Finite Element Modeling for Delamination Analysis of Double Cantilever Beam Specimen

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ABSTRACT: *Delamination is one of the most commonly observed failure modes in laminated composites. The existence of delamination in a structure can significantly reduce the stiffness and strength of the structure. The simulations of delamination are performed by two different methods: Virtual Crack closure Technique (VCCT) and Cohesive Zone Method (CZM).VCCT is a fracture mechanics approach which is widely used to compute energy release rates. CZM is a progressive event governed by progressive stiffness reduction of the interface between two separating faces which uses bilinear material behavior for interface delamination and fracture energies based debonding to analyze delamination of unidirectional Double Cantilever Beam (DCB) specimen. The proposed methods are validated with the benchmark results. The load-displacement response predicted by CZM agreed well with the benchmark results. The other approach, VCCT, also successfully simulated the load-displacement response curve but this method overestimated the critical load. Parametric study is carried out for a range of height of the beam and load-displacement response is studied.*

Keywords *– Critical load, CZM, Delamination, Energy release rates, VCCT*

1. INTRODUCTION

Composites are extensively used in automobile, aerospace, and civil engineering structures due to their high strength-to-weight ratios. The brittle nature of the fiber reinforced polymer (FRP) composites follows some forms of energy absorption mechanisms such as matrix cracking, fiber breakage, debonding at the fiber-matrix interface and most importantly plies delamination, which are the major reasons for progressive failure modes and energy absorption in composite structures.

Delamination is a frequent mode of failure affecting the structural performance of composite laminates. The interface between laminas offers a low-resistance path for crack growth because the bonding between the adjacent laminas depends only on matrix properties. Delamination originatedue to the manufacturing imperfections such as cracks produced by low velocity impact or fatigue or stress concentration near geometric/material discontinuity. The analysis of delamination requires the combination of geometrically nonlinear structural analysis with fracture mechanics.

1.1 Strain Energy release rate

The general form of strain energy release rate, G_0

$$G_0=\frac{P^2}{2B}\frac{dC}{da}(1)$$

For DCB specimen shown in the Fig.1 for the rectangular cross section of the cantilevers, $I=Bh^3/12$, where ‘h’ is the depth of a cantilever and ‘B’ is the thickness of the DCB specimen. Using this, we have for DCB specimen.

$$C=8\frac{a^3}{E_1 Bh^3}(2)$$

Differentiating and substituting in equation (1), we get

$$G_0=\frac{12}{E_1}\frac{a^2}{B^2}\frac{P^2}{h^3}(3)$$

In the present study for the sake of comparison, the value obtained by the analytical calculation using the equation 3 is denoted by G_0 while the same obtained by ANSYS is G_I. Thus the ratio G_I/G_0 is shown in Fig.8.

2. REVIEW OF RELATED RESEARCH

Many research studies have been carried out to analyze the delamination of composite coupons, this section will sum up the few research work related to inter laminar fracture specimens namely Double Cantilever Beam (DCB), End Notched Flexure (ENF), Mixed Mode Bending (MMB).

Die Xie et al. [1] performed progressive analysis of a 2Dcrack growth under mixed-mode loading by using interface elements. Strain energy release rates based on the fracture mechanics approach (VCCT) can be computed by interface elements. With this interface element, strain energy release rates for mode I (G_I)and mode II (G_{II}) is calculated. By using fracture criteria, crack growth can be also predicted. Three examples on stationary cracks and static crack growths were examined and there was no convergence difficulty during the crack growth analyses. Therefore the interface element for VCCT issimple and efficient and for analyzing crack growth problems in 2D.

Ronald Krueger et al. [2] computed strain energy release rates for DCB, and SLB specimensalongthe straight delamination fronts using Virtual Crack Closure Technique (VCCT). The results were based on ABAQUS predictions agreed well for all the three specimens which are modeled using different elements.The models were made of solid eight-nodded elements and twenty-node hexahedral elementsboth elements gavethe same results. Models made in ABAQUS using brick elements and reduced integrationelements did not properly capture the energy release ratedistribution across the width of the specimens. For differentelementtypes with same method gaveclose results. Strain energy release rates for Mixed-mode condition were calculated by ABAQUS using the VCCT.

