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Nonlinear Analysis for Interlaminar Stresses of Skew FRP Laminates with Circular Cutout

Dr. V. V. Sridhara Raju[1*]
[1] Mech. Engg. Dept.,
P. V. P. Siddhartha Institute of Technology,
Vijayawada, India.

Dr. V. Bala Krishna Murthy[2]
[2] Mech. Engg. Dept.,
V. R. Siddhartha Engineering College,
Vijayawada, India.

Dr. J. Suresh Kumar[3]
[3] Mech. Engg. Dept.,
JNTUH College of Engineering,
JNTUH, Hyderabad, India.

Abstract **- Interlaminar stresses are responsible for interlaminar failure and influencing the magnitude of the other stresses in laminated FRP composites. These stresses are developed mainly due to the interaction of the layers with in the laminate due to the restriction of uneven deformations in the constituent layers. In the present analysis the interlaminar stresses are predicted for a bidirectional skew laminated unidirectional continuous fiber reinforced plastic (FRP) composite with a circular cut out at the geometric centre of the plate using three dimensional finite element method with geometric nonlinear option. The effect of material stiffness on geometric nonlinearity is studied by analyzing the structure for three different materials. The problem is modeled in ANSYS software and executed for satisfactory results by performing convergence of the finite element mesh. The limitations of the linear assumption and the need for nonlinear analysis are stated.**

Keywords: FEM, FRP Laminate, Cutout, Geometric Nonlinearity, Interlaminar stresses.

1.0 INTRODUCTION

Composite materials produce properties that cannot be achieved by their constituents alone. Some of the properties that can be improved by forming a composite material are stiffness, specific strength, weight reduction, corrosion resistance, thermal properties, fatigue life, and wear resistance. These properties made the use of composites increasing in applications like aerospace and ship building industries etc. The skew or oblique plates made of these materials are important structural components of ship hulls and swept wings of aeroplanes. A common structural detail that is present in many laminated plates is a cutout. The cutouts are used for many reasons like to reduce weight, to provide access to various locations inside an aircraft, and to permit hydraulic and electrical lines to pass through the structure.

The existence of interlaminar stresses means that laminated composite materials can delaminate near free edges whether they be at the edge of a plate, around a hole. The loss of adhesion between the laminae of a composite laminate is well recognized as a phenomenon which may drastically reduce the mechanical performance of the material. Often, it originates with the material manufacturing process, due to flaws or imperfections in the interlaminar surfaces. The delamination growth is essentially produced by the action of normal and tangential interlaminar stresses. These interlaminar normal and shear stresses, on the other hand, are believed to play a significant role in prediction of dominant cause of failure in composite laminates. These stresses that exhibit highly localized concentration near the edges of the laminate are the basis for damage in the form of free-edge delamination and the subsequent delamination growth in the interior region of laminates, leading to premature failure at loads below those corresponding to in plane failure.

The composite laminate plates in service are often subjected to transverse forces that may cause failure of structure when the magnitude of these forces is not with in limits of safe design. Hence, structural instability becomes a major concern in safe and reliable design of the composite plates. Thus the stability analysis of such plates is of interest to the designers. In laminated composites, the designer may specify different materials, fiber orientations, and layers at various locations through the thickness or over the plane of laminate to improve its response to mechanical and thermal loads. The non-orthogonal co-ordinate system used in the derivation of governing differential equations and finding the solution to the coupled equations is a complicating factor in the analysis of skew laminated plates. Hence, due to difficulty to obtain exact solution for these equations and associated boundary conditions, numerical methods such as finite element method, finite difference method, Rayleigh-Ritz method, etc. are used to investigate the structural mechanics of Skew laminated plates.

