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Structural Analysis and Progressive Failure Analysis of Laminated Composite Joints-Single Pin Configuration

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***Abstract*—A composite material is prepared by joining two or more materials of different properties. The joined materials work together and give a new material with unique properties. Use of composite is provoked by low weight- to- stiffness and weight- to- strength ratios. Complex damage behaviour is shown by composites due to their anisotropic nature and heterogeneity. Thus the detailed analysis of composite structures is a formidable task. A joint is a structural connection between two or more members intended for load transfer. Most structures contain one or more joints. All structures contain joints. Joints are one of the greatest challenges in the design composite structures because of their anisotropic nature and heterogeneity, introduce high local stress concentrations. Damage initiation and propagation is the greatest concern in understanding the behaviour of bolted connections in composites. To support laboratory tests, a finite element modelling can be done to support joint design and predict propagation of damage. In this present study the analysis of a double lap joints are done using continuum shell elements and a progressive failure analysis was done using Tsai-Hill failure criteria and material stiffness degradation mechanism. . Progressive failure analysis was also done to determine the mode of failure and showed good correlation with the stress results. Primarily two modes of failure observed i.e. fibre failure and matrix failure.**

***Index Terms*—Composite, anisotropic, progressive failure analysis, mode of failure.**

I. Introduction

A composite material is prepared by joining two or more materials of different properties. Use of composite is provoked by high specific stiffness and high specific strength [1]. Improved weight savings, increased fuel efficiency, enhanced durability, and superior structural proper-ties make composite materials ideal for aerospace applications [2]. From the library of elements available composites can be modeled using shell elements, continuum shell elements and solid elements [3].

A joint is a structural connection between two or more members intended for load transfer. All structures contain joints. Joints are one of the greatest challenges in the design composite structures because of their anisotropic nature and heterogeneity, introduce high local stress concentrations. Thus overall structural capacity is determined by the joints.

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Several researchers have done studies on the strength of single lap composite bolted joints [4-6]. Effect of bolt-hole clearance was investigated on single-lap, single-bolt composite joints. Increasing clearance was found to result in reduced joint stiffness and increased ultimate strain in all tested configurations. In single-lap joints, clearance caused three-dimensional variations in the stress distribution in the laminate. These variations dependent on the lay-up sequence. A highly efficient user-defined finite element model and empirical expressions were developed to determine the bolt-load distribution in large-scale composite structures [7, 8].

Damage initiation and propagation is the greatest concern in understanding the behavior of bolted connections in composites. To support laboratory tests, a finite element modeling can be done to support joint design and predict propagation of damage. Failure modes and trends in material response evaluated to assess the progression of failure in composite joints. Various progressive damage mechanisms are a) continuum damage mechanics (CDM) or material properties/stiffness degradation method (MPDM) all forms of damage is represented as local stiffness reduction in individual elements. Poisson's ratios are not degraded and only the Young's moduli and shear modulus are modified for a failed element. b) Discrete damage modeling (DDM) in which matrix cracks and delamination are explicitly introduced into model as displacement discontinuities, which they create. c) X-FEM formulations, degrees of freedom are added to elements along the crack surface to describe the displacement discontinuity. d) Cohesive elements or the element failure method (EFM) model formulation was used for crack opening [9, 10]. Prediction of the failure carried out using various failure criteria such as Hashin S, Tsai-Hill and Tsai-Wu failure theory. The results obtained were compared and plotted against some available experimental findings [11,13].

In this present study, validation procedure was carried out to determine the accuracy of SC8R continuum shell elements and to verify the modeling strategy. The analysis of a double lap joints were carried out using continuum shell elements and a progressive failure analysis was done using Tsai-Hill failure criteria and material stiffness degradation mechanism.

II. Failure Criteria

A successful design requires efficient and safe use of materials. Composite materials have many mechanical characteristics that are different from those of more conventional engineering materials. Composite materials are inhomogeneous (i.e. constitute non-uniform properties over the body) and non-isotropic (orthotropic or more generally anisotropic). An orthotropic body has material properties that are different in three mutually perpendicular directions. Have three mutually perpendicular planes of material property symmetry. Thus the properties depend on orientation at a point in the body. Isotropic materials mainly have two strength parameters such as normal strength and shear strength. Failure is initiated for an isotropic material if any of the parameters is greater than the corresponding ultimate strengths.

