Progressive Damage Analysis of Sandwiched GFRP Laminates Under Different Loading

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Abstract- *In this article two open-hole laminates (for each [0/90]s and [+45/-45]s) were modelled, one with the presence of intermediate epoxy layer and the other, without its presence. The models were compared to study the effect of introduction of epoxy layer on damage initiation loads. Each model was then analysed using Hashin's failure criterion and Modified Yamada-Sun failure criterion separately, to gain a comparative knowledge. The models were then analysed with transverse bending load for damage behaviour. At the end, inter-laminar stress behaviour in open-hole laminated composites was studied. Modified Yamada-Sun failure criterion was seen to estimate more loading capacity before damage than Hashin's criteria. Hence, Hashin's criterion gives more conservative results.*

Keywords- Hashin's failure criterion, Modified Yamada-Sun failure criterion, open-hole laminated composites

I. INTRODUCTION

Composites are most widely used materials in almost each and every day of our life. Owing to its light-weight and high-strength capabilities, it is now used in many sectors which mostly include automobile, aerospace, defence sectors and many more. It is this extensive use of composites that has made it necessary for testing and simulation of composites. Along with this, numerous research activities on composites are being carried on continually. The problem of delamination and other failure modes are under constant scrutiny. The stress analysis, failure analysis and implementation of concepts like progressive damage modelling and cohesive zone methods are being carried out as a method to predict damage behaviour.

The worst mode of failure in composites is delamination. Different failure criteria have been evolved under different loading cases, like Puck's criteria, Hashin's criteria which are still under processing. For complete and close numerical analysis of the case of delamination, theories like progressive damage modelling, cohesive zone modelling e.t.c have come to existence. They are being used in conjunction with different failure theories for yield more accurate results. Different material laws have been tested and implemented on the cohesive zone material properties for approximate representation of what actually happens at the site of delamination initiation.

Separate damage evolution laws have been used to evaluate the damage parameter and to estimate the extent of damage. The use of progressive damage modelling along with cohesive zone elements is being encouraged under these circumstances.

Effect of uniaxial loading on an open-hole laminate

Problem definition

Model A- Two open hole composite laminate ([+45/-45]s and [0/90]s) having Graphite/Epoxy material properties each, were simulated for damage onset and progressive damage propagation under the action of a uniaxially applied load. The FE model of such laminate was made up with the help of SOLSH190 elements with one element in through-the-thickness direction per ply. So, there were a total of 4 elements in through the thickness direction.

The dimensions of the composite were taken as following: Length of the laminate=200mm

Width of the laminate=50mm Thickness per ply=0.25mm Diameter of hole=5mm (W/D=10).

Model B- In another case, two other composite laminates with same ply orientations having same material properties but with a thin epoxy layer (1/10th the thickness of a ply) in between 0º and 90º layers have been simulated for the same study under uniaxially applied load. The FE model for such laminate includes one element per ply in through-the thickness direction which made it 6 elements per laminate in through the thickness direction.

Thickness of each epoxy layer = 0.025mm

Further the use of CONTA178 elements have been made in this model only.

Finite element modelling

The above-mentioned laminates were modelled and were subjected to following boundary conditions:

a. At x=0, the laminate was fixed or rigidly held.
b. At x=l, laminate was loaded with uniaxial load along global X-direction.

