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STRESS AND LOAD-DISPLACEMENT ANALYSIS OF FIBER-REINFORCED COMPOSITE LAMINATES WITH A CIRCULAR HOLE UNDER COMPRESSIVE LOAD

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ABSTRACT

This paper is focused on the analysis of stress-strain and displacement for compressive load on the fibre-reinforced composite laminates. Three different orientations of fibers are analyzed with and without the circular cut-outs. Also different dimensions of circular cut-outs are applied on the laminates at different compressive loading conditions. This analysis is carried out using the finite element software ANSYS. From the result, it is identified that cross-ply composite laminates posses the highest strength as compared to other types of angle orientations. Also it is concluded that the maximum load bearing capacity decreases as the cut-out size increases.

Keywords: fibre-reinforced composite laminate, stress, strain, load displacement analysis, compressive load, ANSYS.

1. INTRODUCTION

Composite laminates are composed of thin layers (plies) consisting of reinforcement and a matrix. The reinforcement is typically a strong, stiff material, in the form of long fibers. The matrix is typically a material that is applied in a liquid form and then cured and hardened. The matrix is applied to support the reinforcement, and to distribute the load through the reinforcement and plies. It is common to have plies with fibers at one direction or several directions in a weave. The orientation of the fibers and stacking sequence has a large effect on the deformation and stress throughout the laminate. Composite laminates have been used increasingly in a variety of industrial areas due to their high stiffness and strength-to-weight ratios, long fatigue life, resistance to electro chemical corrosion, and other superior material properties of composites. A true understanding of their structural behavior is required, such as the deflections, buckling loads and modal characteristics, the through-thickness distributions of stresses and strains, the large deflection behavior and, of extreme importance for obtaining strong, reliable multi-layered structures, the failure characteristics. Finite element method is especially versatile and efficient for the analysis of complex structural behaviour of the composite laminates.

The largest damage feature is usually delamination, which may cause significant reductions in flexural stiffness and buckling loads. The effect of delamination has been a subject of extensive research, and fairly reliable methods are now available for prediction of growth of artificial single delamination [1]. Cut-outs commonly appear in the structures due to the requirement of stability maneuverability, low weight optimization and accessibility of other systems. During operation, these structural elements may experience compressive loads and thus lead to buckling and post buckling. Their buckling and post buckling behaviors play an important role in determining safe operating conditions and effective designs for these structures [2].

Engineers have been in the continuous state of experiments and analysis using woven fabric composites. This is because of light weight of the woven fibers and their higher strength. They have been the subject of research and experiments since their introduction. Work by de Freitas and Reis [3] showed the failure mechanisms on composite specimens subjected to compression after impact. The delaminated area of composite plates due to impact loading depends on the number of interfaces between plies and it influence more on the buckling failure mechanisms than stacking sequences.

An experimental study of the behaviour of woven glass fiber/epoxy composite laminated plates under compression is explained by Hakim S. Sultan Aljibori and W.P. Chon [2]. Compression tests were performed on to 16 fiber-glass laminated plates with and without circular cut-outs using the compressed machine. The maximum load of failure for each of the glass-fiber/epoxy laminated plates under compression has been determined experimentally. According to M. de Freitas and L. Reis [3], impact loading in composite plates lead to damage with matrix cracking, inter-laminar failure and eventually fiber breakage for higher impact energies. Even when no visible impact damage is observed at the surface on the point of impact, matrix cracking and inter-laminar failure can occur, and the carrying load of the composite laminates is considerably reduced.

Another study by Takeda *et al.*, [4] developed the progressive failure methodology for glass/epoxy plain weave fabric reinforced laminates subjected to tensile loading under cryogenic temperatures. Kelkar *et al.*, [5] examined the biaxial braided carbon/epoxy composites with different braid angles i.e., 25°, 30°, 45° carbon/epoxy unstitched, stitched and Z-pinned plain under tension and compression fatigue loading for aerospace applications.

Several investigations have been done by Hilburger *et al.*, [6] and Ghannadpour *et al.*, [7] showed the buckling behavior of composite laminated plates with cut-outs under compression. The buckling behavior is affected by the cut-out size, plate curvature, boundary

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conditions and ply angles. The laminated fibre-reinforced composite plates are known to be susceptible to damage resulting from accidental impact of foreign objects. Yin *et al*., [8] conducted compressive after impact test to evaluate mechanical performance of the laminated composites before and after crack healing. High performance composite components often consist of layers (plies) of unidirectional FRP stacked in a specified sequence to form a laminate Construction. Zhu *et al*., [9] presented an experimental study of in-plane large shear deformation of woven fabric composite. During the test, the cross-sectional profiles of fabric samples were traced, helping to build up a theoretical model of the composite sheets during their large shear deformation.

The findings of this paper give an increased understanding of the behavior of woven glass fiber/epoxy composite laminated plates under compression loading. This knowledge will assist engineers, researchers and composite community to use composite material for automotive and aerospace industry.

2. OBJECTIVES

Composites are found to have great strength to weight ratio. It can be further increased by making use of perforated plate in case of complete composite sheet. This results in the loss of strength but increase in strength to weight ratio. A study of the stress-strain and displacement of woven glass fiber/epoxy composite laminated plates under compression load is presented. The maximum load of failure for each of the glass fiber/epoxy laminated plates under compression load has been determined through simulation software (ANSYS). The effects of varying the centrally located circular cut out sizes and fiber angle ply orientations under the ultimate load has been simulated. The crack propagation in the drilled laminate sheets is focused. The study of stress-strain development and displacement on composite plate with circular hole of three different diameters and three different orientations under varying compression load is performed.

