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INFLUENCE OF NOTCH ON PROGRESSIVE DAMAGE OF MULTI-LAYER COMPOSITE LAMINATES

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Key words: Damage mechanics, ABAQUS user-defined subroutine, Composite laminates, Finite element analysis, Strength, Degradation.

Summary: *A finite element progressive damage model considering solid brick element, is developed for the failure analysis of notched multi-layer composite laminates. The material constitutive relations and the progressive damage algorithms are implemented into the FE code ABAQUS, using user-defined subroutine UMAT. Four failure modes namely: fiber tensile/compressive failure, matrix tensile/compressive failure, fiber/matrix shear failure and delamination failure, are included in the present model. The efficiency of the constitutive model and the computational scheme is verified by simulating the progressive damage of composite laminates comprising of through hole laminates, subjected to in-plane uniaxial tensile loading. It has been shown that the estimated results agree well with the experimental data reported in the literature. The proposed progressive damage model has also proven to be capable of accurately predicting the load-deflection relations of notched laminated composites. A parametric study has been carried out for the progressive damage simulations of notched composite laminates with various hole sizes, position of hole and hole diameter to laminate thickness ratio etc.*

1 INTRODUCTION

Use of fiber reinforced plastic (FRP) materials in engineering applications are increasing day-by-day due to numerous advantages over the conventional construction materials. FRP composite materials show numerous superior material properties such as: light weight, good corrosion resistance, ability to be moulded in any shape etc. For these reasons, ranging from various sports accessories to advanced aerospace and ship structures, FRP materials are now very popular. In many of these structures, notches are unavoidable for different components and they tend to decrease the strength. For these structural components, local damages may be initiated at an early loading stage and can propagate as the load increases. The progressive failure analysis of these composite laminates are required to predict their accurate mechanical behaviour under various loading conditions. However, their failure mechanisms are rather complex due to their inhomogeneous and layered configuration. Defects namely: fibre breakage, matrix cracking, fibre/matrix de-bonding occurring in a ply do not cause the immediate collapse but, accumulate gradually within the laminates which leads to progressive degradation of the material properties.

Chang and Chang [1] was first to propose a finite element progressive damage model for predicting tensile strength of laminated composites containing stress concentrations.

Progressive damage by partially discount method was introduced by them. Although, their model results in underestimation of failure strength in some cases [2]. Later, Chang and Lessard [3] extended the progressive damage model to investigate the compressive failure strength of laminated composites. Progressive damage model is already proved as very powerful model in damage analysis and prediction of failure strength. Researchers like: Lessard and Shokrieh [4], Shahid and Chang [5], Su et al. [6], Icten and Karakuzu [7] studied damage accumulation in composite laminates. Several damage models for fiber reinforced plastics have also been published based on the continuum damage mechanics [8–11]. There are many such papers which have already been reported to predict the failure strength and damage propagation of composite laminates with notches, but only few of them can give precise result. The cause behind this is that, still there have unavailability of well-established failure criterion and stiffness degradation rules for laminated composites, and is still an area of research.

In this paper, a finite element progressive damage model has been presented, which can predict the failure load of laminated composite plates with stress concentration. The present model is applicable for the composite laminates, which shows some non-linearity but not up to the plastic behaviour and type of failure is brittle in nature. This type of behaviour is generally visible for the laminated composites like: E-Glass/Epoxy, commonly used for heavy civil engineering application. In the present model, a user-defined subroutine UMAT is written for the progressive damage analysis considering 3D solid brick elements. Progressive damage analysis of notched composite laminates using UMAT and considering 3D solid brick element is currently rare in literature. This type of element is required for better representation of damage propagation through the thickness of laminate. The present model can also predict progressive damage of thick laminates accurately because of use of this type of solid elements. The existing failure criteria available in literature for the composite laminates has also been modified here to predict fiber/matrix shear damage and delamination effects. The results generated from the present model, agree well with the available results in literature. The effect of change in diameter and position of hole with different laminate thicknesses have been studied here. This type of study is very much helpful to choose correct dimensions of a joint to get a desired behaviour.