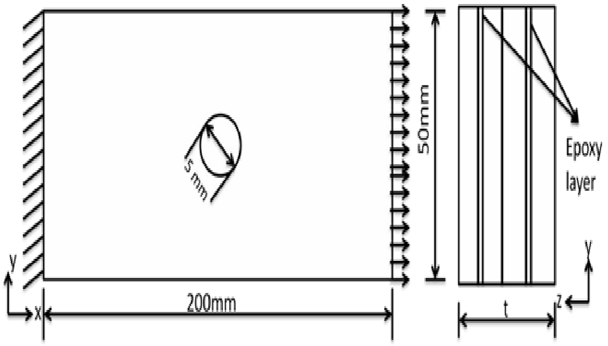


Figure 1 The boundary value problem for model-A

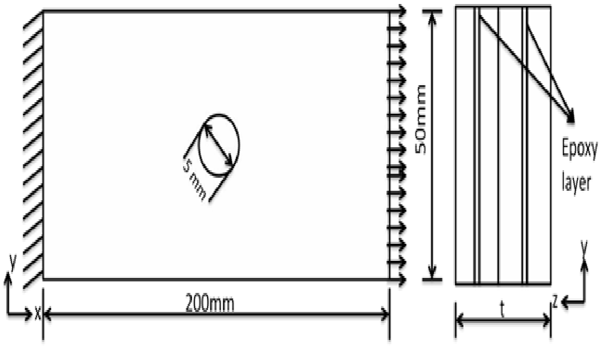


Figure 2 The boundary value problem for model-B

Table 1 gives the details of the material about the materials properties of Gr/Eply

Table 1Material properties of Gr/E lamina ($V_f = 0.6$)

Longitudinal Elastic Modulus, E_X (GPa)	180
Transverse Elastic Moduli, $E_Y = E_z$ (GPa)	10.8
Poisson's ratio, $\vartheta_{xy} = \vartheta_{xz}$	0.28
Poisson's ratio, ϑ_{yz}	0.49
Shear Modulus, Gxy=Gxz (GPa)	7.17
Shear Modulus, Gyz(GPa)	3.57

Table 2Material Properties for epoxy (isotropic)

Elastic Modulus, E (GPa)	3.5
Poisson's ratio, ϑ	0.28

Table 3CONTA178 Element real constants used

Contact Status	1 (Initially Open)
Normal Stiffness (GPa)	540
Tangential Stiffness (GPa)	360

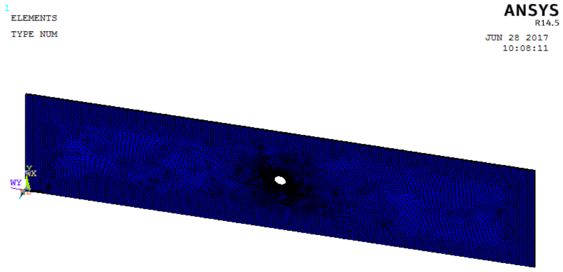


Figure 3Finite element modelling of model-A

Table 4 Strength properties of Gr/E lamina (in MPa). [26]

σ_{1t}	1500
σ_{1c}	1500
σ_{2t}	44.8
σ_{2c}	246
σ_{3t}	46
σ_{3c}	248
τ_{12}	62.1
τ_{13}	78
τ_{23}	78

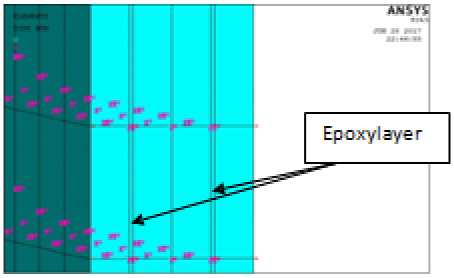


Figure 4Finite element modelling of model-B

The finite element analysis was done in ANSYS APDL and subsequent failure criteria were applied. In order to study the effect of the load in the region nearby the hole for damage initiation and propagation, the interfaces were modelled with constraint equations (CEs) binding all the coincident nodes together. As and when the nodes failed, the constraint equations were released as a means to convey the onset of damage.

Numerical Simulation

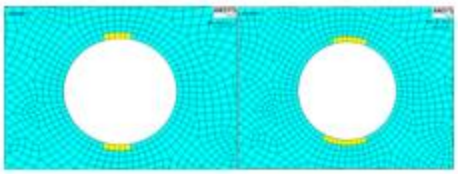
Model-A

Damage onset and propagation

In our present analysis, use of two failure criterion, Hashin's criteria and Modified-Yamada Sun criteria has been used for comparative study of damage analysis.

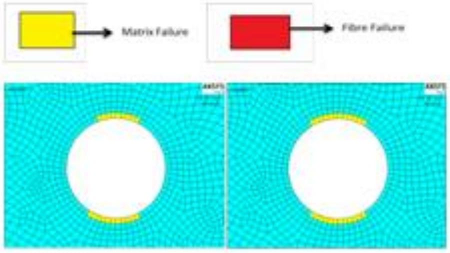
Load was gradually applied and failure criteria were being employed continually to check for initiation of damage. It was observed that damage initiated from the periphery of the hole and accumulated in the region near the periphery before propagating into the middle portion of the laminate. Further, the initial damage was through matrix failure mode and it started at nearly same load for both 0º and 90º plies in [0/90]s. In the case of [+45/-45]s laminate, it was seen to start at a comparatively lower load and was seen to propagate perpendicular to the 45º plies.

