination is the main damage mechanism occurring in advanced fibre composites used in aerospace components. Interlaminar fracture leads to stiffness reduction and earlier part damage. To measure ability of a composite structure to withstand crack propagation, fracture mechanic (FM) tests are applied [1,2].

The mode I crack opening test using a double cantilever beam (DCB) sample is a common experimental method to characterize fracture resistance under interlaminar normal stress in terms of strain energy release rate (ERR), G_{Ic} [3]. During this test, a length of a crack propagating through the sample is recorded together with corresponded applied force and displacement data. Standard test methods such as ISO15024 [4] and ASTM D 5528 [5] suggest to use a traveling microscope or an equivalent magnifying device to follow a crack tip, while an action button in a testing machine software can be used to extract the force and displacement values at every crack increment. Therefore, the measurements highly depend on the reaction and carefulness of the machine operator.

To make the measurements easier and less depended on a 'human factor', real-time health monitoring techniques can be applied. For example, Albertsen *et al.* [6] used the acoustic emission (AE) technique additionally to an optical microscope to follow mode I crack propagation in carbon fibre reinforced epoxy specimens. The authors concluded that the critical load when a crack initiation occurs can be determined with the AE, but the AE signal had a high frictional noise. Sorensen *et al.* [7] predicted delamination growth in carbon fibre PPS samples based on loading with strains obtained from the fibre Bragg grating (FBG) strain sensor. Xavier *et al.* [8] used the spectra of the FBG sensor to detect local strains near the crack tip in DCB samples made out of wood and to define the development of the fracture process zones. However, the evaluation of FBG spectrum is a time-taking and complex process. In addition, the FBG has to be implemented into the sample at a manufacturing step, what makes this method not very convenient.

Another real-time measurement technique applied to follow crack propagation are non-contact methods such as digital image correlation (DIC). The working principle of DIC is tracking changes in images made during sample testing. Prior to testing, a contrast stochastic dot pattern is introduced on the sample surface. Correlation of actual coordinates of the speckles with their initial coordinates enables calculations of strain and displacement fields by a comparison of grey intensity inside subsets virtually created on the sample surface [9]. Mogadpalli and Parameswaran [10] applied the DIC to obtain a displacement field near a crack tip in unidirectional glass-fibre reinforced epoxy laminates with an extended compact tension (ECT) geometry. The stress intensity factor (SIF) calculated with obtained displacement from DIC was in a good agreement with the FM theory. Grabois *et al.* [11] showed the applicability of DIC in mode I loading of PMMA tapered double cantilever beam samples to measure the crack opening displacement for SIF calculations.

To conclude, there is a lack of studies using the DIC technique to estimate the strain energy release rate for DCB samples. This can be attributed to a relatively small investigating area around the crack in the DCB samples in comparison with ECT samples. The present study suggests to use DIC as a technique to monitor the crack length in mode I DCB testing by following the high strain concentration near the crack tip.

2. Experimental part

2.1 Specimen manufacturing

The automated fibre placement (AFP) process was used to manufacture laminate plates made of unidirectional carbon fibre reinforced polyphenylene sulfide (PPS) tapes. DCB specimens with dimensions of 148±1 mm of length, 20.1±0.2 mm of width and 3.8±0.1 mm of thickness were cut out of the manufactured laminate plate. A thin teflon film with a length of about 64 mm was placed at the midplane of the laminates during the manufacturing process with regard to a crack initiation. Steel blocks were glued to the samples with a two component epoxy adhesive (Scotch-Weld™ DP490 from 3M UK PLC) and cured in an oven for 1 hour at 80°C.