2 NUMERICAL MODEL

The proposed progressive material damage model has been assimilated with Abaqus/Standard finite element software package using the user-subroutine UMAT. The Cauchy nominal stresses are updated as well as the consistent tangent stiffness matrix are derived at each time step. Solution-dependent state variables have been used to store calculated failure indexes. In the present progressive damage model, material properties are degraded according to type of failure. For example, if fibre failure is occurred, the longitudinal modulus, E_{11}, is discounted to simulate the loss of load carrying capacity in that direction, whereas the transverse moduli, E_{22} and E_{33}, could be considered to be unaffected and consequently not altered. So, for performing progressive failure analysis of composite laminates, it is mandatory that the failure mode should be evaluated accurately, so that, the material properties can be degraded appropriately. A well-known failure theory for laminated composite materials developed by Hashin [12] that can predict failure mode as well as failure load has been implemented with some modification in the present program.

2.1 Failure criterion

The Hashin failure criteria [12] has been considered here along with delamination failure criteria and fiber/matrix shear failure criteria [4,13] for determining failure of a material point of the composite laminate. The failure criteria considered here are:

Tensile fibre failure, $\sigma_{11} > 0$

$$\frac{\sigma_{11}^2}{X_t^2} + \frac{\sigma_{12}^2 + \sigma_{13}^2}{S_{12}^2} = 1 \tag{1}$$

Compressive fibre failure, $\sigma_{11} < 0$

$$\sigma_{11} = -X_c \tag{2}$$

Tensile matrix failure, $\sigma_{22} + \sigma_{33} > 0$

$$\frac{(\sigma_{22} + \sigma_{33})^2}{Y_t^2} + \frac{\left(\sigma_{23}^2 - \sigma_{22}\sigma_{33}\right)}{S_{23}^2} + \frac{\left(\sigma_{12}^2 + \sigma_{13}^2\right)}{S_{12}^2} = 1 \tag{3}$$

Compressive matrix failure, $\sigma_{22} + \sigma_{33} < 0$

$$\frac{(\sigma_{22} + \sigma_{33})}{Y_c}\left\{\left(\frac{Y_c}{2S_{23}}\right)^2 - 1\right\} + \frac{(\sigma_{22} + \sigma_{33})^2}{4S_{23}^2} + \frac{\left(\sigma_{23}^2 - \sigma_{22}\sigma_{33}\right)}{S_{23}^2} + \frac{\left(\sigma_{12}^2 + \sigma_{13}^2\right)}{S_{12}^2} = 1 \tag{4}$$

Fibre/matrix shear failure,

$$\frac{\sigma_{11}^2}{X_c^2} + \frac{\sigma_{12}^2}{S_{12}^2} + \frac{\sigma_{13}^2}{S_{13}^2} = 1 \tag{5}$$

Delamination tension/compression failure,

$$\left(\frac{\sigma_{33}}{Z_r}\right)^2 + \left(\frac{\sigma_{13}}{S_{13}}\right)^2 + \left(\frac{\sigma_{23}}{S_{23}}\right)^2 = 1 \tag{6}$$

2.2 Stiffness discount strategy

The correlative elastic constants (ECs) have been discounted by multiplying with a very small value (*c*) if failure occurred in one direction. It is given as very small value rather than zero, because, it would result in numerical instability during stress analysis. The following discount strategy has been considered in the present formulation:

Tensile fibre failure: $E_{11} = c.E_{11}^0, G_{12} = c.G_{12}^0, G_{13} = c.G_{13}^0$
Compressive fibre failure: $E_{11} = c.E_{11}^0, G_{12} = c.G_{12}^0, G_{13} = c.G_{13}^0, G_{23} = c.G_{23}^0$
Tensile/Compressive fibre failure: $E_{22} = c.E_{22}^0, E_{33} = c.E_{33}^0, G_{23} = c.G_{23}^0$
Fibre/matrix shear failure: $G_{12} = c.G_{12}^0$
Delamination tension/compression failure: $E_{33} = c.E_{33}^0, G_{13} = c.G_{13}^0, G_{23} = c.G_{23}^0$

Where, superscript ‘0’ denotes the initial undamaged material constant value.

