ISSN: 2319-5967
ISO 9001:2008 Certified
International Journal of Engineering Science and Innovative Technology (IJESIT)
Volume 2, Issue 4, July 2013

Delamination Studies in Fibre-Reinforced Polymer Composites

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Abstract- ***FRP laminated composites have been extensively used in Aerospace and allied industries due to their inherent advantages over conventional materials. However these are also susceptible to damages especially under transverse loading. Failure modes of such laminated structures are different than those of conventional metallic materials. One important and unique mode of failure in such components is Delamination. Delamination is separation of adjacent plies/laminate due to existence of interlaminar stresses. This mainly occurs at free edges or around discontinuities depending upon the stacking sequence of the laminate. Once Delamination occurs, it becomes important to know whether the laminate could still be used with the existing delamination or up to what size of the Delamination the laminate could be used. The present Paper is to analyzing a laminate having Delamination to determine the severity of the existing Delamination and the propensity of the Delamination growth. 3DFE analysis along with concept of LEFM will be used the FRP laminated composites.***

Key words: **LEFM, Anasys12.0 glass epoxy, delamination.**

I. INTRODUCTION

A Composite material is a material brought about by combining materials differing in composition or form on a macro scale for the purpose of obtaining specific characteristics and properties. The constituents retain their identity such that they can be physically identified and they exhibit an interface between one another. In addition, three other criteria are normally satisfied before we call a material as composite. First, both the constituents have to be present in reasonable proportions. Second, the constituent phases should have different properties, such that the composite properties are noticeably different from the properties of the constituents. Lastly, a synthetic composite is usually produced by deliberately mixing and combining the constituents by various means. The constituent that is continuous and is often, but not always, present in the greater quantity in the composite is termed the matrix. The aim is to improve the properties of the matrix by incorporating another constituent. A composite may have a polymeric, ceramic or metallic matrix. Polymers have low strength and Young's moduli, ceramics are strong, stiff and brittle, and metals have intermediate strength and Young's moduli, together with good ductility's. The second constituent is known as the reinforcement, as it enhances the mechanical properties of the matrix. Strength and stiffness properties of reinforcing elements are generally 10-1000 times higher than those of the matrix. At least one of the dimensions of the reinforcement is small; say less than 500 μ m and mechanical properties of composites are function of the shape, dimensions, orientation and quantity of reinforcement.

In fibrous composites, the reinforcing fibres with high aspect ratio (it is the ratio of length to a cross section dimension) are the components bearing the main load, whereas the function of the matrix is confined mainly to load distribution and transfer to the fibres. The diameter of the fibres varies from 0.1 to 100 μ m. The fibre volume fraction varies from 10-70%. The distinguishing feature of this class of composite is that one of the dimensions of the reinforcing elements is large compared with the other two. Single layer composite can either formed by continuous high aspect ratio fibres or by short discontinuous fibres of low aspect ratio. The orientation of the discontinuous fibres may be random or preferred. The most common preferred orientation in the case of a continuous fibre composite is termed unidirectional (UD) and the corresponding random situation can be approximated by bidirectional woven reinforcement. The frequently encountered fibre reinforced composites are multilayered composites, which includes laminates and hybrids. Laminates are sheet constructions and made by stacking plies or laminate in specified sequence.

Hybrid composites are the cost effective composites and designed to benefit from the different properties of the fibres employed. Interply, intraply, interply-intraply and superhybrid are the different types of hybrids. Interply hybrids consists of plies from two or more different UD composites stacked in a required sequence. Intraply hybrids contain two or more different fibres mixed in the same ply. Interply-Intraply hybrids consist of plies from interply and intraply hybrids stacked in a specific sequence. Super hybrids consists of resin-matrix composite plies stacked in a desired manner and fabricated by adhesive bonding metal foils, the metal matrix composites(MMC), the resin matrix unidirectional composites(UDC) and resin-fibre prepreg, with an adhesive that has the same curing cycle as the prepreg tape.