2.2 The testing procedure

Five samples were prepared according to the description in paragraph 2.1. Prior to testing, both sides of the samples were coated with white typewriter correction fluid using a paint brush to enable better visualization of the crack onset. One side of the samples was sprayed with a black spray paint to introduce a stochastic dot pattern on the surface for DIC. Equidistance dots were additionally marked every 5 mm along the sample edge on the sprayed surface for easier visual orientation on the taken pictures. The first mark was located near the end of the teflon film. A scale with 5 mm marks was introduced on the other side of the samples to follow the delamination with a magnification glass.

The mode I interlaminar fracture toughness measurements were carried out on a servo-hydraulic test machine (MTS 810, MTS Systems Corporation, Berlin, Germany) with a 100 kN load cell and a test speed of 2 mm/min in accordance with ASTM D 5528 [5].

As described in the relevant testing standards, all samples were initially pre-loaded to create a sharp crack tip and to avoid an influence of the inserted released film on measured results. After the first force drop (Fig.1a), which indicated the crack propagation in the specimen, the specimen was unloaded. Then the specimen was loaded again to the total crack length of about 100 mm. The force-displacement curve from the second testing part is shown in Fig.1b. An increment of 5 mm was chosen to follow the crack tip with a magnification glass. The force and the displacement were recorded in the machine software with an action button.

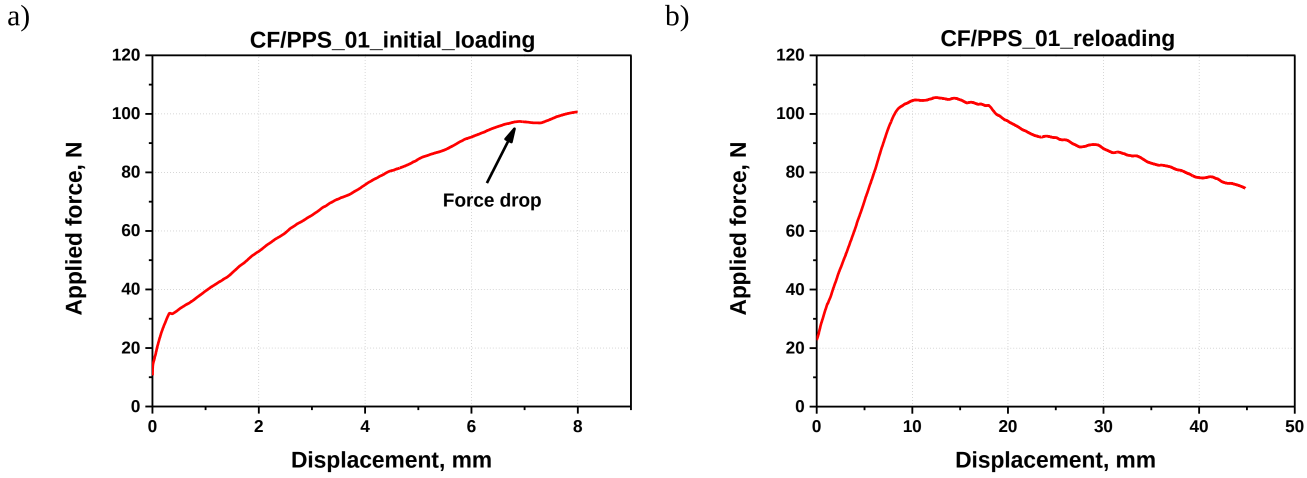


Figure 1. Force-displacement curves from: (a) initial loading and (b) reloading of the DCB specimen.

2.3 Digital image correlation

Aramis optical system (GOM GmbH, Germany) with two 4 mega pixel cameras available in Montanuniversitaet Leoben were used to take pictures of the speckled side with a frequency of 1 image per second. Before measurements, the DIC system has to be calibrated with a special calibration plate for a correlation of the data from cameras and further distance evaluations [12,13]. Corresponded calibration deviation was 0.039 pixel. After the tests, a processing of the images was done in GOM Correlate Professional software with subset size of 25 pixels with step of 9 pixels and spatial averaging filter of 3 pixels. Strains in the loading direction, ε_y were obtained along a line built in the crack propagation plane. In results, such built line had got the data of strains and their corresponded coordinates.

