GLOBAL JOURNAL OF ENGINEERING, DESIGN & TECHNOLOGY
(Published By: Global Institute for Research & Education)
www.gifre.org

Prediction of Delamination Growth Behavior in a Carbon Fiber Composite Laminate Subjected to Constant Amplitude Compression-Compression Fatigue Loads

J. Raju[1*], D.S. Sreedhar[2], & C.M. Manjunatha[1]
[1]Structural Technologies Division, CSIR-National Aerospace Laboratories, Bangalore-560017, India
[2]Infosys, Electronics City, Bangalore 560100 India
[*] Corresponding Author

Abstract

A quasi-isotropic lay-up carbon fiber composite of 150mm x 150mm containing a central circular delamination of 30 mm diameter placed between 11th and 12th layer was modeled using 2D shell elements. Constant amplitude compression-compression fatigue load with P_{max}= 87kN and stress ratio, R=10 was applied. The strain energy release rate (SERR) in front of the delamination contour was obtained using virtual crack closure technique (VCCT) from non-linear finite element analysis using ABAQUS code. The SERR were estimated from B-K law. Delamination extension due to the driving force G_{II} was estimated from the mixed mode delamination growth law. The new delamination shape factor after application of a certain number of load cycles was determined. The results show that delamination grows sub-critically under compressive loads to attain new shapes.

Key Words: Delamination, VCCT, SERR, Fatigue, Mode II

1. Introduction

Fiber reinforced polymer composites are widely used in structural applications due their high strength to weight ratio. Motivated by the increasing use of composites in primary structural components, research has been focused on the disbond of two adjacent fiber reinforced layers of a laminate which is a prevalent stage of damage, commonly known as delamination. One of the most common failure modes for laminated composite structure is delamination, or interlaminar cracking. To characterize the onset and propagation of delamination, the use of fracture mechanics has become common practice over the past two decades (O'Brien, 1982., Tay, 2003., O'Brien,2001). If a delamination caused by impact or even occurring during the manufacturing process exceeds certain size, it will progressively grow under the service load conditions. The resulting loss in strength and stiffness of the affected component will lead to a structural failure at a load level which is significantly lower than the maximum load for which component has been designed. For an optimal utilization of potential offered by fiber reinforced material, it is essential to be able to predict delamination growth. It has been observed that delaminations occur only at the interface between plies with different orientations [Abrate , 1998]. and treated as a fracture process between anisotropic layers, rather than to consider it, more precisely, as a fracture between constituents or within one of the constituents (such as the material matrix) [Pagano, et.al., 1971].Thus, fracture mechanics principles [Janssen, et.al., 2004], may be found quite easily by using finite element method also for complex geometry, Indeed, the VCCT is generally used for the evaluation of the Strain Energy Release Rate (SERR) in finite element analyses.

The first VCCT approach to compute SERR, starting from forces at the crack tip and relative displacement of the crack faces behind it, was proposed for four noded elements [Rybicki,et.al., 1977].After it was extended to higher order elements [Raju, 1987] and to 3D cracked bodies [Shivakumar,et.al 1988]. A comprehensive review of VCCT formulae for different element types was given by Krueger [Krueger ,2004] and Whitcomb [Whitcomb, 1989] was one of the first to introduce the use of the VCCT to determine SERR for a circular delmination. Since then, a lot of numerical analyses have been performed by using this technique, many of them dealing with delamination growth initiations [Mukherjee,et.al., 1994., Whitcomb,1992], others with growth evolution [Klug, et.al., 1996., Shen, et.al., 2001]

In the present study, it has been assumed that there is no energy dissipation except that which is associated with the creation of the delamination surface. This means that we assume that elastic fracture mechanics is applicable for carbon fibers, it is therefore assumed that critical energy release rates G_{Ic}, G_{IIc} and G_{IIIc} exist, which may be defined as the threshold value below which no delamination growth occurs. Further, we assume that these critical energy release rates are material properties independent for the geometry and stacking sequence, but dependent on the ply orientations of the layers adjacent to the plane of delamination. Delamination propagation therefore is to be expected when the applied mixed mode energy release rate, which depends on the external loading, exceeds a critical value G_{cr}.

Strain energy release rate, G_T is typically used as a measure of the driving force for delamination growth in composite laminates. Depending upon external loading, G_T can be any combination of its three components,G_I,G_{II} and G_{III} to predict delamination onset or propagation G_TG is compared to the interlaminar fracture toughness, G_c which is dependent on the relative proportions of the three components[Adrain, et.al., 2012].