All the constraint equations associated with the failed nodes were released and the iteration was run again at the same load to check for any further damage. It was seen that, the number of damaged nodes attained saturation after some number of iterations. Thereafter some load increment was done and the simulation was run again.



(a) Failure initiation

(b) Second iteration failed elements



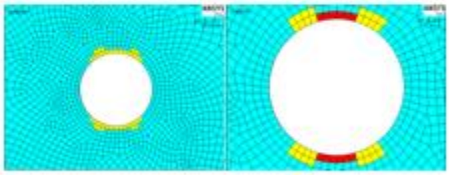
(c) Third iteration failed elements

(d) Fourth iteration failed

Figure 5 Failure of elements in 0º ply at 4200N load (Hashin's criteria)

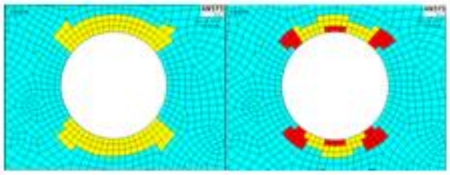
Following the same pattern, various iterations were done at different loads and the number of failed nodes was recorded. It was observed that before the first fiber failure initiation, a considerable amount of damage had been already done by matrix mode of failure. The fiber failure initiation took place in the 90º plies in case of [0/90]s and propagated in direction perpendicular to the 90º fiber axis, suggesting a fiber-matrix shear out. There was hardly any fibre failure in 0º ply. In case of [+45/-45]s laminate, fibre failure propagates in direction parallel to fiber direction.

All these above observations are in accordance with available literature from Liu et al[14] and Tserpes[15].



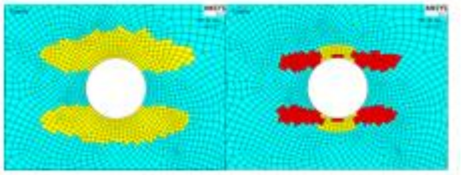
(a) Damage in 0° ply

(b) Damage in 90° ply



(c) Damage in 0° ply

(d) Damage in 90° ply

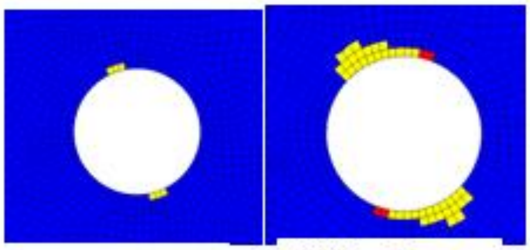


(e) Damage in 0° ply

(f) Damage in 90° ply

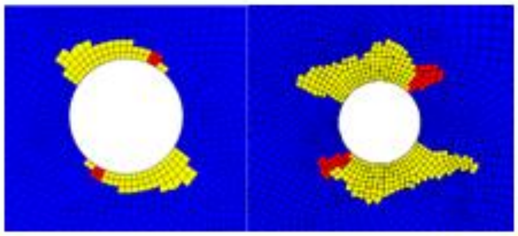
Figure 6 Shows the damage accumulation in [0/90]s laminate at (a) and (b) at 7000N, (c) and (d) at 7600N, (e) and (f) at 8400N

In case of [+45/-45]s laminate, the individual layer behaved, more or less, in similar fashion. Further, the matrix mode damage propagation was seen to be perpendicular to the fibre orientation direction and fibre mode along the fibre direction.



(a) Damage initiation

(b) Fiber Damage initiation



(c) Damage accumulationat7400 N

(d) Damage accumulationat8200 N

Figure 7Damage accumulation in [+45/-45]s laminate

Comparative analysis of failure criteria

Using Hashin’s criteria and Modified Yamada-Sun criteria, damage onset load values, number of nodes failed and failure index were calculated.

