A comparative numerical study of standard 3D composite plate using virtual crack closure technique and cohesive zone modelling method

B R Sindhu1*, J Raju2 and Kiran Kamath1

1Department of Civil Engineering, Manipal Institute of Technology, Manipal-576104, India.
2Structural Technologies Division, CSIR-National Aerospace Laboratories, Bangalore-560017, India.

E-mail : *kashyap.sindhu95@gmail.com

Abstract. A standard square plate specimen made up of Carbon Fibre Reinforced Polymer (CFRP) and Glass Fibre Reinforced Polymer (GFRP) laminates with an artificially-introduced delamination was considered for evaluation of fracture parameters using Abaqus-Standard software. Though there are several methods to evaluate the initiation of delamination using software, Virtual Crack Closure Technique (VCCT) and Cohesive Zone Modelling (CZM) method are commonly used. By using the above-mentioned methods, the Quasi-Isotropic (QI) composite laminates were analysed for varying compressive loads. The Load-Displacement responses were reported and seen to be in overall good statement with each other, while the modelling effort and computational time required were quite higher in CZM method compared to VCCT. Onset of delamination growth for CFRP and GFRP laminates was studied using VCCT by evaluating Strain Energy Release Rates (SERR). The results for both the specimens were compared and reported.

1. Introduction

Fibre reinforced polymer composites are being extensively used by most of the aerospace industries due to its high strength-to-weight ratio. The use of such composites will be sensitive to matrix cracking, fibre breakage, debonding at the fibre matrix interface and interlaminar delamination. Most frequently observed failure mode is delamination which considerably decreases the strength and stiffness of the structure. Several works on the delamination onset and propagation are performed both experimentally and using Finite Element (FE) analysis. VCCT, generally used for evaluation of SERR was first proposed for four-nodded elements considering crack tip forces and relative displacement of cracks [1]. A review of formulae to determine SERR for circular delamination for various element types was given by Krugger [2] and Whitecomb [3]. Delamination growth behaviour for a two-dimensional plate was predicted when subjected to constant amplitude fatigue loads by Raju [4]. A comparative study was performed on three-dimensional (3D) double cantilever beam subjected to fatigue loads using cohesive zone and VCCT by Pirondi [5].

In the present study, FE principles were applied on a 3D CFRP and GFRP laminated plate specimens of a pre-determined circular delamination of 60 mm diameter. The QI plate of dimensions 200 mm x 200 mm and thickness of 2.88 mm was used to evaluate the mixed-mode fracture parameters. Analyses were carried out using commercially available Abaqus-Standard software. For both VCCT and CZM methods, the composite plate was subjected to compressive loads in terms of displacements.

For these compressive loads, the analysis was carried out and Load-Displacement (P-δ) responses were studied. Further, the P-δ responses were plotted to determine the correspondence of results. In order to evaluate the fracture modes, only VCCT method was adopted and analysed. The critical SERR in three modes of fracture i.e., opening mode (GI), sliding mode (GII) and scissoring mode (GIII) were determined using VCCT and the onset of delamination was predicted by computing the
total SERR (GT) which is the sum of three fracture modes. The details of the results are presented.

2. Finite element modelling of the specimens
A QI lay-up in the sequence [(+45/-45/0/90)2]s made up of unidirectional CFRP and GFRP laminated specimens having individual ply thickness of 0.18mm was modelled using Abaqus-Standard software. The material properties of CFRP and GFRP laminates were extracted from existing literature [3,6] and are presented in table 1 and table 2 respectively.

### Table 1. Material Properties of CFRP laminates [3].

| Young’s Modulus (GPa) | Fracture Toughness (N/mm) | Poisson’s Ratio | Shear Modulus (GPa) |
|-----------------------|---------------------------|----------------|---------------------|
| E₁₁ = 128             | G₁₂C = 0.212              | v₁₂ = 0.31     | G₁₂ = 4.80          |
| E₂₂ = 10              | G₂₃C = 0.48               | v₂₃ = 0.52     | G₂₃ = 4.80          |
| E₃₃ = 10              | G₁₃C = 0.48               | v₁₃ = 0.31     | G₁₃ = 3.20          |