3. STRESS-STRAIN AND DISPALACEMENT ANALYSIS

The finite element analysis (FEA) software ANSYS is used to simulate and analyze stress-strain and displacement behaviour of glass fiber/epoxy composite laminated plates. The laminates of the composite plates is designed and analysed under gradually varying compression load. Proper element type is chosen to design our composite laminate. A material property has been chosen from the Wu Zhen [10] and Det Norske Verit [11]. Orthotropic material has been chosen for the analysis as their property varies in different direction which is true for fibre reinforced composites. Three plates of different orientation with same dimension but varying dimensions of the cut hole located centrally in the plate are designed. The dimension for composite laminate with orientation [0/90/0] s with central hole diameter of 28mm is shown in Figure-1.

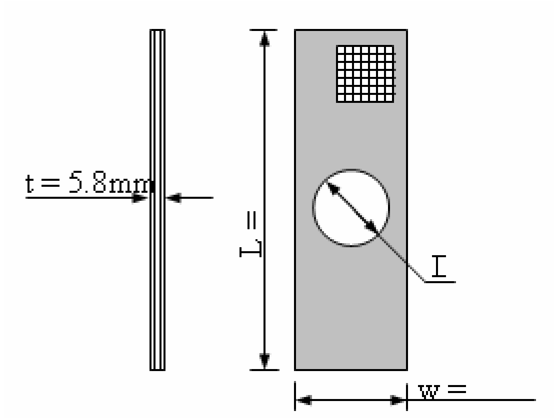

Figure-1. Geometry of a fibre-glass laminated with centrally cut hole.

These plates have 6 ply laminates symmetric from the centre. One side of the laminate is kept fixed and other is applied with the load increasing gradually. For the analysis, the load is increased in the steps of 500N. For each application of load values stress-strain and displacement values are noted. The load and boundary conditions are selected as shown in Figure-2.

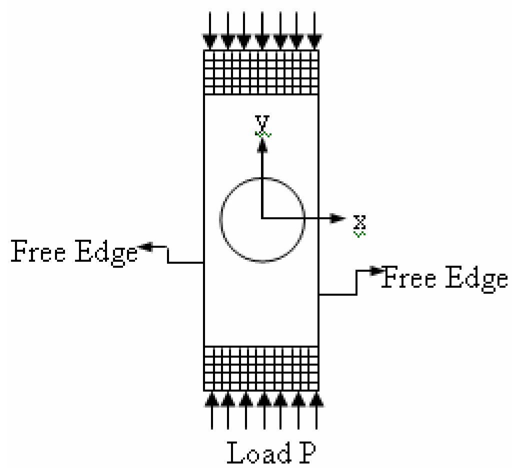

Figure-2. Load and boundary condition for the specimen.

The four different cases of the plates are considered as shown below.

a) Without hole
b) With circular hole of dia. 22 mm at the centre
c) With circular hole of dia. 28 mm at the centre
d) With circular hole of dia. 38 mm at the centre

The three different orientations of the plates are considered as shown below.

a) [0°/90°/0°]ŝ
b) [0°/60°/30°]ŝ
c) [90°/45°/0°]ŝ

The solid elements 191 and 86 are considered for making the discretization of the plate. Solid 191 is 3-D 8

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node layered structural solid element. It is defined by eight nodes having three degrees of freedom at each node. It has plasticity, hyper elasticity, stress stiffing, creep, large deflection, and large strain capabilities. It also has mixed formulation capabilities for simulating deformations of nearly incompressible elastoplastic materials, and fully incompressible hyper elastic materials. It allows for prism and tetrahedral degeneration when used in irregular regions.

Solid 86 is a higher node 3-D 20- node solid element that exhibits quadratic displacement behaviour. It is defined by 20 nodes having three degrees of freedom per node. It supports plasticity, hyper elasticity, creep, stress stiffening, large deflection and large strain capabilities. It also has mixed formulation capability for simulating deformations of nearly incompressible hyper elasticity materials. It allows up to 250 different layers.

The displacement, stress and strain values for the plate without circular hole at the orientation of [0°/90°/0°]ŝ is analysed and presented in the Figures 3, 4 and 5, respectively.

Plate without circular hole at [0°/90°/0°] ŝ:

