Experimental and simulation study of flexural behaviour of woven Glass/Epoxy laminated composite plate

Sushree S Sahoo*, Vijay K Singh and Subrata K Panda
National Institute of Technology-Rourkela, Odisha, India, 769008

*E-mail: sushree.sahoo101@gmail.com

Abstract. Flexural behaviour of cross ply laminated woven Glass/Epoxy composite plate has been investigated in this article. Flexural responses are examined by a three point bend test and tensile test carried out on INSTRON 5967 and Universal Testing Machine INSTRON 1195 respectively. The finite element model is developed in ANSYS parametric design language code and discretised using an eight nodded structural shell element. Convergence behaviour of the simulation result has been performed and validated by comparing the results with experimental values. The effects of various parameters such as side-to-thickness ratio, modular ratio on flexural behaviour of woven Glass/Epoxy laminated composite plate are discussed in details.

1. Introduction
Laminated composite materials over the last many years have been the dominant emerging materials, penetrating and conquering markets of aerospace, marine and civil infrastructure relentlessly owing to their advantages like light weight, high strength/stiffness, superior fatigue response characteristics, facility to vary fibre orientation, material and stacking pattern, resistance to electrochemical corrosion, and other superior material properties of composites. Based on the design requirement, the laminated structural materials must have enough strength against complex loading, deformation capability and excessive vibration to increase the service life since these materials are prone to fail under such circumstances in real life situation. Hence, the need of the hour is to understand the load deformation behaviour of laminated structure and predict the exact structural responses for various loading for final design of desired component. In order to do so, the finite element method has been ascertained as a versatile tool for the analysis of complex structural behaviour, especially the laminated composite structures as they are statically indeterminate due to their geometry. It is well known that, the deflection behaviour of composites has a great importance on their design and analysis because they are flexible in comparison to the other available conventional materials.

In order to foresee the realistic responses of laminated structures several attempt have been made in past by the researcher. Reddy et al. [1] carried out numerous finite element analysis for various parameters to study the effect of transverse shear deformation on deflection and stresses of laminated composite plates subjected to uniformly distributed load in ANSYS environment. Catangiu et al. [2] used a bending fatigue testing machine to obtain results of bending fatigue tests of composites plates of orthogonal woven Glass/Epoxy composite made up in hand lay-up method preceded by a preliminary degradation. Gupta et al. [3] investigated the static response of laminated composite plate subjected to uniformly distributed loading using finite element approach based on first-order shear deformation theory considering geometric nonlinearity and damage evolution. Ahmed et al. [4] analysed static and
dynamic response of Graphite/Epoxy laminated composite plates under transverse loading based on First Order Shear Deformation Theory. Parhi et al. [5] evaluated laminated composite plates with randomly located multiple delaminations subjected to transverse static and impact by applying finite element analysis procedure using first order shear deformation via eight-node isoparametric quadratic elements. Kumar et al. [6] investigated the transverse deflection and stresses of laminated composite skew plate with elliptical hole when the plate is subjected to transverse pressure loading via a finite element method based on three dimensional theory of elasticity. Aagaah et al. [7] analysed deformations of a rectangular multi layered laminated composite plate due to mechanical loads by deriving its linear dynamic equations based on a third order shear deformation plate theory in conjunction with the Von Karman strains. Dash and Singh [8] presented transverse bending analysis of shear deformable laminated composite plates in Green–Lagrange sense using finite element approach based on the higher order shear deformation theory considering ten degree of freedom per node. Pandya and Kant [9] applied finite element formulation to obtain flexure of an orthotropic plate based on higher-order displacement model and a three-dimensional state of stress and strain. Lal et al. [10] examined nonlinear transverse central deflection of laminated composite plates subjected to transverse uniform lateral pressure and thermal loading and the effect of sensitivity of randomness in system parameters on central deflection applying higher order shear deformation theory in the von-Karman sense. Kommineni and Kant [11] studied linear and geometrically non-linear finite element analysis of fibre reinforced composite and sandwich laminates applying a refined higher order shear deformation theory in von Karman sense considering nine degree of freedom per node. Raju and Kumar [12] developed an analytical procedure to examine the bending features of laminated composite plates based on higher order shear displacement model with zig-zag function. Sahoo and Singh [13] proposed a trigonometric zigzag theory for the static analysis of laminated composite and sandwich plates employing a displacement based C0 finite element model. Goswami [14] incorporated refined higher-order shear deformation theory and 3-dimensional state of stress and strain for thick and thin laminated composite plates to a C0 plate bending element formulation. Liu et al. [15] presented static and free vibration analyses of isotropic composite plates through a linearly conforming radial point interpolation method whose mesh-free shape functions were constructed by combining the radial and polynomial basis functions. Park et al. [16] presented quasi-conforming formulation of four node stress resultant shell element for the linear static and dynamic analysis of composite plates and shells which uses interrelated displacement-rotation interpolations applicable for moderately thick and thin composite shells. Derras et al. [17] established a new refined shear deformation theory for the nonlinear cylindrical bending behaviour of functionally graded plates which are subjected to pressure loading, and their geometric nonlinearity is introduced in the strain-displacement equations based on Von-Karman assumptions.

