International Conference on Innovative Research in Engineering, Management and Sciences
International Journal of Scientific Research in Computer Science, Engineering and Information Technology
© 2019 IJSRCSEIT | Volume 4 | Issue 9 | ISSN : 2456-3307

Performance Analysis of Bank Conference Room AC Design: A Case Study

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ABSTRACT

Delamination in laminated composite structures usually initiate from discontinuities such as matrix cracks and free edges or from embedded defects due to the manufacturing processes. Therefore, it is important to analyze the progressive growth of delamination in order to predict the performance of a composite structure and to develop reliable and safe designs. Virtual Crack closure Technique (VCCT) is a fracture mechanics approach which is widely used to compute energy release rates. Cohesive Zone Method (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 these two methods are used to analyze the delamination of multidirectional composite Double Cantilever Beam (DCB) specimen in a Commercial Finite element Package called ABAQUS. The proposed methods are validated with the benchmark results and load-displacement curves are plotted using both the methods. The strain energy release rates are found out using VCCT and a parametric study is performed by varying the crack lengths.

Keywords: Delamination, Virtual Crack closure Technique (VCCT), Cohesive Zone Method (CZM), stiffness, Double Cantilever Beam (DCB)

I. INTRODUCTION

Delamination forms on the interface between the layers in the laminate. The analysis of delamination is commonly divided into the study of the initiation and the analysis of the propagation of an already initiated area. Delamination may form from matrix cracks that grow into the inter-laminar layer or from low-energy impact. De-bonding can also form from production non adhesion along the bond line between two elements and initiate delamination in adjacent laminate layers. Under certain conditions, delamination's or de-bonds can grow when subjected to repeated loading and can cause catastrophic failure when the laminate is loaded in compression.

The Double Cantilever Beam (DCB) is used to access the mode I failure strength of composite laminate with all plies. In this type of failure mode, the load is applied on the cantilever arms and the crack propagates in the direction perpendicular to the applied load. In this case, no shear at the crack tip of delamination exists. Hence, the crack growth is due to the out-of-plane load. For this crack growth, we term as "Mode-I" fracture. When the crack advances, the de-bonding takes place between the interfacial surfaces leading to the fracture, releasing the energy which is resulting in delamination. The energy that is dissipated in this process is coined as strain energy release rate or fracture energy pertaining to the DCB. During this process of crack propagation, the applied load will assist in increasing the energy associated with the cantilever arms and thus succeeds in attaining an energy level which is equal to or greater than the threshold barrier energy.

The strain energy release mechanism is controlled at least partially by the structural interaction between plies during loading the laminate. Since this interaction can be altered by the kinematics of the crack, the energetic argument provides not only a criterion for crack growth but also for the kinematic effects such as growth stability.

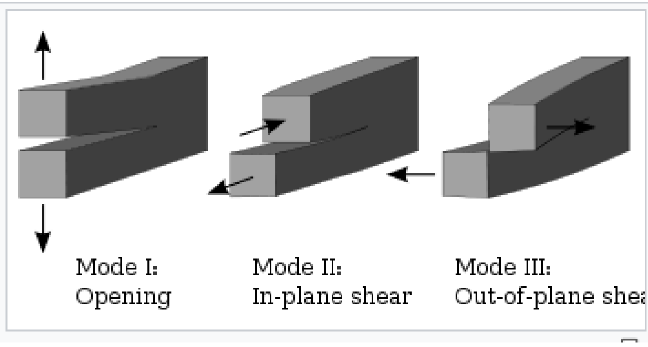

Fig 1: Modes of Failure

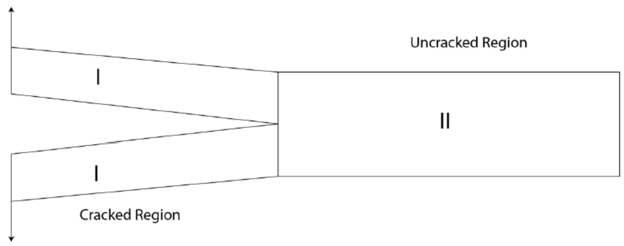

Fig 2: Double Cantilever Beam with Load

II. THEORY AND CALCULATION

This paper evaluates to perform progressive damage simulation of the below mentioned DCB specimens with both unidirectional and multi directional composites by using Virtual Crack Closure Technique (VCCT) and Cohesive Zone Models (CZM)