Load(N) Criteria	Matrix Failure Initiation Load [0/90]s	Fibre Failure Initiation Load [0/90]s	Matrix Failure Initiation Load [+45/-45]s	Fibre Failure Initiation Load [+45/-45]s
Hashin’sCriteria	4200	7000	3900	6450
ModifiedYamada-Sun	4350	7250	4100	6600

From the above table we observe two things,

a. Modified Yamada-Sun criteria overestimate the damage initiation load as compared to Hashin’s criteria.
b. Matrix failure mode occurs well before the onset on fibre failure mode. A plot of Load versus Strain describes it.

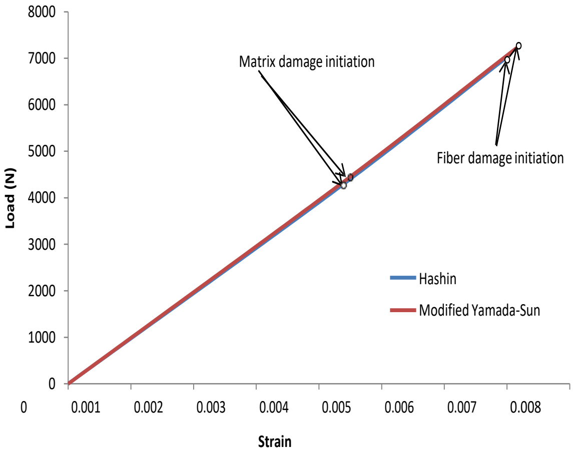


Figure 8 Plot of strain versus load applied showing fibre and matrix mode damage initiation.

From the tabular comparison above, it was established that Hashin’s criteria provides for a more conservative failure criteria as compared to Modified Yamada-Sun’s criteria. Similarly, in case of [+45/-45]s laminate the plot reveals the same.

The possible reason for such overestimation in case of Modified Yamada-Sun failure criteria could be due to neglecting of through-the thickness direction stresses. Transverse through-the thickness stresses play an important role in damage onset and propagation and hence they should not be neglected. Further this could be possible due to dissimilarities in failure index formulation.

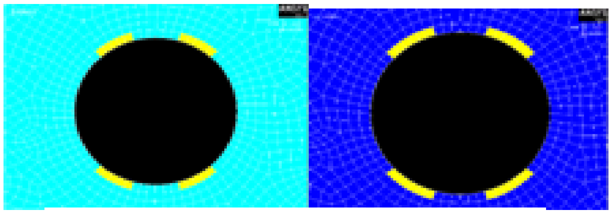
Analysing the failure indices, it was found that, the value of maximum failure index increases rapidly with the increase in load increment. This is as expected, because of increase in stress concentration near the already damaged area.

Model-B

Damage onset and propagation

The model was simulated for damage initiation using respective failure criteria and in this model the effect of presence of epoxy layer was observed. The damage onset took place from near the vicinity of the hole periphery and first accumulated around the periphery itself. In order for higher iteration to take place, the material properties of the epoxy layer next to the failed nodes were reduced to a near-zero value with the use of Ansys APDL in-built command EKILL and the nodes in the interface of 0º-epoxy and epoxy-90º were connected by CONTA178elements.

The damage onset took place in a symmetric manner around the hole and started accumulating around the periphery as shown below.

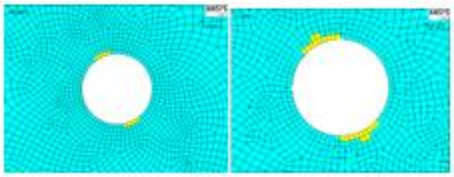


(a)Matrix modedamageiniti

(b)Second iteration

Figure 9 Damage initiation and propagation in [0/90]s laminate at load=4800N.

In the similar fashion the damage onset was observed in [+45/-45]s laminate to be around the periphery and tends to propagate normal to the fibre orientation direction.



(a)Matrix modedamageiniti

(b)Second iteration damagepropagatio

Figure 10 Damage initiation and propagation in [+45/-45]s laminate at load=4500N.

Comparative study of failure criterion

Failure initiation in the model was based on two different failure criteria, Hashin's criteria and Modified Yamada-Sun's criteria. The matrix mode damage was observed to happen during the time of first failure. But it was seen that Modified Yamada-Sun overrates the load of damage initiation.

