Finite Element Modelling for Mode-I Fracture Behaviour of CFRP

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Abstract. Debonding is a major failure mechanism in Carbon Fiber Reinforced Polymer (CFRP) due to presence of many adhesion joins, in between many layers. In the current study a finite element simulation is carried out using Virtual Crack Closure Technique (VCCT) and Cohesive Zone Modelling (CZM) using Abaqus as analysis tool. A comparative study is performed in to order analyze convergence of results from CZM and VCCT. It was noted that CZM results matched well with published literature. The results from VCCT were also in good comparison with experimental data of published literature, but were seen to be overestimated. Parametric study is performed to evaluate the variation of input parameters like initial stiffness, element size, peak stress and energy release rate 'G'. From the numerical evaluation, it was noted that CZM simulation relies largely on element size and peak stress.

INTRODUCTION

Composites are used extensively in all sorts of application, especially where strength to weight ratio is top most priority. Hence forth, polymer composite finds a greater application especially in aerospace and automobile sectors, where there is continuous improvement in performance and cost reduction. There are many applications which make use of hybrid or multi material composites. The composites are now serving as structural replacement for conventional materials in many areas due to higher stability and integrity of structures offered by these materials. Polymer composites also allow to tailor the required stiffness in the structural composites according to cross sectional requirements. This property also poses a problem of debond, leading to delamination or failure of structural components. Delamination can happen due to abrupt change in cross selection area due to plydrops, free edges, bonded and bolted joints. It is mainly because of the different constituent materials employed which results in one of the major concerns in layered composites interface debonding. The cracks may initiate naturally from small material defects (voids, microcracks or inhomogeneities) and propagate along the weakest path, potentially leading to rapid deterioration of the entire structural component and/or assembly.

Although the importance of these interlaminar failures is known, still a determining factor that the use of structural elements made up of fiber reinforced composites subsist. There is an extensive use of bonded joints and other structural parts with dissimilar layers, which are prone to failure. Thus, it becomes important to design FEA or analytical models in order to analyze strength and failures of these structures. Linear Elastic Fracture Mechanics (LEFM) is most suitable to predict this failure using fracture toughness as property to describe crack propagation or resistance to crack propagation. Currently there are many well-known fracture mechanics based approaches to simulate debonding failure in composites: Virtual Crack Closure Technique (VCCT) and Cohesive Zone Modelling (CZM) [1]. VCCT simulation is based on LEFM approach, which computes strain energy release rate (G) and compares it will critical energy release rate (G_c). Another approach is to use CZM elements in FE modelling based

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on traction separation law. This concept was initially studied for brittle materials and then adopted to ductile material fracture based on Elastic Plastic Fracture Mechanics (EPFM) approach [2]. It is assumed that fracture is a gradual and slow process in which separation of layers is resisted by cohesive traction force.

Both methodologies have their own pros and cons. The CZM has the ability to predict initiation and growth of debonding without prior assumption of crack locations as well as its direction and more over it is even applicable to complex structures. On the other hand, it is difficult to access the required data for simulation. VCCT makes use of 'G', which makes it simpler to analyze with inbuilt tool options. But assumption that need to be made for crack location, size and difficulty in analyzing complex loading condition. In the literature, there have been reported several experimental works on fracture behaviour of composite bonded joints [3-7]. The majority of them have focused on the mode-I loading as it is considered to be the most critical. The current work concentrates on the FE modelling and simulation of mode-I loading. For simulation, experimental results from previous work are considered [8]. There are substantial number of literature work, which used to simulate crack propagation using both CZM [9-18] and VCCT [19-22]. Many commercially available softwares are used in order to simulate fracture behavior of CFRP. Present work uses Abaqus 6.14 software for the analysis. A comparison is being done between results obtained from CZM and VCCT, to conclude on the most feasible methodology to simulate delamination or debond in composites.

Energy Release Rate (G)

Energy release rate is energy dissipated during fracture, i.e energy involved in per unit creation of new surface. It is denoted by symbol 'G'. This is most commonly utilized method to characterize the delamination simulation in composites. This is usually suitable for brittle materials, as it does not account for plastic zone ahead of the crack tip [22,23]. For elastic plastic materials another approach of 'J' integral can be applied or 'G' can be used with plastic zone correction factor. Energy release rate would be a measure of toughness of material against delamination and can be calculated using load versus deflection curve. Consider a DCB specimen as shown in Fig.1 with thickness 'h', 'a_0' being initial crack length, 'a' being propagated crack length, 'd' be crack opening under the loading and let 'δ^*' be crack opening at the tip of notch.