Particulate composites consist of particles, whose dimensions are approximately equal in all directions, immersed in matrices such as alloys and ceramics. The arrangement of particulate reinforcement may be random or with a preferred orientation. Random orientations are widely used and have isotropic properties with increased strength and increased operating temperature. Typical examples include use of aluminium particles in rubber, gravel, sand and cement to make concrete. Flake composites consist of flat reinforcement of matrices. They have high theoretical modulus and low cost compared with fibrous composites. As long as flakes are parallel, flake composites can provide uniform mechanical properties in the plane of the flakes. Typical flake materials are glass, mica and aluminium. Flakes can be easily incorporated in to the matrices but obtaining parallel orientation is not easy.

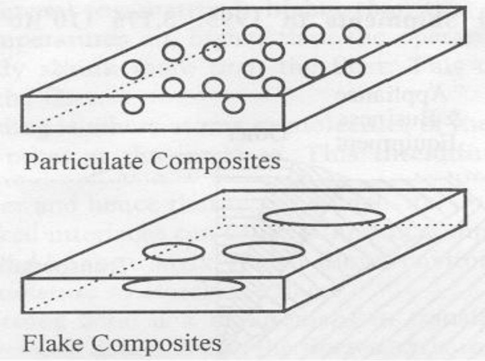

Fig 1: Particulate and Flake composites

II. DELAMINATION IN FRP COMPOSITES

Delamination or interlaminar debonding occurs in laminate when it is subjected to loading because of engineering property mismatch between successive layers. Once delamination initiated, that area becomes the weakest link and it propagates leading to the final failure of the laminate. Delamination may also occur due to number of reasons such as fibre breakage, matrix cracking and especially due to low velocity impact, which causes some fibre breakage or matrix cracking at specific layers and delamination initiates and propagates till the final failure of the component. As soon

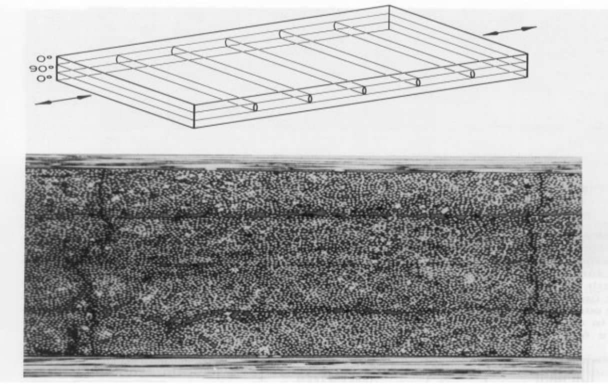

Fig 2: Matrix crack

As delaminating initiates, the structural component starts degrading. So, study of delamination under different types of loading is of significant importance from design point of view.

A. Fracture Mechanics Approach

In fracture mechanics approach, we analyze, whether a pre-existing crack on a component will grow or not under a given loading conditions. The different modes of crack growth are shown in figure 3

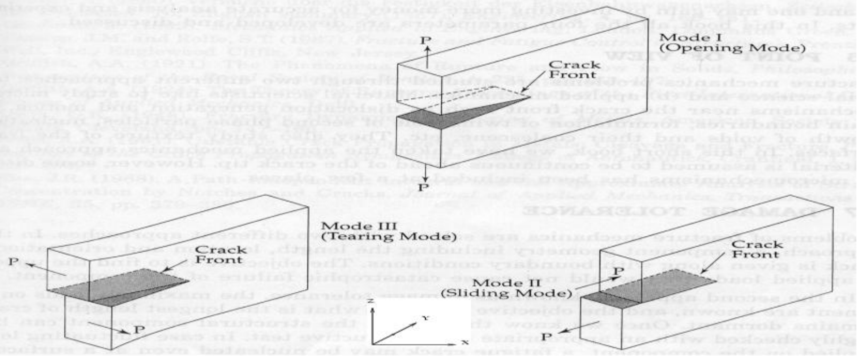

Fig 3: Three Modes of Failures

III. RESULTS AND DISCUSSION

A. Axial loading in FRP composites

A plate made of *Glass/Epoxy* having a stacking sequence $[0/45]_s$ (as shown in figure 3.0) has been considered. For this plate, the distributions of interlaminar stresses along the width of the plate have been considered, when axial force of 200 N is acting at one end and the other end is fixed. In order to assess the interlaminar stresses responsible for delamination a full 3D finite element analysis has been performed. The laminate has been described by eight noded solid 46 element.