Load(N) Criterion	Matrix Mode Initiation Load [0/90]slaminate	Matrix Mode InitiationLoad [+45/-45]slaminate
Hashin's	4800	4500
ModifiedYamada-Sun's	4980	4700

Before the following approach could be used for further analysis, certain modelling difficulties arose and we had to stop the approach. After re-modelling and removing such inconsistencies, this analysis can be reused to study the effect of damage onset and propagation when epoxy layer is introduced in between the interface.

Effect of bending load on an open-hole laminate

Problem definition

The above two models were now simulated for a case of transverse bending load where the loads are applied in the direction of thickness of the laminate. The laminates are supported in cantilever beam type (fixed at one end and free at other) and loaded at the other.

A similar approach was followed for study of damage onset and propagation. But here, only Hashin's criterion has been used because Modified Yamada-Sun's criterion ignores the thickness direction stresses (which are predominant in this case).

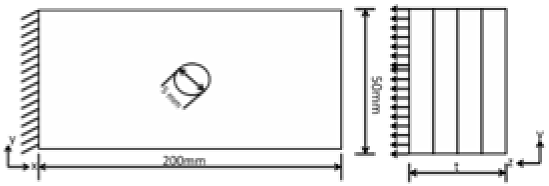


Figure 11Boundary value problem and cross-sectional view of model-A.

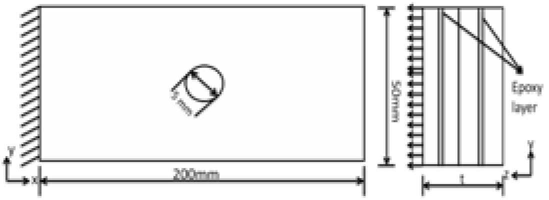
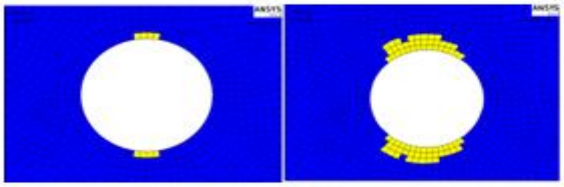


Figure 12Boundary value problem and cross-sectional view of model-B

Numerical simulation

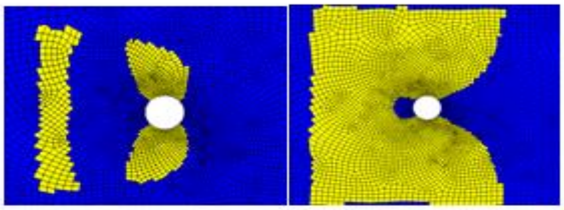
Model-A

In [+45/-45]s and [0/90]s laminates, the damage was seen to initiate around the hole periphery and in the ply which is most stretched, that is, outermost ply on the bending curve.



(a)Matrix damage onset in 0°plies(10N)

(b)Damage propagation in 0° ply (15N)

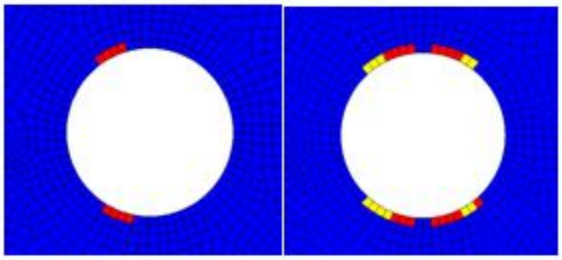


(c)Damage propagation in 0°ply(20N)

(c)Damage propagation in 0° ply(25N)

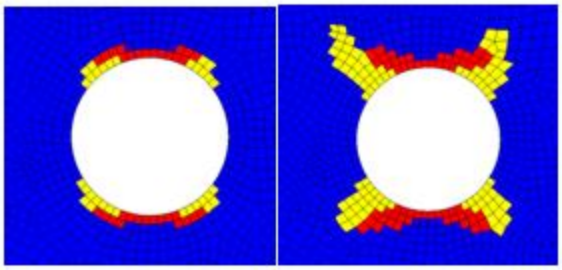
Figure 13Damage initiation and propagation in 0º ply due to bending load.