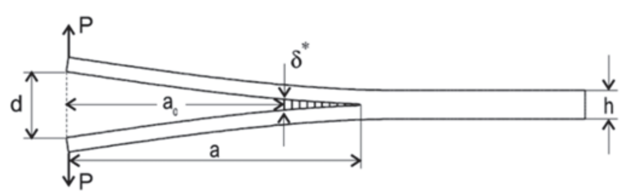

FIGURE 1. Crack propagation in DCB specimen

Energy release rate in DCB specimen can be given by

$$G = \frac{\partial \pi}{b \partial a} \tag{1}$$

where π is potential energy and 'b' is width of specimen. Potential energy is given by

$$\pi = \frac{1}{2}\int_v^u \sigma \in dv - \int_0^u P(\mathrm{u})\,\mathrm{du} \tag{2}$$

σ and $\in$ are stress and strain in material due to applied load 'P'. Expressing the above equation in terms of applied load and displacement.

$$\pi = \frac{1}{2} Pu - \int_0^u P(\mathrm{u})\,\mathrm{du} \tag{3}$$

Determining the energy release rate using Eq.3, we get

$$G = \frac{1}{2b}\frac{\partial P}{\partial a}u - \frac{1}{2b}\frac{\partial u}{\partial a}P$$

$$G = \frac{P^2}{2b}\frac{\partial c}{\partial a} \tag{4}$$

The term ‘C’ denotes compliance. The Eq.4 is very widely used and no assumption are made about the crack tip structure. Thus, it should be valid for any bridging law and specimen shape. By using deflection of beam and load expression, the full opening of DCB specimen equals twice the deflection.

$$\text{Compliance,} \quad C = \frac{u}{P} = \frac{2a^3}{3EI}\,;\; u = d = \frac{2a^3 P}{3EI} \tag{5}$$

Using Eq.5 in Eq.4, we get

$$G_{(P,a,d)} = \frac{3Pd}{2ab} \tag{6}$$

Substituting value $a^2 = \left(\frac{3EId}{2P}\right)^{\frac{2}{3}}$ in above equations, we get

$$G_{(a,d)} = \frac{9EId^2}{4a^4 b} \tag{7}$$

The Eq.7 can be directly used to calculate energy release rate ‘G’, by knowing crack tip opening ‘d’ and crack length ‘a’.

FE MODELLING

It is an efficient methodology which subdivides the given domain in to discrete shapes known as elements, forming an inter connected network of concentrated load for several types of analysis. For materials like composites which possess multiple thin as well as thick different stacking sequence, brittle interfacial failure acts as a major source of initiation of crack or delamination. There are many such analysis techniques being developed to gain the insights of crack initiation. The current work mainly focuses on modelling the experimental test using Virtual Crack Closure Technique (VCCT) and Cohesive Zone Modelling (CZM) with Abaqus 6.14. For simulation studies experimental results by Floros *et al.* [8] have been utilized. The Fig.2 shows the specimen configuration of Double Cantilever Beam (DCB). It was noticed that, each CFRP plates contained a total of 16 layers of unidirectional plies, with the quasi-isotropic stacking sequence of $[0/+45/90/-45/0/+45/90/-45]_s$. For ease of modelling, each ply was assumed to be a modelled as single layer and considering equivalent property for all constituent laminae. The composite specimen was modelled using the proprieties of CFRP of hexply and adhesive [26]. The properties of carbon fiber are as mentioned in the Table 1. To model CFRP and epoxy adhesive, a four noded CPE4 elements were used.

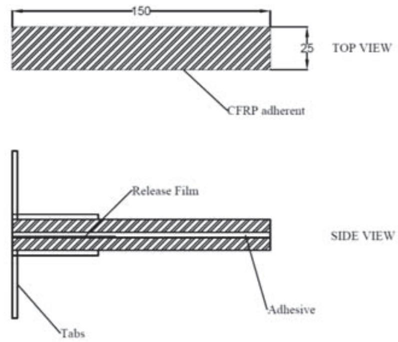

FIGURE 2. DCB specimen configuration

TABLE 1. Material property of carbon fiber

Sl.No.	Property	Value
1.	Young modulus E_1 (GPa)	139.3
2.	Young modulus E2 (GPa)	9.72
3.	Young modulus E3 (GPa)	9.59
4.	Shear Modulus $G_{12} = G_{13}$ (GPa)	5.59
5.	Poisson's ratio $\nu_{12} = \nu_{13}$	0.29
6.	Poisson's ratio ν_{23}	0.40
7.	Strength Data σ_T (MPa)	1517
8.	Strength Data σ_c (MPa)	1593
9.	Critical Energy release rate (J/m^2)	G_I =1018; G_{II}= 783.41 G_{III}= 935.78

