Effect of Fiber Angle on Interlaminar Stresses of FRP Angle Ply Laminate

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Abstract: The present research work deals with the prediction of interlaminar stresses in FRP angle-ply laminate with cutout under transverse load using 3-D finite element analysis. The finite element analysis software ANSYS has been successfully executed and the finite element model is validated. The interlaminar stresses are evaluated by varying fiber angles. And it is observed that Interlaminar stresses are maximum for symmetric laminate having angle 45^0. The present analysis will be useful in designing laminated structures with cutouts to prevent interlaminar failure.

Keywords: *Interlaminar stresses, FRP laminate, angle ply laminate*

1. Introduction

The out-of-plane stresses at the interfaces of laminated structures are termed as interlaminar stresses. In isotropic material, the normal loads produce only normal strains and the shear loads produce only shear strains. In a laminate, either normal or shear load may produce both normal as well as shear strains in all the three directions depending up on the arrangement of layers. This effect is generally termed as coupling between extension, shear and bending. In addition the free edges in a laminated structure cause for introduction of reaction forces as well as out-of-plane stresses at the laminate interfaces. As a result, the magnitude of interlaminar stresses is high near the free edges such as unconstrained edges of the laminate and boundaries at various types of cutouts in the laminate. These stresses will even influence the in-plane stresses. In most of the cases the interlaminar stresses is the basis for the design of laminates. Hence it is required to estimate the interlaminar stresses most accurately and to find the parameters that influence the interlaminar stresses.

There are three types of interlaminar stresses problems associated with three types of laminates: [± θ] angle-ply laminates, [0/90] cross-ply laminates and laminates combining both angle-ply and cross-ply configurations.

The interlaminar stresses in symmetric laminates under uniform axial extension were first evaluated by Pipes and Pagano [1] by applying a finite difference technique to solve the Navier equations of elasticity for off-axis plies. Srinivas and Rao [2] and Srinivas *et al*. [3] presented a set of complete analytical analyses on bending, buckling and free vibration of plates with both isotropic and orthotropic materials. That the interlaminar stresses are affected by the laminate stacking sequence (arrangement of laminate, e.g., $[+45°/-45°/+15°/-15°]_s$ versus $[+15°/-15°/+45°/-45°]_s$) is significant to design analysis. Foye and Baker [4] hypothesized fatigue strengths differing by about 173 MPa for $[\pm15°/\pm45°]_s$ angle-ply laminates when the positions of the ±15° laminate and the ±45° laminate were reversed. Bhaskar and varadhan [5] used the combination of Navier's approach and a Laplace transform technique to solve the dynamic equations of equilibrium. E.F. Rybicki [6] found approximate three dimensional solutions for symmetric laminates under in-plane loading. **R. Byron Pipes [7]** used the Moiré technique to examine the surface displacements of the symmetric angle-ply laminate under axial extension. Pagano et al. [8] has given exact solutions for the deflections and stresses of a cross- ply laminated rectangular composites using elasticity theory. Another lamination parameter known to influence edge delamination is the thickness of the plies. [9] Rodini, B.T. and Eisenmann performed An Analytical and Experimental Investigation of Edge Delamination in Composite