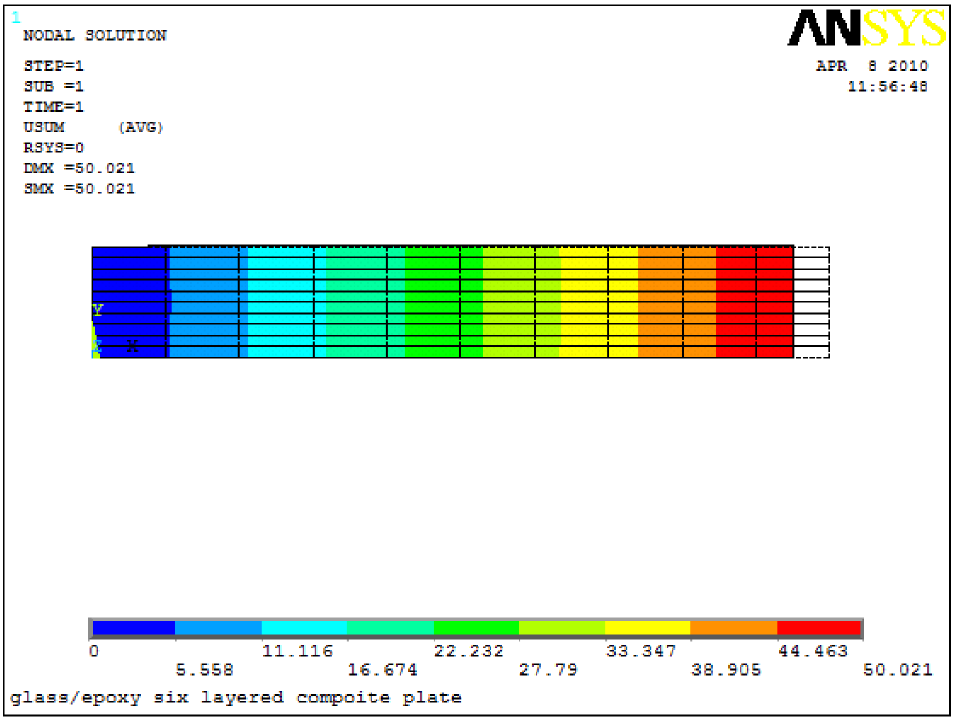

Figure-3. Displacement plot of composite plate without hole at orientation [0°/90°/0°] ŝ.

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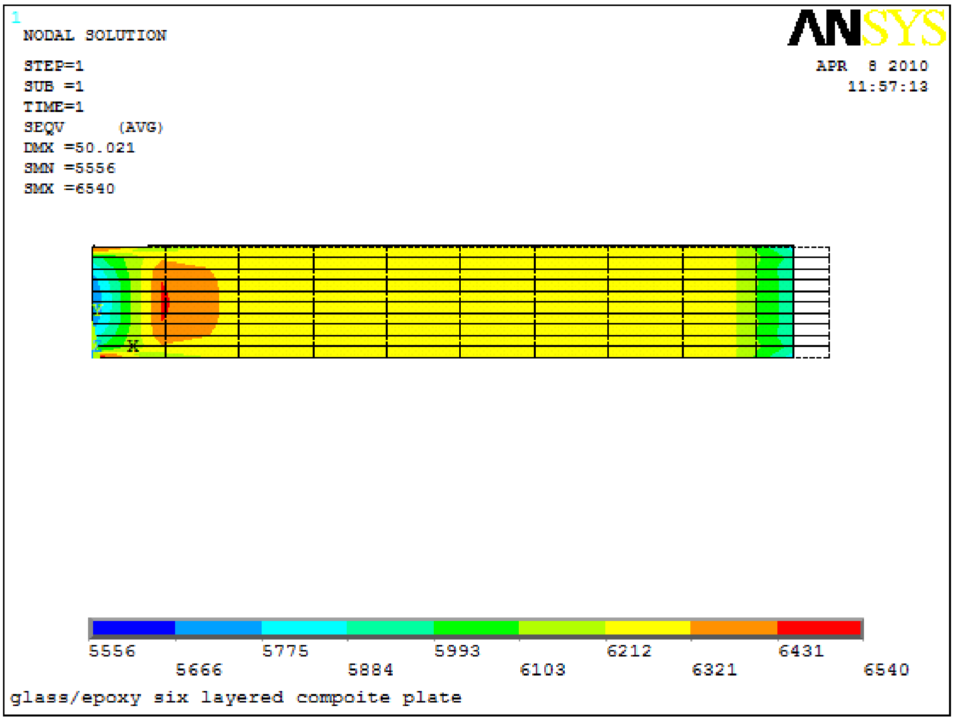

Figure-4. Stress plot of composite plate without hole at orientation [0°/90°/0°]ŝ

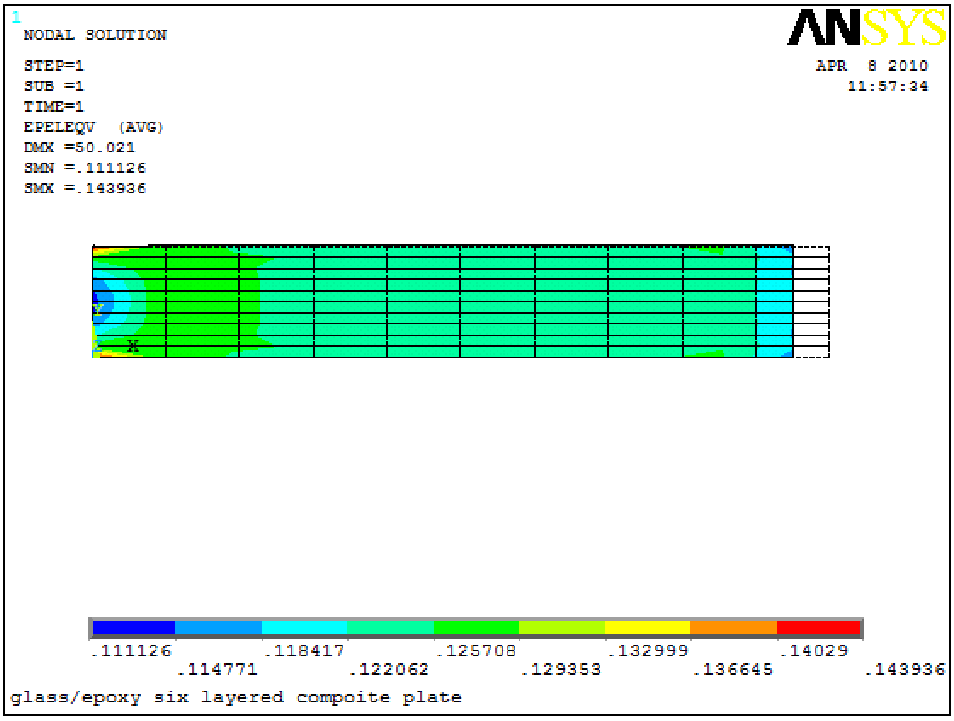

Figure-5. Strain plot of composite plate without hole at orientation [0°/90°/0°] ŝ.