3. Data analysis and discussion

The methodology to obtain the crack length for calculations of ERR from the DCB test by means of the DIC technique was developed with a following procedure.

The strain values ε_{ij} with corresponded coordinates l_{ij} were extracted along the crack propagation line from every i-image of the tested sample. If strain ε_{ij} along the drawn line is greater than or equal to ε_{th} and less than or equal to $\varepsilon_{th} + \Delta\varepsilon$, then the crack length a_i is equal to a difference between total length l_{total} and the length coordinate l_{ij} of ε_{ij} (Fig. 2).

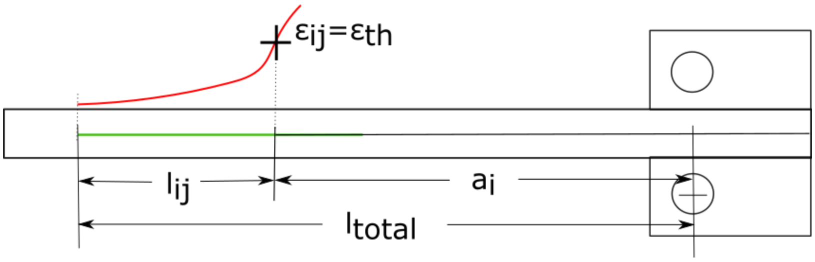
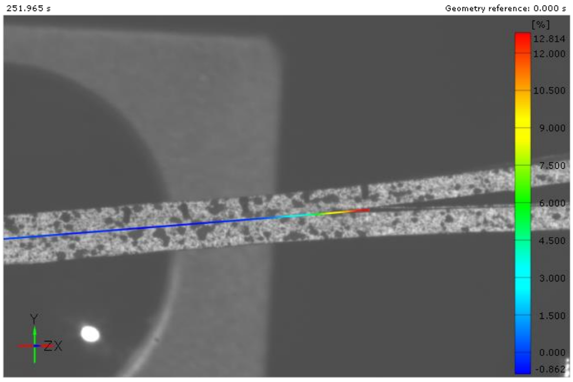


Figure 2. Schematic picture of a strain distribution in the DCB sample for calculations of the crack length.

Typical strain distribution along the built line obtained with DIC is presented in Fig.3a through the example of an image made at the 252 second of the test. The strains are around zero in the undamaged part, and grow up to 13% closer to the crack tip (Fig.3b). By extracting coordinates for strains between 1 and 3% as a position of the crack tip, it is possible to find the best match between ERR values calculated with DIC and values calculated with crack length, which was measured with a magnification glass.

a)



b)

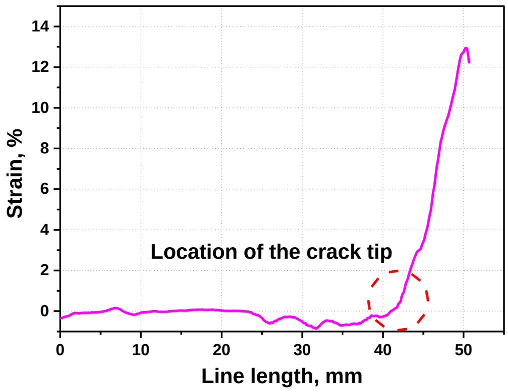


Figure 3. a) Strain distribution along a built line in the crack propagation direction; b) Plot of strains versus length of the built line.

Considering the DIC results, several thresholds of ε_{th} between 0.5% and 3% with a deviation $\Delta\varepsilon$ of 0.5% were used as a criterion to define a location of the crack tip. A code to process the big amount of data (more than 800 files) was written in a programming language Python with a following sequence of actions presented in Fig.4. The ERRs were calculated according to the beam theory (BT), the corrected beam theory (CBT) and the modified compliance calibration (MCC) method [14–16]. The data reduction was done with both methods, with values of the crack length detected with a magnification glass and with DIC.