Laminate. CH. Siva Sankara Babu [10] discussed the effect of thickness on interlaminar stresses in simply supported beams with cutout. Herakovich [11] studied the relationship between engineering properties and delamination of composite materials. The Effect of stacking sequence on the critical interlaminar stresses in quasi-isotropic [0/90/±45]s T-300 carbon-epoxy laminates is presented. Wang and Choi [12, 13] assumed the form of the stress functions in order to analytically solve the compatibility equations for two adjacent off-axis plies in the state of strain dependent on two coordinates. A singular stress field at the free edge was obtained. While this provides a rigorous prediction of the free-edge interlaminar stresses, its mathematical complexity makes it unsuitable for practical multilayer laminates. Other existing analytical approaches are based on ad hoc assumptions regarding the stress or strain fields in addition to the classical 2-D formulation of the 3-D strain state. A number of finite element models were subsequently developed, a brief review is provided in Ref. [13]. An approximate semi-analytical method for determination of interlaminar shear stress distribution through the thickness of an arbitrarily laminated thick plate was presented by Reaz A. Chaudhuri and Paul Seide [14]. The method was based on the assumptions of transverse inextensibility and layer wise constant shear angle theory (LCST) and utilized an assumed quadratic displacement potential energy based finite element method (FEM). Centroid of the triangular surface was proved, from a rigorous mathematical point of view (Aubin-Nitsche theory), to be the point of exceptional accuracy for the interlaminar shear stresses. Numerical results indicated close agreement with the available three-dimensional elasticity theory solutions. A comparison between the proposed theory and that due to an assumed stress hybrid FEM suggests that the (normal) traction-free-edge condition was not satisfied in the latter approach. Furthermore, the paper was the first to present the results for interlaminar shear stresses in a two-layer thick square plate of balanced un-symmetric angle-ply construction. A comparison with the recently proposed Equilibrium Method (EM) indicated the superiority of the method, because the latter assures faster convergence as well as simultaneous vanishing of the transverse shear stresses on both the exposed surfaces of the laminate. Superiority of the method over the EM, in the case of a symmetric laminate, was limited to faster convergence alone. It was also demonstrated that the combination of the method and the reduced (quadratic order) numerical integration scheme yields convergence of the interlaminar shear stresses almost as rapidly as that of the nodal displacements, in the case of a thin plate. Erian A. Armanios and Jian Li [15] predicted the interlaminar stresses in a symmetric laminate under extension, bending, torsion and their combined effect using a simple analytical formulation. The method was based on a shear deformation theory and a sub laminate approach. The solution was obtained in closed form and the controlling parameters were isolated. Extensive comparisons with a finite element solution were made to verify the model for the case of laminates subjected to torsion loading. An assessment of the induced curvature predicted from classical lamination theory and the present approach was provided. The influence of the induced curvature on the interlaminar stress prediction was investigated for torsion loading. The interlaminar stresses in laminates subjected to combined bending and torsion ware obtained by superposition. O. Allix and P. Ladeveze [16] aimed to focus on the interface modeling and first identification. A laminate was modeled as a stacking sequence of homogeneous layers and interlaminar interfaces. Kong and Cheung [17] proposed a displacement-based, three-dimensional finite element scheme for analyzing thick laminated plates by treating the plate as a three dimensional inhomogeneous anisotropic elastic body. An iterative method for one-term approximate solution of partial differential equations was developed by Makeev [18].

From the study of the existing literature, it is found interesting to explore the effects of fiber angle on interlaminar stresses for angle Ply laminate with simply supported and clamped boundaries.

2. Finite Element Modeling

Three-dimensional finite element analysis of a four layered symmetric balanced angle-ply laminate has been taken up in the present work. The finite element model created in ANSYS software is validated and extended to evaluate the interlaminar stresses at interfaces by varying the fiber angle. A square plate of length 100 mm is considered for the present analysis. Four layers of equal thickness with the various fiber angles 15°, 30°, 45°, 60°, 75° and 90° are arranged to observe the balance as well as symmetry across the thickness of the laminate with three interfaces I-1,I-2 and I-3. The length-to-thickness ratio ‘s’ is taken as 10 mm so that the thickness of each layer of the plate is 2.5 mm. A circular cutout with diameter-to-length ratio (d/l) 0.2 is considered at the centre of the plate. Fiber angles considered for the analysis are 15°/-15°/-15°/15°, 30°/-30°/-30°/30°, 45°/-45°/-45°/45°, 60°/-60°/-60°/60°, 75°/-75°/-75°/75°, 90°/-90°/-90°/90°.

The finite element mesh is generated with SOLID45 of ANSYS software. SOLID45 is a 8 node brick element having three degrees of freedom per node: translations in the nodal x, y, and z directions. The element has orthotropic material properties. Orthotropic material directions correspond to the element coordinate directions .The element has plasticity, creep, swelling, stress stiffening, large deflection, and large strain capabilities.

2.1 Material Properties

The following material properties [10] of graphite epoxy laminate are considered for the present analysis.

i) Young’s Modulus, E_1=127.5GPa, E_2 = 9.0GPa, E_3=4.8GPa.

ii) Poisson’s Ratio, ν_{12}=0.28, ν_{23}=0.41, ν_{13} = 0.28.

iii) Rigidity Modulus, G_{12}=G_{13}= 4.8GPa, G_{23}=2.55GPa.