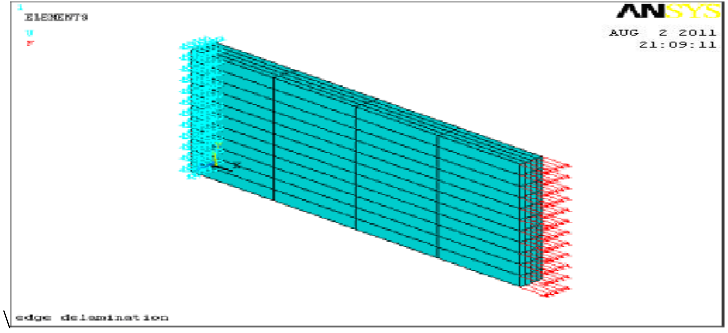

Fig 4: 3D FE mesh of the laminate specimen

B. Interlaminar stress distribution in FRP composites

Interlaminar stresses σ_{zz} , σ_{xz} and σ_{yz} are responsible for delamination growth. For the above FE model the distributions of interlaminar stresses across the width of the plate are shown in figures 4-6,and the trends have been in agreement with the published results [6] From these results, we can observe that the stress σ_{zz} is very high at the edges of the considered plate as compared to σ_{xz} and σ_{yz} . σ_{zz} causes mode-I (opening mode) delamination. So, from the results of figures 3.1-3.3, the mode-I delamination growth is more predominant as compared to other two modes of delaminations viz., mode-II, mode-III.

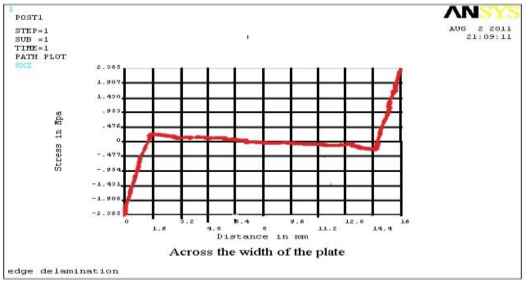

Fig 5: Variation of interlaminar shear stress(σ_{xz}) across width of the plate

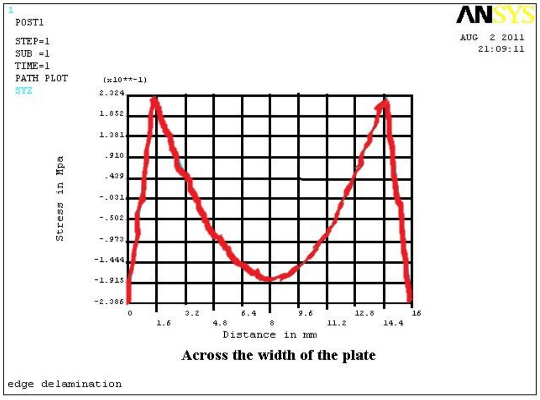

Fig 6: Variation of interlaminar shear stress (σ_{yz}) across width of the plate

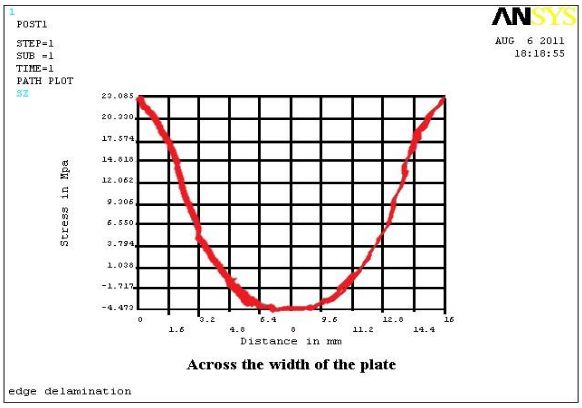

Fig 7: Variation of interlaminar shear stress (σ_{zz}) across Width of the plate

For reducing the intensity of interlaminar stresses at the edges of the plate, two cups of one-fourth size of width of the plate at the edges perpendicular to width direction have been considered. For this, another FE model has been developed, and is shown in figure 8. By considering two cups of stacking sequence $[0/45]_s$ at the edges, the intensity of interlaminar stresses have been reduced as compared to the interlaminar stresses due to the axial loading without cups on the plate. The effect of using cups at the edges is shown in figures.