2. Finite Element Modeling

2.1 Specimen description

A quasi-isotropic lay-up $[(+45/-45/0/90)_2]_S$ carbon fiber composite of 150mm x 150mm containing a central circular delamination of 30 mm diameter placed between 11th and 12th layer was modeled using standard 2D shell element of ABAQUS code. Individual properties for commonly used graphite/epoxy materials were obtained from the open literature [Krueger,2010., Krueger,2008] to create this set to represent a typical graphite epoxy. The material properties are given in table 1.The composite material used is graphite epoxy (T300/1076) with material properties given in Table 1. The geometrical data are given in Table 2.

Table 1 Material Properties

Properties	**Values**	**Properties**	**Values**
E_{11}	139.40 GPa	G_{12}	4.6 GPa
E_{22}	10.16 GPa	G_{13}	4.6 GPa
v_{12}	0.30	G_{23}	4.6 GPa
Fracture Toughness values			
G_{Ic}	0.17N/mm	$G_{IIc}=G_{IIIC}$	0.49N/mm
η	1.62		

Table 2 Geometrical Data

Size of the plate 150mm X150mm
Layup: $[(+45/-45/0/90)_{2S}]_{Sym}$
circular delamination = 30 mm Ø placed between 11th(-45) and 12 (45) layer
Layer thickness = 0.15 mm Total Thickness t = 2.40 mm

A representative finite element model of the specimen is shown in figure 1 with typical lamina sequence with 11 layers in the lower plate and 5 layers in the upper plate. The delamination has been modeled between 11th (-45) and 12th (+45) ply, the delamination is modeled using two superimposed shell elements with contact constraint defined to prevent penetration of elements. The debonding has been simulated in the finite element model by maintaining not merged nodes on two adjacent faces of the surfaces representing two sub laminates. i.e., the two layers of elements were tied at the interface, except for the delamination area where contact boundary conditions prevented the penetration of elements during the processing of compression, the rest of the region is modeled using similar concept except that the two super imposed elements are connected by multipoint constraints. The bottom edge of the plate is constrained where as the top edge is loaded in terms of uniform prescribed displacement.

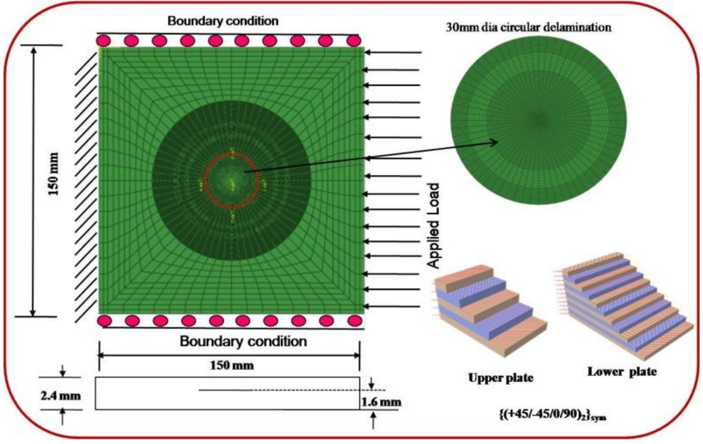

Fig.1 Finite element model of composite plate containing delamination

2.2 Computation of Strain Energy Release Rate (SERR) or G

The problem of single delamination between two plies of different orientations within a laminated composite can be considered as that of crack embedded between two dissimilar orthotropic materials. The most significant step in this investigation is the accurate computation of energy release rates along the delamination crack front. using virtual crack closure technique method (also called modified crack closure (MCC) method [Buchholz, et.al., 1998], this method is advantageous for the study as it provides up the possibility to easily split up the total energy release rate G_{tot} into the contributing modes G_I,G_{II} and G_{III}, in conjunction with a criterion proposed by Benzeggagh and kenane [Benzeggagh, et.al., 1996] (B-K criterion) to determine the delamination growth for the SERR contributing to delamination growth is usually obtained in the finite element analyses. and extracted SERR values from the FE result, based on the assumption that the strain energy released during crack propagation is equal to that closing the opened crack surfaces. Also the VCCT allows the total SERR value to be divided into three loading mode components: opening, sliding shear and tearing shear, making a good conjunction with the B-K criterion. The critical energy release rate G_{equivC} calculated by B-K criterion is defined as:

$$G_{equiv\,C} = G_{IC} + (G_{IIC} - G_{IC})\,(G_{shear}/G_T)^{\eta} \qquad (1)$$

