Numerical modeling and experimental verification of the DCB test configuration applicability to mechanically coupled composite laminates

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Abstract

The paper deals with numerical analysis of the DCB test configuration together with the data reduction scheme described in the ASTM D 5528 Standard for determination of the mode I fracture toughness in case of the laminated composites with mechanical couplings. Numerical analysis based on the FEM approach was performed with the Abaqus software exploiting the VCCT technique. The experiments on the DCB beams made of coupled laminates were also performed. The results show, that the distribution of the Strain Energy Release Rate can be asymmetric. A need for appropriate data reduction schemes has been revealed.

Keywords: laminated composite, mechanical coupling, energy release rate, double cantilever beam

1. Introduction

The laminated Continuous Fiber Reinforced Polymers (CFRP) are commonly used in the engineering structures. There is however an unexplored domain of mechanically coupled laminates [11,12]. In composite structures damage can be induced during manufacturing or maintenance. It can be dangerous considering the structure health and safety. The experiments on laminated composite structures in compression [4,5,10] revealed delamination as the main type of damage in compression. A numerical Finite Element Method study on the influence of the general ply layup with possible different mechanical couplings and the boundary conditions on the actual distribution of mode I fracture toughness along delamination front has been performed in Abaqus/CAE [1]. The simulations based on the virtual crack closure technique (VCCT) [6,8,9,13] allowed proper planning of the experimental tests such as the double cantilever beam (DCB) test [2] having in target determination of the critical strain energy release rate (SERR) - G_{Ic} being a material constant, for different ply angle interfaces.

2. Couplings in laminates

The coupling phenomena can be phenomenologically described with the following matrix equation [11, 12]:

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

where A is the extensional stiffness matrix, B – the coupling stiffness matrix and D is the bending stiffness matrix.

3. Numerical simulations

The VCCT technique was used in simulations of delamination, i.e. interlaminar crack onset and propagation. It is based on the linear elastic fracture mechanics (LEFM) [3]. The simulations of the DCB test configuration in the case of non-UD laminates turned out to be very useful in preparation of the experiment and in selection of the most interesting composite layups, concerning mechanical couplings. The ASTM 5528-D Standard [2] was followed in the experiments.

The numerical models of composite beam were composed of the *Shell* type S4R finite elements [1]. Delamination initiation and its expansion was ruled by the Benzeggagh-Kennane (B-K) fracture criterion, incorporated in the VCCT modeling technique.

4. Experiments

The object of the experiments performed so far was determination of the tensile properties of the polymer matrix composite material and its interlaminar fracture toughness.

In order to determine the mode I interlaminar fracture toughness of composite material in the form of G_{Ic} the double cantilever beam (DCB) tests were performed. Specimens were loaded using piano hinges bonded to the top and bottom legs of a specimen. A tensile force acting in the direction normal to the crack surface caused quasi-static opening of the specimen – see Fig. 1. During the DCB 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 [7]. Fig. 1 shows the deformed DCB specimen with the test parameters, including the applied load P, the load point displacement δ and the crack length a.

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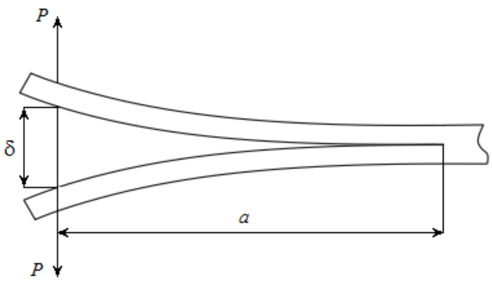

Figure 1: Deformed DCB Specimen.

5. Results and discussion

On contrary to the reconnaissance study performed in [9] before the stand tests now the material data for the FE models were taken from the authors own experiments. Nevertheless, both the experimentally obtained widthwise distributions of the mode I SERR and the results of new simulations exhibited similar deviations from symmetry, as those foreseen in the previous paper. The G_{I} values calculated for the FE nodes located along delamination front at the very moment of propagation onset did not form flat graphs. Discussion of any possible implementation of the standardized data reduction schemes was performed.

6. Conclusions

The critical analysis of the DCB test configuration and direct applicability of the ASTM D5528 Standard in case of the mechanically coupled laminated composite beams was performed. The non-symmetric distribution of the SERR for mode I delamination (G_{I}) was described with two additional parameters to be incorporated into the data reduction procedure. The obtained results can lead to reasonable planning of the experiments for composites with general ply layups. The versatility of the VCCT-enhanced FEM in modeling of coupled composites was proved.

References

[1] Abaqus/CAE User's Manual 6.11, Dassault Systémes, 2011

[2] ASTM D 5528: Standard test Method for Mode I Interlaminar Fracture Toughness of Unidirectional Fiber-Reinforced Polymer Matrix Composites. ASTM International, 2001.

[3] Burlayenko, V. and Sadowski, T., FE modeling of delamination growth in interlaminar fracture specimens, *Bud. i Arch.*, 2, pp. 95–109, 2008.

[4] Debski, H., Teter, A., Kubiak, T. and Samborski, S., Local buckling, post-buckling and collapse of thin-walled channel section composite columns subjected to quasi-static compression, *Comp. Str.*, 136, pp. 593-601, 2016.

[5] Kubiak, T., Samborski, S. and Teter, A., Experimental investigation of failure process in com-pressed channel-section GFRP laminate columns assisted with the acoustic emission method, *Comp. Str.*, 133, pp. 921-929, 2015.

[6] Krueger, R., The virtual crack closure technique for modeling interlaminar failure and delamination in advanced composite materials, *Num. M. of Failure in Adv. Comp. Mat.*, pp. 3–53, 2015.

[7] de Moura, M.F.S.F, Campilho, R.D.S.G. and Goncalves, J.P.M., Crack equivalent concept applied to the fracture characterization of bonded joints under pure mode I loading, *Comp. Sci. Tech.*, 68, pp. 2224-2230, 2008.

[8] Rybicki, E.F. and Kanninen, M.F., A finite element calculation of stress intensity factors by a modified crack closure integral, *Eng. Fract. Mech.*, 9 (4), pp. 931–938, 1997.

[9] Samborski, S., Numerical analysis of the DCB test configuration applicability to mechanically coupled Fiber Reinforced Laminated Composite beams, *Comp. Struct.*, 152, pp. 477-487, 2016.

[10] Teter, A., Debski, H. and Samborski, S., On buckling collapse and failure analysis of thin-walled composite lipped-channel columns subjected to uniaxial compression, *Thin-Walled Struct.*, 85, pp. 324-331, 2014.

[11] York, C.B., Unified Approach to the Characterization of Coupled Composite Laminates. Benchmark Configurations and Special Cases, *J. Aerosp. Eng.*, 23(4), pp. 219-242, 2010.

[12] York, C.B., Tapered hygro-thermally curvature-stable laminates with non-standard ply orientations, *Comp. Part A*, 44, pp. 140–148, 2013.

[13] Zou, Z., Reid, S.R., Soden, P.D. and Li, S., Mode separation of energy release rate for delamination in composite laminates using sublaminates, *Int. J. Sol. Struct*, 38 (15), pp. 2597–2613, 2001.