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Stress Concentration of Laminated Composite Plate Containing Circular Hole

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Abstract – In this study, an attempt has been made to understand the effect of stress concentration in different laminated composite (Graphite-epoxy, Glass-epoxy, Boron-epoxy) plates with single circular hole subjected to uniaxial tension and pure shear. Mathematical formulations are generated by using MATLAB simulation tool. The effect of fiber orientation, E1/E2 ratios on the stress concentration of the laminated composite plate with a central circular hole is investigated. ANSYS FEM tool is used to understand the effect of geometrical parameters on the stress distribution around the circular hole. Ratio of the diameter of hole to length (D/L) and width (D/A) of the orthotropic plate are analysed.

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1. INTRODUCTION

Composite materials have gained considerable importance because of their impressive mechanical and physical properties. This enabled them to use in high end engineering applications like automobiles, aerospace, pressure vessels, marine engineering etc. Most of the times composite materials, will be used in the form of plates and/or shells. The structures used in modern engineering applications will have non-uniform geometry (Rivet or bolt holes, sudden reduction in cross section etc.), which will cause the localized stress due to stress concentration. Considerable work has been done in past few decades on composite plate with different geometric nonlinearities [1-15]. Kaltakci et al. [1, 2] studied the effect of fiber orientation and E1/E2 ratio on the stress concentration of symmetrically laminated composite plates and anisotropic plates containing circular hole. H. Murat [3, 4, 5] investigated the effect of E1/E2 ratio and ply orientation on the stress concentration of composite plate with circular hole subject to shear loading condition. The investigation was then extended to study the effect of stress concentration on the cross-ply laminate composite plate with circular hole. Shubhrata et al. [6] analysed the mitigation techniques for stress concentration factor for rectangular composite plate containing a circular hole. They concluded that the providing the auxiliary holes at specific distance will reduce the stress concentration in the plate. Ahmed M [7] compared the stress distribution and the deflections in isotropic and orthotropic composite plates with circular hole under uniaxial tensile loading condition. Danyong Wang et al. [8] studied the progressive damage of composite plate with circular hole subjected to compressive loading using ANSYS simulation tool. V.G.Aradhye [9] studied the stress concentration in the isotropic and orthotropic material using both experimental and FEA techniques.

In this paper, analytical and finite element methods are adopted to avoid incorrect modeling of the composite plates. Numerical equations available in literatures are used to analyze the composite plates with circular hole. The codes are generated using MATLAB simulation tool to understand the effect of fiber orientation and E1/E2 ratio on the stress concentration factor of the composite plate with circular hole. Effect of geometrical parameters like diameter of the hole, length and width of the plate on stress around the circular hole is studied using ANSYS simulation tool.

2. THEORETICAL MODEL

The relation for the circumferential stress around the hole in an infinite orthotropic plate with a hole loaded along the fiber direction (tension or compression) was given by Green and Zerna in 1954.

$$\sigma_\theta^i = \frac{(1+\gamma_1)(1+\gamma_2)(1+\gamma_1+\gamma_2-\gamma_1\gamma_2-2\cos 2\theta)}{(1+\gamma_1{}^2-2\gamma_1\cos 2\theta)(1+\gamma_2{}^2-2\gamma_2\cos 2\theta)}\sigma_x^i \qquad (1)$$

Where,

$$\gamma_1 = \frac{\sqrt{\left[\left(\frac{E_2}{2G_{12}} - \vartheta_{21}\right) + \sqrt{\left(\frac{E_2}{2G_{12}} - \vartheta_{21}\right)^2 - \frac{E_2}{E_1}}\right] - 1}}{\sqrt{\left[\left(\frac{E_2}{2G_{12}} - \vartheta_{21}\right) + \sqrt{\left(\frac{E_2}{2G_{12}} - \vartheta_{21}\right)^2 - \frac{E_2}{E_1}}\right] + 1}} \quad (2)$$

and,

$$\gamma_2 = \frac{\sqrt{\left[\left(\frac{E_2}{2G_{12}} - \vartheta_{21}\right) - \sqrt{\left(\frac{E_2}{2G_{12}} - \vartheta_{21}\right)^2 - \frac{E_2}{E_1}}\right] - 1}}{\sqrt{\left[\left(\frac{E_2}{2G_{12}} - \vartheta_{21}\right) - \sqrt{\left(\frac{E_2}{2G_{12}} - \vartheta_{21}\right)^2 - \frac{E_2}{E_1}}\right] + 1}} \quad (3)$$

