Progressive Damage Modelling of Fiber-Reinforced Polymer Laminated Composites

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Abstract- *Owing to their superior properties, like-high strength, high modulus, and lightweight, composites find their applications in many engineering fields. Along with its heavy use comes the importance of predicting the damage behaviour of composites under different loading conditions. Modelling of composites for implementing different concepts, like-Progressive Damage Modelling, Cohesive Zone Modelling, etc., has been ever-evolving. In the present work, one such idea of Progressive Damage Modelling has been used along with the implementation of failure criteria to characterize damage initiation and propagation sites in different laminated composites. First, rectangular [0/90]sand [+45/-45]s laminates under uniaxial load were validated for delamination behaviour at the free end. Then, the probable sites of delamination initiation were located on the plates using the Quadratic stresscriterion using ANSYS Mechanical APDL software.*

Keywords- composite, Progressive damage modelling, Delamination ANSYS mechanical APDL software.

I. INTRODUCTION

Composite materials consist of a combination of materials that are mixed to achieve specific structural properties. The individual materials do not dissolve or merge completely in the composite but act together. Usually, the components can be physically identified as they interface with one another. The properties of the composite material are superior to the properties of the individual materials from which it is constructed. One constituent is called the reinforcing phase, and the one embedded in it is called the matrix. The reinforcing phase material may be in the form of fibers, particles, or flakes. The matrix phase materials are generally continuous.

Preventing failure of composite material systems has been an important issue in engineering design. In the case of composites, the failure of a lamina or laminate needs special attention. In the case of laminates, there are several local failures before it completely breaks into two or more pieces. The local level failure is called "damage." In the case of fibrous composites, the term damage refers to the individual constituent phases – fiber and matrix. It is important to note that the ultimate failure (rupture/breaking) of the laminate occurs by the gradual accumulation of damage. This is manifested at the lamina or laminate level by some form of failure. Thus, the first failure in laminates does not mean the final failure. The development of additional local failures with increasing loads or time is termed damage accumulation. The two types of physical failures that occur in laminated composite structures and interact in a complex manner are Intra laminar failure and Inter laminar failure.

II. PROBLEM DEFINITION

The laminated composite was tested for free-edge inter-laminar stresses using ANSYS Mechanical APDL software. Two laminated Glass/Epoxy composites were modeled using SOLSH190 elements. The dimensions of the composites were taken to be:

L=Length of the laminate=100 2b=width of the laminate=10 T=total thickness of the laminate=1

III. ANALYSIS PROCEDURE

Finite element modeling

The above-dimensioned laminate was modelled using SOLSH190 element, and the following boundary conditions were applied to both the laminates:

- At x=0, the laminate is fixed or held rigidly.
- At x=L, the laminate is loaded by a load of 10 on each node at that cross-section for both the laminates in all the cases mentioned.

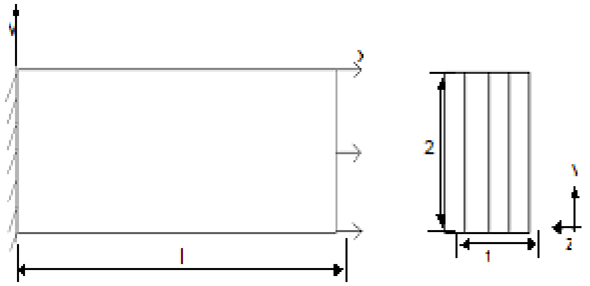

Figure 1 The boundary condition problem and a cross-sectional view

ANSYS Mechanical APDL software has been used for the 3D modelling of a sample composite laminate. The element used to create mesh is SOLSH190(Solid Shell 190). The element features eight-node connectivity with three degrees of freedom at each node: translations in the nodal x, y, and z directions.The element has plasticity, hyper-elasticity, stress stiffening, creep, large deflection, and large strain capabilities. It also has mixed u-P formulation capability for simulation of deformations. The element formulation is based on logarithmic strain and true stress measures. Advantages of using solid-shell elements:

- Unlike solid elements, it ensures lock-free deformations. So, even in the cases of bending problems, it conforms to the experimental values.
- It does not require any special attention as is required by shell elements while joining to solid elements.
- It performs well and is up-to-mark for a wide range of shell thickness.
- The element shape functions and FE formulations are as shown below:

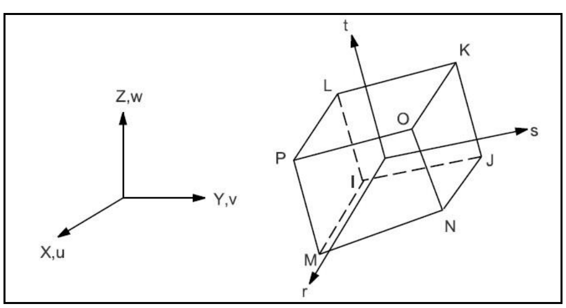

Figure 2Element geometry in natural coordinates system (Ansys 14.5 Help)

Numerical analysis was done on two laminates with different [+45/-45]s and [0/90]s layouts. Table 1 details the material properties of the Glass/Epoxy lamina used.

