Cohesive zone modeling (CZM) in prediction of delamination failure in laminated composite structures

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Abstract: The ply delamination which is known as a principle mode of failure of layered composites due to separation along the interfaces of the layers is one of the main concerns in designing of composite material structures. In this paper first the double cantilever beam (DCB) and three-point-end-notched flexure (3ENF) specimens were fabricated from carbon/epoxy twill-weave fabrics and they were tested under quasi-static condition to determine the interlaminar fracture toughness in Mode-I (G_{IC}) and Mode-II (G_{IIC}) of the selected lay-up. The cohesive zone modeling (CZM) which is known as a variation in the cohesive stresses with the interfacial opening displacement along the localized fracture process zone was used in ANSYS to predict the Mode-I and Mode-II delamination failure in laminated composite structures. The numerical results were verified with the relevant experimental results.

Keywords: : delamination; failure; CZM; composite; ANSYS;

1. Introduction

The brittle nature of most fiber reinforced polymer (FRP) composites accompanying other forms of energy absorption mechanisms such as fiber breakage, matrix cracking, debonding at the fiber-matrix interface and especially plies delamination, play important roles on progressive failure mode and energy absorption capability of composite structures. Delamination can occur during the manufacturing process due to contaminated reinforcing fibers, insufficient wetting of fibers, machining and mechanical loading such as impact loading. Delamination can also occur due to the lack of reinforcement in the thickness direction and, also, since interlaminar stresses exist in the boundary layer of laminates under transverse loading [1-3]. In this regard prediction of delamination failure is one of the most important factors to design of composite structures. The cohesive zone modeling (CZM) is known as a variation in the cohesive stresses with the interfacial opening displacement along the localized fracture process zone, a small zone in front of the crack tip, in which small-scale yielding (SSY), micro-cracking or void growth, and coalescence take place. The CZM, also known as embedded process zone (EPZ), damage zone model (DZM), or fictitious crack model (FCM), is used to characterize crack growth at the interfaces [4-5]. In this paper CZM is used using ANSYS to predict the Mode-I and Mode-II delamination failure in laminated composite structures.

2. Mode-I & Mode-II Delamination

For determining the Mode-I interlaminar fracture toughness, G_{IC}, BS ISO 15024 standard [6] was followed. Also the corrections for the end-block, double cantilever beam (DCB) arm bending and root rotation were considered [7]. The

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3-point end-notched flexure (3ENF) specimens were made according to ESIS protocol [8] with the width of 20mm and the total length of 160mm, while the thickness varied from 5 to 6mm. This thickness is required to avoid large displacement, plastic deformation and intraply damage. A precrack length of 55mm from the free end of specimen was inserted using a Teflon film (see Figure 1). The lamination of DCB and 3ENF beams was laid-up by carbon/epoxy twill-weave fabrics according to the laminate design of $[0]_4$ with respect to weft direction. Loading was carried out at a constant crosshead displacement rate of 2 mm/min. The details of specimen preparation and testing method were explained in [1]. However, due to rapid crack propagation without any clear mouth opening in 3ENF Mode-II tests, the initiation fracture toughness is more accurate than propagation. Force at each crack length was retrospectively obtained from the recorded force-displacement diagram to calculate G_{IC} and G_{IIC}.