Another typical loading case is transversely loading plate to the fiber orientation. The circumferential stress around the hole for this case can be calculated by equation 4.

$$\sigma_\theta^i = \frac{(1-\gamma_1)(1-\gamma_2)(1-\gamma_1-\gamma_2-\gamma_1\gamma_2-2\cos 2\theta)}{(1+\gamma_1^2+2\gamma_1\cos 2\theta)(1+\gamma_2^2+2\gamma_2\cos 2\theta)}\sigma_x^i \quad (4)$$

Under pure shear loading the stress concentration characteristics are defined by equation 5.

$$\sigma_\theta^i = \frac{4(\gamma_1\gamma_2-1)\sin 2\theta}{(1+\gamma_1^2-2\gamma_1\cos 2\theta)(1+\gamma_2^2-2\gamma_2\cos 2\theta)}S_\theta^i \quad (5)$$

3. RESULTS AND DISCUSSION

MATLAB coding has been generated to study the effect of stress concentration factor on the performance of composite plates. Initially the effect of fiber orientation on the stress distribution around the hole was investigated for Glass-epoxy material. The results obtained (Fig. 1) were compared with the published results [5]. It is observed that the results were in good agreement with each other. The investigation is further extended by considering fiber angle orientation in equal intervals of 10, and the same are plotted in Fig 2. Effect of fiber orientation on the stress concentration factor is also studied for Graphite-epoxy material (Fig. 3). From Fig. 2 it is evident that maximum stress concentration values are around 5 for all the fiber orientations and the critical circumferential angles are around 45° and 135°. Whereas for graphite epoxy, the maximum stress concentrations values are around 10 to 15. The critical circumferential angles are around 10°, 90° and then curves have maximum values from 100° to 180°.

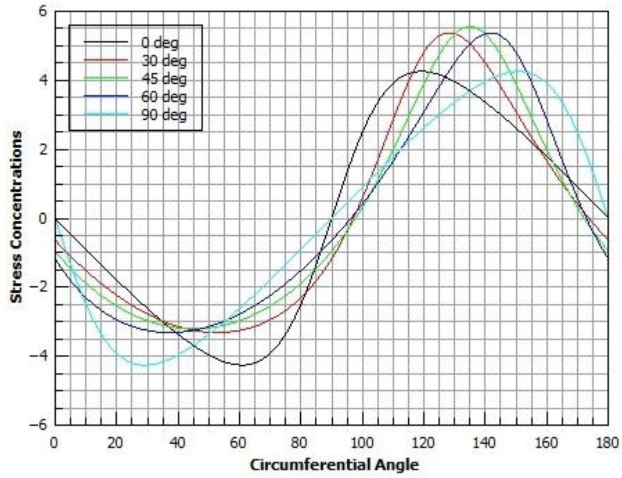

Fig. 1: Stress concentration versus θ for glass-epoxy composite subjected to pure shear

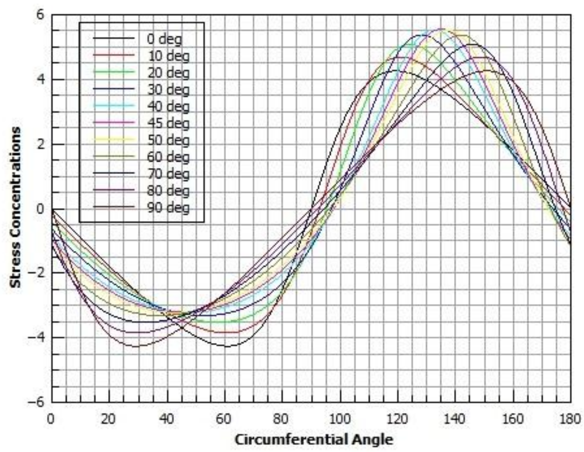

Fig. 2: Stress concentration versus θ for glass-epoxy composite for varying ply orientation

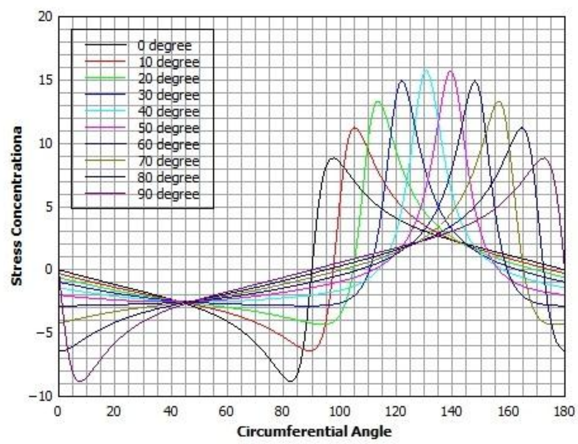

Fig. 3: Stress concentration versus θ for graphite-epoxy composite for varying ply orientation.