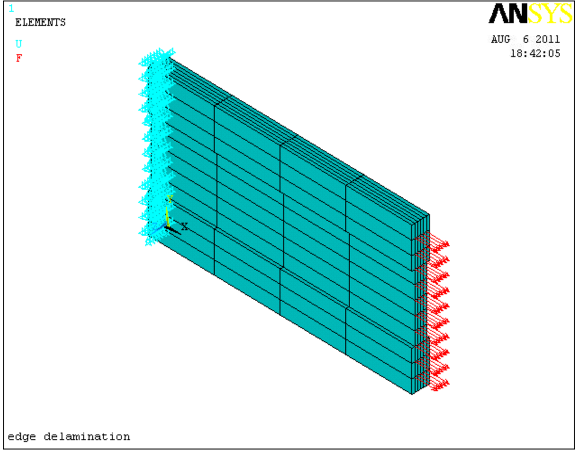

Fig 8: 3D FE mesh of the laminate with cups at the edges width of the specimen

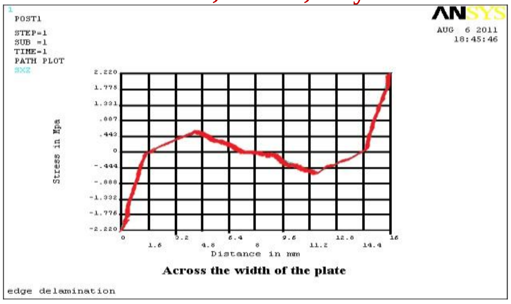

Fig 9: Variation of interlaminar shear stress (σ_{xz}) across width of the plate with cups

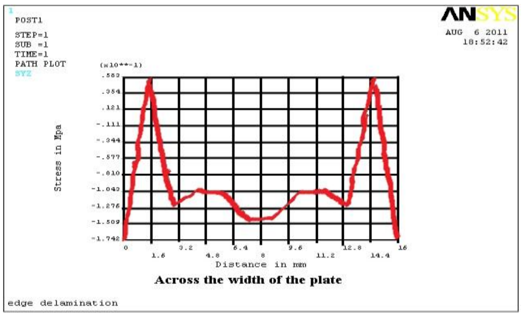

Fig 10: Variation of interlaminar shear stress (σ_{yz}) across width of the plate with cups at the edge.

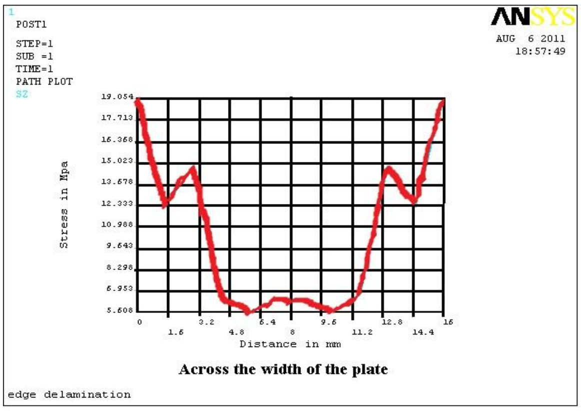

Fig 11: Variation of interlaminar shear stress (σ_{zz}) across width of the plate with cups at the edge.

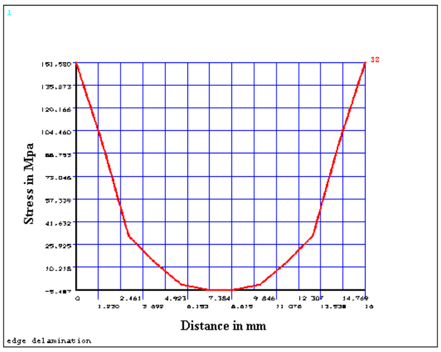

Fig 12: Variation of interlaminar shear stress (σ_{zz}) across width of the plate without cups for the ratio Ex/Ey =15