Theories were developed to compare the state of stress in a material to failure criteria. The two failure theories used are Tsai–Hill Failure Theory and Tsai–Wu Failure Theory, in which the strength parameters (Xt, Yt, Xc, Yc and S) are determined through experiments and stress induced (S11, S22 and S12) are results obtained from Finite element (FE) model.

Xt –Tensile strength in X direction
Yt – Tensile strength in Y direction
Xc- Compressive strength in X direction
Yc- Compressive strength in Y direction
S- Shear strength
S11- Stress induced in principal direction
S22-Stress induced in transverse direction
S12-Shear stress induced

a) Tsai–Hill Failure Theory

$$I_F = \frac{S_{11}^2}{X^2} - \frac{S_{11}S_{22}}{X^2} + \frac{S_{22}^2}{Y^2} + \frac{S_{12}^2}{S^2} \qquad (1)$$

If I_F >1, failure have occurred.

b) Tsai–Wu Failure Theory

$$I_F = F_1S_{11} + F_2S_{22} + F_{11}S_{11}^2 + F_{22}S_{22}^2 + F_{66}S_{12}^2 + 2F_{12}S_{11}S_{22}$$
(2)

If I_F >1, failure have occurred.

Where,

$$F_1 = \frac{1}{X_t} + \frac{1}{X_c} \qquad F_2 = \frac{1}{Y_t} + \frac{1}{Y_c}$$

$$F_{11} = \frac{1}{X_tX_c} \qquad F_{22} = \frac{1}{Y_tY_c}$$

$$F_{66} = \frac{1}{S^2} \qquad F_{12} = {}^{*}f\sqrt{F_{11}F_{22}}$$

*f – constant default value is zero

III. Model Configuration

In this configuration the width of the composite plate is changed and the effect of change in width is been investigated. The plate is subjected to a load of 14 kN. The centre to centre distance between bolts is taken as 100mm and the edge distance is 15mm as shown in Figure 1. The diameter of bolt is 10mm. The widths of the composite plate are 50mm, 40mm, 35mm, 20mm and 15mm.

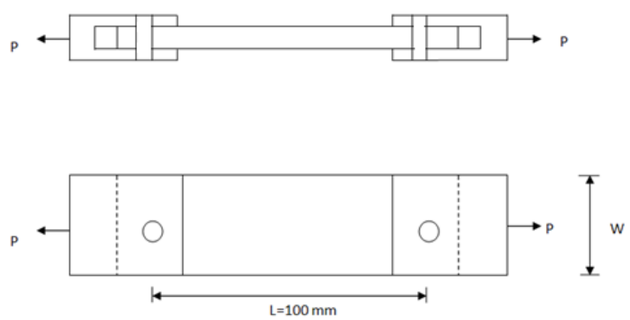


Fig. 1. Configuration

A. Material Properties

The materials used for the composite laminate are carbon -epoxy, Glass- epoxy and steel. The material properties are shown in the Table 1 and Table 2.

Table 1. Normalized material properties of carbon -epoxy and Glass epoxy

Property	Carbon-epoxy	Glass-epoxy
E_L/E_T	16.63	2.47
ν_{LT}	0.31	.229
G_{LT}/E_T	0.67	0.25
X_L/X_T	2.03	1.70
Y_L/X_T	0.04	0.3
Y_T/X_T	0.09	0.45

Table 2. Material properties of steel

Property	Steel
E_L (MPa)	200000
ν_{LT}	.31

B. Composite layup configuration

The total thickness of the composite layup is 4mm and the layup sequence is as shown in the Table 3. The composite plate is symmetric about mid layer thus only half thickness is been considered for analysis. Continuum shell elements are used to mesh a composite layup. Figure 2 shows the ply stack diagram of composite plate. Figure 3 shows the orientation of ply with respect to loading direction.