Cohesive Zone Modelling

To simulate crack or a delamination in composite there exists various numerical models. Among those CZM is found to be more the efficient technique. This numerical analysis is taken from the frame work of fracture mechanics with nonlinear behaviour of materials. The separating faces of a delamination are assumed to be not lost completely at damage initiation, but rather is a progress event governed by progressive stiffness degradation of interface between separating layers. For analysis, a bilinear CZM with interface and contact element was used as shown in the Fig.3 and Fig.4. In the Fig.3, the length from point A to B shows that the material has not suffered any damage, thus unloading curve would follow elastic line. The region from point B to C depicts damage accumulation of material. However, there is still no separation of lamina, as shown in the Fig.3. At point C when damage has reached unity, the lamina separates from each other leading to propagation of crack. The total area under the curve denotes the fracture energy, i.e energy required to create total debond or delamination between the layers.

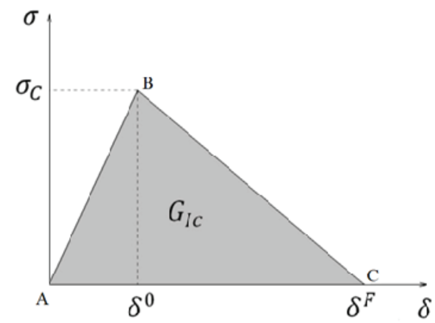

FIGURE 3. Bilinear traction separation law for mode-I

In the current simulation study, Abaqus 6.14 is utilized with standard library available for cohesive zone element to define along the bonding line. Both layers are modelled separately with a traction layer in between to define CZM elements as shown in Fig.4. The fracture energy, elastic stiffness and peak stress at point B are given as input to the defined model. It was noted that from previous studies that the fracture toughness values need to be accurate, but initial stiffness and the peak stress values need not be so precise. Camanho and Davila [27] used a constant value $10\times E^{+6}$ for all materials and called it "penalty stiffness". The same value has been used in the present model. Then, in order to keep the fracture toughness (area under the triangle) correct, the peak stress has to be adjusted accordingly. As the Abaqus doesn't provide any standard option for evaluation of energy release rate G_I, Eq.7 was utilized to get change in G_I with crack growth.

The crack model is modelled using C0H3D8 cohesive element defined in plain stress condition from Abaqus 6.14 standard library, with thickness of cohesive layer to be 2mm. The Fig.4 shows the boundary conditions applied. The simulation is done for mode-I loading, with strain rate to be 1mm/min and other end to be fixed as per experimental observation. The response plot is as depicted in Fig. 5.