Table 1Material properties of Glass/Epoxy (V_f=0.58), [11]

Longitudinal Elastic Modulus, E_X(GPA)	44.6
Transverse Elastic Moduli, $E_Y=E_Z$(GPA)	16.5
Poisson'sratio, $\vartheta_{xy} = \vartheta_{xz}$	0.263
Poisson'sratio, ϑ_{yz}	0.35
Shear Modulus, $G_{xy}=G_{xz}$(GPA)	3.6
Shear Modulus, G_{yz}(GPA)	7.7

For finite element discretization and convergence of the results obtained, the following cases of mesh variables were modelled, in the case of both the laminates mentioned above, as shown in table2.

Table 2Different types of mesh used for discretization of FEA.

MeshType	Number ofNodes	Number ofElements
Case(a)	5220	3248
Case(b)	8700	5488
Case(c)	13920	8848

Fig 3gives the modelled view of the problem defined with the above-mentioned boundary conditions andloads.

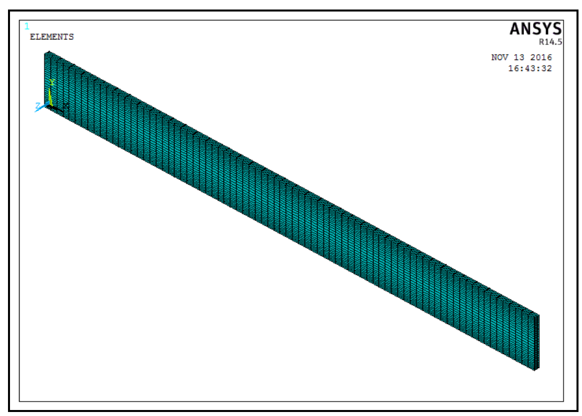

Figure 2Finite element modelling of the laminate

The examination of interlaminar stresses is to be done on the interface between two differently oriented laminas. To achieve this aim, the interface between +45 and -45 plies (and between 0 and 90 plies) was modelled with Multi-Point Constraints (MPCs) applied between each pair of nodes lying on theinterface.

Figure4 demonstrates the effect of mesh refinement on the numerical results obtained when the mentioned cases of mesh refinement (as in Table 2) were applied to analyze the inter-laminar stresses on [+45/-45]s. Figure 4 shows the variation of the inter-laminar shear stress τ_{xz} along the width of the laminate when all the cases were employed.

Similarly, figure5 demonstrates the effect of mesh refinement on the numerical results obtained when the mentioned cases of mesh refinement (as in Table 2) were applied to analyze the inter-laminar stresses on [0/90]s. Figure5 & figure 6 shows the variation of the inter-laminar normal σ_z and shear stress τ_{yz} along the width of the laminate when all the cases were employed.

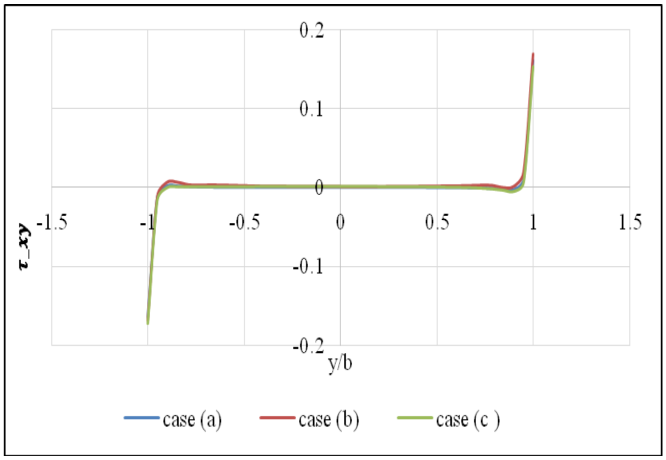

Figure 3 Variation of τ_{xz} along the width of [+45/-45]s laminate.