Layup Sequence is: [90/0/-45 /45/0/90/0- $G^{-1/2}$]s

Table 3. Layup configuration of composite plate

Layer No.	Material	Thickness (mm)	Fiber orientation (degree)
1	Carbon– epoxy	0.3	90
2	Carbon– epoxy	0.3	0
3	Carbon– epoxy	0.3	-45
4	Carbon– epoxy	0.3	45
5	Carbon– epoxy	0.3	0
6	Carbon– epoxy	0.3	90
7	Glass – epoxy	0.3	0
8	Carbon– epoxy	0.3	90
9	Carbon– epoxy	0.3	0
10	Carbon– epoxy	0.3	45
11	Carbon– epoxy	0.3	-45
12	Carbon– epoxy	0.3	0
13	Carbon– epoxy	0.3	90

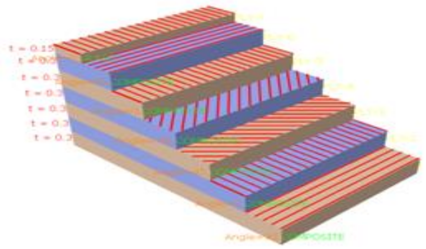


Fig. 2. Ply stack plot of composite plate.

Fig. 3. Orientation of ply with respect to loading direction

IV. Progressive Failure Analysis

Failure of composite structures is a progressive series of events. It often starts as a tiny crack between the fibres and matrix. These cracks reduce the stiffness of the composite. Capturing stress redistribution is the key to realistic simulation of failure in composite structures. Progressive failure analysis is done on the same configuration at failure load. Progressive failure analysis helps us in knowing the mode of failure. The damage in composite structures is generally a combination of matrix cracking, fibre breakage in tension and compression, and delamination. The first two damage modes, matrix cracking and fibre breakage in tension and compression are considered.

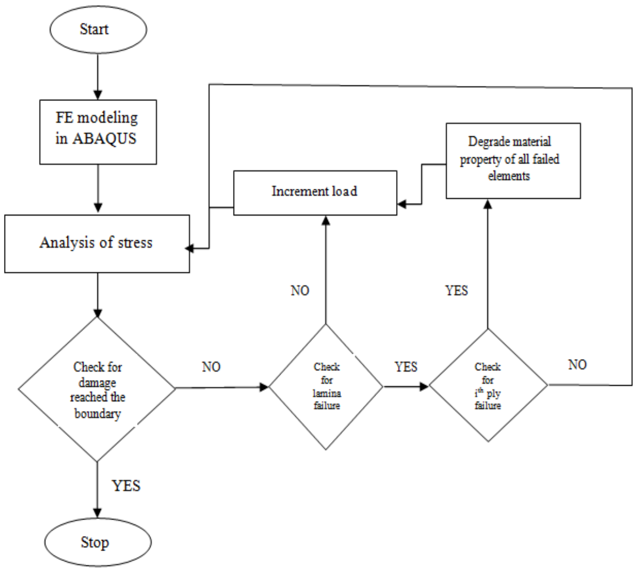


Fig. 4. Flow chart showing process of progressive failure analysis

The procedures for predicting the growth of the damage path are developed using the progressive failure analysis methodology implemented within finite element analysis. The progressive failure analysis methodology generally consists of three steps Figure 4 shows the flow chart of methodology of progressive failure analysis: a) calculating the lamina stress {Stresses computed in principal, transverse and shear directions} b) Estimating failure index and c) degrading the material stiffness in the failed elements to represent damage. In the study intra-laminar failure modes considered. Geometric and material nonlinearity were included in the model. The third and final step in the progressive failure analysis is to apply the material degradation model to the failed material points. The material properties are degraded based upon the damage mode. The progressive failure analysis is implemented in Abaqus. The process is invoked at each material point of an element to evaluate the failure criterion. When failure is detected, the degradation model is applied accordingly. In this model, the material stiffness E_{11}, E_{22} and G_{12} are instantaneously reduced by 1000.