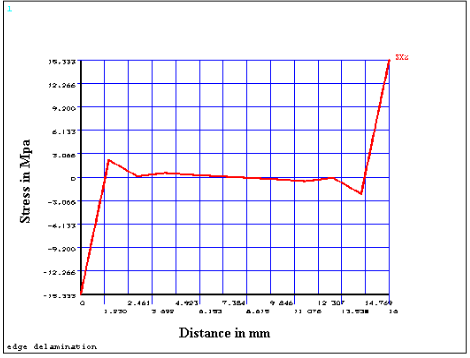

Fig 13: Variation of interlaminar shear stress (σ_{xz}) across width of the plate without cups for the ratio Ex/Ey=15

So from the results of figures (3.8 – 3.9) for without cups and figures (3.10-3.13) with cups the intensity of maximum value of interlaminar stresses have been increased in axial loading by increasing the ratio of young’s moduli(Ex/Ey)

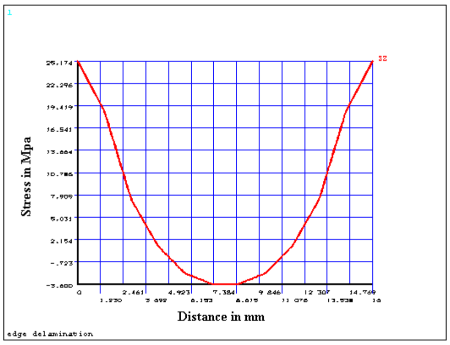

Fig 14 : Variation of interlaminar shear stress (σ_{zz}) across width of the plate without cups for the ratio Gxy/Gyz =15

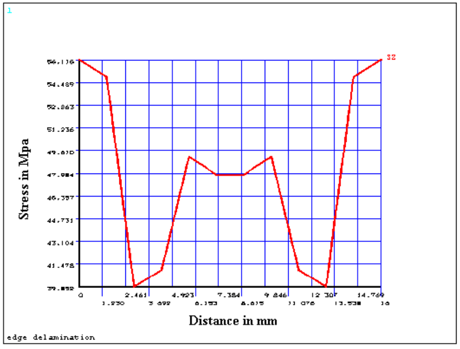

Fig 15 : Variation of interlaminar shear stress (σ_{zz}) across width of the plate with cups for the ratio Ex/Ey =15

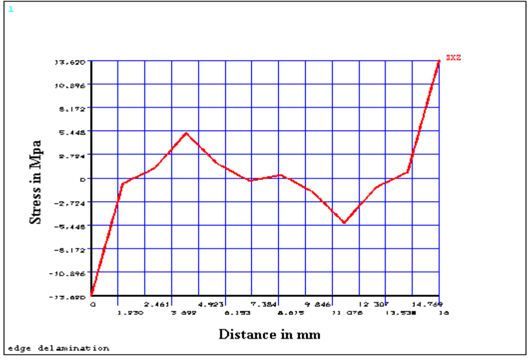

Fig 16 : Variation of interlaminar shear stress (σ_{xz}) across width of the plate with cups for the ratio Ex/Ey=15

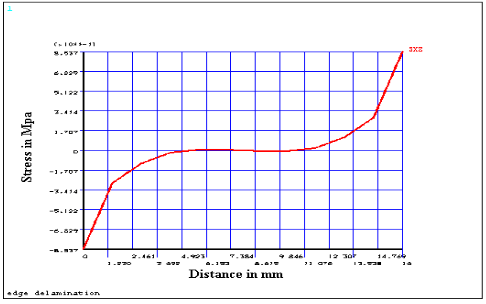

Fig 17: Interlaminar shear stress in XZ- Plane without cups for the ratio of Gxy/Gyz = 15

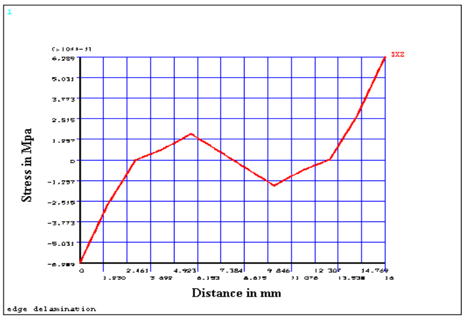

Fig 18: Interlaminar shear stress in XZ- Plane with cups for the ratio of Gxy/Gyz = 15