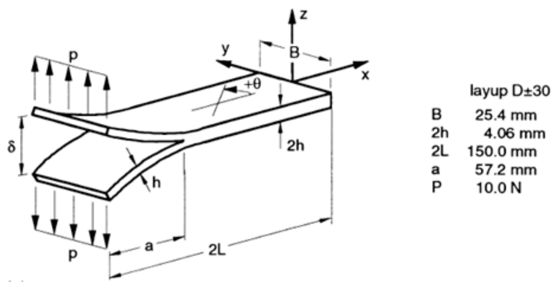

Fig 3 : Multidirectional Double Cantilever Beam specimen

The Carbon-Epoxy multidirectional composite double cantilever Beam specimen is as shown in the above Fig 3. It has 32 plies having stacking sequence and the delamination is at the 16th ply. For this specimen progressive damage simulation of a Double Cantilever Beam specimen is carried out and the strain energy is evaluated using Virtual Crack Closure Technique method.

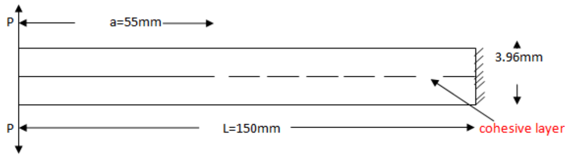

Fig 4 : Unidirectional Composite Specimen specification

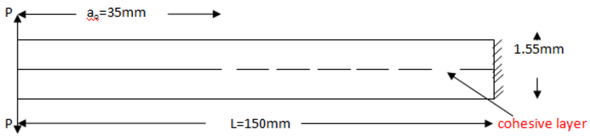

Fig 5 : Multidirectional composite beam specifications

Table 1: Material Properties of the DCB specimen

Material	Graphite/Epoxy
Young's Modulus in 1st direction	146.9 Gpa
Young's Modulus in 2nd direction	10.6Gpa
Young's Modulus in 3rd direction	10.6Gpa
Poisson's ratio 1-2 direction	0.33
Poisson's ratio 2-3 direction	0.33
Poisson's ratio 3-1 direction	0.33
Shear modulus 1-2 direction	5.45Gpa
Shear modulus 2-3 direction	5.45Gpa
Shear modulus 3-1 direction	3.99Gpa
Stacking Sequence for multidirectional specimen	[30/-30/0/-30/0/30/0$_4$/30/0/-30/0/ 30/30±30/30/0/30/0/-30/0$_4$/-30/0/30/0/30/-30]

Table 2: Material Properties of the unidirectional specimen

Material	Graphite/Epoxy
Young's Modulus in 1st direction	150 Gpa
Young's Modulus in 2nd direction	11 Gpa
Young's Modulus in 3rd direction	11 Gpa

Poissons ratio 1-2 direction	0.25
Poissons ratio 2-3 direction	0.45
Poissons ratio 3-1 direction	0.25
Shear modulus 1-2 direction	6 Gpa
Shear modulus 2-3 direction	3.7 Gpa
Shear modulus 3-1 direction	3.7 Gpa
Mode 1 critical energy release rate G1C	0.352N/mm
Maximum Normal stress σ_c	60 Mpa

Virtual Crack Closure Technique

The virtual crack closure technique (VCCT) is a well-established method for calculating the energy release rate (ERR) when analyzing fracture problems via the finite element method (FEM). The technique is based on the numerical implementation of Irwin's crack closure integral, as first proposed for two-dimensional problems and later extended to three-dimensional problems.. In recent years, the VCCT has gained great popularity for the study of mixed-mode fracture problems, such as the delamination of composite materials and interfacial fracture between dissimilar materials.