To understand the effect of longitudinal and transverse Young's modulus of materials the E1/E2 ratio was investigated for the orthotropic plate with

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circular hole under pure shear loading. The values of stress concentrations around the circular hole for 0° ply orientation are plotted in Fig. 4 for varying E1/E2 ratio values. The simulation results are in good agreement with results obtained by H. Murat [5]. Further, the analyses were carried out for different fiber angles to understand the behavior of the composite plate for different E1/E2 ratios. For proper understanding, the results are plotted for 0° to 90° ply orientation in the steps of 10°.

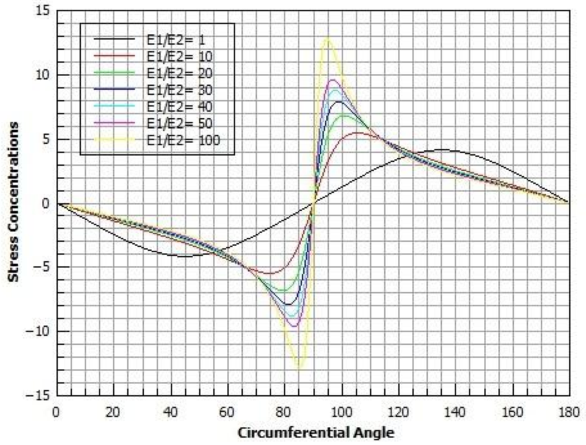

Fig. 4: Stress concentration versus θ for varying E1/E2 ratio with 0° fiber orientation (Validation)

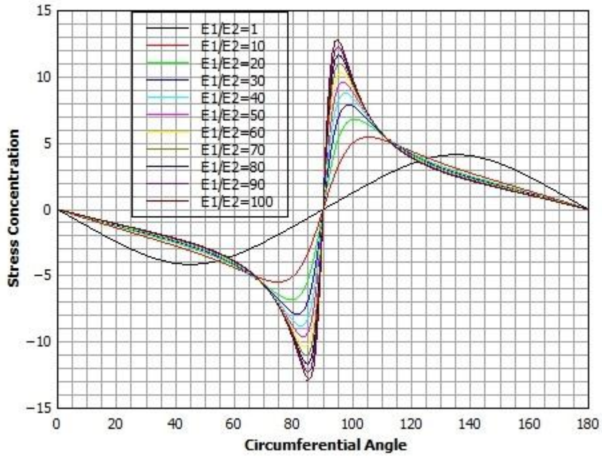

Fig. 5: Stress concentration versus θ for varying E1/E2 ratio with 0° fiber orientation

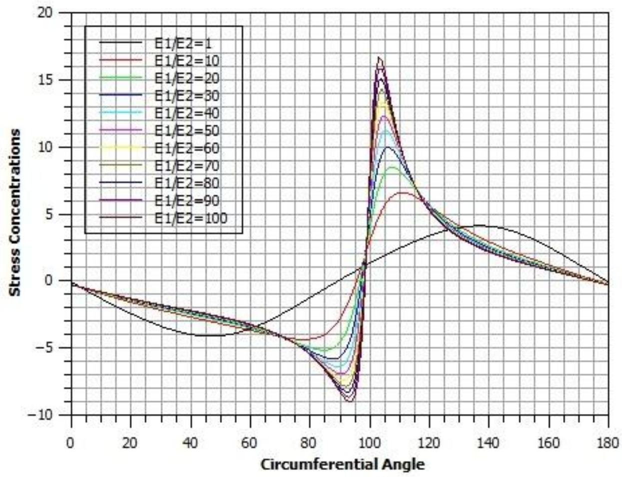

Fig. 6: Stress concentration versus θ for varying E1/E2 ratio with 10° fiber orientation