The above plots reveal that even in bending loads, 0º ply fails only by matrix mode predominantly by transverse matrix cracks in through-the thickness direction.



(a)Fiber damage initiations at 90° ply (12N)

(b)Matrix damage initiations at 90° ply (15N)



(c)Damagepropagation (20N)

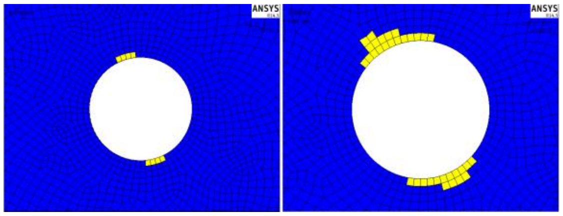
(d) Damage propagation (25N)

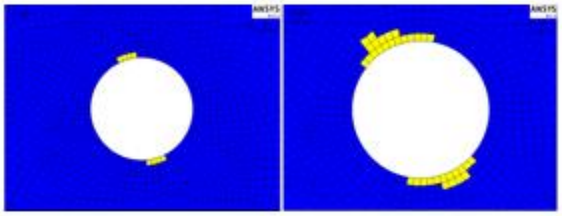
Figure 14Damage onset and propagation in 90º ply under bending load.

It was observed that, damage onset in case of 90º ply takes place by fibre failure and at a later stage matrix mode failure was observed.

Also, before the damage the damage initiation in the innermost ply, a considerable damage had already happened in the outermost layer.

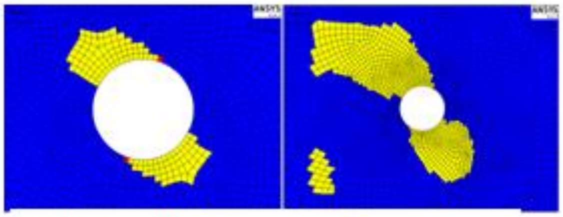
In case of [+45/-45]s laminate, the outermost layer of 45º was seen to be damaged by matrix mode damage initiation and propagation. This layer took most of the damage throughout the course of loading.





(a)Matrix modeinitiation (12N)

(b)Damage propagation(15N)

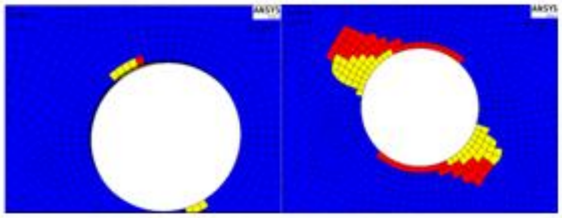


(c)Damagepropagation(20N)

(c)Damage propagation(25N)

Figure 15 Damage onset and propagation in 45º ply under different bending load.

The damage analysis in -45º ply revealed its damage by a mixed mode. There was not a clear picture as to which damage mode initiated first. Both the damage modes were responsible for damage in thisply.



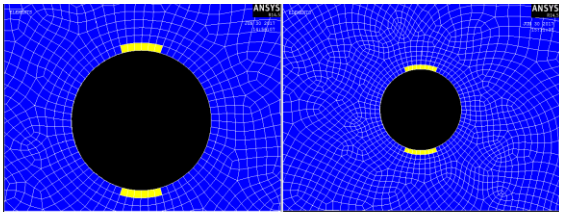
(a)Damage onset mixedmode(13N)

(b)Damage propagation(25N)

Figure 16 The damage onset and propagation in -45º ply with different bending loads.

Model-B

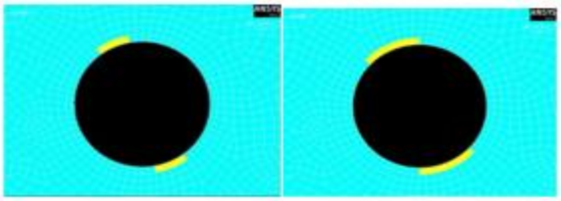
Similar to the previous analysis of model-B in axial loading case, here the use of CONTA178 element and full degradation of the epoxy layer properties was followed.



(a)Matrix mode damageonset(11N)

(b)Seconditeration damage(11N)

Figure 17 Damage onset and propagation in [0/90]s laminate under bending load.