### Table 2. Material Properties of GFRP laminates [6].

| Young’s Modulus (GPa) | Fracture Toughness (N/mm) | Poisson’s Ratio | Shear Modulus (GPa) |
|-----------------------|---------------------------|----------------|---------------------|
| E₁₁ = 50              | G₁₂C = 0.15               | v₁₂ = 0.34     | G₁₂ = 3.0           |
| E₂₂ = 10              | G₂₃C = 0.30               | v₂₃ = 0.38     | G₂₃ = 2.79          |
| E₃₃ = 10              | G₁₃C = 0.30               | v₁₃ = 0.34     | G₁₃ = 3.0           |

A 3D FE model of the plate specimen was generated using solid C3D8I elements. In order to establish a pre-existing delamination, the plate was initially divided into two sub-laminates (Upper and Lower plate). For smooth propagation of delamination, a fine mesh was introduced at the delamination front. A coarser mesh was used away from the vicinity of the delamination to reduce the computational time required for the analysis. An illustrative FE model of the 3D specimen having lay-up sequence with eight layers in the upper plate and eight layers in the lower plate and its meshing pattern are shown in figure 1.

For both the plate, an artificial delamination of 60 mm size was introduced between 8th (+90) and 9th (+90) layer of the laminate-thickness and was analysed by subjecting it to a compressive load ranging from 1 mm to 7 mm.

In bottom plate, all degrees of freedom at one of the edges were held and compressive loads were applied on the opposite edge. The remaining free edges were held so that the growth of delamination would initiate from the centre of the plate specimen [3] as schematically shown in figure 2.

![Figure 1. FE model of the composite plate containing delamination.](image-url)
3. Methodology

3.1. Fracture Criteria

In the delamination analysis of composite laminates, Linear Elastic Fracture Mechanics (LEFM) is used to compute the SERR values GI, GII and GIII. Total SERR (GT) which is the sum of three loading mode components, GI, GII and GIII respectively, in conjunction with Benzeggagh and Kanane criterion (B-K law) [7] is used to determine the onset of delamination. According to B-K law, for a mixed mode ratio, delamination is predicted to initiate when GT exceeds critical SERR (GC).

\[
\frac{G_T}{G_C} > 1
\]  \hspace{1cm} (1)

\[
G_C = G_{IC} + (G_{IIIC} - G_{IIIC}) \left[ \frac{G_T}{G_C} \right]^{\eta}
\]  \hspace{1cm} (2)

Where, 
- \(G_S = G_I + G_{III}\)
- \(G_T = G_I + G_{II} + G_{III}\)
- \(\eta\) = an experimental value.
- \(G_{IC}\) = Critical SERR-mode I.
- \(G_{IIIC}\) = Critical SERR-mode II.
- \(G_{IIIIC}\) = Critical SERR-mode III.

3.2. Virtual Crack Closure Technique

Composite plate with a pre-determined delamination was analysed using VCCT based on LEFM approach. In this method, delamination was modelled using two super imposed elements with contact constraints used to avoid the penetration of elements. Master surface was specified at the bottom of the upper part and slave surface was specified at the top of the lower part. The debonding was established by maintaining non-merged nodes between the adjacent faces of master and slave surfaces of the two sub laminates. VCCT is a popular method for the extraction of SERR and it is assumed that the energy released during propagation of crack is always same as the energy required to close the opened crack [2].

3.3. Cohesive Zone Modelling Method

In VCCT, the initiation and growth of delamination was predicted when a combination of SERR is equal to, or higher than a critical value. Whereas in CZM method, which was established within the frame work of damage mechanics, modelling was carried out on cohesive zone concept, where the interface which encloses the delamination was modelled by a damageable material and assumes that the delamination is said to begin when a maximum limit is reached by a damage variable.
The cohesive-models offer an advantage of incorporating initiation of delamination so that initiation of damage is achieved by considering strength-criteria but fracture parameters are required to govern the final separation. The 3D surface based-CZM method was carried out by using traction-separation description procedure of the interface, specified as per Abaqus codes. The software assumes linear elastic behaviour. Surface-based cohesive behaviour framework using LEFM was used to model the propagation in partially bonded surfaces similar to VCCT. Surface interaction property was defined by assuming linear elastic traction separation law prior damage i.e., considering delamination as a progressive loss of cohesion between adjacent layers.