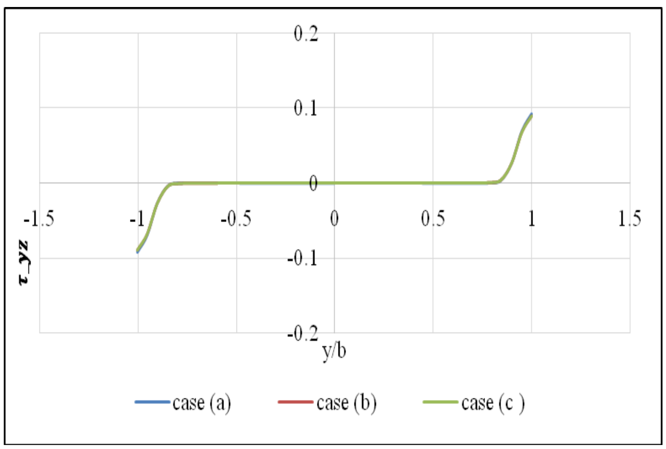

Figure 4Variation of τ_{yz} along the width of [0/90]s laminate.

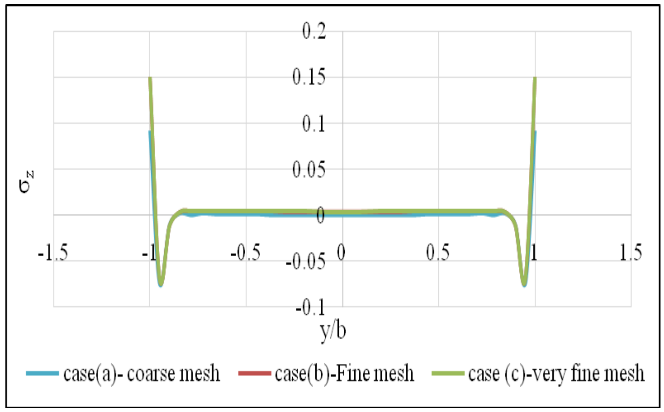

Figure 5Variation of σ_z along the width of [0/90]s laminate

As the plots are obtained for both types of laminates, the stress values converge as the mesh gets increasingly refined. One should note that the mesh refinement is near the free edge rather than at the laminate's center. Hence, in order to be able to predict approximately, one should employ fine meshing around the point of discontinuity like hole boundaries, free-edge, etc.

Numerical Results

Fig 7 shows numerically analyzed variation of τ_{xz} for a [+45/-45]s laminate along the width of the laminate.

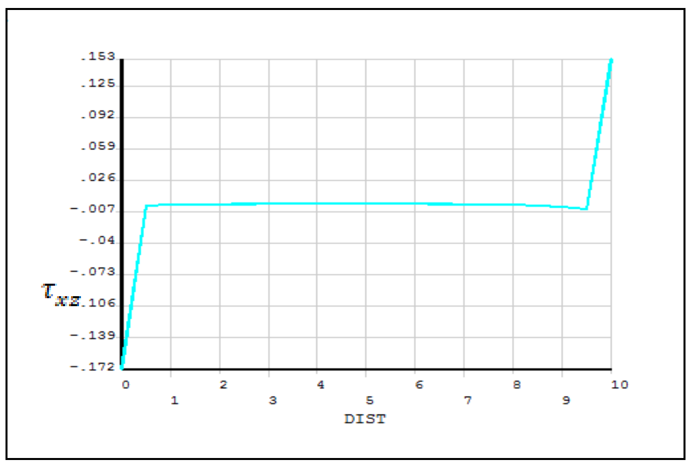

Figure 6 Plot of τ_{xz} with respect to the width ofthe laminate

It has been observed that the out-of-plane shear stress τ_{xz} exists only near a very small region (of the order of the thickness of lamina) around the free-edge. The plot of the stress above is validated with reference to the Pipes-Pagaonanalysis of inter-laminar shear stress. Figure 8 and figure 9shows numerically analyzed inter-laminar stresses on [0/90]s laminate.

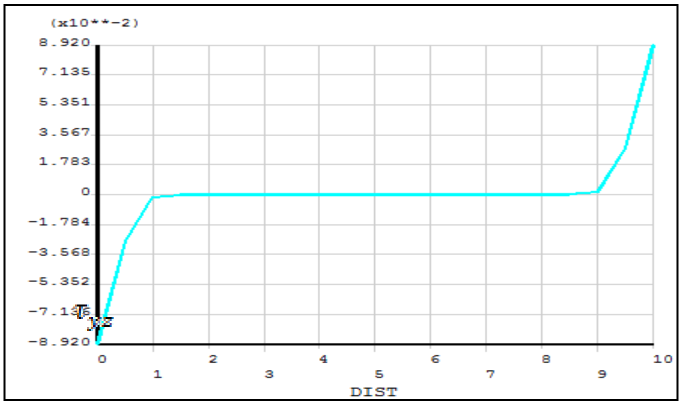

Figure 7 Variation of τ_{yz} along the width of laminate.