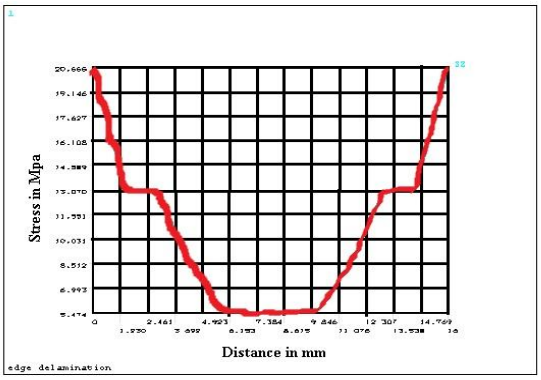

Fig 19 : Variation of interlaminar shear stress (σ_{zz}) across width of the plate with cups for the ratio Gxy/Gyz =15

So, from the results of the above figures, without cups and with cups the change in the intensity of maximum value of interlaminar stresses is negligible in axial loading by increasing the ratio of shear moduli (Gxy/Gyz) If the material of cup is different, which is stiffer than the plate material, that will increase the effect i.e. reduce the interlaminar stresses. From these results by using cups at the edges, the severity of mode-I has been reduced because σ_{zz} has been reduced a little bit. So from the above results, the interlaminar stresses at the edges of the plate are high, so it is better to consider small embedded defect at the edges of the plate. For this, small opening at the edge of size 2 mm is modelled as shown in figure .

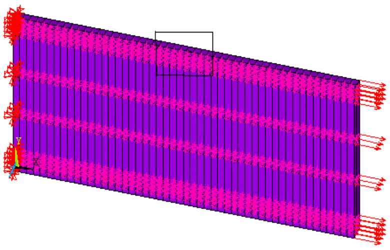

Fig 20: 3D FE mesh of the laminate specimen with small edge delamaination of size 2 mm

IV. THREE DIMENSIONAL FE ANALYSIS OF DELAMINATION

Figure shows the 3D full finite element model of the composite laminate having small edge delamination. Eight noded layered solid element (Solid 46) embodied in ANSYS has been used to model the laminate. In order to simulate delamination, two sub laminates (above and below the delamination interface) have been modeled and duplicate nodes at the interface have been constrained by multipoint constraint equations (CE). The fine mesh is used at the edges to give better results.

A.1 Fatigue loading

The exaggerated view of the small opening at the edge is shown in figure 4.0. Now for this model, static load of 10 N is applied axially in x-direction. Then using ANSYS the problem is solved. Then the maximum stress due to loading is considered and it is taken as the amplitude of cyclic loading for fatigue analysis. As a result of fatigue analysis, the fatigue life of the component as well as degradation behaviour of the plate due to stiffness reduction has been obtained.

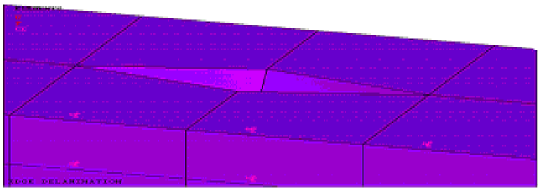

Fig 21: Exaggerated view of the small opening at the edge of laminate

Similarly, this analysis is used for full edge delamination of composite laminate of stacking sequence of $[0/45]_s$. The 3D FE model of the composite laminate with full edge delamination has been developed and is shown in figure 21. The exaggerated view of full edge Delamination is shown in figure 22.