3 RESULTS

The present model has been verified with the results available in literature. The proposed model has been verified with a simple solid laminated plate without any notch and also with a notched laminated plate. A parametric study of progressive damage have also been presented to study the effect due to change in lamination scheme.

3.1 Progressive failure analysis of laminated plate

Progressive damage analysis have been performed on IM7/5250-4 composite laminates, considering three different type of lamination scheme namely: L1, L2 and L3 as shown in Table 1. The width of the laminate L1 and L2 is 25.4 mm and for laminate L3 the width is 31.75 mm. All laminates have been considered to have layers of thickness 0.132 mm each. The material properties for the IM7/5250-4 composite are presented in Table 2 and Table 3. The material property values have been taken from Reddy et al. [14].

Laminate	Lamination scheme	Experimental [14] (kN)	Present (kN)
L1	$[45/90/-45/0]_{3s}$	78.822	79.97
L2	$[45/90/-45/0_3/-45/0_3/45/0]_s$	123.038	137.86
L3	$[45/90/-45/45/-45/0/45/-45/45/-45]_s$	39.260	44.44

Table 1: Lamination schemes and ultimate load values.

E_1 (GPa)	E_2 (GPa)	G_{12} (GPa)	G_{23} (GPa)	v_{12}	v_{23}
161.337	9.653	5.998	3.378	0.34	0.49

Table 2: Material properties of IM7/5250-4.

X_t	X_c	Y_t	Y_c	S_{12}	S_{23}
2709.64	1075.582	64.535	258.553	92.39	67.5686

Table 3: Material strength (MPa) data for IM7/5250-4.

The load vs displacement plots from the present simulation and by Reddy et al. [14], for the laminate L1 and L2 have been shown in Figure 1 and Figure 2 respectively. From these figures it is clearly visible that, the present load vs displacement behaviour matches almost exactly with the published literature. Although, Table 1 shows that, numerical model gives slight higher value in some cases as compared to experimental results [14], which is quite common and expected due to some deviations during sample manufacturing.