The displacement, stress and strain values for the plate with circular hole of 22mm at the orientation of [0°/90°/0°]ŝ is analysed and presented in the Figures 6, 7 and 8, respectively.

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Plate with circular hole of 22 mm at [0°/90°/0°] ŝ:

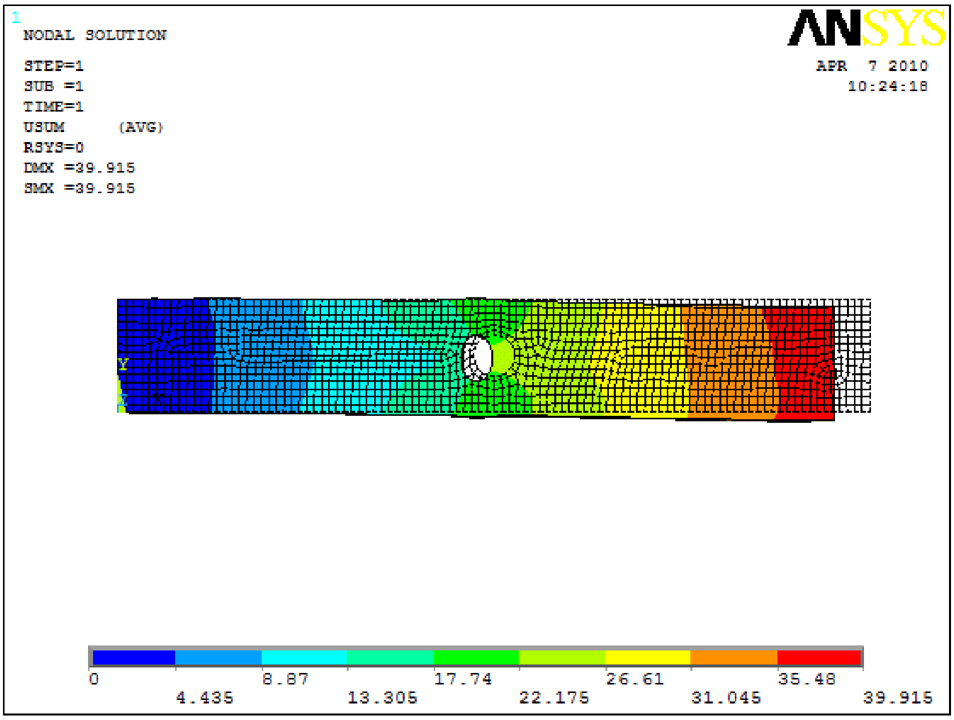

Figure-6. Displacement plot of composite plate with 22mm dia hole at orientation [0°/90°/0°] ŝ.

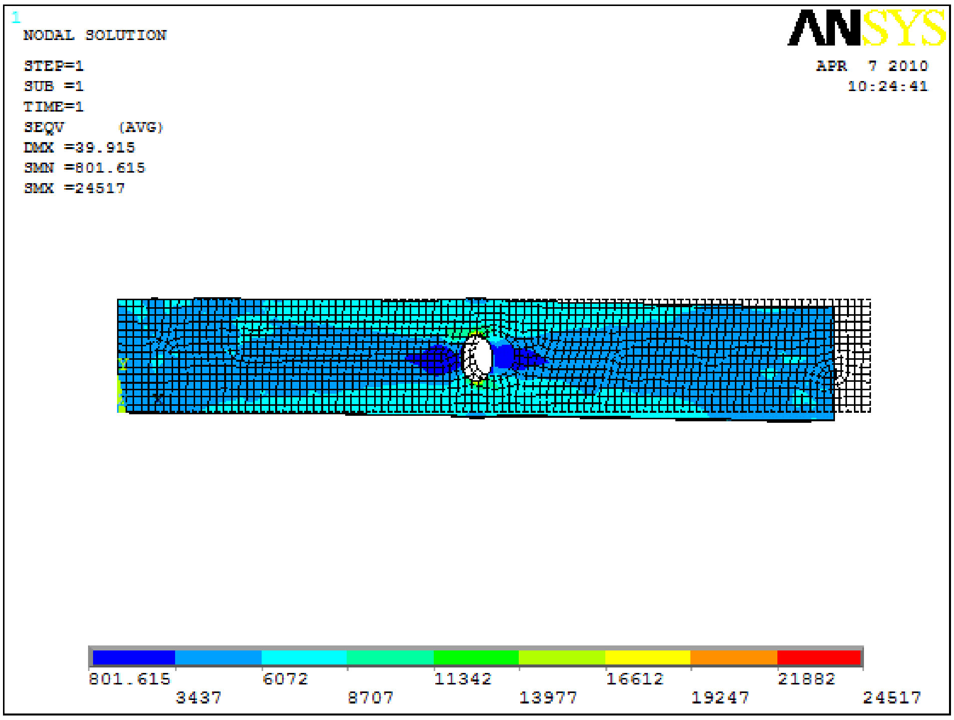

Figure-7. Stress plot of composite plate with 22mm dia hole at orientation [0°/90°/0°] ŝ.