Mi et al. [3] performed Cohesive Zone Model (CZM) for the analysis of delamination in fiber composites. Mi et al. proposed the well-known method for the mixed mode delamination in the scope of damage mechanics and indirectly using fracture mechanics. The study is applied in the Double Cantilever Beam (DCB) test, the overlap specimen and Mixed Mode Bending(MMB) test by using finite element model for the capability and the reliability of the method. Consequently, the mixed mode interaction is analyzed. Typically, they compared the results with the analytical ones and the results showed quite good results. In addition, Mi et al. initiated discussions on the mesh size effect and the convergence related issues.

Qui et al. [4] embedded the study of Mi. et al. to analyze the convergence effects by artificially varying the critical displacements instead. In fact, their study focuses on the application, detailed in FE codes like finite element implementation and resulting influence to convergence

3. PROBLEM STATEMENT

The focus of this study is on the finite element modeling for the assessment of static delamination and to evaluate strain energy release rates for Double Cantilever Beam (DCB) specimen as shown in Fig.1.

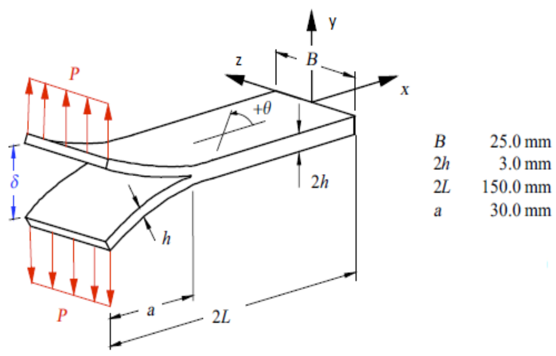

Fig.1: Double Cantilever Beam specimen

Table 1.Material properties and Fracture toughness of the Specimen

Material	Graphite/Epoxy
Young's Modulus in the 1-direction (E_1)	126 GPa
Young's Modulus in the 2-direction (E_2)	7.5 GPa
Young's Modulus in the 3-direction (E_3)	7.5 Gpa
Poisson's ratio in 1-2 direction (ν_{12})	0.263
Poisson's ratio in 2-3 direction (ν_{23})	0.263
Poisson's ratio in 1-3 direction (ν_{13})	0.263
Shear Modulus in 1-2 direction (G_{12})	4.981 GPa
Shear Modulus in 2-3 direction (G_{23})	3.321 GPa
Shear Modulus in 3-1 direction (G_{13})	4.981 GPa
Fracture toughness	
Fracture toughness for mode I (G_{IC})	0.281 kJ/m^2
Fracture toughness for mode II (G_{IIC})	0.494 kJ/m^2
Exponent , η	1.62

Table 2. Interface properties for Cohesive Zone Model (CZM)

CZM (Interface Delamination)	
Maximum normal stress (σ_{max})	25 MPa
Normal displacement jump at thecompletion of debonding (δ_n^c)	0.0224 mm
Maximum tangential traction (τ_{max})	-25 MPa

Tangential displacement jump at the completion of debonding (δ_t^c)	-0.0224
Non-dimensional weighting parameter (β)	1
CZM (Contact Debonding)	
Maximum normal contact stress (σ_{max})	1.7e6 Pa
Fracture Energy for Normal separation (G_{IC})	280 J/m^2
Maximum Tangential Contact stress (T_{max})	1e-30 Pa
Artificial Damping Coefficient (η)	1e-08 s

4. METHODOLOGY

4.1 Fracture criteria

LinearElastic FractureMechanics (LEFM) is used for delamination analysis in composite laminates which determines the total strain energy release rate, $G_T$which is the sum of individual components G_I, $G_{II}$and G_{III}, The onset of delamination is predicted by using the failure index,

$$\frac{G_T}{G_C} \geq 1 \quad (4)$$

where G_C is the fracture toughness. The fracture toughness is the propertyof a materialwhich describes the ability of material to resist fracture of component containing crack. Table 1 shows the fracture toughness properties for modes I and II respectively.Benzeggah and Kenane [5] suggested a 2D relationship for fracture toughness(G_C)and modes I and II which is given as,

$$G_C = G_{IC} + (G_{IIC} - G_{IC}) \left(\frac{G_{II}}{G_T}\right)^{\eta} \quad (5)$$

where G_{IC} and G_{IIC} are determined experimentally from DCB and ENF tests [5].