V. Modeling

The FEM model is as shown in the Figure 5. The model has symmetry about X, Y and Z direction, thus only 1/8th of the configuration is analysed. The Figure 6 shows the meshed model configuration used for analysis in abaqus software.

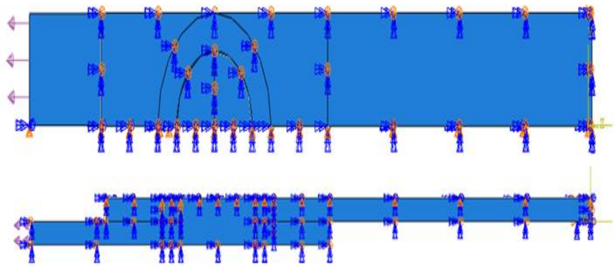


Fig. 5. Configuration model in abaqus

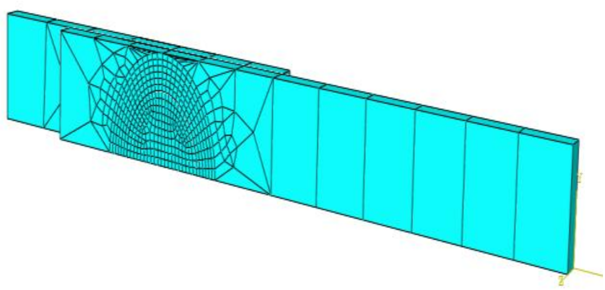


Fig. 6. Configuration meshed model in abaqus

VI. Results

A. Validation

The accuracy of any FE model is dependent on the accuracy of the geometry, the type and number of elements used, and the material property model. Validation is done in this study to check whether the SC8R elements used produce required results for the composite layup and to check the modeling strategy. For that purpose a problem done by Buket Okutan [14] is selected and FE modeling was carried out. The results are verified with the results obtained from previous study.

Geometry: A rectangular composite plate has length L, thickness t and width W with a hole of diameter D. The hole is at a distance E from the free edge of the plate . The configuration of composite plate is shown in Figure 7. In the study [14] it was observed that for the [0/90/0]s laminate, failure modes were found as bearing mode when the E/D ratio is greater than 3. Thus E/D ratio 4 was taken for validation purpose.

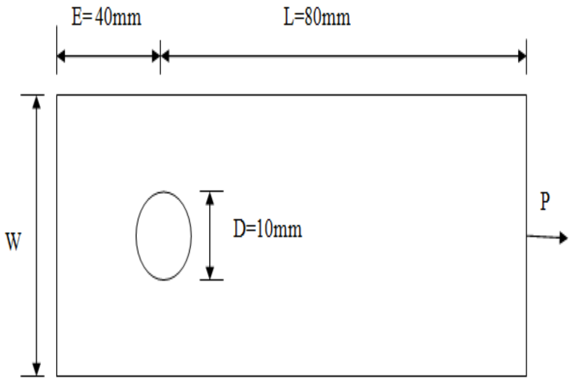


Fig. 7. Geometry of specimen

Material: Table 4 shows the material properties of glass-fiber/epoxy composite. Stacking sequence of composite plate is [0/90/0] s

Load: A tensile load is applied at the hole free edge of the plate resisted by the pin.

FE model and boundary condition: Thus composite plate modeled using abaqus software gives required results. Composite plate was modeled using continuum shell element (SC8R). Widths modeled are 20mm, 30mm, 40mm and 50mm. Figure 8. shows FE model done for the joint configuration. 1/4th of configuration was modeled due to symmetry in Y and Z direction. Symmetric boundary conditions was been applied. Tensile load is applied at the hole free end of composite. In the problem pin was assumed to be rigid and thus not modelled. The degrees of freedom were arrested in the quarter portion of bolt hole to simulate support conditions.