Finite-difference solution techniques are employed by Pipes and Pagano to investigate Interlaminar Stresses, displacements in Composite Laminates under Uniform Axial Extension [1]. Pagano presented an approximate method to define the distribution of the interlaminar normal stress, along the central plane of a symmetric, finite-width, composite laminate [2]. Wang and Crossman based on the formulation presented by Pipes and

Pagano[1] studied the free-edge stresses in symmetric balanced laminates under uniaxial tension using a finite element procedure [3]. Kim and Atluri developed a stress-based variational method to obtain interlaminar stresses under combined thermo-mechanical loading [4]. A relatively comprehensive review of the various techniques of evaluation of interlaminar stresses is presented by Kant and Swaminathan in their survey paper [5]. A comprehensive examination of interlaminar stresses in general cross-ply laminates has been presented by Tahani and Nosier [6]. Kuppusamy and Reddy presented a three-dimensional, geometrically nonlinear; finite-element analysis of the bending of cross-ply laminated anisotropic composite plates [7]. Andrade et.al formulated and implemented an eight-node hexahedral isoparametric element with one-point quadrature for the geometrically nonlinear static and dynamic analysis of plates and shells of laminate composite materials in the analysis [8]. Alinia and Ghannadpour studied the nonlinear analysis of square plates subjected to pressure loading and made of functionally graded materials [9]. The geometric nonlinearity is introduced in the strain–displacement equations based on Von-Karman assumptions. Park et.al performed a structural dynamic analysis of skew sandwich plate with laminated composite faces based on the high-order shear deformation plate theory [10]. Aydin Komur and Mustafa Sonmez studied the elastic buckling behavior of rectangular perforated plates using the finite element method [11]. The effect of cutout location on the buckling behavior of plates is investigated by considering circular cutout at different locations along the principal x-axis of plates subjected to linearly varying loading. Kubair and Bhanu-Chandar investigated the effect of the material property inhomogeneity on the stress concentration factor due to a circular hole in functionally graded panels under uniaxial tension [12]. Ersin Eryigit et.al investigated the effects of hole diameter and hole location on the lateral buckling behaviour of woven fabric laminated composite cantilever beams [13]. After the intensive investigations on the analysis of interlaminar stresses in composite laminates, documented in the literature during the past four decades, it is identified that there is a scope to analyze interlaminar stresses in a skew laminate with cutout for geometric nonlinear behavior and to study the effect of material properties on the nonlinearity of the structure.

1.1 Problem Statement

The objective of the present work is to study the effect of material properties on geometric nonlinear behavior of a four layered symmetric cross-ply skew laminate with circular cutout using three dimensional finite element method with a discussion of interlaminar stresses at different interfaces of the laminate.

1.2 Skew Laminate

The term 'skew' in skew laminate refers to oblique, swept or parallelogram. In case of skew plate the angle between the adjacent sides of the plate is not equal to 90^0. If opposite sides of the plate are parallel, it becomes a parallelogram and when their lengths are equal, the plate is called a rhombic plate. In the present analysis a rhombic laminated plate of a fixed skew angle of 30^0 is considered as shown in Fig.1.