4.2 Virtual crack closure technique (VCCT)

The VCCT can be used to analyze delaminations in laminated materials using a fracture mechanics approach. The method implements LEFM. Only brittle crack propagation is modeled. The energy dissipated by the formation of plastic zones at the crack tip is not considered. The condition for the crack propagation is based on the Griffith's principle, for the case of single mode deformation under mode I conditions, the crack grows when $G_I/G_{IC} \geq 1$, where G_I is the Energy Release Rate (ERR) for mode I crack formation and G_{IC} is a material property representing the critical ERR for mode I crack formation.

4.3 Cohesive Zone Model (CZM)

The CZM method is based on the assumption that the stress transfer capacity between the two separating faces of a delamination is not lost completely at damage initiation, but rather is a progressive event governed by progressive stiffness degradation of the interface between two separating faces.

The bilinear CZM model can be used with interface elements and contact elements. The proposed model is based on Alfano and Crisfield [6] which is shown in Fig.2.The mode I dominated bilinear CZMmodel assumes that the separation of the materialinterfaces is dominated by the displacement jump normal to the interface.

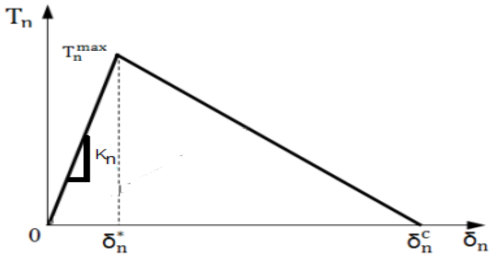

Fig.2: Mode I Dominated Bilinear CZM Law

The relation between normal cohesive traction (T_n) or maximum normalstress(σ_{max}), normal displacement jump (δ_n) and damage parameter(D_n) for mode I can be obtained from the literature [7].

5. AIM AND OBJECTIVE

The main aim of this project is to perform the delamination analysis by using fracture mechanics (VCCT) and Cohesive Zone Models (CZM).The following objectives have to be met in the sequel.

- Delamination Analysis of DCB specimen under the displacement controlled loading.
- Plot the load v/s displacement curve.
- Validation of the finite element model using the benchmark.
- Evaluation of energy release rate (G_I) under mode I loading for a DCB specimen.
- Parametric study is performed by varying the height of specimen and variation of load v/s displacement response is studied.

6. FINITE ELEMENT MODELDEVELOPMENT

A typical 2D FE model of DCB specimen with refine mesh at the crack tip, applied boundary conditions and loading case are shown in Fig.'s 3,4and 5.