Table 4 Properties of glass-fiber/epoxy composite

Longitudinal modulus E1 (MPa)	44,000 (±560)
Transverse modulus E2 (MPa)	10,500 (±420)
Shear modulus G12 (MPa)	388045 (±360)
Poisson's ratio ν_{12}	0.36
Longitudinal tension Xt (MPa)	800 (±59)
Longitudinal compression Xc (MPa)	350 (±42)
Transverse tension Yt (MPa)	50 (±4.35)
Transverse compression Yc (MPa)	125 (±9.34)
Shear strength S (MPa)	120 (±15.28)

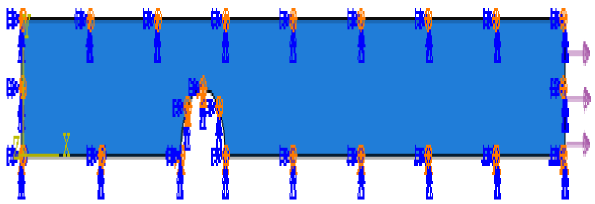


Fig. 8. FE model done for the joint configuration

Results: The obtained results (Figure 9) showed the variation of bearing strength with w/d ratio The results show good correlation and thus the results obtained are validated. Thus SC8R elements can be used to model the composite layup. In the present study bolts are also modeled to replicate the contact property in the real problem.

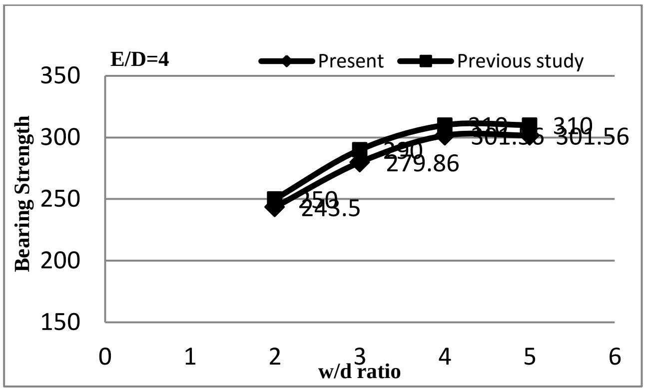
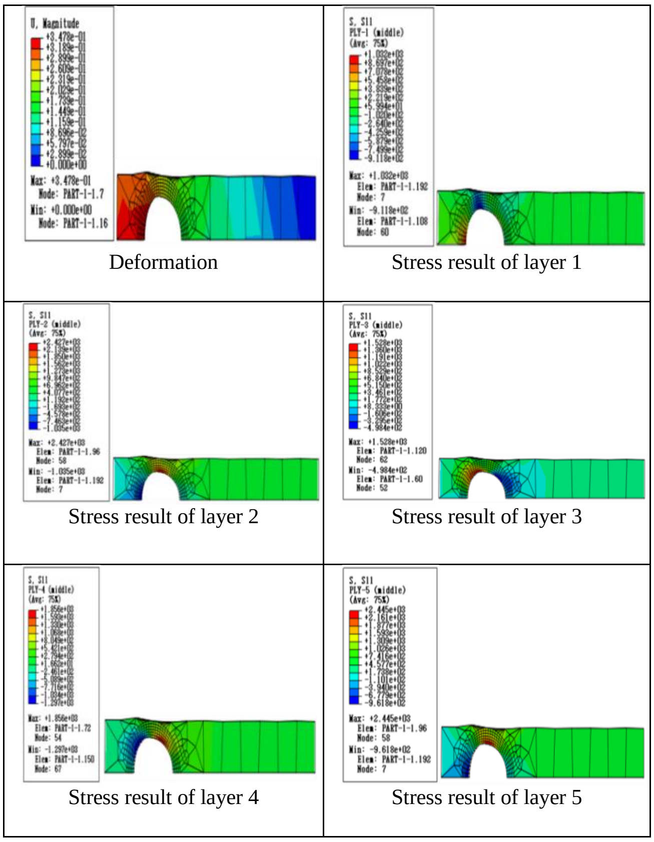