(a)Matrix mode damage onset (13N) (a)Second iteration damage(13N)

Figure 18 Damage onset and propagation in [+45/-45]s laminate under bending load.

Both the models show good agreement with each other in representation of damage onset area and damage propagation front. The only variation they show is the load at which initial damage onset starts and corresponding damage propagation loads.

Inter-laminar stress analysis for open-hole laminate

The [0/90]s open-hole laminated composite was checked for inter-laminar stresses when loaded uniaxially. The behaviour of the inter-laminar stresses (at 4800N load) is as shown below.

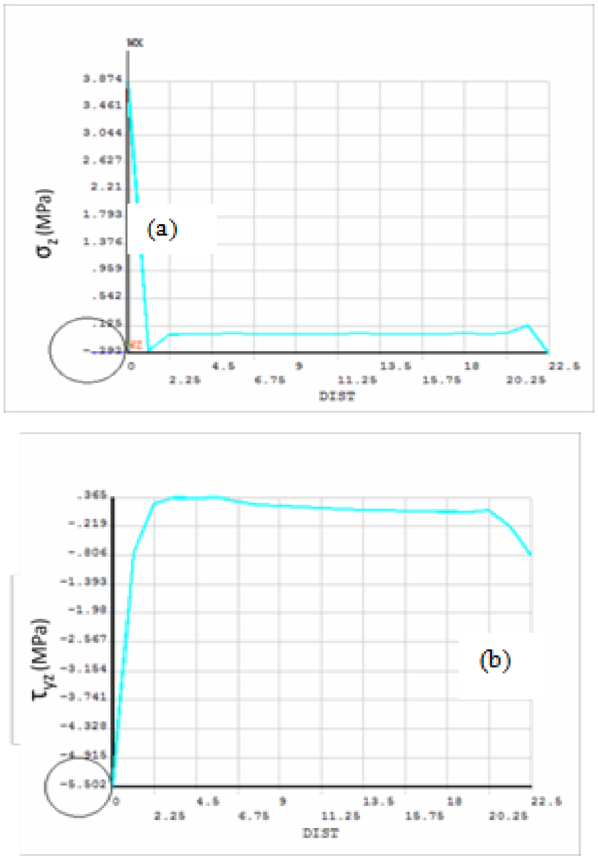
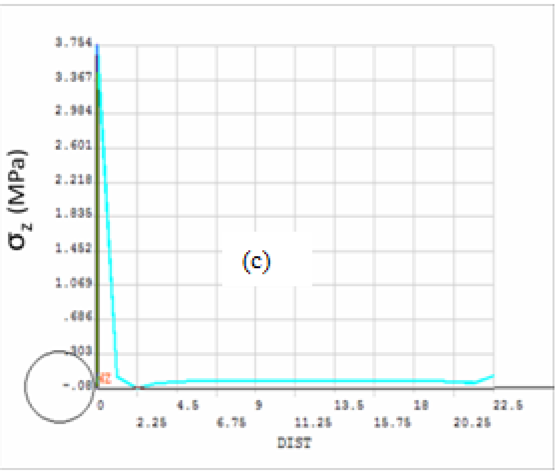


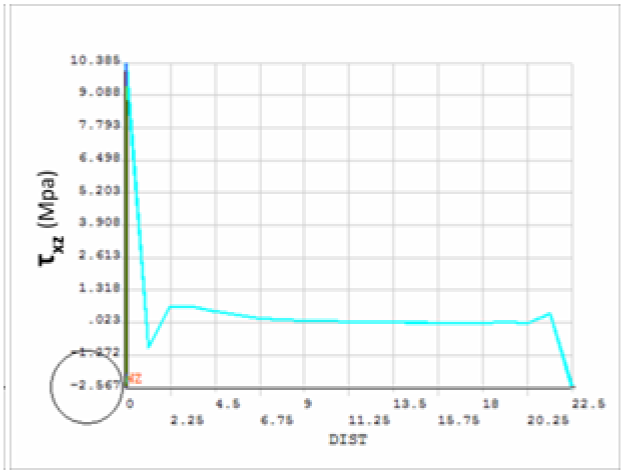
Figure 19Variation of inter-laminar (a) σz, (b) τyz in an open-hole [0/90] laminate across its width.