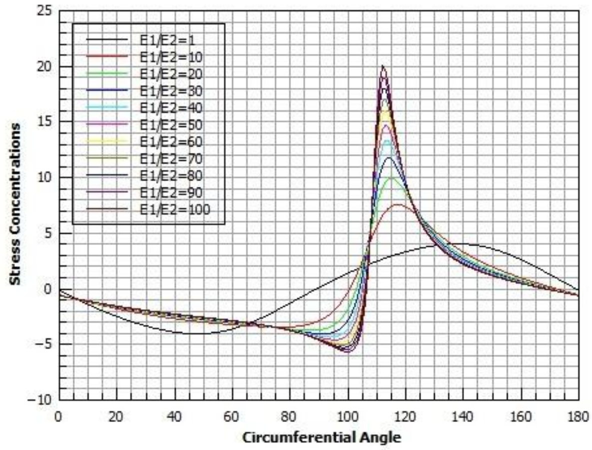

Fig. 7: Stress concentration versus θ for varying E1/E2 ratio with 20° fiber orientation

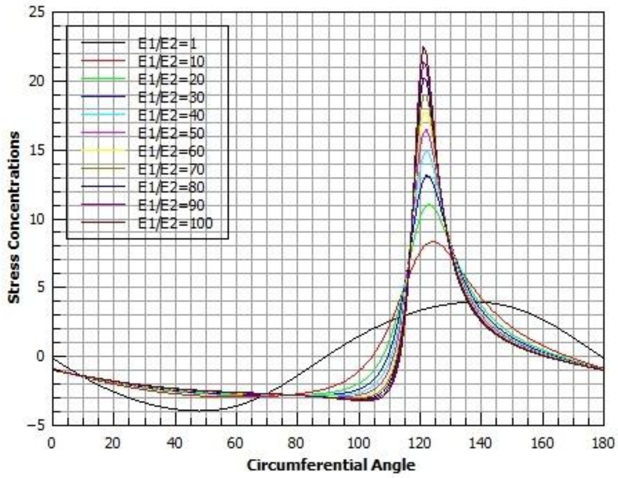

Fig. 8: Stress concentration versus θ for varying E1/E2 ratio with 30° fiber orientation

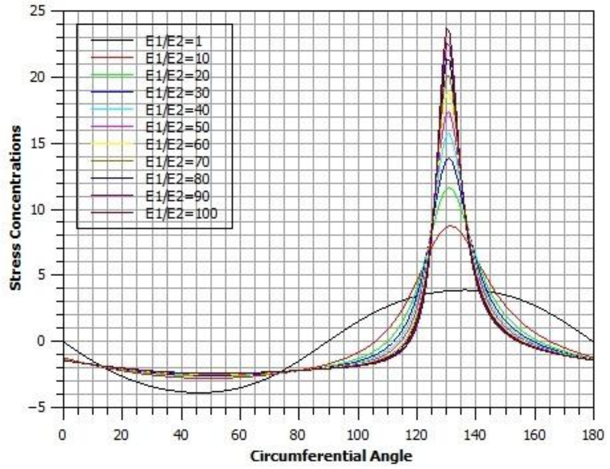

Fig. 9: Stress concentration versus θ for varying E1/E2 ratio with 40° fiber orientation

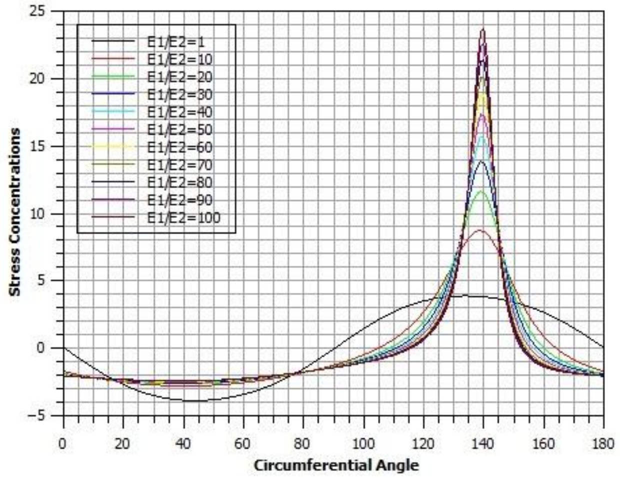

Fig. 10: Stress concentration versus θ for varying E1/E2 ratio with 50° fiber orientation