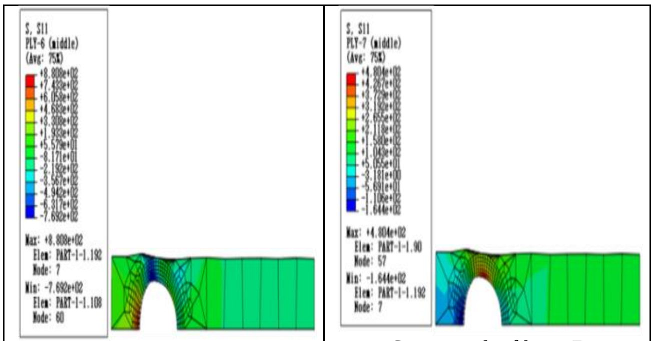
Fig. 9. Variation of bearing strength with w/d ratio

The FEM model is as shown in the Figure 5. The model has symmetry about X, Y and Z direction, thus only 1/8th of the configuration is analysed. The Figure 6 shows the meshed model configuration used for analysis in abaqus software.

B. Stress Results

Figure 10 shows S11 stress distribution in each layer of composite layup of single pin configuration of width 15mm. It can be seen from Figure 10 that, stress is concentrated at the bolt hole. Thus the circumference of bolt hole is set as the region of interest. The Figure 11-Figure 13 shows the variation of stress, i.e. S11, S22 and S12 around the bolt hole in each layer of the composite plate. The S11, S22, S12 stresses are evaluated and are used for the calculation of failure index. Tsai Hill (TSAIH) and Tsai Wu (TSAIW) failure criterion is used to determine the failure index of each layer and the layer in which first failure (first ply failure) occurred is determined. The component that is responsible and the failure load are also determined. Table 5 & Table 6 shows the failure assessment details using Tsai-Hill and Tsai-Wu failure theories.





Stress result of layer 6 | Stress result of layer 7

Fig. 10. Stress S11 in each layer of 15mm configuration

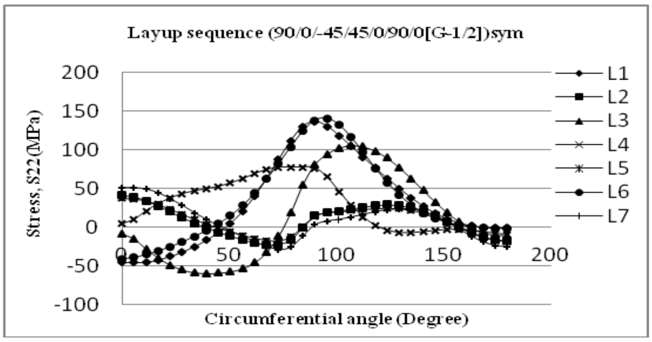


Fig. 12. Variation of stress S22 around the bolt hole in each layer of the composite plate for single pin configuration

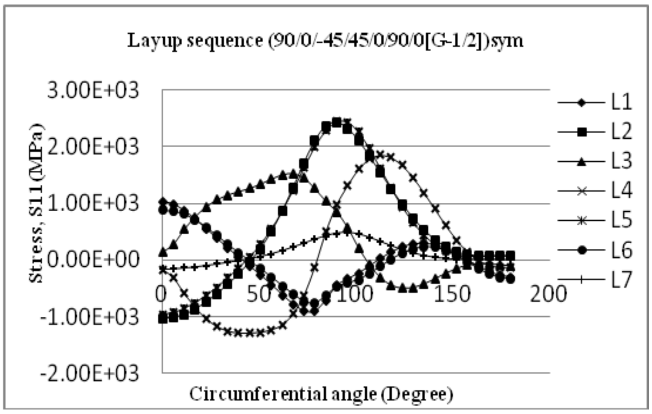


Fig. 11. Variation of stress S11 around the bolt hole in each layer of the composite plate for single pin configuration