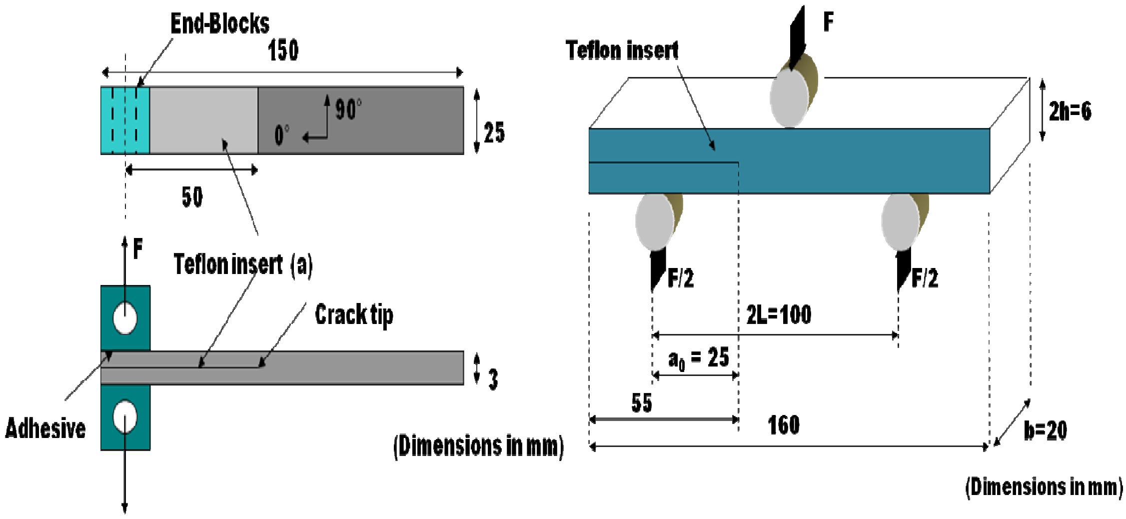

Fig. 1 Geometries of (a) DCB and (b) 3ENF specimens (All dimensions in mm)

Various reasons such as intra-laminar delamination, mixed mode fracture, fiber-bridging, micro-cracking, residual stresses, or a combination of these effects of θ-oriented lamina at interface caused the development of transverse intralaminar and unstable crack propagation in DCB tests. In all DCB tests intra-laminar delamination, fiber-matrix debonding and/or fiber breakage were observed in fracture surface areas. The development of transverse cracking also caused the force to show several continuous increases after initial crack propagation resulting in a rising R-curve (see Figure 2).

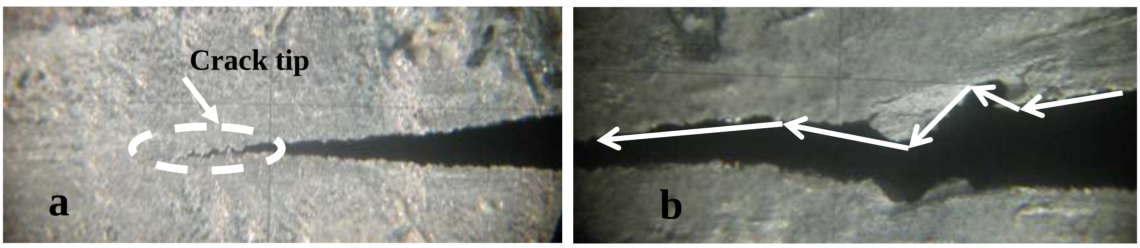

Fig. 2 Transverse cracking in DCB specimen, (a) at crack tip and (b) typical pattern of crack propagation

3. Cohesive zone modeling (CZM)

The composite beams were modeled with various lay-ups using finite element software ANSYS. The size of the DCB composite beam was 25×150mm^2 with a thickness of 3mm. The size of the ENF composite beam was 20×160mm^2 with a thickness of 6mm. In the present work, interface elements were performed to simulate the Mode-I and Mode-II crack propagation in composite beams. The CZM element was located along the crack growth direction from the tip of the initial crack to the end of the specimen. Automatic solution procedure was adapted which led to relatively small displacement increments. In the CZM/FEA the 20-node Non-layered/Layered SOLID 186 was used to model the composite beam (see Figure 3).