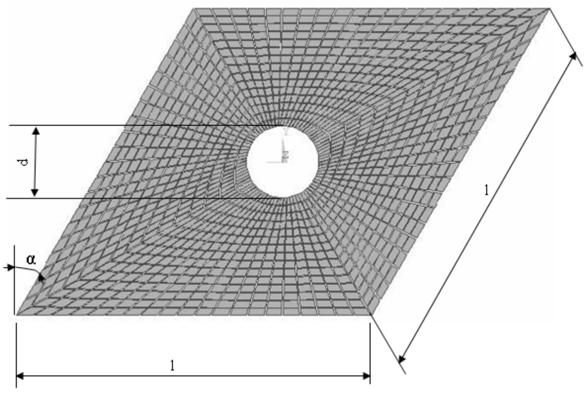
2.0 PROBLEM MODELING

The in-plane dimensions of the laminate considered for the present analysis is as shown in Fig.1. The dimensions for 'l' are taken as 20mm. The value of d is determined from the ratio of d/l. The value of 'h' is determined from the length to thickness ratio l/h (s=40). Laminate consists of four layers of equal thickness (h/4). At higher skew angle, the length of the shorter diagonal of the skew plate decreases causing increase in the stiffness of the plate. Hence a skew angle of 30^0 is considered for the present problem. Present work considers a skew plate with a central cutout of fixed d/l = 0.2 and 's' value of 40 for both linear and Nonlinear analysis. The finite element mesh is generated using a three dimensional brick element 'SOLID 95'of ANSYS[14]. This element is a structural solid element designed based on three-dimensional elasticity theory and is used to model orthotropic solids. The element is defined by 20 nodes having three degrees of freedom per node: translations in the nodal X, Y, and Z directions. The element may have any spatial orientation. The stacking sequence of the laminate is taken as $0^0/90^0/90^0/0^0$.

All the edges of the Cross-ply laminated skew plate are clamped i.e. all the three degrees of freedom (Displacements in global x-, y- and z- directions) of the nodes attached to the side faces of the plate are constrained. A transverse pressure of 0.5MPa is applied on the top surface of the plate in ten equal steps.

Fig. 1: Skew laminated Composite plate with circular cutout.

The material properties of the composite made of



epoxy as matrix and different types of fibers as reinforcement are as furnished below:

T300-Epoxy
E_1 = 134.48 GPa; E_2 = E_3= 9.9177 GPa;
$\nu_{12} = \nu_{13}$ = 0.2571; ν_{23} = 0.3627;
G_{12}= G_{13}= 4.129 GPa; G_{23} = 3.751 GPa

Graphite-Epoxy
E_1 = 141.68 GPa; E_2 = E_3= 12.384 GPa;
$\nu_{12} = \nu_{13}$ = 0.25772; ν_{23} = 0.42057;
G_{12}= G_{13}= 3.880 GPa; G_{23} = 4.360 GPa

Boron-Epoxy
E_1 = 241.87 GPa; $E_2 = E_3$= 25.512 GPa;
$\nu_{12} = \nu_{13}$ = 0.25; ν_{23} = 0.26;
$G_{12}= G_{13}$= 6.7158 GPa; G_{23} = 10.084 GPa

3.0 VALIDITY OF THE PRESENT ANALYSIS

To validate the finite element results, a skew four layered FRP cross-ply laminate having a circular cutout at centre with clamped edges and applied pressure (0.5 MPa) on top surface is considered. A few computed values of stresses at top and bottom surfaces of the plate are obtained after conducting number of convergence tests by varying mesh size. The values of σ_{zz} are nearly equal to zero at bottom surface of plate and equal to applied pressure load at top surface of plate. The shear stresses τ_{yz} and τ_{zx} are nearly equal to zero at both the surfaces of the plate. The same are presented in Table1 and Table2 respectively.

Table 1: A few computed values of stresses on free surfaces (Bottom surface)

x-Position (mm)	y-Position (mm)	σ_{zz} (MPa.)	τ_{yz} (MPa.)	τ_{zx} (MPa.)
-0.57172	-3.77549	-0.0000029288	0.0055260	0.0058589
0.57172	3.77549	-0.0000029284	-0.0055260	-0.0058589

Table 2: A few computed values of stresses on top surfaces (Top surface)

x- Position (mm)	y-Position (mm)	σ_{zz} (MPa.)	τ_{yz} (MPa.)	τ_{zx} (MPa.)
-0.57172	-3.77549	-0.50038	0.0076090	0.0067750
0.57172	3.77549	-0.50038	-0.007609	-0.006775

4.0 RESULTS AND DISCUSSION

Interlaminar stresses are obtained at top, middle and bottom interfaces which are located at 3h/4, h/2 and h/4 distances form the bottom surface of the laminated plate. Numerical results are obtained for pressure loading as mentioned above. The effect of material stiffness on deflection, interlaminar normal and shear stresses with a variation in loads is discussed.

4.1 Nonlinear vs Linear analysis

The results show that there is a variation of stresses and deflection from linear to nonlinear analysis beyond certain load.