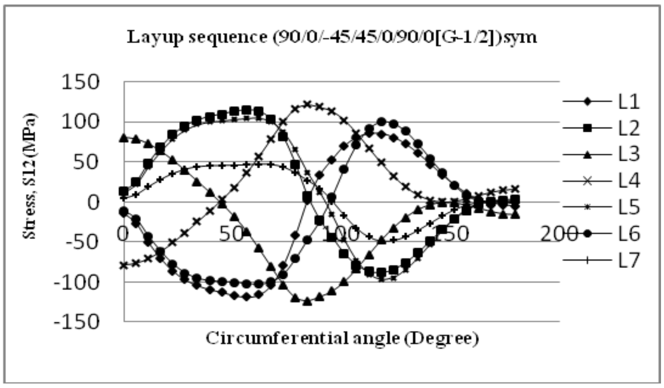


Fig. 13. Variation of stress S12 around the bolt hole in each layer of the composite plate for single pin configuration

Table 5. Failure assessment details of configuration by Tsai-Hill failure criteria

Width (mm)	Load (kN)	Tsai Hill failure index	Initial Failure layer Number	Initial Failure layer orientation	Location of failure with respect to circumference angle (degree)	Failure component
15	3.5	3.286	6	90	95.58	S22
20	3.5	2.161	6	90	95.58	S22
35	3.5	1.740	4	45	52.23	S11
40	3.5	1.726	4	45	52.23	S11
50	3.5	1.72	4	45	52.23	S11

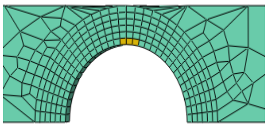
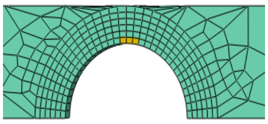
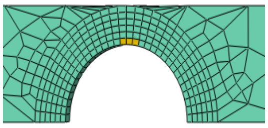
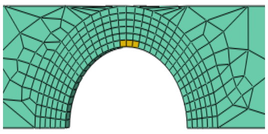
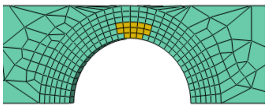
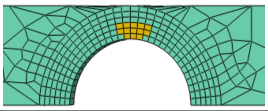
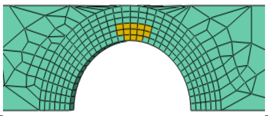
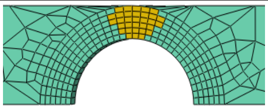
Table 6. Failure assessment details of configuration by Tsai-Wu failure criteria

Width (mm)	Load (kN)	Tsai Wu failure index	Initial Failure layer Number	Initial Failure layer orientation	Location of failure with respect to circumference angle (degree)	Failure component
15	3.5	3.421	6	90	95.58	S22-square
20	3.5	2.270	6	90	95.58	S22-square
35	3.5	1.991	4	45	52.23	S11-square
40	3.5	1.972	4	45	52.23	S11-square
50	3.5	1.971	4	45	52.23	S11-square

C. Progressive Failure Analysis

a) 15 mm width

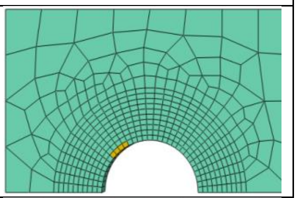
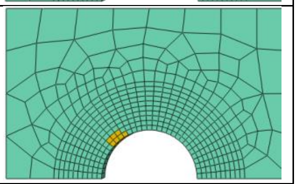
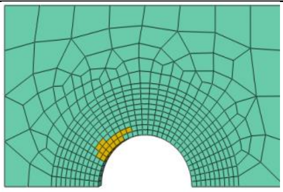
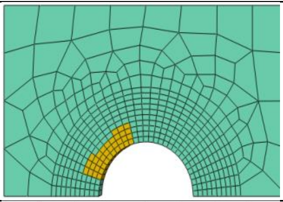
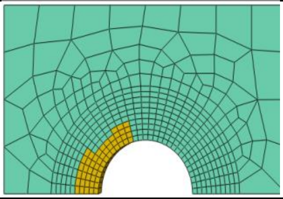
Table 7. Progressive failure analysis of configuration 15mm