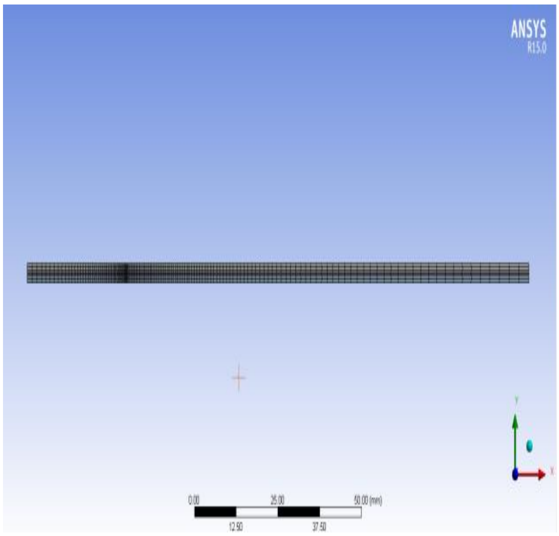

Fig.3: FE model of DCB specimen

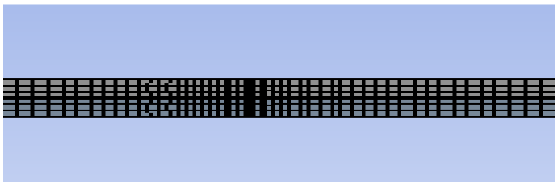

Fig.4: Refine mesh at the crack tip

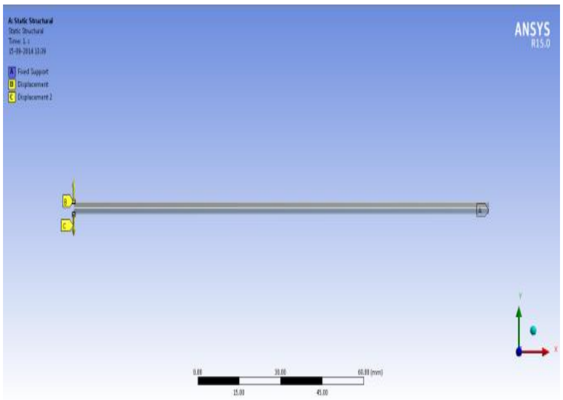

Fig.5: Boundary conditions and loading case

The right end of the beam is fixed and a constant displacement of 5 mm is applied at top and bottom sections of beam as shown in Fig.5. The specimen was modeled by using plane strain elements (PLANE182), 2D 4node cohesive element (INTER202) which is used to setup interface between top and bottom sections, TARGET 169 and CONTA171where used as contact elements for debonding.

7. FINITE ELEMENT MODEL VALIDATION

The present model is validated by a benchmark and is a standard test problem with known target solution in the form of formulae/graphs/tables. A unidirectional graphite /epoxy DCB specimen is validated using the experimental result which is the work of Davies [8].

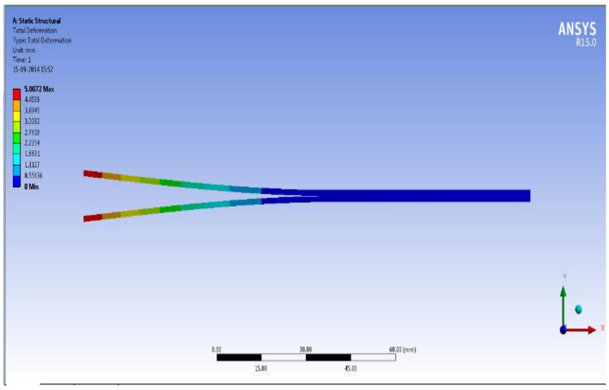

Fig.6: Total displacement of DCB specimen under pure mode I loading

Fig.6shows that both the cantilevers pull apart symmetrically from the crack face, thus signifying the vertical displacement of nodes on the crack face resulting delamination. This implies that there is a strong dominance of mode I loading in this condition.

7.1 Load-displacement response prediction

In Fig.7it can be observed that the experimental curve is linear up to failure (Onset of delamination), therefore critical load (P_{crit}) and displacement (δ_{crit}) were taken as maximum. The Load-displacement response was successfully modeled by both approaches and a good agreement with experimental results is observed. It can be seen that the load displacement curve obtained using VCCT traced a linear path till the critical load, with no softening effect, this implies the binary contact conditions in VCCT, this results in no stiffness degradation as the contact elements at the interface of the crack tip changes from bonded to open, which leads to the over prediction of the critical load. On the other hand a fairly goodcorrelation was observed between the CZM and experimental results, in contrast there is a deviation of the critical displacement form the experimental result this is due to the fact of material defects present in the test specimen.

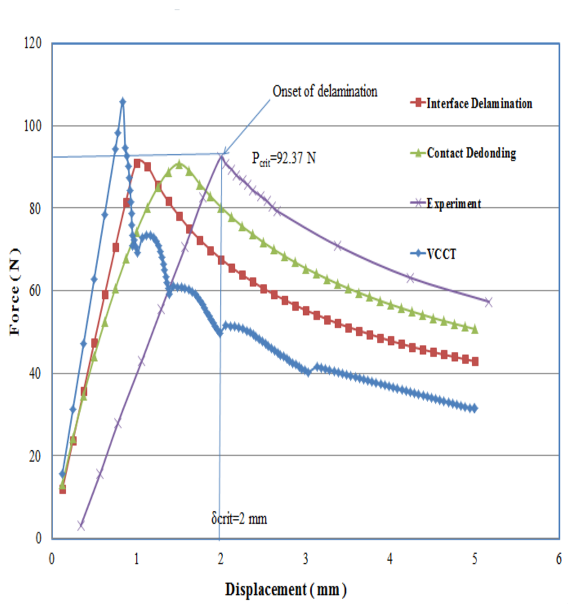

Fig.7: Load v/s displacement response

7.2 Energy release rate prediction

A crack length of 30 mm was kept constant with height of the beam h ranging from 1mm to 3mm are considered for analysis. The results are obtained by refining the mesh at the crack tip to get convergence. The mode I energy release rate obtained is tabulated in Table 3. The G_I values are normalized with respect to G_0, calculated analytically using equation 3; Fig.8shows a plot of G_I/G_0 against a/h ratio.