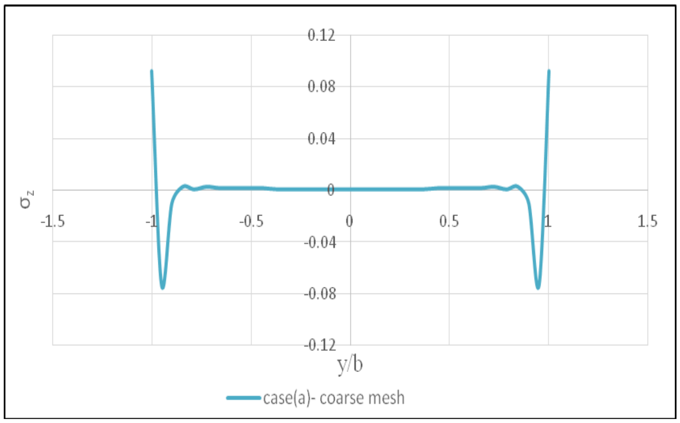

Figure 8 Variation of σ_z along the width of laminate.

From the above plots, it is obvious that the delamination of a [0/90]s laminate is governed by the out-of-plane normal stresses. The graph plotted is an excellent approximation to what is available to us as a Pipes-Pagano [2] analysis of inter-laminar stresses.

Delamination initiation

The quadratic stress criterion of failure for delamination was used to know those nodes of the interface (modeled with MPCs) that went out of the failure envelope while loading the laminate.

In order to achieve this aim, the strength properties in the out-of-plane direction were specified as some variables in the post-processor.

Table 3Strength properties of Glass/Epoxy lamina. [11]

Tensile Stress(MPa) z	31.30
Compressive, S (MPa) z	185.00
Shear strength, Sxz(MPa)	54.40
Shear strength, Syz(MPa)	45.60

The use of these parameters is done to estimate the nodes which are prone to fail by delamination and their respective locations. This analysis is done for all three cases of mesh refinement on both types of laminates.

Figure10 gives the estimate of delamination initiation sites for a [+45/-45]s laminate as estimated from our study of delamination using the failure criteria.

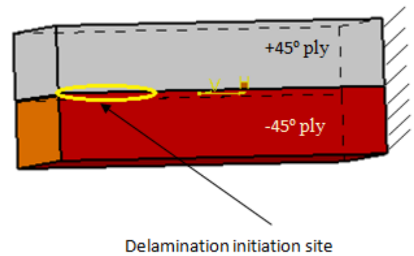

Figure 9Delamination initiation sites in [+45/-45]s laminate.

These initiation sites lie on the free edges of the interface model. This is expected from the literature and Pipes-Pagano's [3] analysis of inter-laminar stresses.

Figure11 estimates the delamination initiation sites for a [0/90]s laminates as estimated from our analysis of inter-laminar stresses and associated delamination.The inter-laminar stress effect on the free edges is observed, and regions of delamination initiation are these free edges.

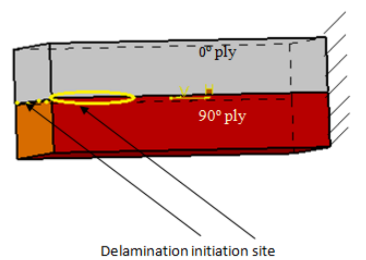

Figure 10Delamination initiation sites for a [0/90]s laminates.

IV. CONCLUSION

Numerical analysis was done on [+45/-45]sand [0/90]s Glass/Epoxy laminated composites to study the nature of inter-laminar stresses and delamination. The laminates were checked for the sites of delamination initiation using the quadratic failure criterion for delamination. The following conclusions were made throughout this process ofanalysis.

- The variation of inter-laminar stresses along the width of the laminates was observed and studied to show that the inter-laminar stresses at the free edges are responsible for phenomena of delamination.

- As expected, the delamination sites, as observed for [+45/-45]s, were found to be along the free edge of the interface model.
- Although the delamination sites for [0/90]swere found to be along the free edges of the interface, some of the sites were also on the loaded edge. A study of this discrepancy revealed the sites as point load application points. Hence such discrepancy.
- A study of damage onset and propagation revealed that in 0º ply, fiber damage is rarely a factor of damage occurrence. Whatever damage occurs due to matrix mode propagates in a direction perpendicular to the fiber orientation. This suggests transverse matrix crack as a means of failure.

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