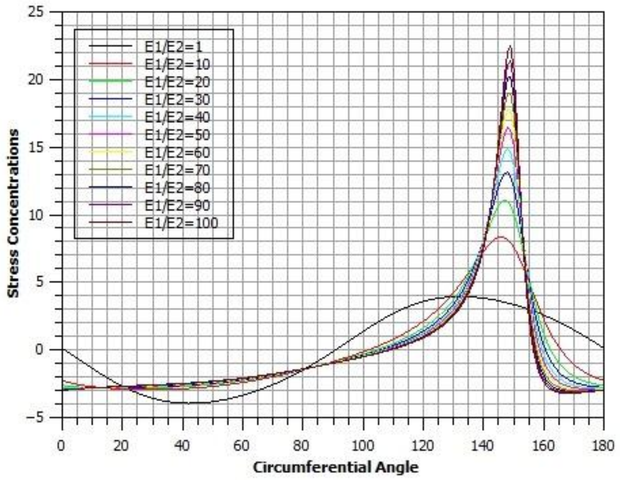

Fig. 11: Stress concentration versus θ for varying E1/E2 ratio with 60° fiber orientation

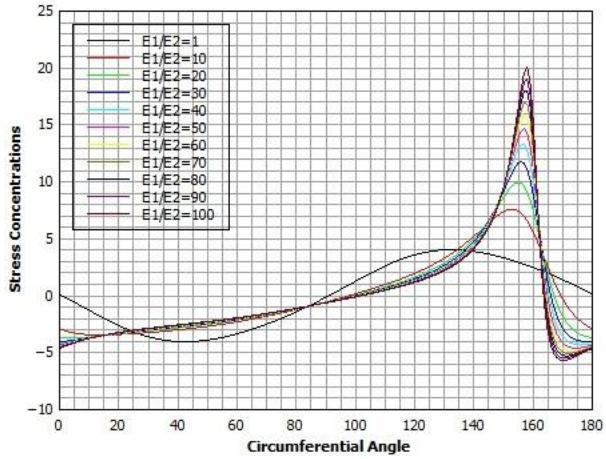

Fig. 12: Stress concentration versus θ for varying E1/E2 ratio with 70° fiber orientation

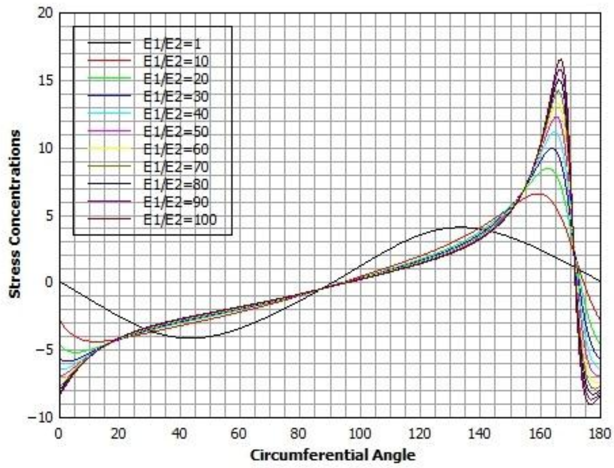

Fig. 13: Stress concentration versus θ for varying E1/E2 ratio with 80° fiber orientation

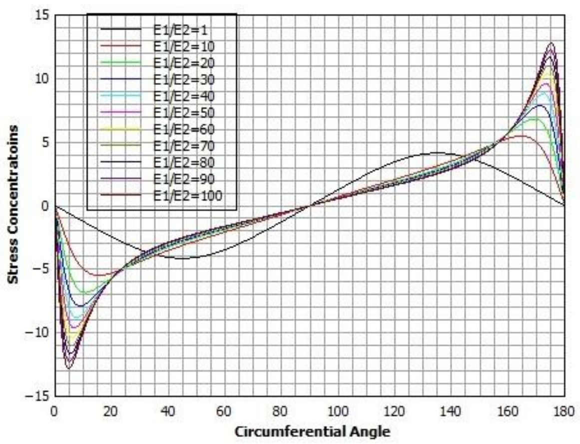

Fig. 14: Stress concentration versus θ for varying E1/E2 ratio with 90° fiber orientation

The maximum stress concentration values and critical circumferential angles are listed in Table. 1.

Table. 1: Effect of E1/E2 ratio on the maximum stress concentration and critical circumferential angle

Fiber orientation (in degrees)	Maximum Stress Concentration	Critical Circumferential Angle (in degrees)
0	12.8	95
10	16.6	103
20	20	112
30	22.5	121
40	23.7	130
50	23.7	140
60	22.5	149
70	20.0	158
80	16.6	169
90	12.8	175

From the above listed results and figures, it is evident that as the E1/E2 ratio increases the critical circumferential angle moves away from 90° circumferential angle. The maximum stress concentration of 23.7 is observed for fiber orientations of 40° and 50°. The magnitude of stress concentration is observed to be maximum for higher value of E1/E2 ratio i.e. 100. From Table. 1, it is apparent that the maximum stress concentration values are symmetric with respect to fiber orientation at 45° .