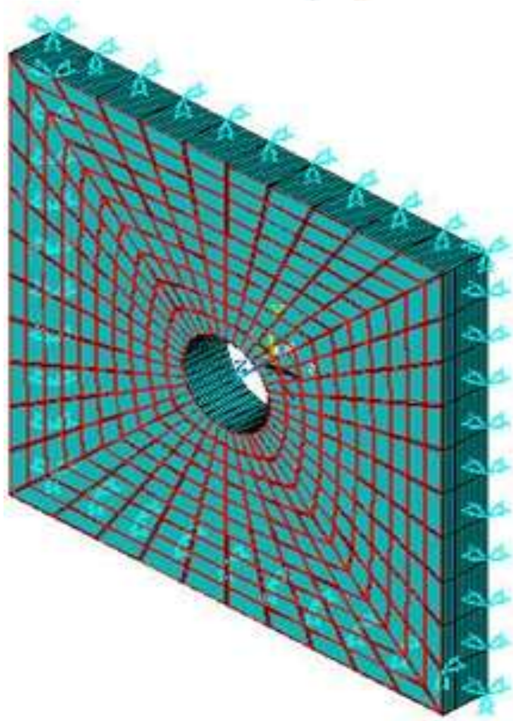


Fig. 1 FE model with a circular cutout for the simply supported plate.

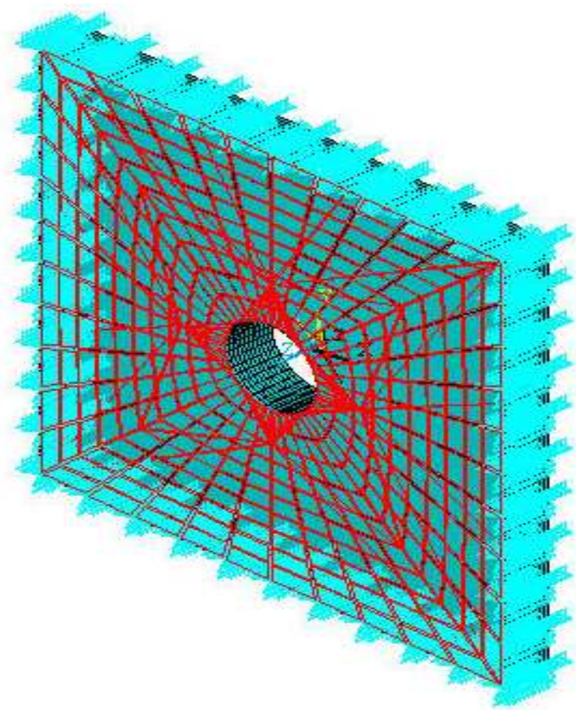


Fig. 2 FE model with a circular cutout for the clamped plate

2.2 Simply Supported Plate

SS-1 refers a simply supported plate along all the four edges shown in Fig. 1. SS-2 refers a simply supported plate along the outer edges parallel to Y-axis. SS-3 refers a simply supported plate along the edges parallel to X-axis. A uniform load of 1 MPa is applied on the top surface i.e z = thickness of the FE model.