Where,

G_{IC} ,$G_{IIC,}$ G_{IIIC} are the critical strain energy release rate of mode I, II and III respectively,

$G_{shear} = G_{II} + G_{III}$

$G_T = G_I + G_{II} + G_{III}$

η an experimental parameter

FE analysis calculations of SERR are compared with the failure criterion to determine whether delamination propagation occurs. In order to estimate the distribution of SERR of along the crack front a uniform prescribed displacement is increased incrementally until applied external load reaches the peak compressive load of 87 KN, this is called the zero cycle load, for which G_{II} has been computed and the computed strain energy release rate for G_{II} has been shown in Fig.2 with a maximum value of 0.0559 N/mm has been observed

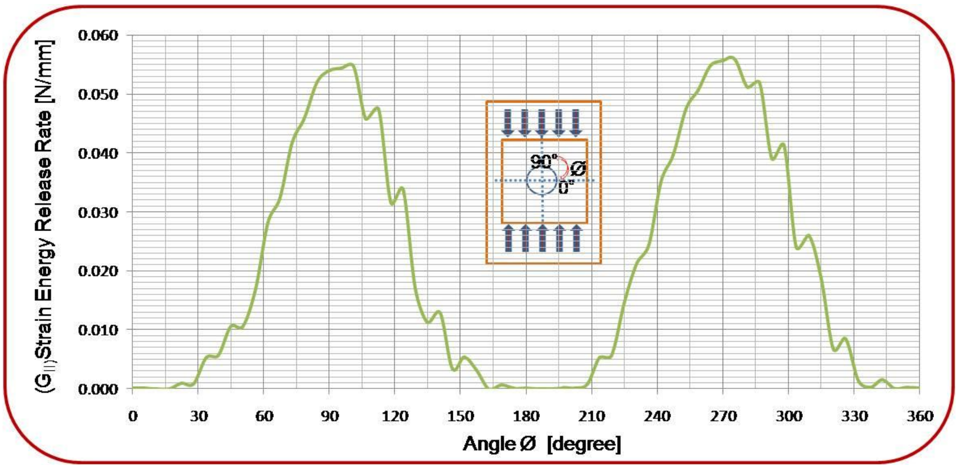

Fig.2 Computed G_{II} at the delamination front for Zero load cycles

2.3 Fatigue Delamination growth

The number of cycles during the stable delamination growth, N_G, can be obtained from the fatigue delamination propagation relationship (Paris Law). The delamination growth rate can be expressed as a power law function:

$$da/dN = c\,(G_{II})^{m} \qquad (2)$$

where, da/dN is the increase in delamination length per cycle and G_{II} is the maximum energy release rate at the crack front at peak loading. The factor c and the exponent m are obtained by fitting the curve to the experimental data [Krueger, 1996] and shown in figure 2a.

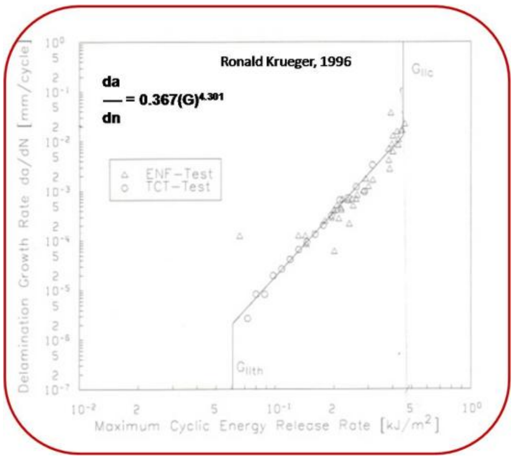

Fig.2a Paris law curve fit

From the finite element analysis, G_{II} value has been computed and a constant amplitude compression-compression fatigue load with P_{max}= 87kN and stress ratio, R=10 was applied and delamination extension due to the driving force G_{II} was estimated from the mixed mode delamination growth law. The new delamination shape factor after application of a $3X10^6$ load cycles has been computed and it has been observed that there was a considerable growth of the crack front. The finite element model has been modified to the new crack front shape and the same has been shown in Fig.3. The computed G_{II} for this load cycle for the modified crack front is 0.08187 N/mm.