The simulation is also carried out on the cross ply laminated plate (with hole) under axial loading. The results (Fig. 15, 16) were in accord with the published results [1].

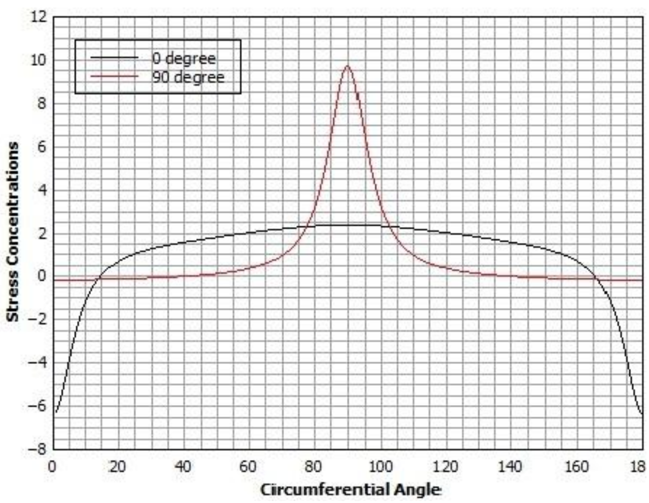

Fig. 15: Stress concentration versus θ for graphite epoxy under axial loading

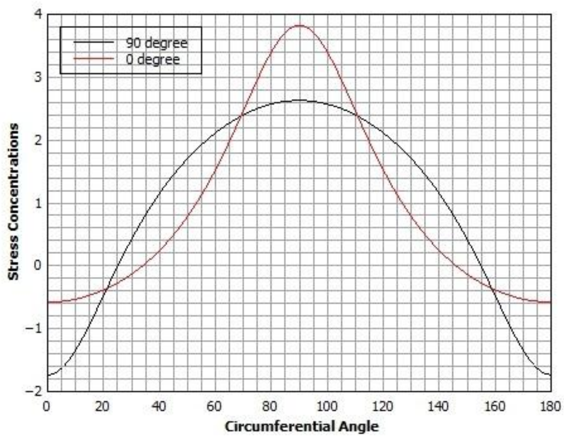

Fig. 16: Stress concentration versus θ for glass epoxy under axial loading

From Fig. 15 and Fig 16 it is evident that the variation of stress concentration is symmetric with respect to the circumferential angle. The critical circumferential angle is observed to be 90° for both the materials and ply orientations.

Orthotropic plate with hole were also analysed by using ANSYS simulation tool. Primarily simulation results were compared with the results obtained by Shubharta et al. [6], it is found that the results are in good agreement with each other. Then, the effect of D/A ratio and L/A ratio on the stresses in X-direction were studied for different materials.

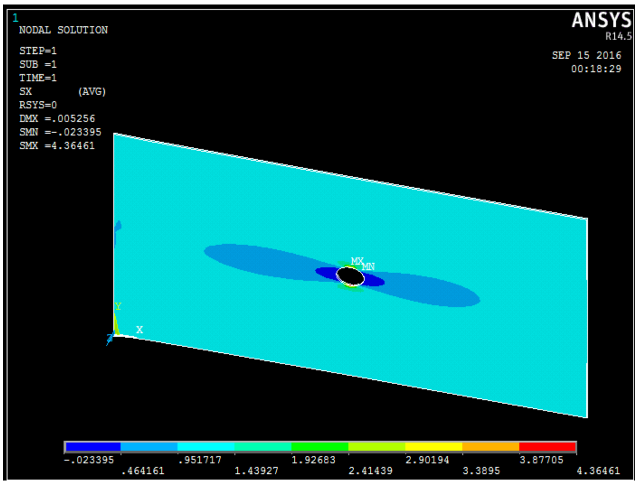

Fig. 17: Stress along X-axis for D/A = 0.1 for glass epoxy composite under axial loading