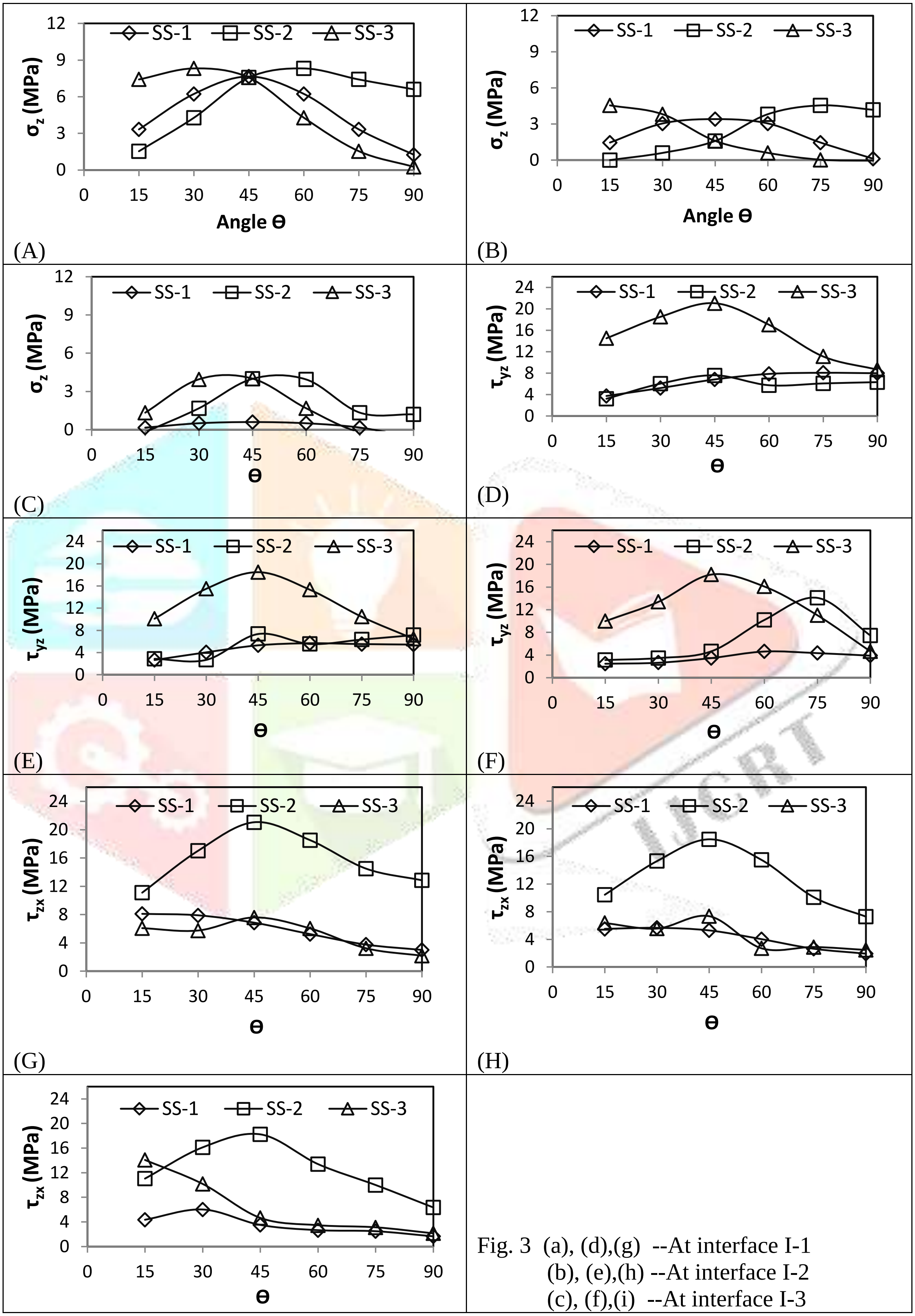


Fig. 3 (a), (d),(g) --At interface I-1
(b), (e),(h) --At interface I-2
(c), (f),(i) --At interface I-3

(I)	