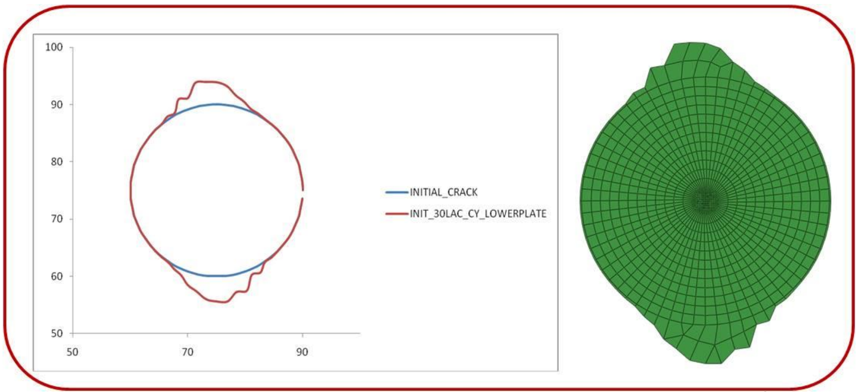

Fig.3 Finite element model of the new delamination shape after $3X10^6$ cycles

3. Results and Discussion

A verified analysis of delamination growth using simple techniques would allow delamination growth predictions in more complex structures and structures in more routine analyses. Such a methodology could also be extended to progressive delamination growth predictions in an automated manner. Critical locations where delaminations would grow to failure when initiated could then be identified so that this type of damage would be avoided [James Reeder, 2002] .

The computation of mixed mode energy release rate along the arbitrarily shaped delamination fronts has been carried out and documented [Krueger, et.al., 1996]. Computed mode II energy release rate (G_{II}) for the 30 mm diameter for zero cycle loads and $3X10^6$ load cycles along the crack front has been shown in Fig.4.

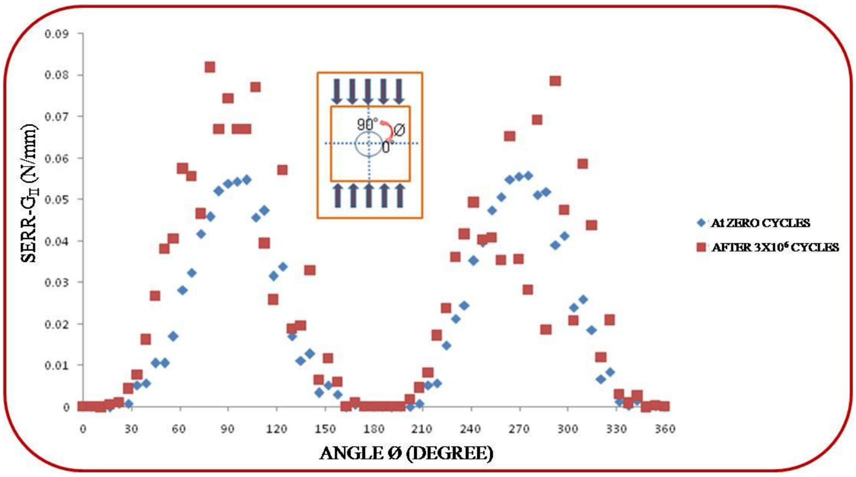

Fig.4 Computed G_{II} for new delamination

For this arbitrarily shaped delamination front, again load was increased to $3X10^5$ cycles and The results show that delamination grows sub-critically under compressive loads to attain new shapes. The same has been shown in Fig.5

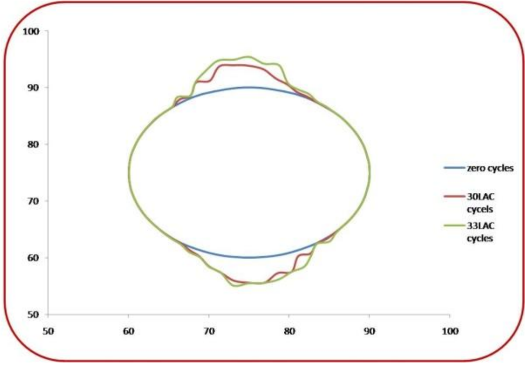

Fig 5 Final shape of the delamination front

4. Conclusions

In this investigation an attempt is made to predict the delamination growth behaviour in a carbon laminate subjected to constant amplitude c compression-compression fatigue loads. CFC plate with circular delamination was modeled and analysed for its growth behavior under constant amplitude fatigue loads. Non-linear finite element analyses are performed and estimated the strain energy release rate by virtual crack closure technique in conjunction with B-K criterion. Delamination extension due to GII was estimated from the mixed mode delamination growth law. The new delamination shape factor after application of a certain number of load cycles was determined and observed a considerable growth along the delamination front. The FE analysis has been carried out after modifying the FE model to the new crack front shape. The results show that the delamination grows sub-critically under compression-compression fatigue to attain new shapes.