VCCT calculates energy release rate G, with the assumption that the energy needed to separate the surface is same as the energy needed to close the same surface area. This technique uses a contact or interfacial elements along a predefined interface of model.

Nevertheless, this type of modeling involves a fracture mechanics technique with large body work. Although the growth criterion is energy release rate, G which is the subject of interest but there are few assumptions that must be accounted for, before proceeding to model. They are

- Number of cracks
- Location of cracks
- Size of cracks

Cohesive Zone Modeling

Cohesive zone (CZ) models have been introduced by Dugdale and Barenblatt and have recently attracted a growing interest in the scientific community to describe failure processes and delamination in particular. Cohesive zones project all damage mechanisms in and around a crack tip on the interface, leading to a constitutive relation, or cohesive zone law, between the traction and opening displacement

As the surfaces (known as cohesive surfaces) separate, traction first increases until a maximum is reached, and then subsequently reduces to zero which results in complete separation. The variation in traction in relation to displacement is plotted on a curve and is called the traction-displacement curve. The area under this curve is equal to the energy needed for separation. CZM maintains continuity conditions mathematically; despite physical separation. It eliminates singularity of stress and limits it to the cohesive strength of the material.
Advantages of Cohesive Zone models are:
1) Interaction between crack faces is automatically incorporated and
2) It can be fitted on experimental data.

Cohesive zone models relate the relative displacement (”opening” Δ) of two associated points of the interface to the force per unit of area (”traction” T) needed for separation. Frequently – but not necessarily – a difference is made between normal (n) and tangential (t) direction, so the cohesive zone law comprises the two relations Tn(Δn) and Tt(Δt).
Cohesive zone laws can be uncoupled or coupled. In an uncoupled cohesive zone law the normal/tangential traction is independent of the tangential/normal opening. In a coupled cohesive zone law, both normal and tangential tractions depend on both the normal and tangential opening displacement. Uncoupled laws are intended to be used when the debonding process occurs under one mode – normal (mode-I) or tangential (mode-II) loading – or is largely dominated by one mode. The majority of cohesive zone laws have a (partial) coupling between normal and tangential directions, which is achieved by introducing coupling parameters in the model.

IV. FINITE ELEMENT ANALYSIS

The finite element method is a numerical technique for obtaining approximate solution by reducing the infinite degree of freedom to finite degree of freedom for a wide variety of engineering problem.