4.2 Effect of different fiber materials

Transverse deflection of the skew plate with respect to the applied load is shown in Fig.2. Magnitude of the transverse deflection and the difference between results from the two analyses types increase with increase in load indicating that nonlinear analysis is required to study the exact behavior of the structure under consideration. The value of deflection increases as the stiffness of the fiber material decreases. The nonlinear behavior is observed beyond 0.2 MPa for T300, 0.3 MPa for Graphite and 0.4 MPa for Boron.

The values of interlaminar normal stress σ_{zz} (Figs. 3 to 5) at all the interfaces of the laminate increases with an increase in load for all the materials under consideration in both linear and nonlinear analysis. The magnitude of σ_{zz} is small at middle interface followed by bottom interface and top interface. The values of σ_{zz} are observed to be more in linear analysis than in nonlinear analysis at middle and bottom interfaces. The values of σ_{zz} are observed to be slightly more in nonlinear analysis than in linear analysis at top interface. The difference between linear and nonlinear results of σ_{zz} that increase with increase in load is observed to be more at middle interface followed by bottom interface and then top interface. The magnitude of σ_{zz} is observed to be lesser for T300 followed by Boron and Graphite at top interface and bottom interface. The magnitude of σ_{zz} is observed to be lesser for Boron followed by T300 and Graphite at middle interface. The nonlinear behavior is observed for σ_{zz} beyond 0.05MPa for all materials under consideration at middle interface and bottom interface, where as it is beyond 0.4MPa for Graphite and beyond 0.45 MPa for boron and T300 at top interface.

The values of interlaminar shear stress τ_{yz}, τ_{zx} (Figs. 6 to 11) at all the interfaces of the laminate increases with an increase in load for all the materials under consideration in both linear and nonlinear analysis. The magnitude of τ_{yz}, τ_{zx} is small at middle interface followed by top interface and bottom interface. The values of τ_{yz}, τ_{zx} are observed to be more in linear analysis than in nonlinear analysis at middle and top interfaces. The values of τ_{yz}, τ_{zx} are observed to be slightly more in nonlinear analysis than in linear analysis at bottom interface. The difference between linear and nonlinear results of τ_{yz}, τ_{zx} that increase with increase in load is observed to be more at top interface followed by bottom interface and then middle interface.

The magnitude of τ_{yz} (Figs. 6 to 8) is observed to be lesser for T300 followed by Graphite and Boron at all the three interfaces of study. The nonlinear behavior is observed for τ_{yz} beyond 0.1MPa for all materials under consideration at top interface, where as it is beyond 0.2MPa for Graphite and T300 and beyond 0.3 MPa for boron at middle and bottom interfaces.

The magnitude of τ_{zx} (Figs. 9 to 11) is observed to be lesser for Graphite followed by T300 and Boron at top interface. The magnitude of τ_{zx} is observed to be lesser for Boron followed by Graphite and T300 at middle interface. The magnitude of τ_{zx} is observed to be lesser for Graphite followed by Boron and T300 at bottom interface. The nonlinear behavior is observed for τ_{zx} beyond 0.15MPa at top interface and beyond 0.25MPa at middle interface for all materials under study, where as it is beyond 0.2MPa for Graphite and T300 and beyond 0.35MPa for boron at bottom interface.

The percentage error between results obtained by nonlinear and linear analysis at maximum load (0.5MPa) is more incase of σ_{zz} for Graphite at top and bottom interfaces and for Boron at middle interface, in case of τ_{yz}, τ_{zx} it is more for T300 at bottom and middle interfaces, whereas at top interface it is more in case of τ_{yz} for Graphite and in case of τ_{zx} for T300.