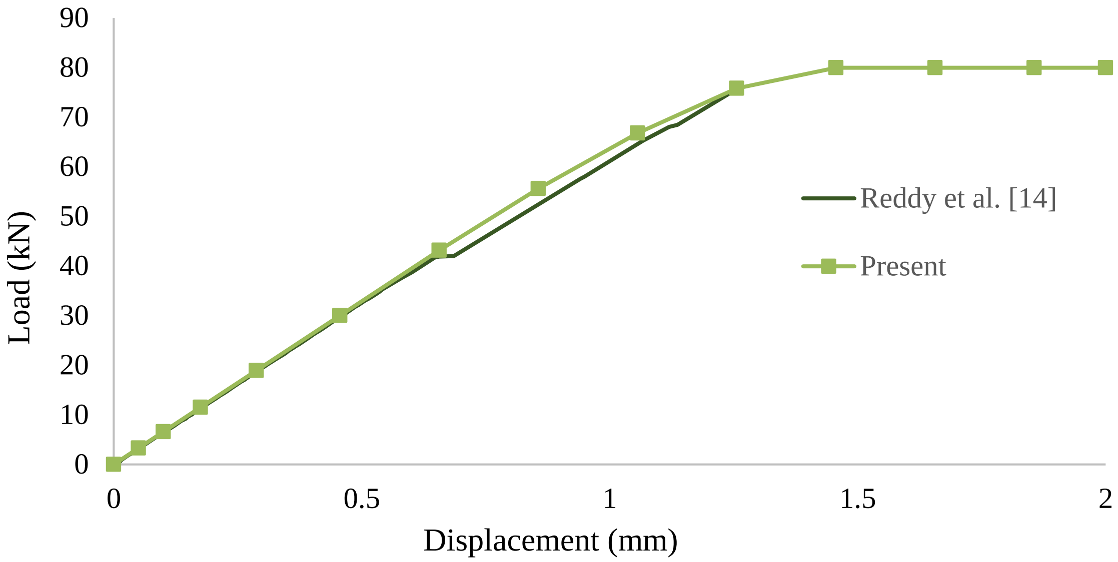


Figure 1: Load vs displacement plot for laminate L1

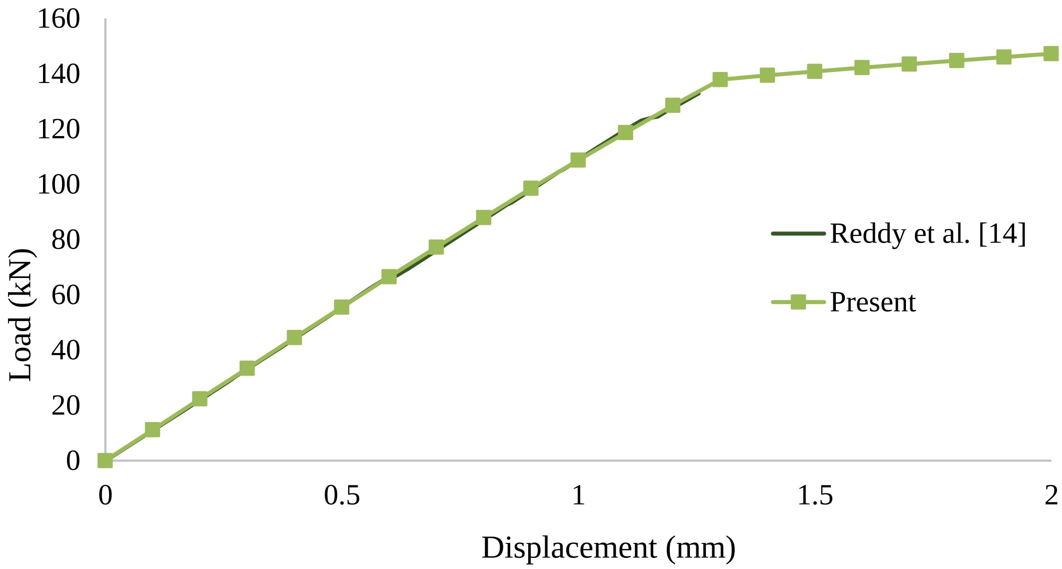


Figure 2: Load vs displacement plot for laminate L2

3.2 Progressive failure analysis of AS4/PEEK composite laminates with hole

The efficiency of the constitutive model and the computational scheme is verified by simulating the progressive damage of AS4/PEEK composite laminates comprising of a central through hole, subjected to in-plane uniaxial tensile loading. Each laminate has length of 100 mm, width of 20 mm and thickness of 2 mm. The diameter of the holes are considered as 2 mm, 5 mm and 10 mm. The laminates are composed of eight layers of equal thickness with lamination scheme $[0/45/90/\text{-}45]_{2s}$. The material stiffness and strength properties considered for the analysis are shown in Table 4 and Table 5, which are taken from Chen et al. [15].

E_1 (GPa)	E_2 (GPa)	G_{12} (GPa)	G_{23} (GPa)	ν_{12}	ν_{23}
127.6	10.3	6.0	3.7	0.32	0.45

Table 4: Material properties of AS4/PEEK.

X_t	X_c	Y_t	Y_c	S_{12}	S_{23}
2023.0	1234.0	92.7	176.0	82.6	82.6

Table 5: Material strength (MPa) data for AS4/PEEK.

Figure 3 shows the present finite element model for the laminated plate with hole diameter of 5 mm. The estimated results are presented in Table 6, which are in good agreement with the results reported in literature.