The flexural behaviour of laminated structure has attracted many researchers not only because it is interesting but also challenging. We note that the experimental study of laminated structure for transverse bending and subsequent simulation study using commercial finite element package and/or computational code are not much in number. Here in this study the bending behaviour of woven laminated composite plate has been investigated experimentally and compared with commercial finite element software package ANSYS parametric design language (APDL) code to study the flexural behaviour. The model has been discretised using Shell 281 element and the responses are compared with the experimental values obtained from three point bend test. The flexural behaviour of laminated composite panels are obtained for different side-to-thickness ratio ($a/h$) and modular ratios ($E_1/E_2$) and discussed in details.
2. Numerical Methodology

A laminated doubly curved shell element is considered with thickness ‘\( h \)’. The radii of curvature in \( x \) and \( y \) direction are \( R_x \) and \( R_y \) respectively as shown in the figure 1. Each of the thin lamina can be oriented at an arbitrary angle ‘\( \phi \)’ with reference to the x-axis. The displacement field is assumed to be in following form:

\[
\begin{align*}
U(x,y,z) &= u_0(x,y) + z \theta_x(x,y) \\
V(x,y,z) &= v_0(x,y) + z \theta_y(x,y) \\
W(x,y,z) &= w_0(x,y) + z \theta_z(x,y)
\end{align*}
\]

(1)

Where \( U \), \( V \) and \( W \) are the displacements at any point within the shell in \( x \), \( y \) and \( z \) directions respectively. \( u_0 \), \( v_0 \) and \( w_0 \) are the associated mid-plane displacements and \( \theta_x \), \( \theta_y \) and \( \theta_z \) are the rotations about the respective axes at \( z = 0 \).

![Figure 1. Laminated composite doubly curved shell.](image)

The stress strain relations for the \( k^{th} \) lamina oriented at an arbitrary angle ‘\( \phi \)’ about any arbitrary axes are given by:

\[
\{ \sigma \} = [\overline{Q}_{ij}] \{ \varepsilon \}
\]

(2)

Stress vector can be rewritten in force form as:

\[
\{ F \} = [D] \{ \varepsilon \}
\]

(3)

The elements of the stiffness matrix \([D]\) are defined as:

\[
[D] = \left[ A_{ij}, B_{ij}, D_{ij} \right] = \sum_{k=1}^{n} \int \left( \overline{Q}_{ij} \right)_k (1, z, z^2) \, dz
\]

(4)

2.1. Finite element formulation

An eight-noded isoparametric element with six degrees of freedom viz., \( u_0 \), \( v_0 \), \( w_0 \), \( \theta_x \), \( \theta_y \) and \( \theta_z \) at each node is used. The displacement vector ‘\( \mathbf{d} \)’ at any point on the mid surface is given by:
\[ d = \sum_{i=1}^{N} N_i (x, y) d_i \]  (5)

Where \( d_i \) and \( N_i \) are the displacement vector and the interpolating function, respectively, associated with the node \( i \). Total strain is written in the linear form:

\[ \{ \varepsilon \} = [B_L]\{d_i\} \]  (6)

Where \([B_L]\) is a strain displacement relation matrix. The virtual work equation for free vibration in Lagrangian coordinate system may be written as:

\[ \int_A \{d\}^T \{ \rho \} \{d\} dA + \int_A \{d\}^T \{ F \} dA = 0 \]  (7)

Where \{\( d \)\} is the generalized displacements, \( \delta \) denotes variation and \([\rho]\) is the mass matrix.