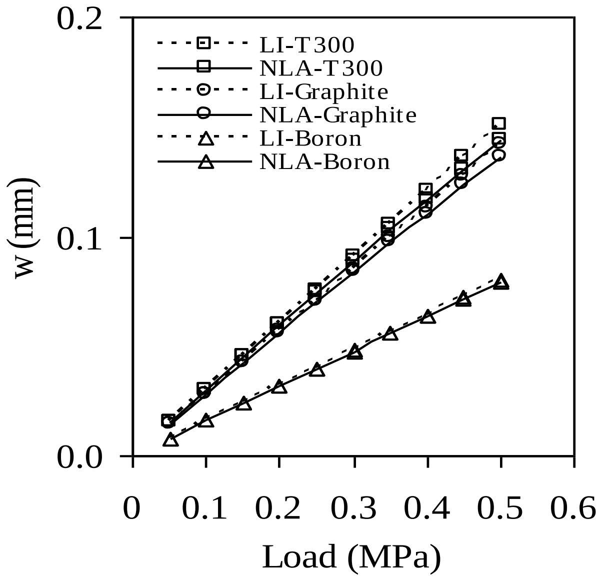


Fig. 2. Variation of ‘w’ with respect to Load.

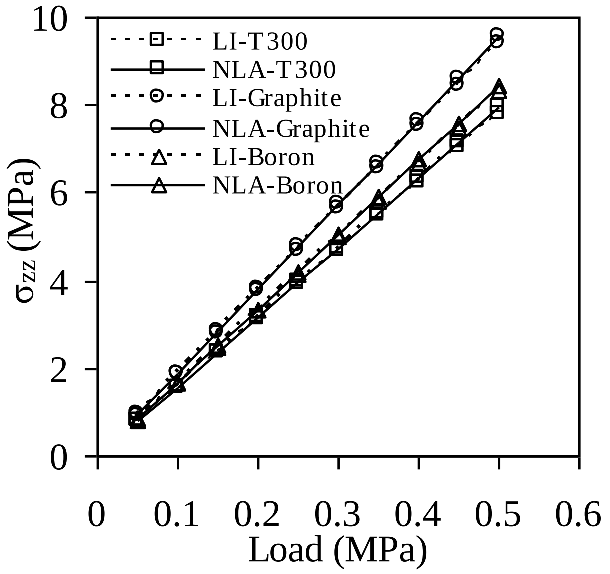


Fig. 3. Variation of σ_{zz} at Top Interface.

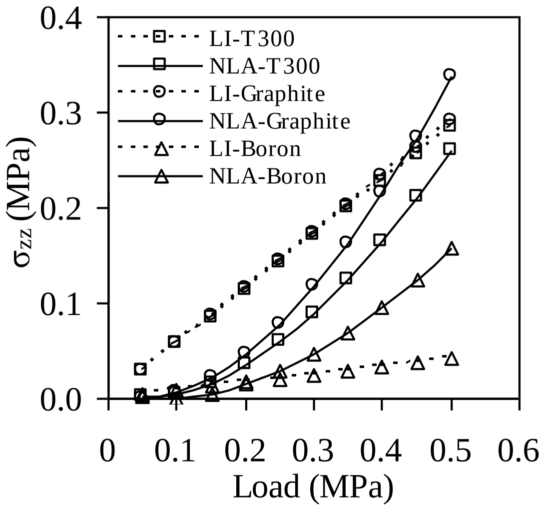


Fig. 4. Variation of σ_{zz} at Middle Interface.

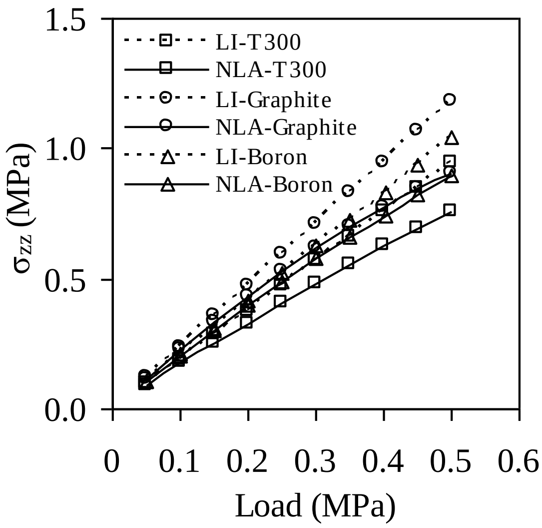


Fig. 5. Variation of σ_{zz} at Bottom Interface.