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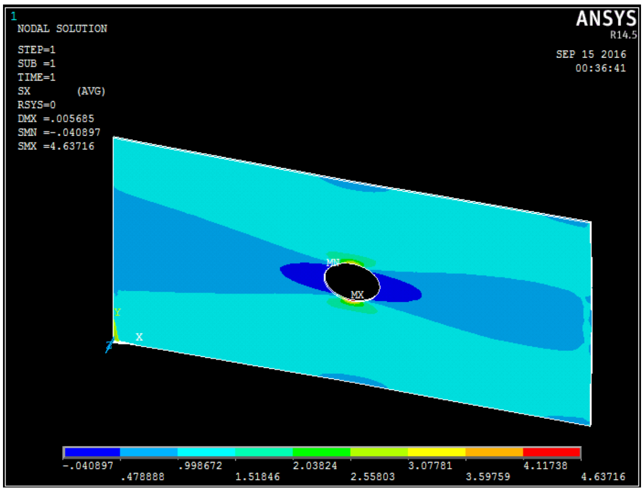

Fig. 18: Stress along X-axis for D/A = 0.2 for glass epoxy composite under axial loading

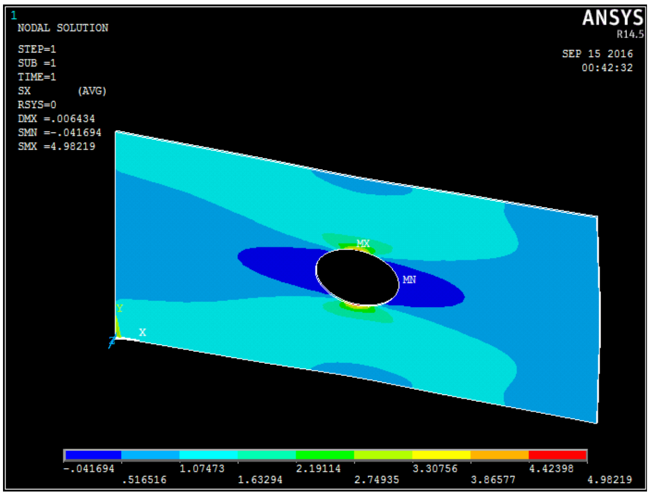

Fig. 19: Stress along X-axis for D/A = 0.3 for glass epoxy composite under axial loading

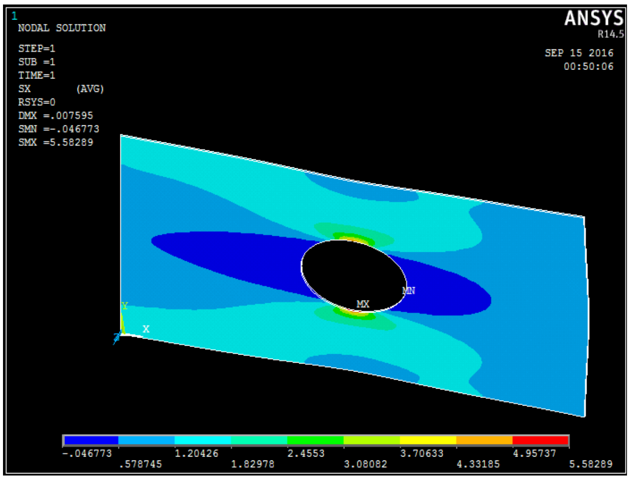

Fig. 20: Stress along X-axis for D/A = 0.4 for glass epoxy composite under axial loading

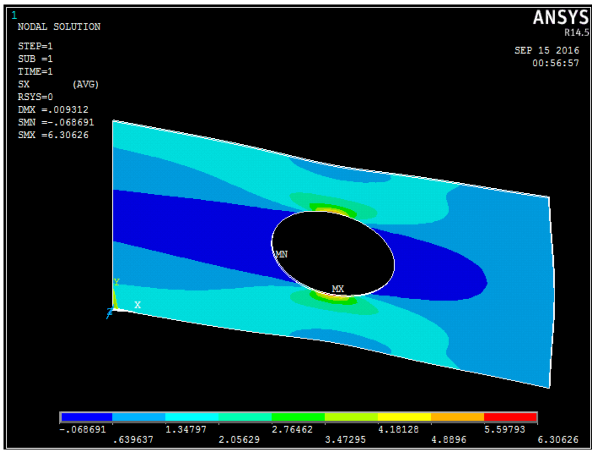

Fig. 21: Stress along X-axis for D/A = 0.5 for glass epoxy composite under axial loading