4. Results and Discussions

A FE analysis of delamination initiation and growth was performed on CFRP and GFRP laminated plate specimens by applying compressive loads in terms of displacements. The P-δ responses were computed using VCCT and CZM methods. The comparison of P-δ response curves are as indicated in the figure 3. It evident from the figure that a good agreement exists between both methods. The computational time required for the completion of analysis by using the two methods are as tabulated in table 3. It can be seen that the computational time required for CZM method is almost four times higher compared to VCCT.

In order to compute SERR, compressive load was varied gradually on a pre-determined delamination of 60 mm diameter CFRP and GFRP laminated plates. The SERR was computed and plotted for all the fracture modes including GT and effective SERR (Geff). Their plots are shown in the figure 4. Figure 5 shows a typical plot of GT for CFRP and GFRP laminate specimens for an applied displacement. From the results of the analysis, in conjunction with B-K Law, it can be seen that for a circular delamination of 60 mm, delamination initiation was observed at 7 mm applied displacement, with a reaction of 27.61 kN for CFRP laminated specimen, whereas 5 mm applied displacement and 10.2 kN reaction for GFRP laminated specimen respectively. The bond state contours which implies the initiation of delamination onset when it reaches a value of 1 for VCCT method and displacement contours required for the determination of delamination initiation in CZM are presented in figure 6 and figure 7. It can be observed that the initiation of delamination in CFRP laminate was delayed in comparison to GFRP laminated specimen. By plotting GT/GC ratio, the onset and delamination growth was computed for different loads and are plotted in the figure 8.
Figure 3. Comparison of P vs \( \delta \) response for CFRP and GFRP laminated specimens.

Table 3. Computational time for Finite Element analysis

| Method adopted | Time required for computation (s) |
|----------------|-----------------------------------|
| VCCT           | 1328                              |
| CZM            | 5186                              |

Figure 4. SERR vs applied displacements in different fracture modes for CFRP and GFRP laminated specimens.

Figure 5. Typical GT plots of CFRP and GFRP laminated specimens for an applied displacement.
Figure 6. Typical bond state contours using VCCT approach.

Figure 7. Typical displacement contours using CZM approach.

Figure 8. Comparison of GT/GC vs applied displacement plot for CFRP and GFRP laminated specimens using VCCT.
5. Conclusion
Numerical analyses were performed on a 3D standard plate specimen using Abaqus-Standard software for both VCCT and CZM methods. The fracture parameters were estimated by introducing an artificial delamination appropriately. An attempt has been made to compare VCCT and CZM methods of analysis for QI, CFRP and GFRP laminated plate specimens. From the P-δ responses of the two plate specimens, it can be seen that a good relation exists between VCCT and CZM method, whereas the modelling effort and computational time required is quite higher in CZM method compared to VCCT.

In order to predict the onset of delamination growth, both CFRP and GFRP laminate specimen models were subjected to a compressive load and were analyzed using VCCT approach. From the analyses, it can be observed that, the SERR obtained in mode II and mode III are more dominant compared to mode I. The results obtained from the GT/GC vs applied displacement for CFRP and GFRP laminates shows that the pattern of delamination onset is comparable in both the materials with a delay in initiation in CFRP laminate as compared to GFRP laminated specimen which implies that, CFRP laminates with delamination is more damage tolerant compared to GFRP laminates.

References
[1] Rybicki E F and Kenninen M F 1977 EngFractMech 9 931–8.
[2] Krueger R 2004 ApplMech Rev 57 109–43.
[3] Whitcomb J D 1989 J. Compos. Mater 23 862–88.
[4] Raju J, Duragkar M S, Jagannathan N and Manjunatha C M 2014 Journal of Materials science Research 3 44–51.
[5] Pirondi A, Giuliese G and Moroni F 2014 J Adhes 90 457–81.
[6] Amaro A M, Reis P N B, Moura M F S F De and Neto M A 2013 Composites: Part B 52 93–9.
[7] Benzegagh ML and Kenane M 1996 Compos. Sci. Technol. 56 439–49.