2.2.1 Validation

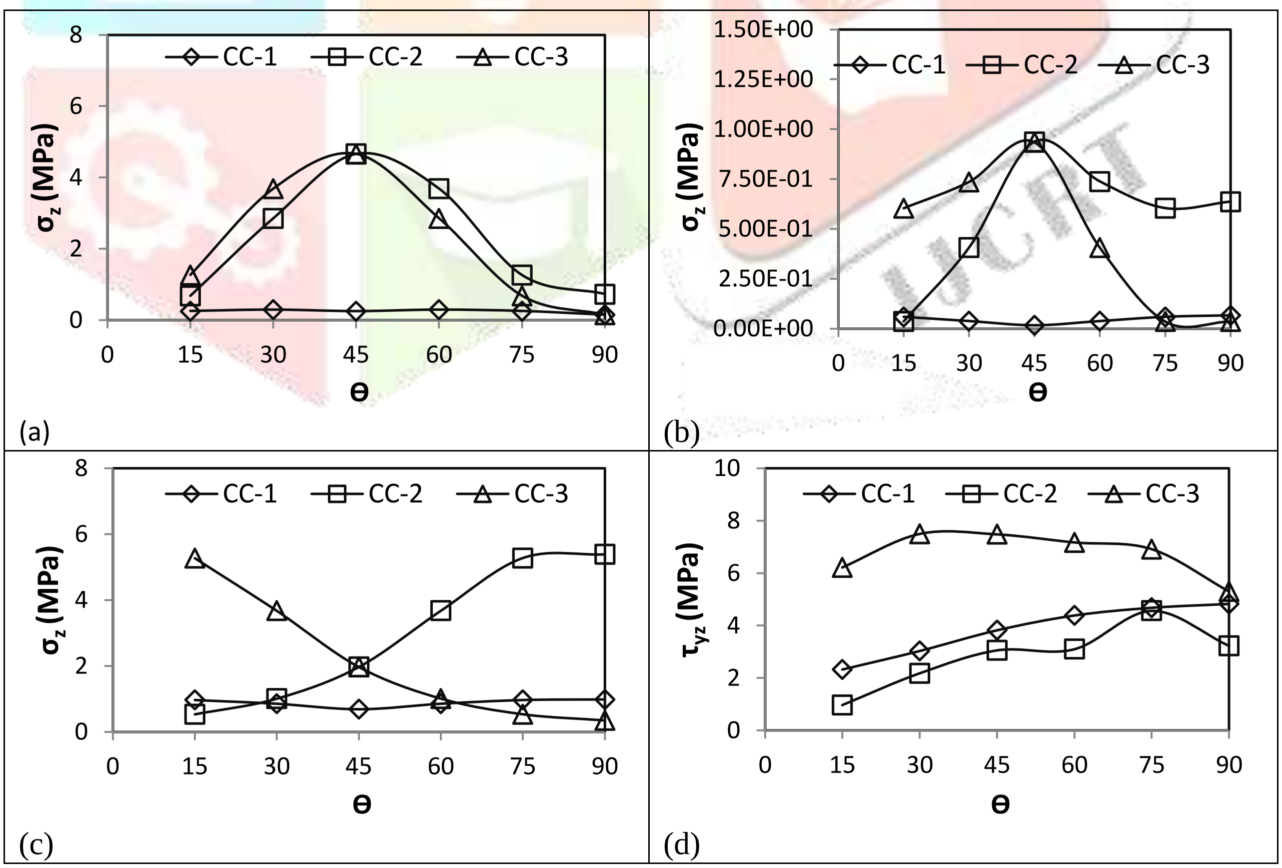
The present finite element model is validated by computing the out of plane stresses at the free surface i.e., at the bottom surface of the plate (z=0) with different fiber angles for the length-to-thickness ratio 's'= 10 and diameter-to-length ratio is 0.2 . The computed stresses are found to be close to zero shown in Table 1.

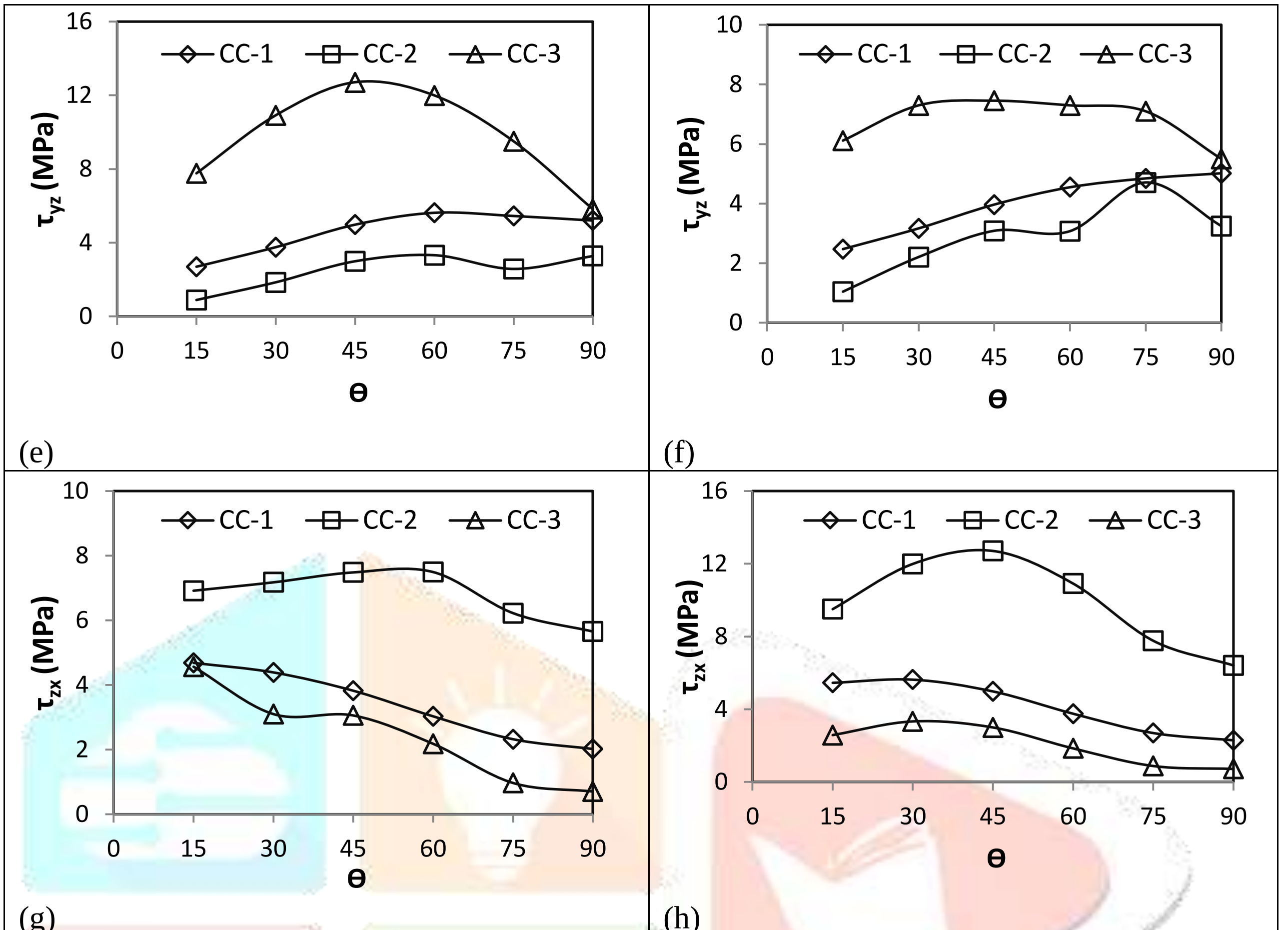
Table 1: Validation of the finite element results for SS-1 plate.