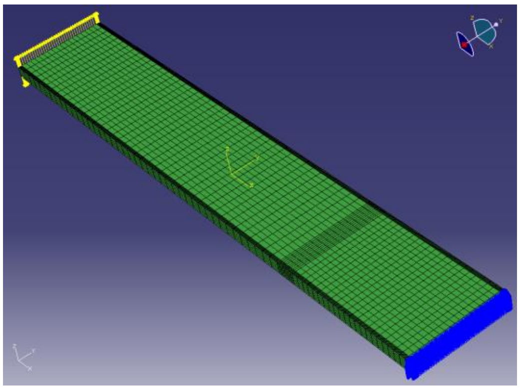

Fig 6 : Finite Element Modeling of DCB specimen with Boundary conditions

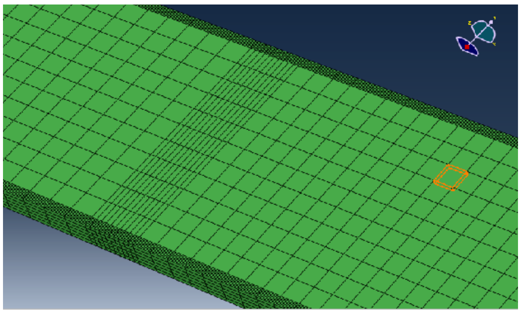

Fig 7 : Refine mesh at the crack tip

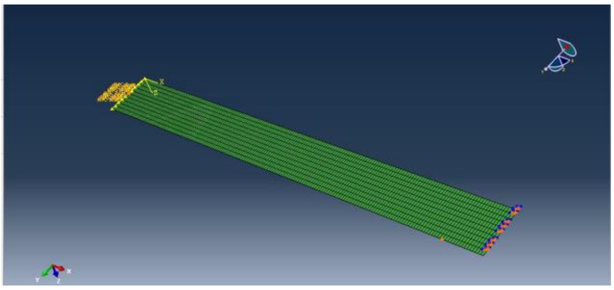

Fig 8 : Finite element modeling of DCB specimen using shell elements

Delamination analysis for a composite double cantilever beam specimen is carried out using commercially available FE package Abaqus. Finite element Modeling of the specimen is done in abaqus software and it is meshed using 3D hexagonal elements as shown in the fig 8. Fine mesh is done near the crack tip and at the edges and coarse mesh at the other surface. Right end of the Double cantilever beam specimen is fixed and a constant loading of 10N is applied at the other end as shown in the Fig 6.

A 3-D model is meshed using a SOLID C3D20R having 20 Nodes elements which is capable of modeling a composite structure up to 250 layers. While meshing the areas the aspect ratio is maintained in order to obtain the results accurately. Theoretically the thickness direction should contain a minimum of three nodes defining the surface and the number of nodes in the length and width (3-D) can be any arbitrary value. The meshing can be coarse at the junction and should be finer where the crack tip is present and the region around the tip. The rest of the specimen is not the subject of interest so the mesh can be coarse enough for the solution to converge.

Typically this de-bonding technique is implemented using a contact and target elements at the interface along with Virtual Crack Closure Technique. The Finite element modeling of the DCB specimen using 3D shell elements are as shown in the Fig 8. The 4 noded shell element with reduced integration scheme (S4R) has been used for the bulk material and the 8noded 3D (COH3D8) cohesive element has been used for model zero thickness cohesive zone. These cohesive elements will have the properties of the adhesives used in the DCB specimen and the young's modulus of adhesive used , normal traction force and tangential traction force are given as input to the Abaqus software.

V. RESULTS AND DISCUSSION

From the Fig 8, It can be noted that both the cantilever beams 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.

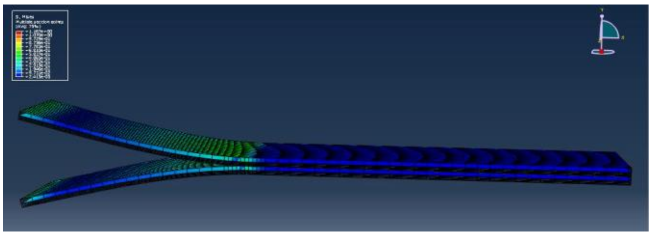

Fig 9: Crack Propagation of DCB specimen using VCCT technique

Fig 9 represents Crack propagation of a double cantilever beam specimen using Cohesive Zone Modeling method. The blue elements in between the cantilever beams represent the cohesive elements. These cohesive elements are nearly zero thickness elements which are introduced in between the cantilever beams and these cohesive elements are introduced along the complete width of the specimen and will have the properties of adhesives and during crack propagation these elements are distorted and it will give clear indication of crack propagation across any direction of the specimen.

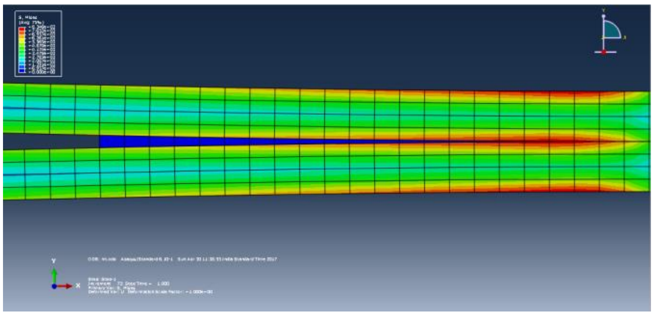

Fig 10: Crack propagation using CZM method

The Load and displacement curves are plotted for the multidirectional Double Cantilever Beam specimen using Virtual crack closure Technique and Cohesive Zone modeling approaches.