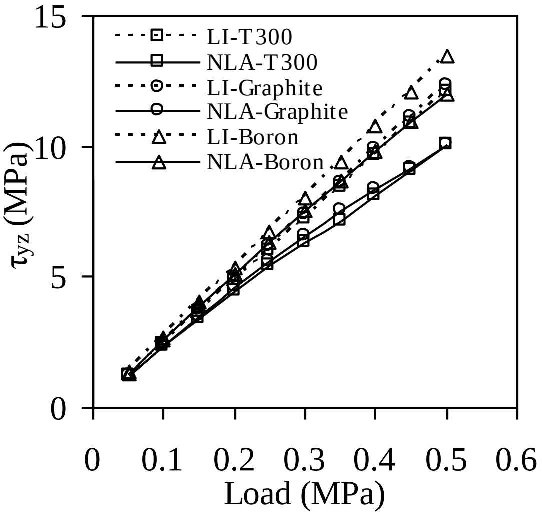


Fig. 6. Variation of τ_{yz} at Top Interface.

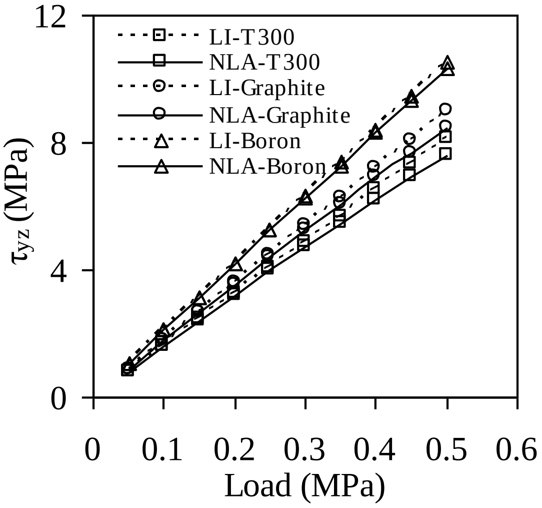


Fig. 7. Variation of τ_{yz} at Middle Interface.

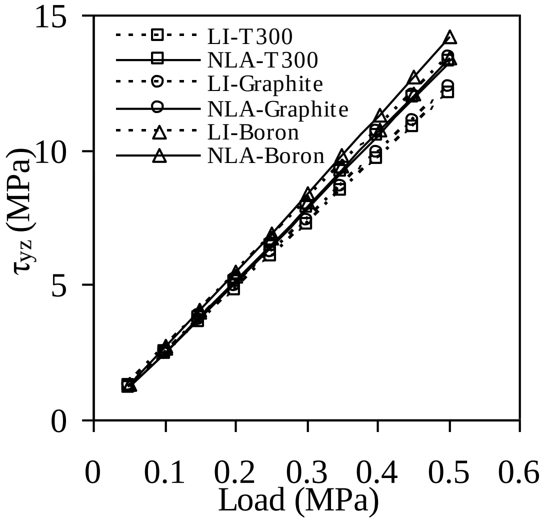


Fig. 8. Variation of τ_{yz} at Bottom Interface.

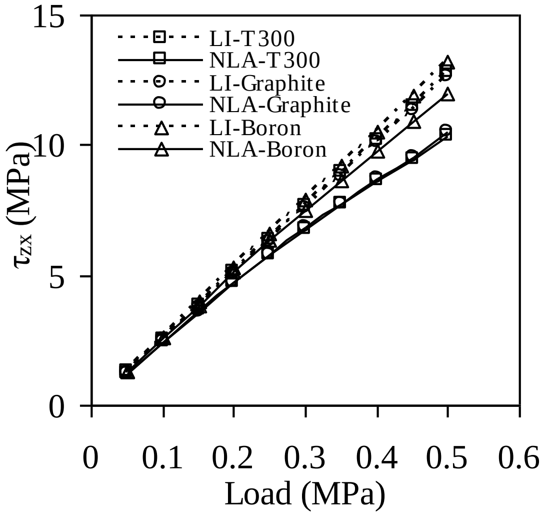


Fig. 9. Variation of τ_{zx} at Top Interface.