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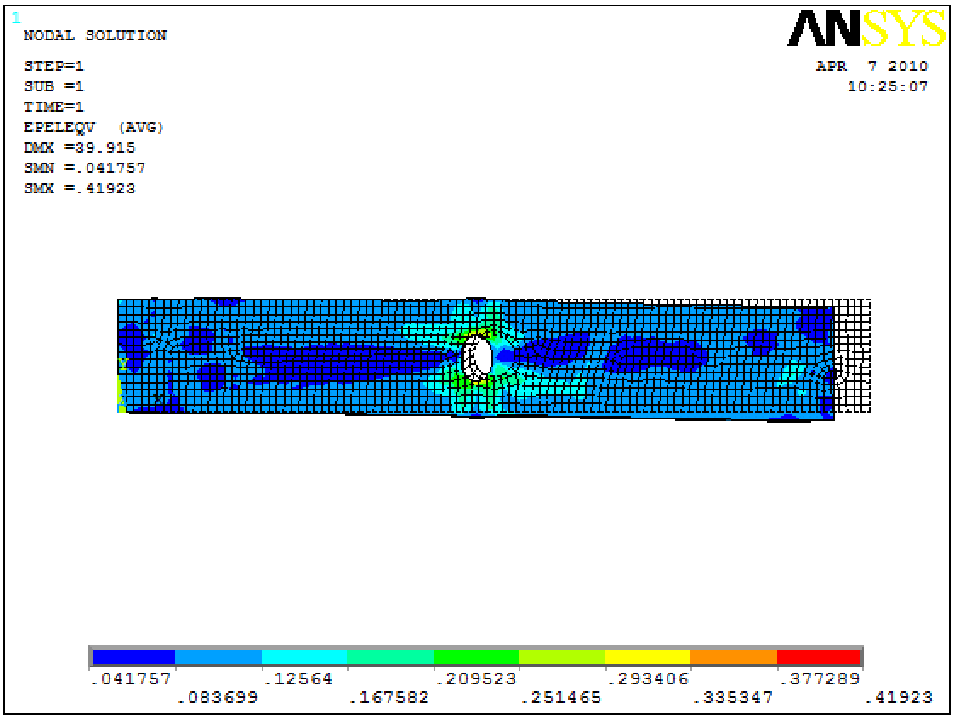

Figure-8. Strain plot of composite plate with 22mm dia hole at orientation [0°/90°/0°] ŝ.

Similarly, the displacement, stress and strain values for the plates with circular holes of diameter 28 and 38mm are analysed at the orientations of [0°/90°/0°]ŝ. Also the plates with cut-out holes of diameter 22, 28 and 30mm are analysed at the orientations of [0°/60°/30°]ŝ and [90°/45°/0°]ŝ.

4. RESULTS

The results obtained from the ANSYS analysis are presented in the following Tables 1, 2 and 3. The compressive load is increased gradually in steps of 500N starting from zero. Thus the values of the displacement, stress and strain are noted for the load of 500N, 1000N, 1500N and so on till the maximum load is achieved. This maximum load which can be applied to this plate either with central hole or without hole is taken from Hakim S. Sultan Aljibori and W.P. Chong [2].

Table-1. Values of the displacement, stress and strain for the load varying from 500N for plate at orientation of [90°/45°/0°] ŝ with 3 different sizes of holes.

Without hole			
Load	**Displacement**	**Stress**	**Strain**
500	3.527	687.947	0.010964
1000	7.053	1376	0.021929
1500	10.58	2064	0.032893
2000	14.106	2752	0.043857
2500	17.633	3440	0.054822
3000	21.16	4128	0.065786
3500	24.686	4816	0.07675
4000	28.213	5504	0.087715
4500	31.739	6192	0.098679
With hole diameter of 22mm			
Load	**Displacement**	**Stress**	**Strain**
500	3.796	2382	0.035411
1000	7.593	4764	0.070822
1500	11.389	7146	0.106233
2000	15.186	9528	0.141644
2500	18.982	11909	0.177056
3000	22.778	14291	0.212466
3500	26.575	16673	0.247877
4000	30.371	19055	0.283288
4500	34.153	21437	0.318699
With hole diameter of 28mm			
Load	**Displacement**	**Load**	**Displacement**
500	3.997	2592	0.040039
1000	7.993	5184	0.080079
1500	11.99	7776	0.120118
2000	15.987	10368	0.160157
2500	19.984	12960	0.200197
3000	23.98	15553	0.240236
3500	27.977	18146	0.280276
4000	31.974	20737	0.320315
4500	35.97	23329	0.360354
With hole diameter of 38mm			

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Load	Displacement	Load	Displacement
500	4.525	3919	0.057723
1000	9.05	7839	0.115445
1500	13.567	11758	0.173162
2000	18.101	15678	0.230891
2500	22.626	19597	0.288614
3000	27.151	23517	0.346336
3500	31.677	27436	0.404059

Table-2. Values of the displacement, stress and strain for the load varying from 500N for plate at orientation of [0°/60°/30°] ŝ with 3 different sizes of holes.