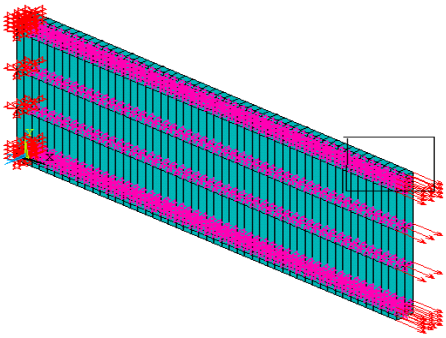

Fig 22: 3D FE mesh of the laminate specimen with full edge delamaination

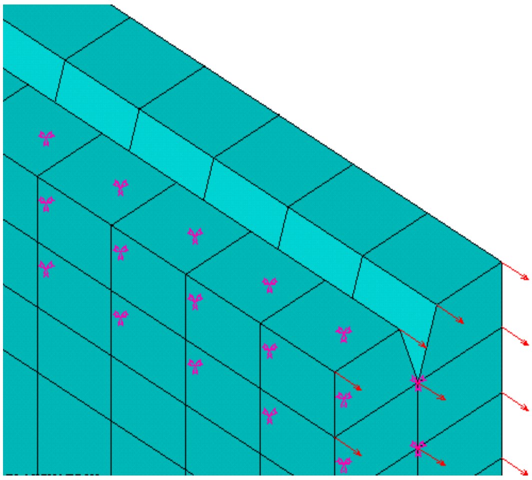

Fig 23: Exaggerated view of full delamination at the edge of laminate

These results (SERR and degradation) are shown in below figures for the plate of sizes, 100mm length 40 mm width and 5mm thickness subjected to axial loading of 10 N. The stiffness degradation, D increases rapidly in the initial applied load cycles and then the rate of growth is gradual. This is in agreement with the experimental investigation of fatigue loading of composite laminates.

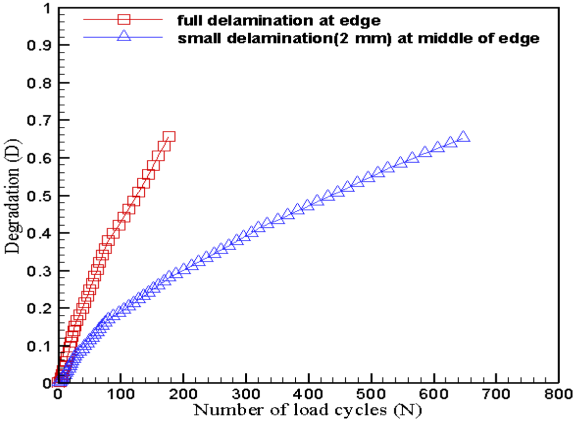

Fig 24: Comparison for variation of stiffness degradation, D with number of cycles for $[0/45]_s$ laminate having small edge delamination (2 mm) and full edge delamination at the edge of plate

The component is assumed to be failed, if its strength is reduced to 65% of the static strength for continuous fibres of laminate. In figure 24, the behaviors of stiffness degradation are shown and compared for both full delamination as well as small delamination under cyclic loading. The laminate has failed after 177 load cycles for full delamination, and in the case of small delamination it is 647 load cycles. i.e. plate having full delamination of edge will fail earlier than that of small delamination. In case of full edge delamination, delamination growth rate is also high.

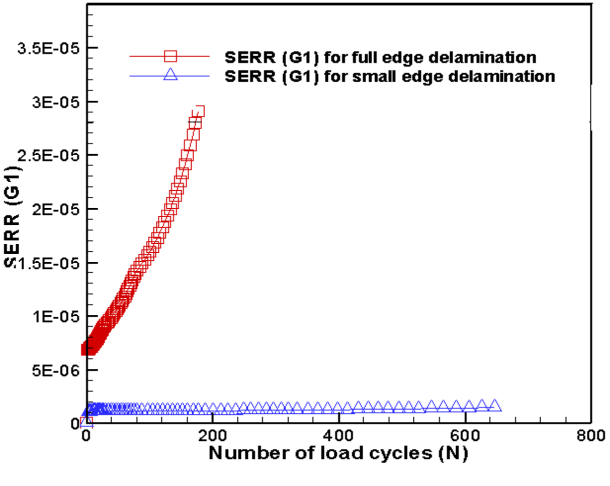

Fig 25: Comparison for variation of strain energy release rate (SERR), G_I with number of cycles for $[0/45]_s$ laminate having small edge delamination (2 mm) and full edge delamination at the edge of plate

From figure 25 it could be observed that for full length edge delamination, the magnitude of mode-I SERR (G_I) is higher as compared to that in case of small delamination (2 mm) and also the rate of increase of G_I is much higher compared to that in small delamination. i.e. the delamination growth of composite laminate for full edge delamination is very high as compared to small delamination considered.