Acknowledgements

Authors wish to thank and acknowledge Mr. Shyam Chetty, Director and Dr. Satish Chandra, Head, STTD,CSIR-National Aerospace Laboratories, Bangalore for their support and encouragement during this research work.

References

1. Abrate, S. (1998), Impact on composite structures, Cambridge University Press.
2. Adrain C. Orifici, Ronald Krueger, (2012), Benchmark assessment of automated delamination propagation capabilities in finite element codes for static loading, Finite elements in analysis and design vol.54,pp. 28-36.
3. Benzeggagh,M., and M.Kename, (1996), Measurement of mixed mode delamination fracture toughness of unidirectional glass/epoxy composites with mixed-mode bending apparatus, Composite Science and Technogly,vol.56, pp. 439-449.
4. Buchholz, F.G., H.Grebner, K.H.Dreyer, and H.Krome, (1988), 2D and 3D- applications of the improved and generalized modified crack closure integral method. Computational mechanics.Springer -Verlag.
5. Janssen, M., J.Zuidema and R.J.H. Wan hill, (2004), Fracture Mechanics, Spon Press Taylor & Francis.,2004.
6. Krueger, R., C.Hansel, M.Konig (1996), Experimental-Numerical Investigation of Delamination Buckling and growth, ISD-Report 96/3. November 1996.

7. Krueger, R., S.Rinderknecht, C.Hansel, and M.Konig, (2002),Computational Structural Analysis and Testing: An approach to understand delamination growth, Fracture of Composites, Engineering materials, volume 120-121, Trans Tech Publications, pp.181-202,1996
8. Krueger, R. (2004), The virtual crack closure technique: History, Approach, and Applications, Applied Mechanics Reviews, Vol. 57, Issue 2, pp. 109-143.
9. Krueger, R. (2008),An approach to Assess Delamination propagation simulation capabilities in commercial finite element codes, NASA/TM-2008-215123.
10. Krueger, R. (2010) Development of a benchmark example for delamination Fatigue growth prediction, NIA Report No.2010-04.
11. Klug, J., X.Wu, and C.T.Sun, (1996), Efficient Modeling of Post buckling delamination growth in composite laminates using plate elements, AIAA journal, vol. 34. pp.178-184.
12. Mukherjee,Y.X., S.N.Gulrajani, S.Mukerjee, and A.N.Netravali, (1994),A numerical and experimental study of delaminated layered composites, journal of composite materials, Vol. 28, pp. 837-870.
13. O’Brien, T.K. (1982), Characterization of delamination onset and growth in a composite laminate-Damage in composite materials. ASTM STP 775, pp. 140-167.
14. O’Brien, T.K. (2001), Fracture Mechanics of composite delamination, in ASTM Hand book,Vol,21,composites, ASTM International; pp. 241-245.
15. Pagano, N.J. and R.B.Pipes, (1971),The influence of stacking sequence on laminar strength, Journal of composite materials. vol. 5, pp. 50-57.
16. Raju, I.S. (1987), Calculation of Strain-energy release rate with higher order a singular finite element, Engineering Fracture Mechanics, Vol. 28. pp. 251-274.
17. Reeder R James, Prasad B. Chunchu, Kyongchan Song, Damodar R. Ambur, (2002), post buckling and growth of delaminations in composite plates subjected to axial compression, AIAA 2002-1746.
18. Rybicki,E.F., M.F.Kanninen, (1977), A finite element calculation of stress intensity factors by a modified crack closure integral, Engineering Fracture Mechanics,Vol.9, pp. 931-938.
19. Shen,F., K.H.Lee,and T.E. Tay, (2001), Modeling delamination growth in laminated composites, Composite Science and Technology, vol. 61, pp. 1239-1251.
20. Shivakumar,K.N., P.W.Tan, J.C.Newman Jr, (1988), A virtual crack closure technique for calculating stress intensity factors for cracked three dimensional bodies, International Journal of fracture, Vol.36, pp. R43-R50
21. Tay, T.E. (2003), Characterization and analysis of delamination fracture in composites- an overview of developments from 1990 to 2001, Appl.Mech.Rev. 56(1), pp. 1-32
22. Whitcomb,J.D. (1989), Three dimensional analysis of a post buckled embedded delamination, journal of composite materials, vol. 23, pp. 862-88.
23. Whitcomb, J.D. (1992), Analysis of a Laminate with a post buckled embedded delmination, including Contact effects, Journal of Composite Materials, vol. 26, pp. 1523-1535.