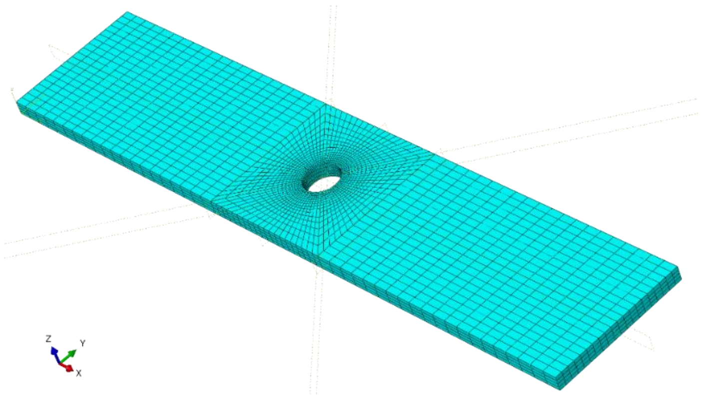


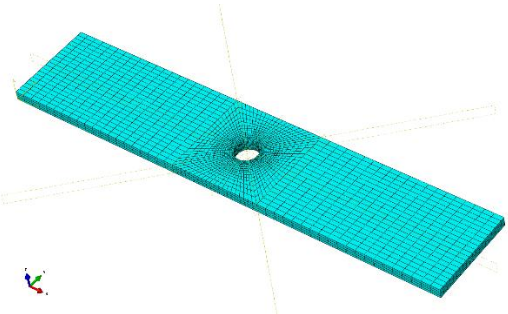
Figure 3: Finite element model of the laminate

Laminate	Hole diameter	Chen et al. [15] (kN)- Continuum Shell model	Present (kN)
L1	2 mm	28.836	27.287
L2	5 mm	23.19	22.493
L3	10 mm	14.99	14.701

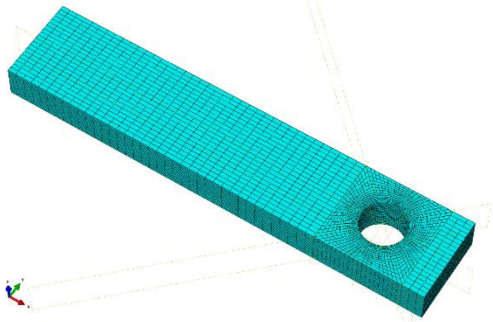
Table 6: Ultimate load values for the laminates with different size of hole.

3.3 Parametric study

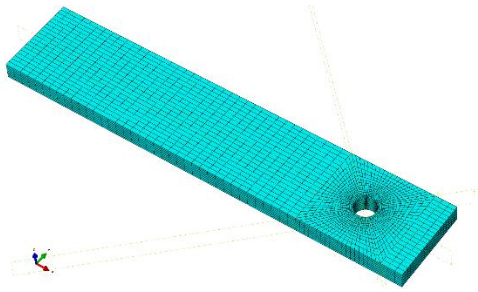
A parametric study has been performed considering different position and diameter of the hole for different laminate thickness and subjected to in-plane uniaxial tensile loading. The hole diameters (*d*) considered here are 2 mm, 5 mm and 10 mm. Three type of edge distances (*e*) from the hole center have been considered such as: 50 mm, 30 mm and 15 mm. Here, the edge distance is the distance of the center of the hole from the loading end. The laminate thicknesses (*t*) are considered as 2 mm, 4 mm and 8 mm. So, total 27 number of simulations has been conducted for each lamination schemes to get results for all type of possible combinations. Some of the developed finite models have been shown in Figure 4. Finer mesh has been considered near the hole periphery due to high stress concentration.