Table 3: Analytical and FE results for varying h value

a/h	h	FEM(G_I) in mJ/mm^2	Analytical (G_0) in mJ/mm^2	G_I/G_0
10	3	0.30731	0.29698	1.035
15	2	0.2837	0.28303	1.002
20	1.5	0.28427	0.2764	1.028
25	1.2	0.28535	0.2863	0.996
30	1	0.28228	0.2861	0.986

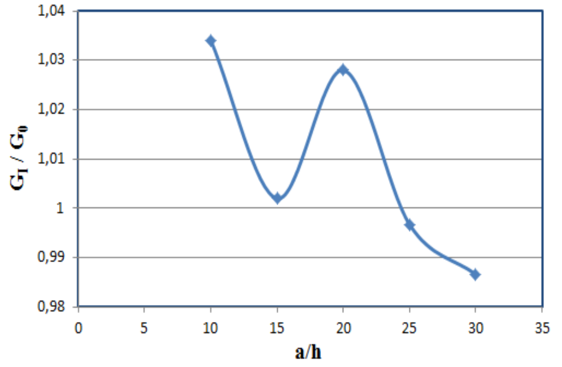

Fig.8: Normalized energy release rate across the height of DCB

8. CASE STUDY

After validation it was possible to perform the case study by varying height of the beam h ranging from 1mm to 3mm, whereas the dimensions, load and boundary conditions are considered to be constant as in benchmark case and the effect of reaction force and displacement was studied by using CZM method. The normal stress and contact stress for interface and contact elements where taken as 45 MPa and 10 MPa respectively.

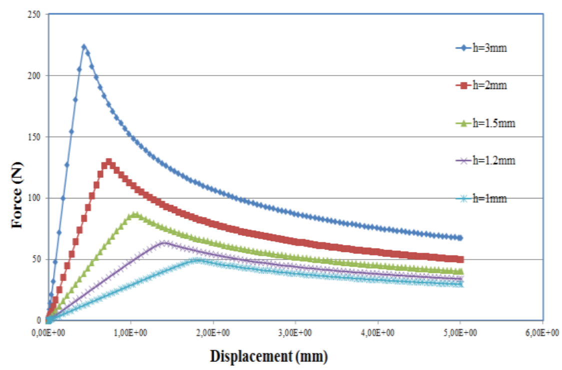

Fig.9: Load v/s displacement response for variation of h by using Interface elements

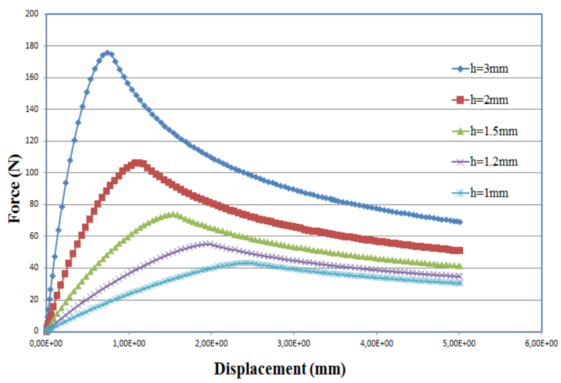

Fig.10: Load v/s displacement response for variation of h by using Contact elements

From Fig.'s 9 and 10it can be seen that the reaction force increases as the thickness of the cantilever arm is increased and thereby decreasing the critical displacements, this load-displacement behavior also depends on stiffness of cohesive zone and interfacial strengths.

9. CONCLUSION

Delamination is analyzed by two different techniques by using VCCT and CZM which are implemented in commercial software ANSYS workbench. Both VCCT and CZM are able to provide a successful simulation of the load-displacement response curve. However, VCCT overestimated the critical load; whereas agood agreement of experimental results was obtained by CZM for both interface and contact elements

For CZM modeling, the interface strength (σ_{max}) is the important parameter for crack initiation load.A lower interface strength (σ_{max}) value results in a lower crack initiation load.

The evaluation of strain energy release (G) is not the final goal. The next step would be able to perform crack propagation analysis. For this valid criteria need to be established and also the methods need to be validated, this is identified as a future work.

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