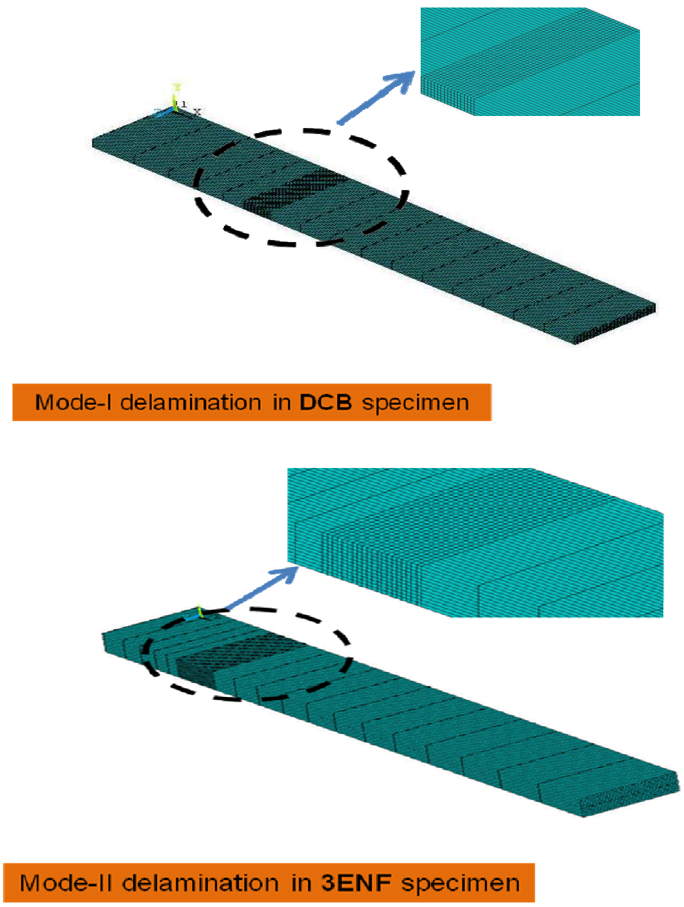

Fig. 3 FEM of DCB (Mode-I) and ENF (Mode-II) specimens in ANSYS

4. Results and discussion

In all DCB tests intra-laminar delamination, fiber-matrix debonding and/or fiber breakage were observed in fracture surface areas. This situation caused the force to show several continuous increases after initial crack propagation resulting in a rising R-curve. Regarding the results and recommendations of other works on DCB-tests on multidirectional laminates G_{IC} value of initiation is reported as interlaminar fracture toughness. Also due to rapid crack propagation without any clear mouth opening in 3ENF Mode-II tests, the initiation fracture toughness is more accurate than propagation and this value is reported as Mode-II interlaminar fracture toughness, G_{IIC} (see Table 1).

Table 1 Interlaminar fracture toughness obtained from DCB and 3ENF tests

Laminate lay-up	**Fracture plane interface**	G_{IC} **(MCC)** kJ/m^2	G_{IC} **(MBT)** kJ/m^2	G_{IIC} **(CCM)** kJ/m^2	G_{IIC} **(SBT)** kJ/m^2
$[0]_4$	0/0	0.9	1.0	2.0	2.4

MCC: Modified Compliance Calibration, MBT: Modified Beam Theory
CCM: Compliance Calibration Method, SBT: Simple Beam Theory

The size of elements in the cohesive zone was varied, but for element size of 0.5mm using σ_{max}= 10MPa and δ =0.2 mm for DCB specimen and σ_{max}= 50MPa and δ =0.2 mm for ENF specimen, the CZM/FEA results were in reasonable agreement with experimental results. During the numerical studies it was found that force-displacement for crack propagation is independent of the choice of the value of σ_{max} but crack initiation point is dependant of this maximum stress. The force versus displacement relationship for DCB and ENF tests were predicted for both initial crack and loading propagation (see Figure 4).