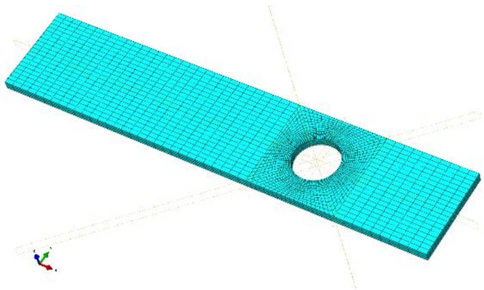
(a) e = 50 mm, d = 5 mm, t = 2 mm



(b) e = 15 mm, d = 10 mm, t = 8 mm



(c) e = 15 mm, d = 5 mm, t = 4 mm



(d) e = 30 mm, d = 10 mm, t = 2 mm

Figure 4: Some of the developed finite element models of the laminates with change in the geometry.

Two types of lamination schemes, as quasi-isotropic $[45/0/-45/90]_{2s}$ and zero-dominated $[0_2/45/90]_{2s}$ have been considered in this present study. Because of simple axial loading, the zero dominated laminate gives higher failure load compared to the quasi-isotropic laminate. Table 7 and table 8 shows the failure loads and displacements at failure for the $[45/0/-45/90]_{2s}$ and $[0_2/45/90]_{2s}$ laminates respectively for different hole diameters (*d*) and thickness (*t*) for the edge distance (*e*) of 30 mm. The variation in the results due to change in edge distance to 50 mm and 15 mm have found to be very negligible compared to edge distance 30 mm and has not presented here.

Sl. No.	Hole diameter (d)	Thickness (t)	Ultimate load (kN)	Displacement at failure (mm)
1	2	2	12.465	1.956
2	2	4	24.93	1.956
3	2	8	49.825	1.956
4	5	2	10.449	1.581
5	5	4	20.896	1.581
6	5	8	41.752	1.581
7	10	2	6.925	1.331
8	10	4	13.866	1.331
9	10	8	27.687	1.331

Table 7: Ultimate load and displacements at failure for the-quasi-isotropic laminates with edge distance (e) 30mm.

The ultimate load has found to be approximately just double when the thickness of the laminate has doubled. But, the displacement at failure remains same when only thickness of the laminates have been varied. A plot of ultimate loads for the quasi-isotropic laminates for change in laminate thickness has been shown in Figure 5.