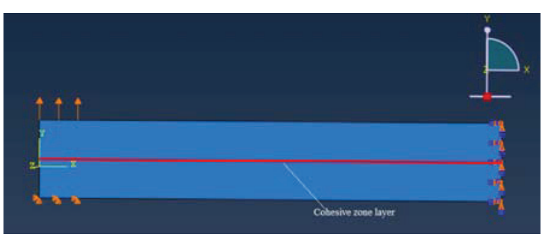

FIGURE 4. Boundary condition

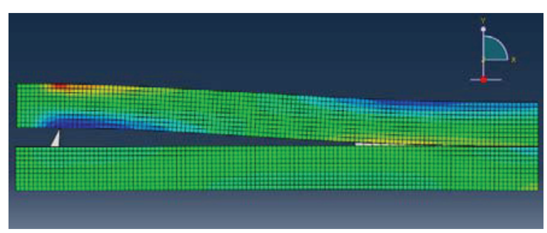

FIGURE 5. Crack propagation simulation using CZM

Virtual Crack Closure Technique

Virtual Crack Closure Technique (VCCT) calculates energy-release rate, with the assumption that the energy needed to separate a surface is the same as the energy needed to close the same surface. It is based on crack growth simulation with various assumptions like crack growth occurs along a predefined crack path. The path is defined via interface elements. The analysis is assumed to be quasi static and does not consider any transient effects. The material considered for analysis is orthotropic or anisotropic. With these assumptions made, VCCT is utilized to extract force and displacements required to close the crack. The current work simulates VCCT in Abaqus 6.14 for a two-dimensional body as per the geometry of the specimen used in the test. The crack is assumed to be one dimensional discontinuity formed by a series of nodes along the interface. The specimen is modelled as two distinct parts and are joined together by treating one as master and the other as slave by having coinciding edges as well as contact pair along both edge surface where crack is simulated. These nodes form the predefined crack. The crack front area is constituted by the nodes which make transition from bonded to unbonded state. In order to ensure no penetration, normal surface behavior is set for the contact pair and bonding to initial condition for bonded portion in contact pair and debonding is initialized during analysis. The debond nodes will be governed by Eq.1. Rest boundary condition as shown in Fig.6, remain same as the previous analysis with CZM. In order to calculate energy release rate per unit crack growth contour integral method is utilized. The response plot is shown in Fig.7.

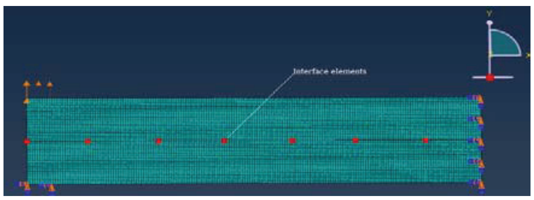

FIGURE 6. Boundary condition for VCCT

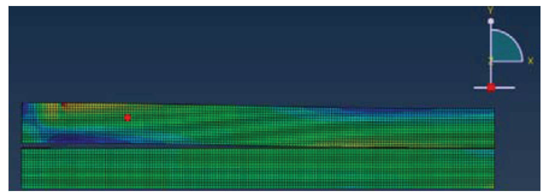

FIGURE 7. Crack propagation simulation using VCCT

RESULTS

Comparison Between CZM and VCCT

Results from both simulations were in well agreement with experimental results [8]. But when considered individually VCCT seemed to overestimate. It can be noted from Fig.8 that VCCT resulted in an entirely linear trend till the peak load, with no change over to other phase or smoothening of curve. It can be due to attributed binary contacts defined in VCCT as the stiffness of specimen remains unchanged until the contact status of the element pairs adjacent to crack tip change from bonded to unbonded. Thus, this method does not capture experimental non-linearity before the tip. On the other hand, CZM provides good result in agreement with experimental and also smoothens up the curve with change in the condition. Even the energy release rate calculated from VCCT and CZM, it was noted that CZM gives more precise values as compared to those from VCCT simulation shown in the Fig.9. However, the CZM largely depends on the initial peak stress and stiffness values assumed. Considering the above results, CZM is found more suitable for simulating the crack for composites structures subjected to complex loading conditions. Thus, a detailed analysis is carried out in order to assess variation of the various parameters.

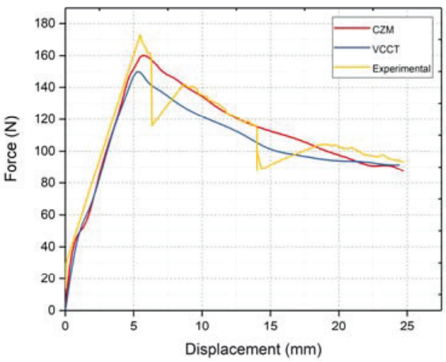

FIGURE 8. Experimental and FE force vs displacement comparison

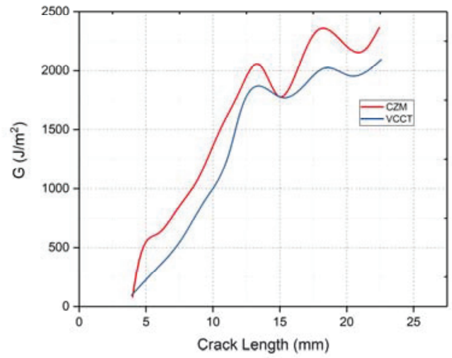

FIGURE 9. G vs crack propagation results for CZM and VCCT

Variation of parameters

Even though CZM is closer to actual results, it has several drawbacks and obtained values do not match experimental results due to lack of properly defined theory involved and the difficulty to measure required input parameters with precision. In order to analyze the variation of results and to achieve convergence of result, various combinations of parameters are analyzed.