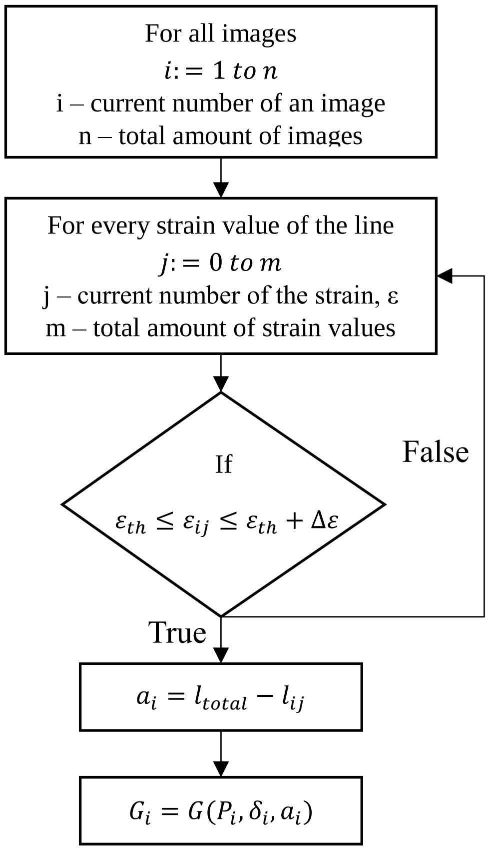


Figure 4. Flowchart of ERR calculations from strain data obtained with the DIC technique of the DCB test ($\varepsilon, a, l, P, \delta$ – strain, crack length, length along the specimen, force and displacement respectively).

Obtained values are presented for one of the samples, which has nearly the same results as the other tested samples and can be used as an illustrative example of the developed methodology. When the crack propagates, the stiffness of the specimen decreases and an increase in the compliance can be justified, that is demonstrated in Fig.5. There is a change in the compliance data obtained with DIC about 55 mm of the crack length, which corresponds to the further crack propagation in the specimen after the first specimen loading, where a pre-crack was created.

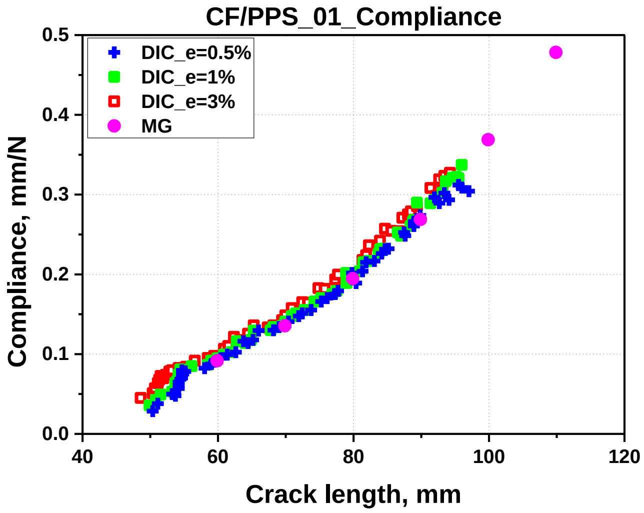
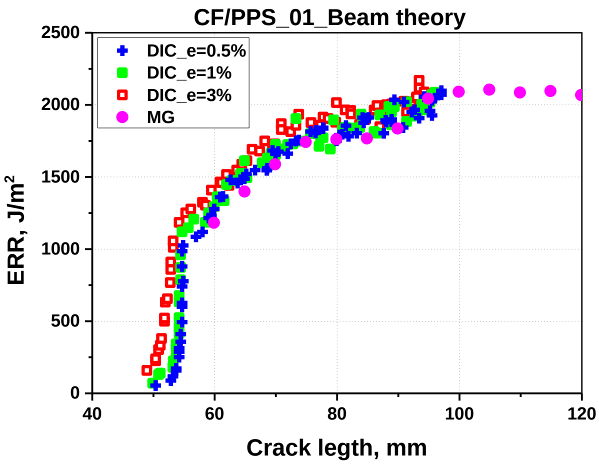
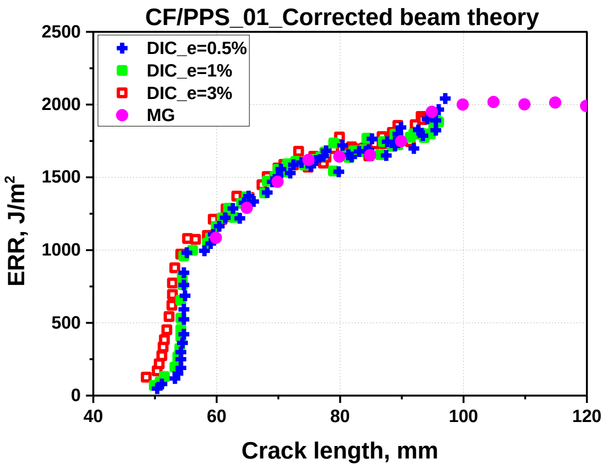