Fiber Angle	σ_z (MPa)	τ_{yz} (MPa)	τ_{zx} (MPa)
15°/-15°/-15°/15°	0.0019520	0.0052643	0.0017592
30°/-30°/-30°/30°	0.0013582	0.0059550	0.0055069
45°/-45°/-45°/45°	0.00010931	0.0030434	0.0023665
60°/-60°/-60°/60°	0.0062865	0.0081417	0.0035454
75°/-75°/-75°/75°	0.0044786	0.0079594	0.0055706
90°/-90°/-90°/90°	0.0062865	0.0081417	0.0035454

2.3 Clamped Plate

CC-1 refers a clamped plate along all the four edges shown Fig. 2. CC-2 refers Clamped conditions are applied along the outer edges parallel to Y-axis. CC-3 refers Clamped conditions are applied along the outer edges parallel to X-axis. A uniform load of 1 MPa is applied on the top surface i.e z = thickness of the FE model





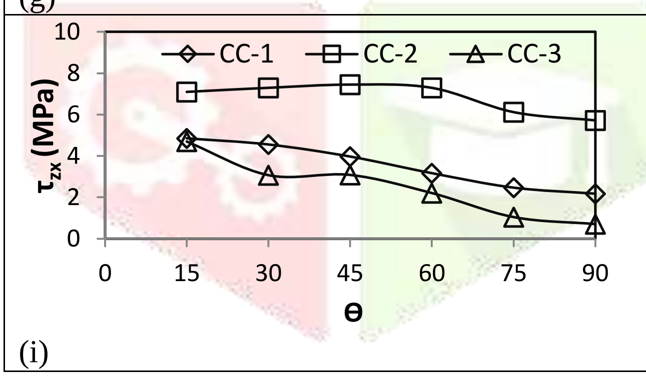


Fig. 4 (a), (d),(g) --At interface I-1
(b), (e),(h) --At interface I-2
(c), (f),(i) --At interface I-3

2.3.1 Validation

The present finite element model is validated by computing the out of plane stresses at the free surface i.e., at the bottom surface of the plate (z=0) with different fiber angles for the length-to-thickness ratio 's'= 10 and diameter-to-length ratio is 0.2. The computed stresses are found to be close to zero (Table 2).

Table 2 Validation of the finite element results for CC-1 plate.