Without hole			
Load	**Displacement**	**Stress**	**Strain**
500	4.085	841.616	0.013114
1000	8.17	1683	0.026228
1500	12.34	2340	0.039343
2000	16.341	3366	0.052457
2500	20.426	4208	0.065571
3000	24.121	5050	0.078685
3500	28.596	5891	0.0918
4000	32.681	6733	0.104914
4500	36.766	7575	0.118028
5000	40.852	8416	0.131142
5300	46.834	9649	0.150347
With hole diameter of 22mm			
Load	**Displacement**	**Stress**	**Strain**
500	4.316	2664	0.04123
1000	8.632	5327	0.082479
1500	12.948	7991	0.123718
2000	17.263	10655	0.164957
2500	21.579	13318	0.206196
3000	25.896	15982	0.247436
3500	30.211	18646	0.288675
4000	34.527	21309	0.329914
4500	38.843	23973	0.371154
5000	43.159	26637	0.412393
5300	45.748	28235	0.437136
With hole diameter of 28mm			
Load	**Displacement**	**Load**	**Displacement**
500	4.5	3009	0.045999
1000	9.001	6017	0.091998
1500	13.501	9026	0.137997
2000	18.001	12035	0.183996
2500	22.501	15043	0.229995
3000	27.002	18052	0.275994
3500	31.502	21061	0.321993
4000	36.002	24069	0.367992
4500	40.502	27078	0.413991
4753	42.78	28600	0.437267
With hole diameter of 38mm			
Load	**Displacement**	**Load**	**Displacement**
500	5.072	4341	0.064678
1000	10.143	8681	0.129356
1500	15.215	13022	0.194034
2000	20.286	17362	0.258712
2500	25.358	21703	0.32339
3000	30.43	26043	0.388068
3500	35.501	30384	0.452746
4000	41.334	35376	0.527125

Table-3. Values of the displacement, stress and strain for the load varying from 500N for plate at orientation of [0°/90°/0°]ŝ with 3 different sizes of holes.

Without hole			
Load	**Displacement**	**Stress**	**Strain**
500	2.855	514.23	0.008294
1000	5.71	1028	0.016587
1500	8.568	1543	0.024881
2000	15.985	2090	0.045997
2500	19.981	2612	0.057496
3000	23.978	3135	0.068995
3500	27.974	3657	0.080495
4000	31.97	4180	0.091994
4500	35.96	4702	0.103493
5000	39.963	5223	0.114992
5500	43.959	5747	0.126491
5800	50.021	6540	0.143936
With hole diameter of 22mm			
Load	**Displacement**	**Stress**	**Strain**
500	3.441	2114	0.036141
1000	6.882	4227	0.072281
1500	10.323	6341	0.108422
2000	13.764	8454	0.144562
2500	17.205	10568	0.180703
3000	20.64	12681	0.216843
3500	24.086	14795	0.252984
4000	27.527	16908	0.289124

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4500	30.968	19022	0.325265
5000	34.409	21135	0.361406
5500	37.85	23249	0.397456
5800	39.915	24517	0.41923
With hole diameter of 28mm			
Load	**Displacement**	**Load**	**Displacement**
500	3.567	2113	0.043227
1000	7.135	4226	0.086454
1500	10.702	6338	0.129681
2000	14.269	8451	0.172909
2500	17.836	10564	0.216136
3000	21.404	12677	0.259363
3500	24.971	14790	0.30259
4000	28.538	16903	0.345817
4500	32.105	19015	0.389045
5000	35.673	21128	0.432272
5500	38.526	22818	0.466853
With hole diameter of 38mm			
Load	**Displacement**	**Load**	**Displacement**
500	4.411	3671	0.062103
1000	8.822	7341	0.124206
1500	13.233	11012	0.18631
2000	17.644	14683	0.248413
2500	22.055	18353	0.310516
3000	26.466	22024	0.372619
3500	30.876	25695	0.434723
4000	36.081	30026	0.508004

From the above data, it is clear that as the central hole diameter increases, the plate breaks or its displacement and stress increases for the same load compared to the plate with lower diameter hole or no hole. This can be clearly shown by comparing the graphs drawn between load-displacements for the orientation with varying diameters of centrally located hole.

For all cases, symmetric angle ply laminates of [0°/90°/0°] ŝ underwent the largest inelastic deformation before failure. These findings suggest that this type of ply configuration is capable of absorbing large amount of energy before fracture, where the energy absorbed is given by the area under the load-displacement curve. A similar trend has been observed from the experimental results, in which the ultimate load of the plate with angle orientation of [0°/90°/0°] ŝ has the highest value, followed by angle orientations of [0°/60°/30°]ŝ and [90°/45°/0°]ŝ.

Also the results revealed that cross plies are better than the angular plies. Graphs are plotted for the comparison of load versus displacement for all the fiber-glass laminated plates with and without holes at different angle orientations. It is interesting to note that all the laminates behave in a similar fashion whereby their behavior is almost linear before reaching the peak load.

Plate strength decreases as hole diameter increases

Graphs to the load versus displacement for different diameter of holse at each orientation are plotted and shown in Figures 9, 10 and 11. In these graphs the orientation is kept constant and the values of displacement for different load cases are noted down. These graphs reveal that the ability to bear the load decreases as the diameter of cut section increases. For some fixed load, the maximum displacement is observed for the plates with maximum hole diameter.

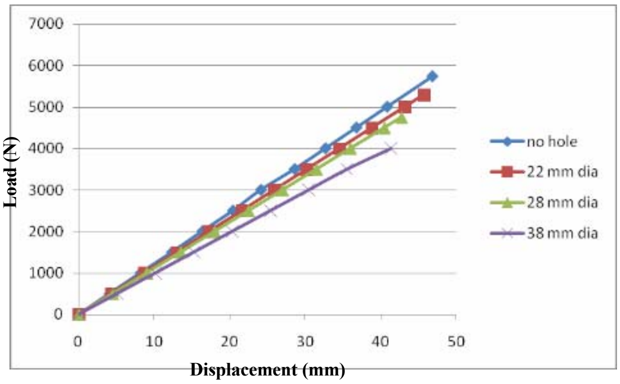

Figure-9. Load vs. displacement for different diameters of hole at the orientation of [0°/60°/30°] ŝ.