Figure 5. Results of compliance versus crack length obtained with DIC and the magnification glass (MG).

a)



b)



c)

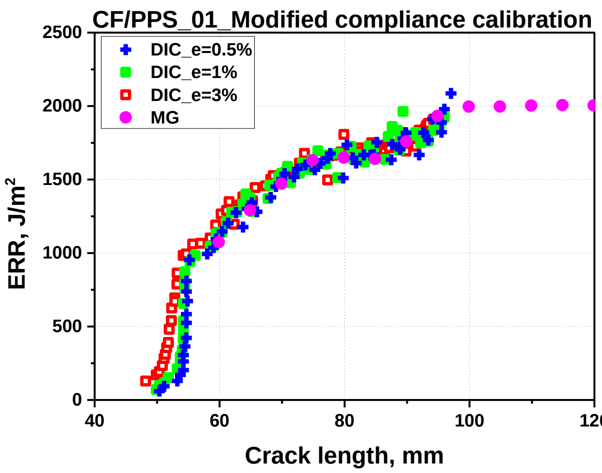


Figure 6. Comparison of the results obtained with DIC and the magnification glass (MG): a) ERRs calculated with the BT; b) ERRs calculated with the CBT; c) ERRs calculated with the MCC method.

The values of ERR versus the crack length are presented in Fig.6. After 55 mm of the pre-crack, the crack further propagates in the specimen, what indicates the critical value of ERR of about 1000 J/m^2. For the BT, strains of 0.5-1% obtained with DIC are in a good correlation with ERRs calculated with the data obtained with the magnification glass (Fig.6a). For the CBT and the MCC method, better correlation is achieved with strains of 0.5-1.5% (Fig.6b, c). Strains of 3% give higher results in all cases. There is no data computed with DIC after 97 mm of crack length because this region was out of the camera view. It should be mentioned that quality of pictures and the stochachastic dot pattern influence the DIC results. The higher camera resolution would provide a higher picture detalization and, as a consequence, a more precise detection of the speckle's positions.

4. Conclusion

The methodology to obtain the energy release rate in mode I fracture mechanics test by means of digital image correlation was developed. It was shown that strains concentration ε_y can be used as an indicator of the crack tip position. The strains of 0.5-1.5% obtained with DIC in CF/PPS samples gave results of ERRs closed to results obtained with a conventional way of the DCB measurements with a magnification glass. It can be concluded, that the suggested methodology can be used to estimate ERR with the DIC technique to reduce man-efforts in the DCB tests.