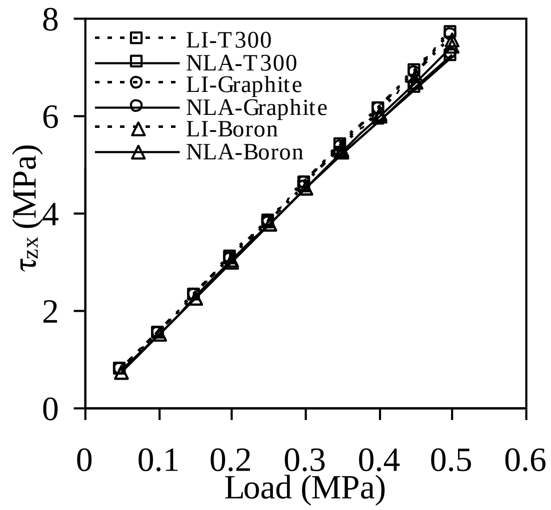


Fig. 10. Variation of τ_{zx} at Middle Interface.

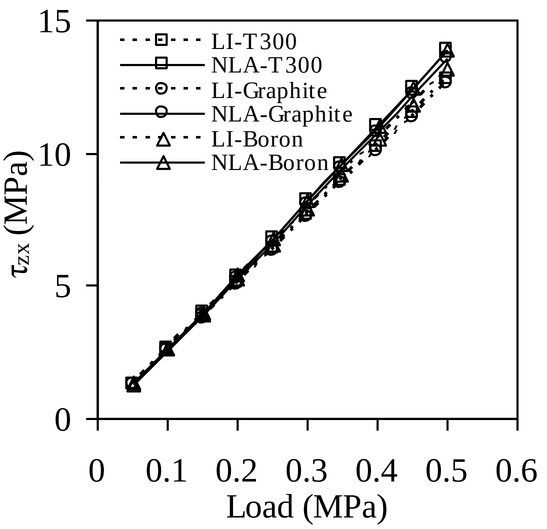


Fig. 11. Variation of τ_{zx} at Bottom Interface.

5.0 CONCLUSIONS

A four layered skew FRP cross-ply laminate having a circular cutout at centre with clamped edges and applied pressure (0.5 MPa) on top surface has been analyzed for linear and geometric non-linear analysis options. Three-dimensional finite element model has been generated with governing boundary conditions for the evaluation of the deflection, interlaminar normal and shear stresses. The following conclusions are drawn:

- Nonlinearity is observed at higher load for boron than graphite and T300 for all values of deflection and stresses because of higher material stiffness of Boron compared to graphite and T300.
- The magnitudes of interlaminar stresses are observed to be more for nonlinear analysis when compared to linear analysis in majority of the cases with respect to load and location, so for safe design of the structure nonlinear analysis is must.
- Based on deflection and interlaminar stresses σ_{zz}, τ_{yz} and τ_{zx} it is required to perform nonlinear analysis for Boron, Graphite and T300 irrespective of load.

Nomenclature

E_1 = Young's modulus of the lamina in the fiber direction
E_2 = E_3= Young's modulus of the lamina in the transverse direction of the fiber
G_{12}= G_{13}= Shear modulus in the longitudinal plane of the fiber
G_{23} = Shear modulus in the transverse plane of the fiber
ν_{12} = ν_{13} = Poisson's ratio in the longitudinal plane of the fiber
ν_{23} = Poisson's ratio in the transverse plane of the fiber
s = Length of the plate (l) / thickness of the plate (h)
l = Length or width of the skew plate
h = total thickness of the plate
d = Diameter of circular cutout
α = Skew angle

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