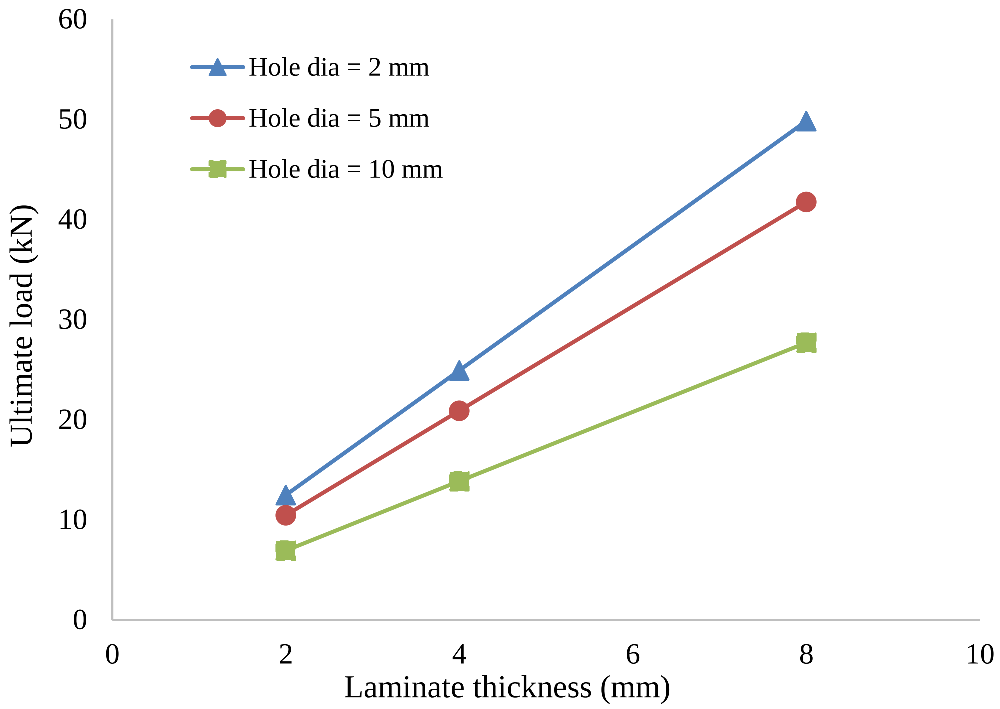


Figure 5: Plot of ultimate loads for different thickness of the quasi-isotropic laminates (e = 30 mm)

A plot of the displacements at failure for different diameter of the hole has been presented in Figure 6. A sharp change in the displacement has been noticed when the diameter of the hole has been changed from 5 mm to 2 mm.

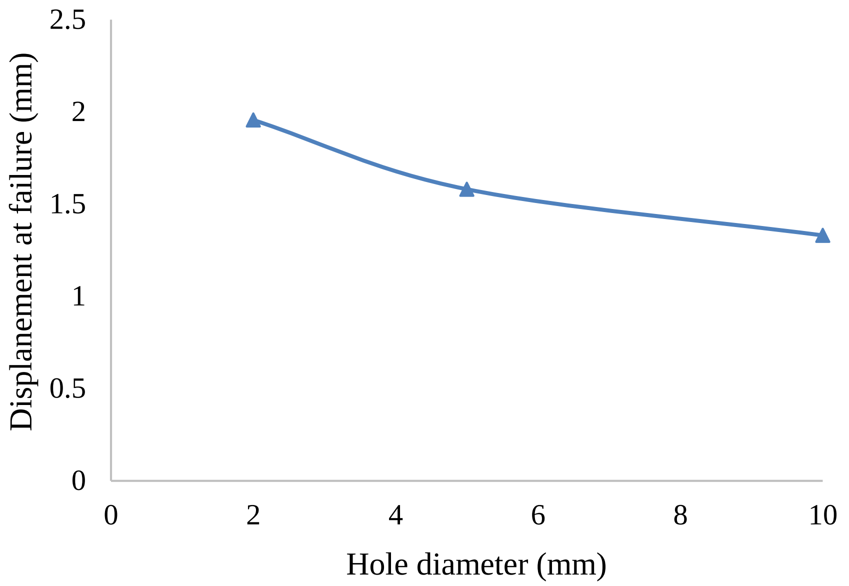


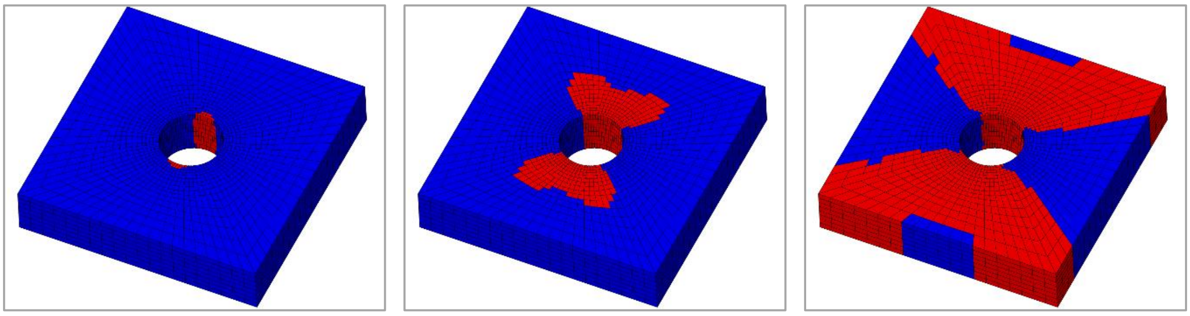
Figure 6: Plot of displacements at failure for different hole diameter of the quasi-isotropic laminates (e = 30 mm)

Same type of results have been obtained for zero-dominated laminates with higher failure load as shown in Table 8. The displacements at failure found to be near about same for the change in the lamination scheme only.