Element Size

The size of meshing plays a crucial role in CZM of composites. Too coarse discretized mesh results in solution jump problem, which results in oscillation of global load displacement behavior of the composite structure. This may be reduced by refining the element size, but on the other hand it may increase the computational time. Thus, step or solution jump is directly related to mesh quality of model. Hence an optimum element size need to be considered in order to avoid such errors in the simulation. In current analysis, simulation is conducted with five different element sizes as shown in the Fig.10. Form the graph it is evident that element size of 0.5 gives more converge solution as compared other element size, which implies for element size greater than 0.5mm and cohesive zone having two or more elements will not be enough to capture fracture process in the composite.

Initial Stiffness and Peak stress

It is assumed an initial stiffness of $10\times E^{+6}$ as a penalty stiffness, as its value doesn't influence much for analysis. Thus, to check variation of response, simulation is done for different values of initial stiffness as well as peak stress. The Fig.11 represents the load versus displacement curve for the analysis. The value of stiffness must be high enough to prevent artificial compliance from being introduced into the model by the cohesive elements, but not too high as to produce convergence problems. It was observed from the figure that, there was no noticeable change in the values for given range of stiffness. Thus, the effect of stiffness on the CZM models is of not much importance.

Critical Energy release rate, G_{IC}

As per the experiment [8], the value of G_{IC} for four trials were in the range of 950 J/m^2 to 1150 J/m^2 . Hence simulation was done to check the variation with respect to change in energy release rate, keeping all other inputs as constants. For the Fig.12 it can be noticed that, regardless of the modelling approach, the increased value of G_{IC} resulted in a higher crack initiation load and also a higher corresponding displacement. With the increase in energy release rate, the area under the curve increase which is directly proportional to change in the $G_{IC.}$

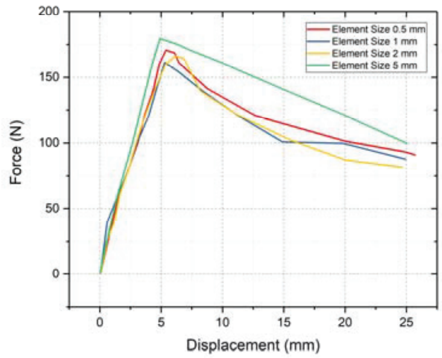

FIGURE 10. Variation in force vs displacement curve with different element size.

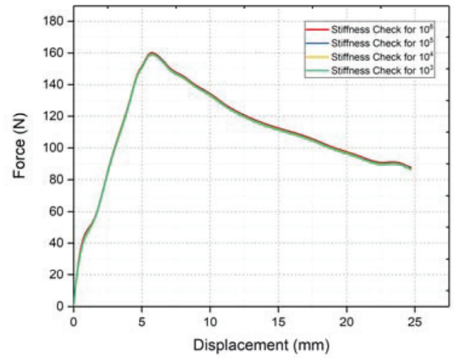

FIGURE 11. Variation in force vs displacement curve with different initial stiffness.

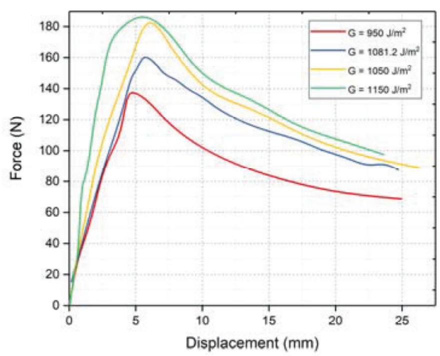

FIGURE 12. Variation in force vs displacement curve with different G values

CONCLUSION

The current work focused on mode-I fracture behavior of carbon fiber reinforced polymer composites. In order to validate a fully characterized mechanical testing, FE modelling techniques like CZM and VCCT were simulated. The following conclusion were drawn from the above study

- Both CZM and VCCT are in good comparison with experimental results, but CZM techniques was found out to be more precise in the results.
- VCCT consumes more computational time as compared to that of CZM.
- CZM can predict crack behaviour without any prior assumption of crack, whereas VCCT required initial crack inputs like location, crack length and element size.
- CZM is greatly influence by element size for accurate results. Higher the mesh, more is the computation time. Smaller the mesh, more chances of solution or step jump occurrence. It was noted that element size of 0.5mm gave a converged solution.
- Variation of initial stiffness values in CZM is regardless. It is mainly dependent on the peak stress values, lower the peak stress less is the initial crack load. Variation in the initial value of G_{IC} was directly proportional to resembling load and fracture toughness.

- In general, it was concluded that CZM techniques suits well for mode-I simulation of crack for complex cases and with accurate estimation of traction separation law parameters.

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