As per the above plot, it can be spotted that near the hole periphery, the inter-laminar stresses have a high value. This value persists up to a very confined region near the hole boundary. The value of these stresses decreases to a near-zero value in the rest of the width of the laminate. At the free end, there are some noticeable variations in stresses. The delamination behaviour hence comes into play in the region very near the hole periphery and the outer free end.

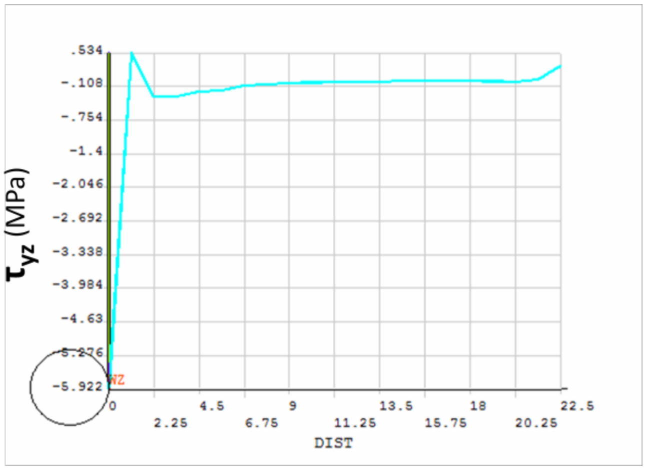
The corresponding plot of stresses was made for [+45/-45]s laminate under axial loading case. And these are plotted at a load at which the first damage initiated(4500N).



(a)



(b)



(c)

Figure 20 Variation of inter-laminar stresses (a) σ_z, (b) τ_{xz}, (c) τ_{yz} across width of the [+45/-45]s plate.

The plots for a [+45/-45]s laminate shows similar fashion for variation of inter-laminar stresses for the first damage initiation load. The delamination starts occurring near the vicinity of the hole. Further, the presence of matrix-mode damage also accelerates the delamination mode of failure of the laminate. The whole such behaviour can be best shown by implementation of Cohesive Zone Element for damage analysis.

II. CONCLUSION

The Numerical analysis was done on [+45/-45]s and [0/90]s Graphite/Epoxy open-hole laminated composites to study the behaviour of damage onset and propagation with and without epoxy layers in between. Use of Hashin's failure criterion and Modified Yamada-Sun failure criterion was done to predict damage mode and loads. A comparison between the two was done. The following conclusions were made throughout this process of analysis.

1. In a 90º ply, under axial load, there was presence of both, fibre as well as matrix damage. Matrix damage pattern suggests matrix cracking in a direction along the orientation of fibre direction. Fibre damage pattern runs perpendicular to the fibre direction, suggesting fibre shear.
2. In 45º plies, under axial load, fibre-mode damage runs parallel to the fibre direction pointing out possible fibre-pull-out. The matrix-mode damage extends perpendicular to the fibre direction indicating transverse matrix cracking.
3. Model-B which has epoxy layer introduced in between the different plies is seen to resist more load as compared to the non-epoxy layered model-A. This is mainly because of the fact that the isotropic epoxy layer tries to arrest damage.
4. Modified Yamada-Sun failure criterion was seen to estimate more loading capacity before damage than Hashin's criteria. The reason for that is, it ignores through-the thickness stresses in its formulation whereas Hashin's criteria (which is known to give best results) implements it. Hence, Hashin's criterion gives more conservative results.
5. Due to damage accumulation and build-up, it was seen that, damage propagates more rapidly at higher loads.

III. SCOPE OF FUTUREWORK

1. Puck's failure criteria can be incorporated to the model to study for fibre failure mode and intra-fibre failure mode.
2. Implementation of cohesive zone models can be done for progressive damage analysis since it catches the delamination behaviour and its damage onset condition is based on strain energy-based failure criteria.
3. A non-linear stress strain relationship can be used to model the finite element model in order to include into the problem the effect of non-linearities in the zone of damage onset and propagation.
4. Element Failure Method can be introduced for study of progressive damage analysis and a comparative study can be made between this approach and the Cohesive-Zone Method.
5. The effect of different W/D ratios can be studied to predict how it affects damage properties.

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