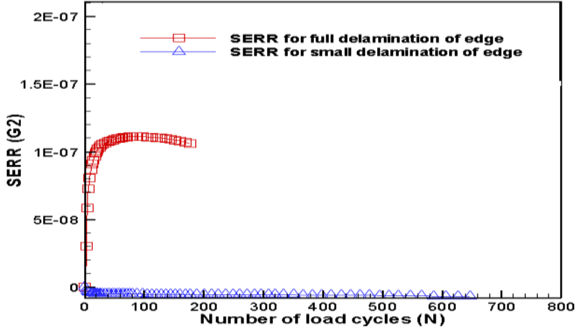

Fig 26: Comparison for variation of strain energy release rate (SERR), G_{II} with number of cycles for $[0/45]_s$ laminate having small edge delamination (2 mm) and full edge delamination at the edge of plate

From figure 26, for full delamination case SERR G_{II} is less as compared to SERR in mode-I, so the mode-I delamination growth is more predominant as compared to mode-II delamination growth. For small delamination the behavior of the curve is entirely different and is increased a little-bit in negative direction. So for both cases the mode-II effect is very less for delamination of composite laminate considered.

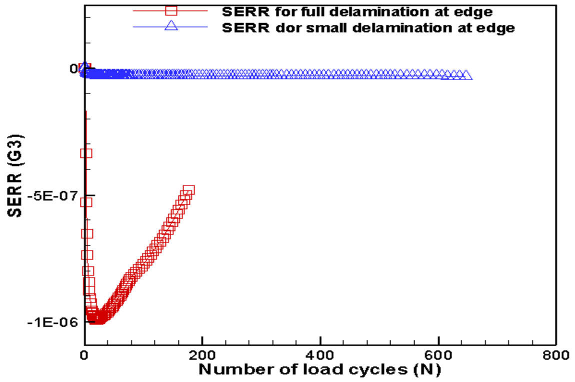

Fig 27: Comparison for variation of strain energy release rate(SERR), G_{III} with number of cycles for $[0/45]_s$ laminate having small edge delamination (2 mm) and full edge delamination at the edge of plate

From figure 27, for full delamination case, the increase in (SERR), G_{III} is very high, but in negative direction at initial stage but decreases after certain cycles. For small delamination case, it is very negligible effect as compared to the delamination growth in mode-I. From the above discussion, the mode-I delamination growth is very predominant as compared to other two modes of delamination viz. mode-II and mode-III for the edge delamination.

Table.1: Percentage variation of maximum interlaminar shear stresses induced across width of the plate without cups between FEA (Present work) and Literature (Ref 6)

Name	Interlaminar maximum shear stresses in Mpa Induced across width of the plate		% Variation
	FEA (Present work)	Literature(Ref 15)	
σ_{xz}	2. 220	2. 263	1. 93
σ_{yz}	0. 582*10**−1	0. 593*10**—1	1. 54

σ_{zz}	**19. 054**	**19. 612**	**2. 90**

Name	**Interlaminar maximum shear stresses in Mpa Induced across width of the plate**		**% Variation**
	FEA (Present work)	**Literature(Ref 15)**	
σ_{xz}	**2. 385**	**2. 432**	**2. 00**
σ_{yz}	**2. 324*10**−1**	**2. 382*10**—1**	**1. 49**
σ_{zz}	**23. 085**	**23. 512**	**1. 84**

Table.2: Percentage variation of maximum interlaminar shear stresses Induced across width of the plate with cups between FEA (Present work) and Literature (Ref 6)

V. CONCLUSIONS & SCOPE OF FUTURE WORK

In case of axial loading, the interlaminar stress distributions of FRP composite laminates are high at the edges due to shear stress variation or due to mismatching of material properties. In the case of axial loading, FRP laminated composites having delamination at edges, the mode-II and mode-III are negligible for $[0/45]_s$ i.e. mode-I delamination is more predominant. The value of σ_{zz} is decreased from 23.085 Mpa (tensile) to 19.054 Mpa (tensile) .By using cups at the edges, the severity of mode-I failure has been reduced. Knowing the degradation behaviour, static strength distribution and the global stiffness reduction of the composite laminate, the present model can be used to predict the fatigue life for different applied cyclic stresses.

The stress redistribution factor at different applied stress levels associated with different damage modes, such as matrix cracking, debonding and local delamination should be re-examined, so that the residual strength and fatigue life of composite laminates can be evaluated in agreement with the damage events which actually occur in the composite.

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