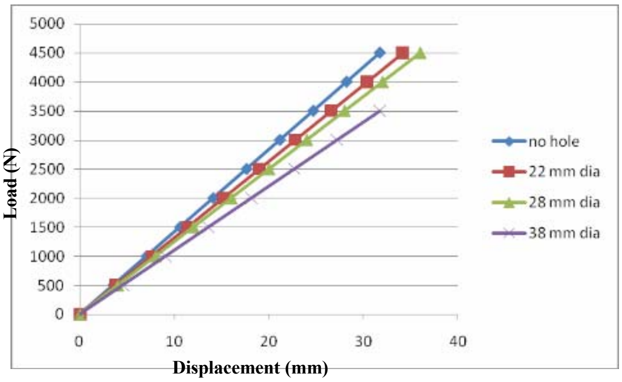

Figure-10. Load vs. displacement for different dia. of hole for the orientation [90°/45°/0°] ŝ.

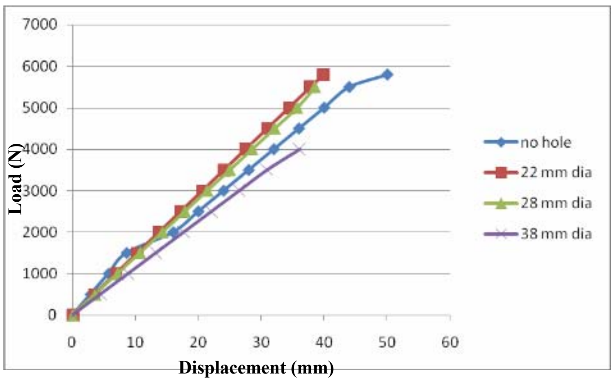

Figure-11. Load vs. displacement for different dia. of hole for the orientation [0°/90°/0°] ŝ.

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Stress vs. strain graph is found to be linear

Graphs to the stress versus strain for different diameter of holse at each orientation are plotted and shown in Figures 12, 13 and 14. It is the material property of the composites that as the stress increases their strain also increases linearly. Thus the stress strain curve for the composite material is a straight line which is one of the characteristics of a composite material.

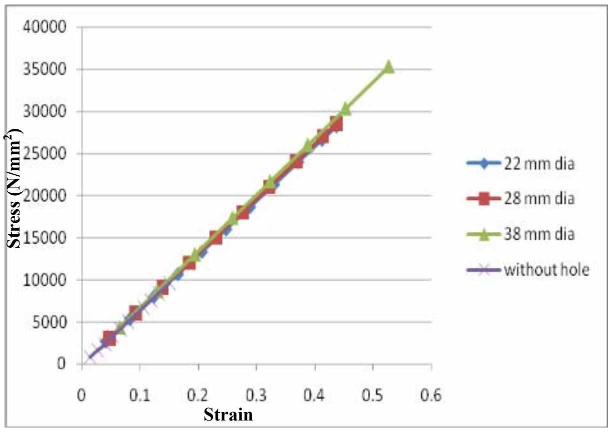

Figure-12. Stress vs. strain for different diameters of hole at the orientation of [0°/60°/30°] ŝ.

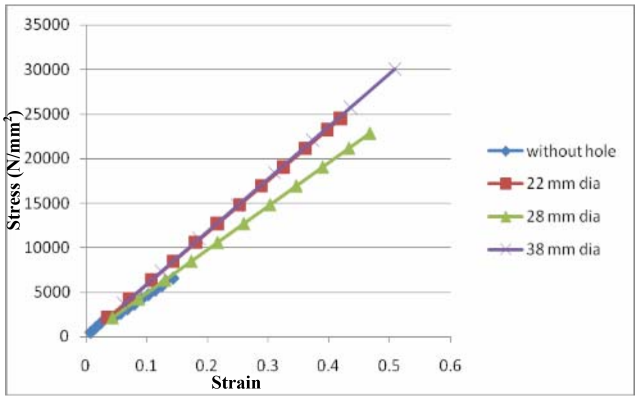

Figure-13. Stress vs. strain for different diameters of hole at the orientation of [0°/90°/0°] ŝ.

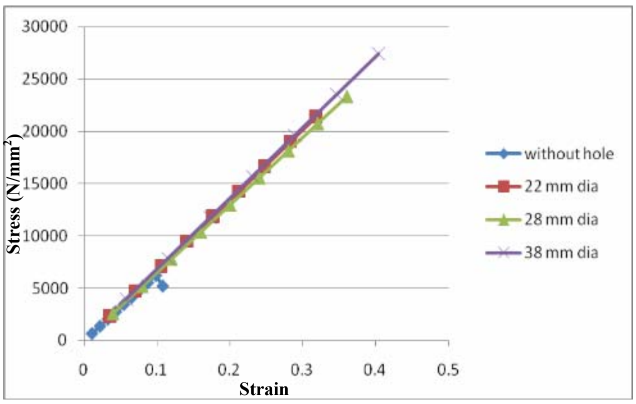

Figure-14. Stress vs. strain for different diameters of hole at the orientation of [90°/45°/0°] ŝ.

Cross plies better than angular plies

Graphs to the load versus displacement for different orientations at each hole diameter are plotted and shown in Figures 15, 16, 17 and 18. From these graphs, it is observed that the cross plies i.e., laminates with orientation [0°/90°/0°]ŝ is better than other orientations of [90°/45°/0°]ŝ and [0°/60°/30°]ŝ which are angular plies. It is found by comparing the displacements of the plate with varying orientation but common hole diameter. In all the four case of holes at the centre and without hole the result was found to be same i.e., cross plies better than angular plies.