Fiber Angle	σ_z (MPa)	τ_{yz} (MPa)	τ_{zx} (MPa)
15°/-15°/-15°/15°	0.0010520	0.0035643	0.0025592
30°/-30°/-30°/30°	0.0035582	0.0058550	0.0022069
45°/-45°/-45°/45°	0.0048587	0.0080682	0.0062795
60°/-60°/-60°/60°	0.0056865	0.0066417	0.0026454

75°/-75°/-75°/75°	0.0088786	0.0086594	0.0075706
90°/-90°/-90°/90°	0.0052865	0.0061417	0.0055454

3. Analysis Of Results

Analysis of the interlaminar stresses with respect to fiber angle in angle-ply laminates subjected to out of-plane transverse load is presented in Fig. 3 and Fig. 4.

3.1 Simply Supported Plate

From Figs. 3(a) to 3(c), it is observed at all interfaces of a laminate, the interlaminar normal stress σ_z is rapidly increasing for different fiber angles and then decreasing. It is observed that the interlaminar normal stress σ_z is same for all boundary conditions at interface I-1 for an angle 45^0 and same for boundary conditions SS-2 and SS-3 at interfaces I-2 and I-3 for an angle 45^0. Normal stress σ_z is maximum at interfaces I-1 in magnitude. At interface I-3 the stress is minimum (SS-1) for all values of 'Ɵ'.

Variation of the interlaminar shear stress τ_{yz} with respect to fiber angle at all interfaces I-1, I-2 and I-3 is shown in Figs. 3(d) to 3(f). It is observed that the stress τ_{yz} is rapidly increasing for different fiber angles at all the interfaces. It is observed that the interlaminar shear stress τ_{yz} is maximum for SS-3 at all interfaces I-1, I-2 and I-3. And minimum for SS-2 at I-3 for all values of 'Ɵ'.

Variation of the interlaminar shear stress τ_{zx} with respect to fiber angle at all interfaces I-1, I-2 and I-3 is shown in Figs. 3(g) to 3(i). It is observed that the stress τ_{zx} is rapidly decreasing for different fiber angles. It is observed that the interlaminar shear stress τ_{zx} is maximum for SS-2 at all interfaces I-1, I-2 and I-3 for all values of 'Ɵ'. And minimum for SS-1 at interface I-3 for all values of 'Ɵ'.

3.2 clamped Plate

From Figs. 4(a) to 4(c), it is observed at all interfaces of a laminate, the interlaminar normal stress σ_z is rapidly increasing for different angles and then decreasing. It is observed that the interlaminar normal stress σ_z is increasing upto the angle 45^0 and then decreasing at interfaces I-1 and I-2. normal stress σ_z is minimum at interfaces I-2. At all interfaces I-1, I-2 and I-3 the stress is minimum for CC-1 for all values of 'Ɵ'.

Variation of the interlaminar shear stress τ_{yz} with respect to fiber angle at all interfaces I-1, I-2 and I-3 is shown in Figs. 4(d) to 4(f). It is observed that the stress τ_{yz} is rapidly increasing for different fiber angles at all the interfaces. It is observed that the interlaminar shear stress τ_{yz} is maximum for CC-3 and minimum for CC-2 at all interfaces I-1, I-2 and I-3 for all values of 'Ɵ'.

Variation of the interlaminar shear stress τ_{zx} with respect to fiber angle at all interfaces I-1, I-2 and I-3 is shown in Figs. 4(g) to 4(h). It is observed that the stress τ_{zx} is rapidly decreasing for different fiber orientations. It is observed that the interlaminar shear stress τ_{zx} is maximum for CC-2 at all interfaces I-1, I-2 and I-3 for all values of 'Ɵ'. And is minimum for CC-3 at all interfaces I-1, I-2 and I-3 for all values of 'Ɵ'.

4. Conclusions

The interlaminar stresses for angle-ply laminates with various fiber angles are subjected to various boundary conditions are modeled, analyzed and the results are obtained. The results are presented in the form of graphs and Validated.

It is observed that the interlaminar shear stresses τ_{yz}, τ_{zx} are maximum for SS-3/CC-3, SS-3/CC-2 respectively for all the fiber angles. $\sigma_{z,}$ follows same trend and minimum for CC-1 boundary condition at all interfaces for all vaues of 'Ɵ'. Shear stress τ_{yz} is minimum for CC-2 boundary condition and τ_{zx} is minimum for CC-3 boundary condition at all interfaces for all vaues of 'Ɵ'

5. References

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