Substituting Equations (3), (5) and (6) into Equation (7), it can be written in the finite element form for an element as:

\[ [M]\{\ddot{d}_i\} + [K]\{d_i\} = 0 \]  (8)

Where \([K]\) \([M]\) are the stiffness and mass matrix respectively can be expressed as:

\[ [K] = \int_A [B_L]^T [D][B_L] dA \]
\[ [M] = \int_A [N]^T [\rho][N] dA \]  (9)

For the flexural analysis:

\[ ([K])\{d\} = \{F\} \]  (10)

For the present analysis, the specimen is applied with point load at the center and two opposite edges of the specimen are clamped. The boundary conditions are as follows:

\[ u_0 = v_0 = w_0 = \theta_x = \theta_y = \theta_z = 0 \quad \text{at} \ x=0 \text{ and} \ a \]  (11)

2. Results and Discussion

2.1. Experimentation

The properties of Glass/Epoxy laminated composite plate can be defined completely by its Young’s modulus, shear modulus and Poisson’s ratio in principal material directions. The desired properties are determined experimentally by performing unidirectional tensile test on specimens (longitudinal and transverse directions and at an angle of 45° inclined to the longitudinal direction) based on ASTM standard: D 3039/D 3039M. A thin flat strip of specimen having a constant rectangular cross section was prepared in all cases with 20cm, 2.25cm and 0.5 cm as its length, breadth and height respectively. For measuring the Young's modulus, the specimen is loaded in UTM INSTRON 1195 with a recommended rate of loading of 1 mm/minute as shown in figure 2(a) and figure 2(b). Poisson’s ratio for the present analysis is taken 0.17 as in Jensen et al. [18]. The shear modulus was determined using the formula as in Jones [19] as:


\[ G_{bl} = \frac{1}{4 E_{45}} - \frac{1}{E_t} - \frac{1}{E_i} - \frac{2\nu_{12}}{E_i} \]  

(11)

The material properties are presented in table 1.

| Property                                      | Value          |
|-----------------------------------------------|----------------|
| No. of layers                                 | 10             |
| Stacking sequence                             | (0/90)\text{s} |
| Young’s modulus x direction (\( E_j \))       | 5.802 GPa      |
| Young’s modulus y direction (\( E_i \))       | 4.966 GPa      |
| Young’s modulus z direction (\( E_z \))       | 4.966 GPa      |
| Shear modulus (\( G_{bl} \))                 | 1.898 GPa      |
| Shear modulus (\( G_{iz} \))                 | 0.949 GPa      |
| Shear modulus (\( G_{iz} \))                 | 1.898 GPa      |
| Poisson’s ratio (\( \nu_{12} \))             | 0.17           |
| Poisson’s ratio (\( \nu_{iz} \))             | 0.17           |
| Poisson’s ratio (\( \nu_{iz} \))             | 0.17           |
| Density (\( \rho \))                         | 1646.00 Kgm\(^{-3}\) |

In order to determine flexural behavior experimentally, three point bend test was conducted on Glass/Epoxy laminated composite plate specimen using UTM INSTRON 5967 with environmental chamber with a commended rate of loading of 2 mm/minute as shown in figure 3(a) and figure 3(b). The dimension of the specimen was taken according to ASTM standard: D790 that is, for depth of 5mm the length and breadth of the specimen was taken to be 9 cm and 2.25 cm, respectively.
2.2. Finite element modelling:

In this section, the flexural behaviour of laminated composite panel has been inspected using APDL code developed in ANSYS environment. An eight-nodded, six degrees of freedom structural shell element (shell281) has been developed for the current analysis which allows modeling thin to moderately
thick plate and shell structures as shown in figure 4(a) and the deformation curve is presented in figure 4(b). The numeric values are compared with the obtained experimental results.

Figure 4 (a). Finite element model of 10-layer cross ply Glass/Epoxy laminated composite plate.

Figure 4 (b). FE model of 10-layer cross ply Glass/Epoxy laminated composite plate.