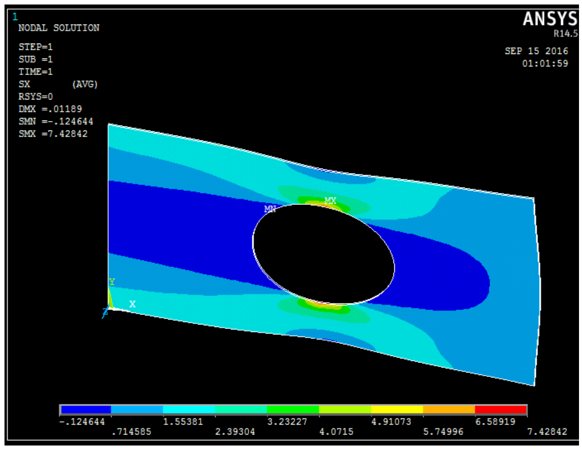

Fig. 22: Stress along X-axis for D/A = 0.6 for glass epoxy composite under axial loading

Figures 17-22 shows the magnitude of stresses obtained along X-axis of plate (i.e. along the length of the plate). The value of D/A ratio is varied from 0.1 to 0.6 and it can be seen that as the D/A ratio increases the magnitude of stress increases. The results obtained by ANSYS are plotted along with the published results [6].

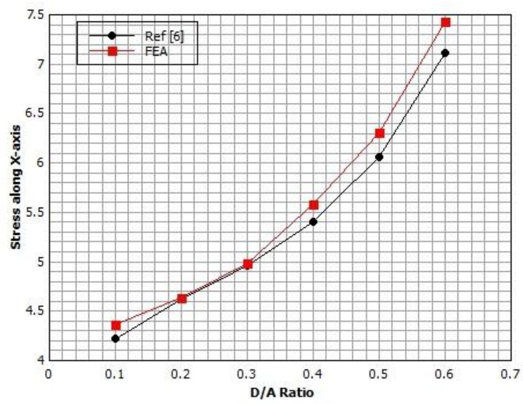

Fig. 23: Stress along X-axis versus D/A ratio for glass epoxy composite under axial loading

From Fig. 23 it is evident that both the results are in good agreement with each other. The simulation is also carried out for different materials for varying D/A ratio and the results are plotted in Fig. 24. Similarly effect of D/L ratio on stress is studied for different materials. From Fig. 25, it is evident that boron-epoxy composite possess more stress values compared to graphite-epoxy and glass-epoxy plates.

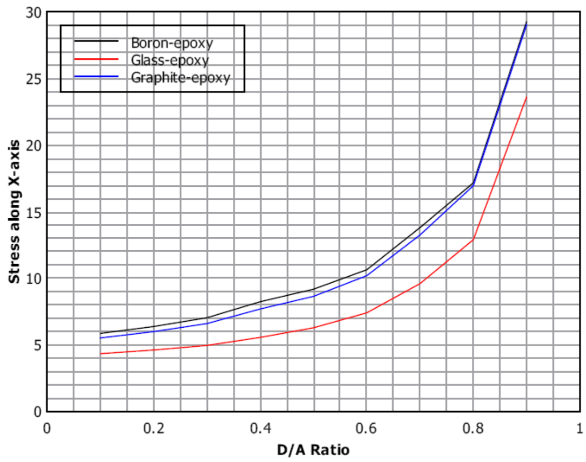

Fig. 24: Stress along X-axis versus D/A ratio for different materials under axial loading

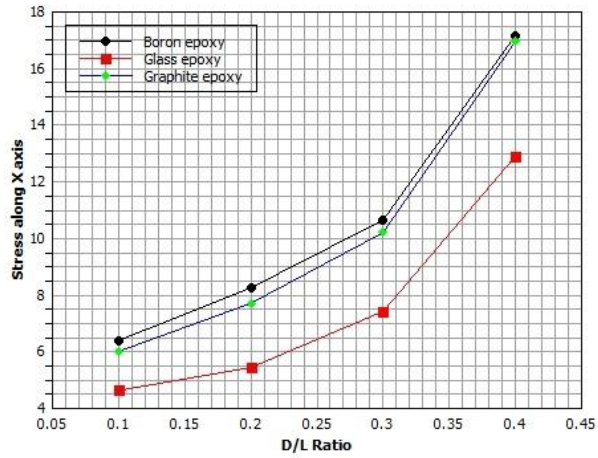

Fig. 25: Stress along X-axis versus D/L ratio for different materials under axial loading

CONCLUSION

In this work, magnitude of stress concentrations around the hole and critical circumferential angles are investigated for laminated composite plates under static loading conditions (tension/ compression and shear). Series of simulations are carried out to find the stress concentration around circular hole for different materials. The investigation was further extended to understand the D/A and D/L ratio of orthotropic plate under static loading using ANSYS simulation tool. It was observed that as D/A and D/L ratio increases the magnitude of stress along X-axis increases continuously.

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