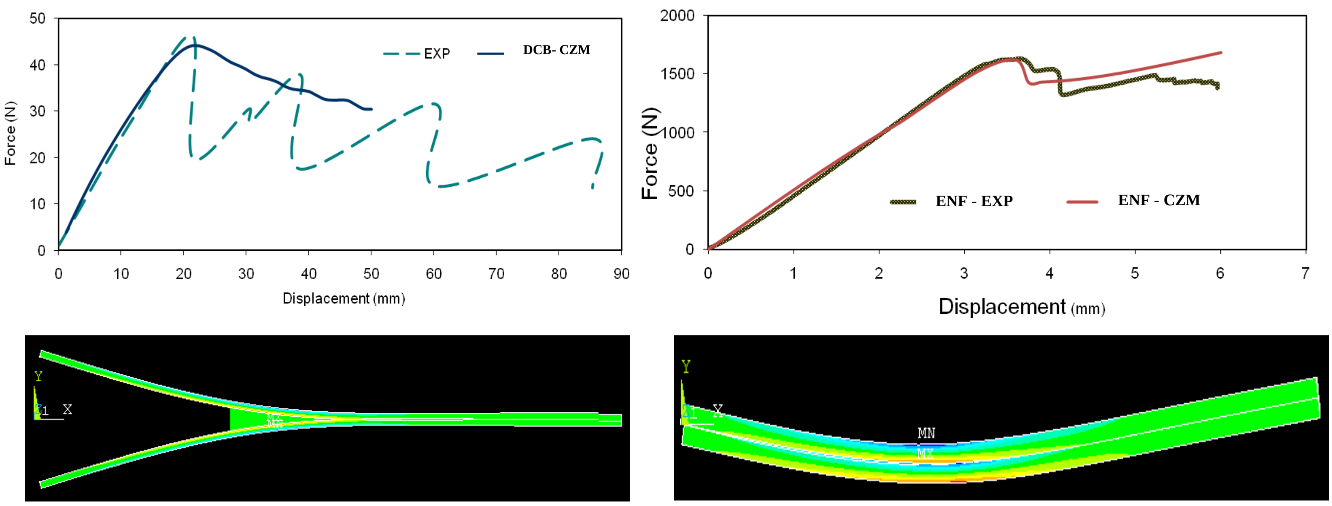

Fig. 4 Comparison of load-displacement results from CZM/FEA and Experiments, the inserts show the stress distribution, σ_Y

5. Conclusion

In the present work, first the interlaminar fracture toughness in Mode-I and Mode-II, carbon/epoxy twill-weave composite box was studied experimentally. Then the cohesive zone modeling (CZM) which is known as a variation in the cohesive stresses with the interfacial opening displacement along the localized fracture process zone was used in ANSYS to predict the Mode-I and Mode-II delamination failure in laminated composite structures. The force versus displacement relationship for DCB and ENF tests were predicted for both initial crack and loading propagation. The CZM/FEA results were in reasonable agreement with the relevant experimental results.

References

[1] H. Ghasemnejad, B.R.K. Blackman, H. Hadavinia and B. Sudall, Experimental studies on fracture characterisation and energy absorption of GFRP composite box structure. Composite Structures 88(2)(2008)253-261.

[2] B.R.K. Blackman, H. Hadavinia, A.J. Kinloch, and J.G. Williams, The use of cohesive zone model to study the fracture of fiber composite and adhesively-bonded joints, 119(2003)25-46.

[3] S. Li, M.D. Thouless, A.M. Waas, J.A. Schroeder, P.D. Zavattieri, Use of a cohesive-zone model to analyze the fracture of a fiber-reinforced polymer–matrix composite, 65(2005)537-549.

[4] J.W. Hutchinson, Linking scale in fracture mechanics. In: Proceedings of the ninth international conference on fracture (ICF9), Sydney; 1–5 April 1997. p. 1–14.

[5] A. Hillerborg, Application of fictitious crack model to different types of materials. Int J Fract 51(1991)95–102.

[6] BS EN ISO 15024:2001, Fiber-reinforced plastic composites. Determination of mode I interlaminar fracture toughness, G_{IC}, for unidirectional reinforced materials. BSI, 2002.

[7] J.G. Williams, End corrections for orthotropic DCB specimens, *Compos Sci Technol*, 35(1989)367–376.

[8] P. Davies, editor. Protocols for interlaminar fracture testing of composites. ESIS-Polymers and Composites Task group; 1993.