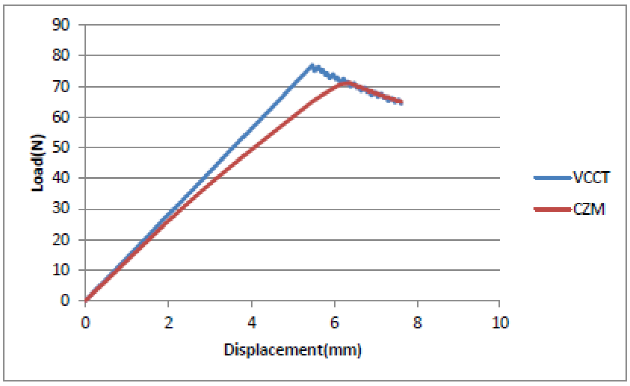

Fig 11: Load-displacement curves for VCCT and CZM

In Fig 10 it can be observed that the curve is linear up to failure (Onset of delamination), therefore critical load (Pcrit) and displacement (δcrit) were taken as maximum. The Load-displacement response was successfully modeled by both approaches. From the graph It can be noted that the load displacement curve which is obtained using VCCT traced a linear path till it reaches the critical load, and without any softening effect which implies that in binary contact conditions using VCCT, no stiffness degradation of the contact elements at the interface takes place and crack tip changes from bonded to open. On the other hand Cohesive Zone Modeling Estimated the Critical Load little less than that the Critical Load obtained from the VCCT because of the presence of the Cohesive elements at the interface which will have the same properties that of the adhesives used to bond the cantilever beams whose stiffness is very less than the beam elements which results in stiffness degradation and thus crack opening takes place little early. A Fairly good correlation can be observed between Virtual Crack Closure Technique and the Cohesive Zone Modeling methods from the graph.

A. Strain energy Release rate

The strain energy release rate is a fracture parameter which is used to measure delamination characteristics of composite laminates and it can be defined as "the energy dissipated during the crack formation for a newly created crack surface area" and denoted as G. the strain energy release rate for the multi direction composite double cantilever beam is calculated using Virtual Crack Closure Technique and the computed strain energy release rate distributions across the width of the specimen are shown in Fig. 11

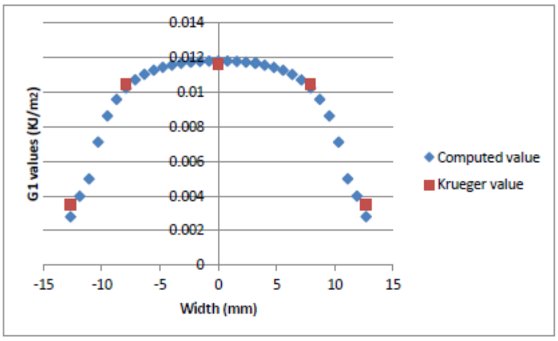

Fig 12: Strain Energy Release Rate vs. Width of the specimen

B. Progressive damage analysis of the DCB with unidirectional composite layups using CZM

Progressive damage analysis of the DCB specimen of unidirectional composite layups is done using Cohesive Zone Modeling method. The 4 noded plain strain elements are used for the bulk material and 4 noded cohesive elements are used for zero thickness cohesive zone. The propagated crack and the failed cohesive elements are as shown in the fig. The white colored elements in the interface show the failed cohesive elements. The Load vs. Displacement curve is plotted for the above specimen and it is compared with the experimental results. Loads are taken in 'N' and the crack opening displacement (COD) is in mm