2.3. Convergence and Comparison Study
The convergence study with respect to mesh divisions of glass epoxy laminated flat panel for flexural behaviour is plotted in figure 5. The central deflections of plate when applied to a various point loads at the centre are compared with the experiment results. It is quite obvious from Table 4 that the present results are showing very small difference with the experimental result and the present model will be able to solve any general type of geometry effortlessly. Based on the convergence, it is noted that a (8×8) mesh is appropriate to obtain the flexural responses.
3. Parametric Study
In this section, some new results are computed for different parameters. The central deflections are plotted for side to thickness ratios \( (a/h) \) and modular ratio \( (E_1/E_2) \) and their effects are discussed in the upcoming subsections.

### 3.1. Effect of side to thickness ratio
In general, with the increase in side to thickness ratio, there is a decrease in stiffness of the material due to which the central deflection tends to increase. From figure 6 it can be concluded that the present model is in clear agreement with the theory as when the side to thickness ratio increases from 30 to 60, the central deflection is seen increasing.
3.2. Effect of modular ratio
Mathematically, it is well known that as the modular ratio increases, the reduced transformed stiffness matrix increases and hence the central deflection decreases. The responses computed using the present model follow the same as depicted in figure 7. As the modular ratio increases from 5 to 20, the central deflection of the plate decreases.

4. Acknowledgement
This work is under the project sanctioned by the department of science and technology (DST) through grant SERB/F/1765/2013-2014 Dated: 21/06/2013. Authors are thankful to DST, Govt. of India for its consistent support.
5. Conclusion
Flexural behaviour of Glass/Epoxy (0/90) laminated composite plate has been investigated in this present study. Flexural responses are examined by a three point bend test carried out on INSTRON 5967 and material properties were found out by performing tensile test on UTM INSTRON 1195, respectively. The experimental results were compared with commercial Finite element package ANSYS using APDL. The model has been discretised using an eight nodded structural shell element (shell 281). The convergence study shows that the present results are converging well with mesh refinement and the difference between the numerical and experimental values are within the expected line. The parametric study indicates that the central deflection of flat panel increases with side to thickness ratio and decreases with increase in modular ratio.

Reference
[1] Reddy B S, Reddy A R, Kumar J S and Reddy K V K 2012 International Journal of Engineering, Science and Technology 4 177-190
[2] Catangiu A, Dumitrescu A T and Ungureanu D 2011 Materials and mechanics 6 47-51
[3] Gupta A K, Patel B P and Nath Y 2013 Acta Mechanica 224 1285–1298
[4] Ahmed J K, Agarwal V C, Pal P and Srivastav V 2013 International Journal of Innovative Technology and Exploring Engineering 3 56-60
[5] Parhi P K, Bhattacharyya S K and Singh P K 2001 Bulletin of Material Science 24 143-149
[6] Kumar M S R N, Sarcar M M M and Murthy V B K 2009 Indian Journal of Engineering and Materials Science 16 37-43
[7] Aagaah M R, Mahinfalah M and Jazar G N 2003 Composite Structures 62 27-39
[8] Dash P and Singh B N 2010 Communication Nonlinear Science Numerical Simulation 15 3170-3181
[9] Pandya B N and Kant T 1988 Computers & Structures 28 119-133
[10] Lal A, Singh B N and Kumar R 2011 Archive of Applied Mechanics 81 727–743
[11] Kommineni J R and Kant T 1992 Computers and Structures 45 511-520
[12] Raju T D and Kumar J S 2011 ARPN Journal of Engineering and Applied Sciences 6 106-110
[13] Sahoo R and Singh B N 2014 Aerospace Science and Technology 35 15-28
[14] Goswami S 2006 Composite Structures 72 375–382
[15] Liu G R, Zhao X, Dai K Y, Zhong Z H, Li G Y and Han X 2008 Composites Science and Technology 68 354–366
[16] Parka T, Kimb K and Han S 2006 Composites: Part B 37 237–248
[17] Derras M, Kaci A, Draiche K and Tounsi A 2013 Journal of Theoretical and Applied Mechanics 51 339-348
[18] Jensen D W, Crawley E F and Dugnani J 1979 Journal of Composite Materials 13 195
[19] Jones R M 1975 Mechanics of Composite Materials (Philadelphia: Taylor and Francis) p 97
[20] Ansys Mechanical APDL 15.0 User Manual