Acknowledgements

The research work was performed within the COMET-project VI-2.06 "New strategies towards laser assisted manufacturing of fibre reinforced thermoplastic composites" at the Polymer Competence Center Leoben GmbH (PCCL, Austria) within the framework of the COMET-program of the Federal Ministry for Transport, Innovation and Technology and the Federal Ministry of Science, Research and Economy with contributions by Technical University of Munich (Lehrstuhl für Carbon Composites) Montanuniversität Leoben (Institute of Material Science and Testing of Polymers), Boeing and AFPT. The PCCL is funded by the Austrian Government and the State Governments of Styria, Lower Austria and Upper Austria.

References

[1] S. Stelzer, G. Pinter, M. Wolfahrt, A. J. Brunner, and J. Noistnernig. Cyclic Interlaminar Crack Growth in Unidirectional and Braided Composites. Fatigue Behavior of Fiber Reinforced Polymers 2012.

[2] Mohammed Waseem, H. S., and N. Kiran Kumar. Finite element modeling for delamination analysis of double cantilever beam specimen. International Journal of Mechanical Engineering (SSRG-IJME) 2014;1(5).

[3] Newaz GM, Ahmad J. A simple technique for measuring mode I delamination energy release rate in polymeric composites. Engineering Fracture Mechanics 1989;33(4):541–52.

[4] ISO, BSEN. "15024: 2001.". Fibre-reinforced plastic composites. Determination of mode I interlaminar fracture toughness, GIC, for unidirectional reinforced materials.(15024): BSI; 2002.

[5] Standard, A. S. T. M. "D5528-01." Standard test method for mode I interlaminar fracture toughness of unidirectional fiber-reinforced polymer matrix composites (2007).

[6] Albertsen, H., et al. Interlaminar fracture toughness of CFRP influenced by fibre surface treatment: Part 1. Experimental results. Composites Science and Technology 1995;54(2):133–45.

[7] Sorensen L, Botsis J, Gmür T, Humbert L. Bridging tractions in mode I delamination: Measurements and simulations. Composites Science and Technology 2008;68(12):2350–8.

[8] Xavier J, Fernandes JRA, Frazão O, Morais JJL. Measuring mode I cohesive law of wood bonded joints based on digital image correlation and fibre Bragg grating sensors. Composite Structures 2015;121:83–9.
[9] Mehdikhani M, Aravand M, Sabuncuoglu B, Callens MG, Lomov SV, Gorbatikh L. Full-field strain measurements at the micro-scale in fiber-reinforced composites using digital image correlation. Composite Structures 2016;140:192–201.
[10] Mogadpalli GP, Parameswaran V. Determination of Stress Intensity Factor for Cracks in Orthotropic Composite Materials using Digital Image Correlation. Strain 2008;44(6):446–52.
[11] Grabois TM, Neggers J, Ponson L, Hild F, Toledo Filho RD. On the validation of integrated DIC with tapered double cantilever beam tests. Engineering Fracture Mechanics 2018;191:311–23.
[12] Wolfahrt M, Grosser J, Fleischmann M, Schubert M. Characterization of the Mechanical and Fatigue Behavior of Braided Composites Made of Twisted Yarns. MSF 2015;825-826:876–82.
[13] Grytten F, Daiyan H, Polanco-Loria M, Dumoulin S. Use of digital image correlation to measure large-strain tensile properties of ductile thermoplastics. Polymer Testing 2009;28(6):653–60.
[14] Hashemi S, Kinloch AJ, Williams JG. The Analysis of Interlaminar Fracture in Uniaxial Fibre-Polymer Composites. Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences 1990;427(1872):173–99.
[15] Williams JG. On the calculation of energy release rates for cracked laminates. International Journal of Fracture 1988;36(2):101–19.
[16] Kageyama, K., T. Kobayashi, and T-W. Chou. Analytical compliance method for Mode I interlaminar fracture toughness testing of composites. Composites 1987;18(5):393-399.