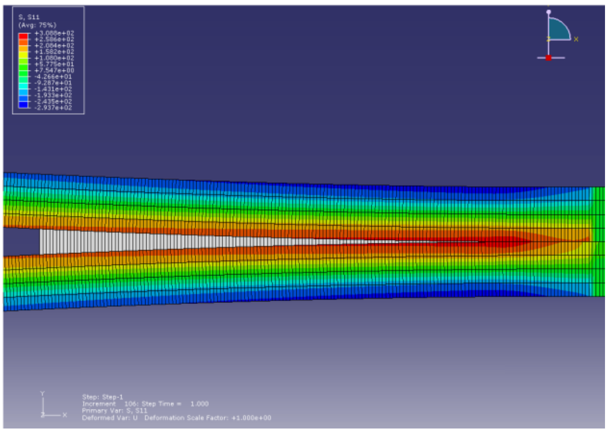

Fig 13: Crack propagation of DCB specimen using CZM method

The Load-deflection curve is plotted for the above shown unidirectional specimen and it is compared with the experimental results and the trends shows good agreement with the experimental results. The curve is linear upto the elastic portion (the rising curve). The load for which the 1st node in the cohesive zone fails, can be predicted by the finite element modeling. In the softening zone the trend first decreases which agree with the bilinear traction separation law which is specified as the constitutive law of the cohesive zone model. The later portion shows the diverging effect as the mesh becomes course. As the elements become finer the curve tends to come down. More the finer mesh the diverging curve will change and follow the bilinear law specified.

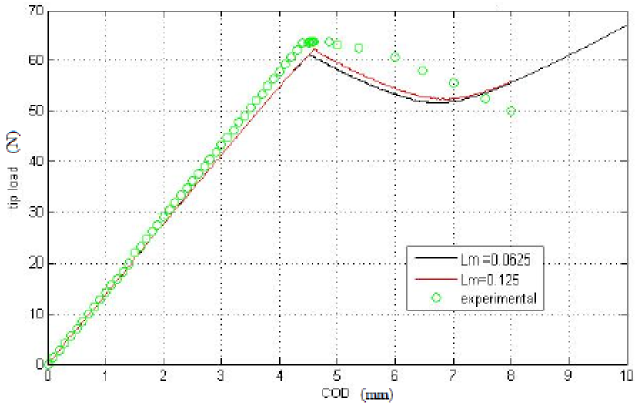

Fig 14: Load-deflection curve for the DCB specimen

C. Progressive Damage Analysis Of The DCB With Multi Directional Composite Layups Using CZM

The propagated crack and the failed cohesive elements are as shown in the Fig 14. The white colored elements in the interface show the failed cohesive elements. The Load vs. Displacement curve is plotted for the above specimen and it is compared with the experimental results. Loads are taken in Newton and the crack opening displacement (COD) is in mm.

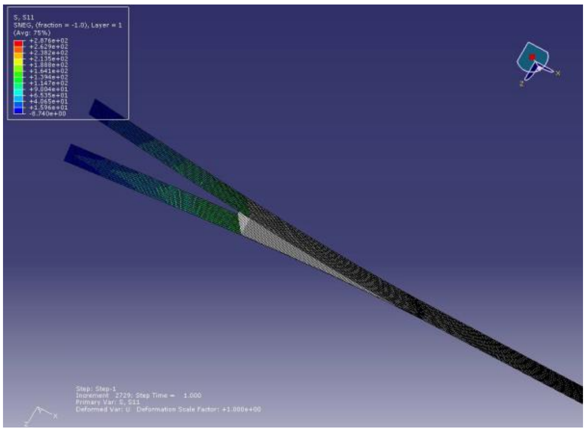

Fig 15: Crack propagation of Multidirectional DCB specimen with shell elements

The Load-deflection curve is plotted for the above shown multi directional specimen and it is compared with the experimental results as shown in the Fig 15. It can be seen that the results obtained from the Abaqus agrees well with that of the experimental results. The use of shell elements gives better simulation than using the plain strain elements.