No	Failure load (kN)	Layer failing Sequence	Figure
1	1.095	L6,L1	
2	1.095	L6,L1,L3	
3	1.095	L6,L1,L3, L4	
4	1.095	L6,L1,L3,L4 ,L5,L2	
5	1.095	L6,L1,L3,L4 ,L5,L2,L7	
6	1.095	L6,L1,L3,L4 ,L5,L2,L7	
7	1.095	L6,L1,L3,L4 ,L5,L2,L7	
8	1.095	L6,L1,L3,L4 ,L5,L2,L7	

Failure of laminate is assumed to occur when the element degradation reached up to the plate edge. Progressive failure analysis results of 20mm configuration are similar to Table 7.

b) 35mm width

Table 8 Progressive failure analysis of configuration 35 mm

No	Failure load (kN)	Layer failing Sequence	Figure
1	2.03	L4	
2	2.03	L4,L1,L2,L5 ,L6	
3	2.03	L4,L1,L2,L5 ,L6, L3,L7	
4	2.03	L4,L1,L2,L5 ,L6, L3,L7	
5	2.03	L4,L1,L2,L5 ,L6, L3,L7	

Failure of laminate is assumed to occur when the element degradation reached up to maximum displacement limit. Similar failure results Table 8. are obtained for 40mm and 50mm configurations.

VII. INFERENCES

- The stresses are concentrated at bolt-hole regions.
- The location of maximum stress concentration depends on the fibre orientation of each layer.
- The stress plot around the circumference of hole follows a particular trend for a fibre orientation.
- The stress concentration is larger for carbon epoxy layer than glass epoxy layer.

Table 9 describes the mode of failure of composites. There are two modes of failure mainly fibre failure and matrix failure.

Table 9 Mechanics of failure of composites

	Stress component	Mode of failure
1	S11	Fibre failure
2	S22	Matrix failure

Table 10 shows the summary of progressive failure analysis. Figure 14. variation of failure load with width.

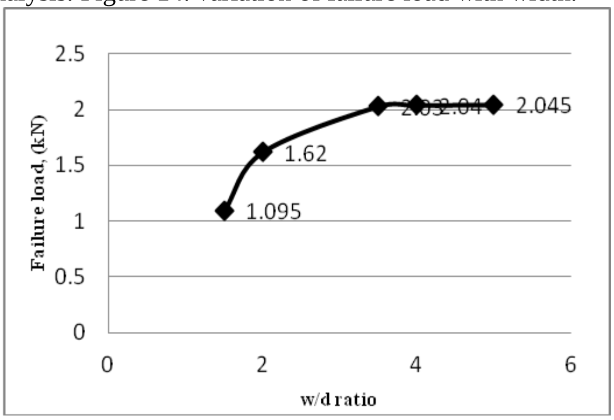


Fig. 14. Variation of failure load and width of configuration

Table 10. Summary of analysis of Single pin configuration

Width (mm)	Failure Load (kN)	Initial Failure layer No:	Initial Failure layer orientation	Location of failure with respect to circumference angle (degree)	Failure type	REMARK
1.5	1.095	6	90	95.58	Tensile Failure	S22 stress is Tensile
2.0	1.62	6	90	95.58	Tensile Failure	S22 stress is Tensile
3.5	2.03	4	45	52.23	Bearing Failure	S11 stress is compressive
4.0	2.04	4	45	52.23	Bearing Failure	S11 stress is compressive
5.0	2.045	4	45	52.23	Bearing Failure	S11 stress is compressive

VIII. Conclusion

The use of composites in load bearing structures is primarily motivated by high specific stiffness and high specific strength. The stress distribution depends on the layup sequence and materials used. First ply failure occurs when the first ply or ply group fails in a multidirectional laminate. Progressive failure analysis was carried out to determine the mode of failure and showed good correlation with the stress results.

- The stresses are concentrated at bolt-hole regions.
- The stress concentration is larger for carbon epoxy layer than glass epoxy layer.
- Modes of failure considered are fibre failure and matrix failure.
- When, w/d ≤ 2 : Failure type is tensile failure
- When, w/d>2 : Failure type is Bearing failure
- Failure load increases as the width of plate increased.

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