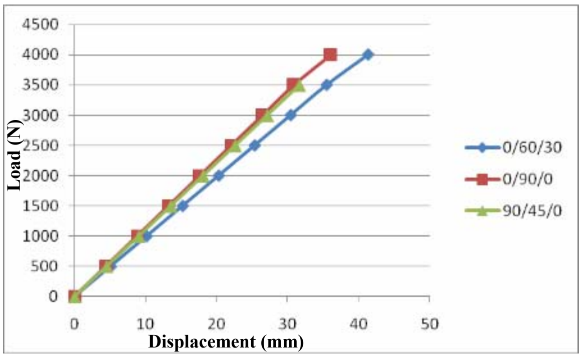

Figure-15. Load vs displacement graph showing the comparison between three orientation for the plate hole dia. of 38 mm.

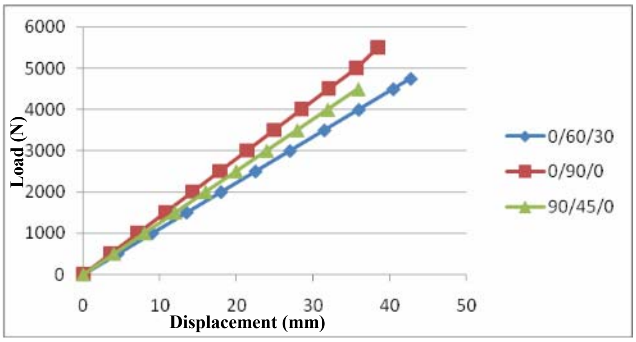

Figure-16. Load vs displacement graph showing the comparison between three orientation for the plate hole dia. of 28 mm.

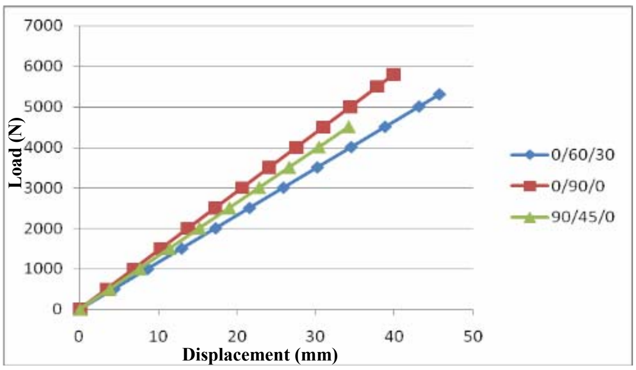

Figure-17. Load vs displacement graph showing the comparison between three orientation for the plate hole dia. of 22 mm.

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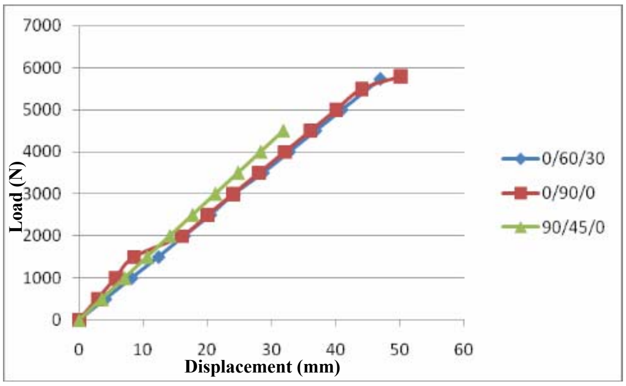

Figure-18. Load vs displacement graph showing the comparison between three orientation for the plate without hole.

The results obtained from this analysis are validated by finding the percentage of variation with the experimental works carried by Sultan and Chong [2]. The % of variation is calculated for the maximum displacement and presented in the Table-8. It is clear that nearly all the above results are in close agreement to the experimental work.

Table-8. Variation between Sultan and Chong [3] and software analysis values.

Stacking sequence	**Central hole dia.** (mm)	**Max. load** (kN)	**Maximum displacement by Sultan and Chong** [3] (mm)	**Maximum displacement ANSYS result** (mm)	**% variation**
[0°/90°/0°]ŝ	Without hole	6.3	52.7662	50.021	5.2%
	22	5.84	34.7604	36.519	4.8%
	28	5.42	35.0368	38.526	7.8%
	38	4.0	36.3502	36.081	0.74%
[0°/60°/30°]ŝ	Without hole	5.73	46.4215	46.834	0.88%
	22	5.25	46.9224	45.748	2.5%
	28	4.7	40.1546	42.78	6.1%
	38	4.07	50.3712	41.334	17%
[90°/45°/0°]ŝ	Without hole	5.0	40.0675	40.33	0.65%
	22	4.5	34.5310	34.168	1.05%
	28	4.0	38.5859	35.977	6.76%
	38	3.2	39.7767	31.677	20.34%

CONCLUSIONS

In a composite material, the fibers are the main constituents which are responsible for the strength of the composite. Thus the fibers play an important role in the load bearing capacity of the composite. Thus fiber orientation is very important in determination of the strength of the composite. In this paper, the different fiber orientation like [0°/90°/0°] ŝ, [0°/60°/30°] ŝ and [90°/45°/0°] ŝ are analyzed under different compressive loading and with and without circular cut-out conditions. Out of these orientations, it is found that the [0°/90°/0°] ŝ configuration is the best and has the maximum load bearing capacity and strength than the other orientations. i.e., the cross plies have maximum load carrying capacity as compared to angular plies. For the same load, the plate with orientation [0°/90°/0°] ŝ has the least deflection indicating the best strength as compared to the others. As the diameter of the cut hole is increased the strength of the plate decreases. It is because of the material removal from the plate reduces its strength and the load bearing capacity also reduces accordingly. The larger diameter of holes reduces the load bearing capacity and thus the displacement or the deflection of the plate also increases upon the application of the load.

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