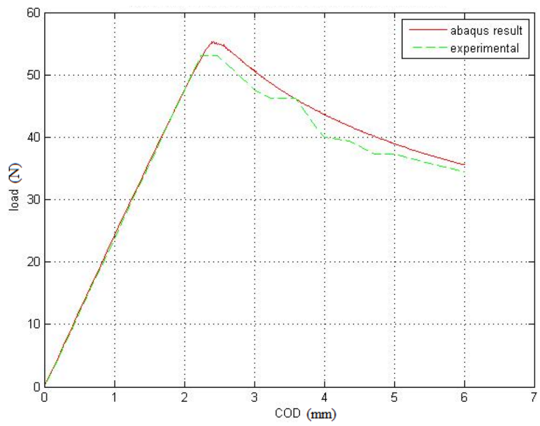

Fig 16: Load-deflection curve for multi directional DCB

It shows good agreement with experimental results both in elastic region and the softening portion. It can be seen that the graph follows bi-linear traction separation law with critical load occurring at 55.3 N and critical displacement at 2.30 mm which agrees well with the experimental results.

Table 3: Load-displacement values for multi directional DCB

Crack opening displacement (mm)	Load (N)	
	Experimental results	Abaqus results
1	24.33	24.35
2	47.88	47.88
2.30	53.11	55.32
3	47.61	50.64
4	39.90	43.62
5	37.29	38.12
6	34.40	35.64

D. Parametric Study For Different Crack Lengths

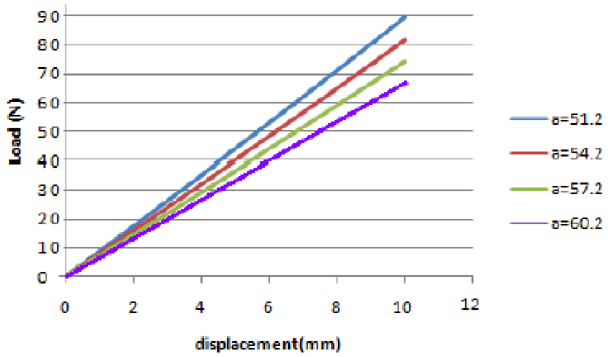

Fig 17 : load vs. displacement graph for different crack lengths

Parametric study is performed by varying the crack lengths for the Double cantilever beam specimen using Virtual Crack Closure Technique method. In the above graph Y axis denotes load and X axis denotes the crack opening displacement. From the graph it can be noted that as the crack length is increased, the load required for the crack initiation decreases. From the graph it is evident that for the same crack opening displacement the load required for the crack initiation decreases.

V. Conclusion

Progressive damage simulation of different Double Cantilever Beam specimens is carried out using Virtual Crack Closure Technique and Cohesive Zone Modeling methods. Load and displacement curves are plotted using both the methods. The results agree well for both the methods and it is validated with the experimental results.

Strain energy release rates is evaluated for the multidirectional double Cantilever Beam specimen for the given loading using Virtual Crack Closure technique and it is validated with the results obtained from the literature review "A shell/3D modeling technique for the analysis of delaminated composite laminates", the results agrees well with the reference paper results and from the results it can be concluded that the strain energy release rate is maximum at the centre of the specimen and the energy release rates progressively dropping towards the edges.

A parametric study is also carried out by varying the crack lengths to study the behavior of crack propagation in a composite double cantilever Beam specimen to study the delamination. From the results it can be concluded that as the crack length increases the critical load i.e the load required for the crack initiation decreases and the crack propagates more early.

ACKNOWLEDGMENT

The authors wish to thank N.H.C.E.(VTU) Bangalore for the valuable technical support. The authors declare that there is no conflict of interests.

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