Sl. No.	Hole diameter (d)	Thickness (t)	Ultimate load (kN)	Displacement at failure (mm)
1	2	2	17.78	1.956
2	2	4	35.558	1.956
3	2	8	71.066	1.956
4	5	2	14.497	1.644
5	5	4	28.954	1.644
6	5	8	57.829	1.644
7	10	2	9.32	1.269
8	10	4	18.673	1.269
9	10	8	37.318	1.269

Table 8: Ultimate load and displacements at failure for the-zero-dominated laminates with edge distance (e) 30mm.

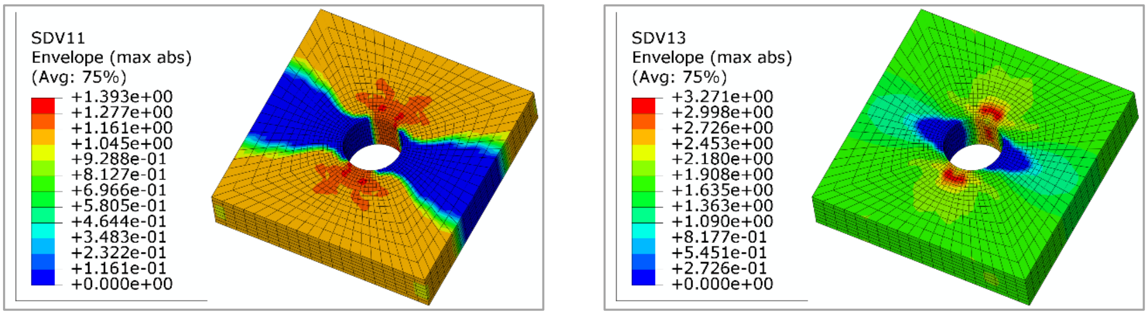
The propagation of failure for a typical specimen with quasi-isotropic lamination scheme is shown in Figure 7. For this figure, it is clearly visible that, failure initiates near the periphery of the hole and propagates to the edges of the laminates which causes failure of the whole sample.



(a) Failure initiation (b) Propagation of failure (c) At ultimate load

Figure 7: Propagation of damage for the quasi-isotropic laminate for *e* = 30, *d* = 5, *t* = 4.

The plot of two significant failure indexes due to tensile fiber failure and due to tensile matrix failure, for the same laminate is presented in Figure 8. Other failure criterions namely: compressive fiber failure, compressive matrix failure are not significant for this case because the loading type is tensile load in axial direction only.



(a) Tensile fiber failure (b) Tensile matrix failure

Figure 8: Plot of different type of failure indexes for the quasi-isotropic laminate for *e* = 30, *d* = 5, *t* = 4.

4 CONCLUSIONS

In this paper, a three dimensional finite element progressive damage model has been presented, which can predict the failure load of laminated composite plates with stress concentration. The material constitutive relations and the progressive damage algorithms are implemented into FE code ABAQUS, using user-defined subroutine UMAT. Four failure modes such as: fiber tensile/compressive failure, matrix tensile/compressive failure, fiber/matrix shear failure and delamination failure, have been considered in the present model. The existing failure criteria available in literature for the composite laminates has been modified to predict fiber/matrix shear damage and the delamination effects. This type of progressive damage model using UMAT and considering 3D brick element is rare in literature. Results from this model can display the propagation of damage through the thickness of laminate also.

The results generated from the present model, agree well with the available results in literature. A parametric study has been carried out for the progressive damage simulations of notched composite laminates for different hole size, position of the hole and thickness of the laminate. This kind of study may help to choose the right dimension for a specific need. It has been noticed that, there is no significant change in results due to change in edge distance, keeping all other parameters unchanged. The failure load directly proportional to the thickness of the laminate, i.e. if thickness of the laminate is doubled the failure load will also be approximately doubled but, there will be no noticeable change in the displacement at failure.

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