Effect of magnetostrictive material layer on the stress and deformation behaviour of laminated structure

S D Suman¹, C K Hirwani², A Chaturvedi³, S K Panda⁴

Department of Mechanical Engineering, National Institute of Technology Rourkela India.

Email¹: shardasuman92@gmail.com

Abstract. In the present investigation, static bending and strength behaviour of the laminated composite plate embedded with magnetostrictive (MS) material has been computed numerically using commercial finite element tool. For the analysis purpose, a simulation model of the laminated plate embedded with and without MS material is derived using the batch input technique popularly termed as ANSYS parametric design language (APDL). The MS bonded composite model is discretised with the help of available suitable element from ANSYS element library. The elements are chosen suitably by considering the compatibility between the mechanical and the magnetic fluxes indices. For the calculation of the necessary responses, APDL code has been prepared in ANSYS environment. Further, the stability of the model has been checked by computing the responses for various mesh sizes. Subsequently, the accuracy of the model has also been checked by conducting the comparison test. For the comparison, central deflection of the clamped Graphite/Epoxy laminated plate embedded with Terfenol-D has been evaluated and compare them with those of the available earlier published literature. The comparison study clearly indicates that, the present responses are in-line and showing good agreement with that of the reference. Further, the versatility and the applicability of the simulation model has been proven by solving the different illustrations. In the illustration, the influence of the different geometrical parameter such as thickness ratio and aspect ratio on the bending behaviour has been investigated and discussed in detail.

1. Introduction

The necessity of increasing the safety margin of the structure and the structural component of almost all the sphere of industries such as automobile, aerospace, aircraft and marine industries, increases the application as well the demand of smart composite material since last two decades. The smart materials are the material having one or more physiochemical properties which can be changed significantly due to external stimuli such as temperature, pressure, magnetic or electric field, etc. When smart materials are get stuffed or embedded with composite material or structure, the composite material or structure is known as smart composite material or smart composite structure. The smart composite structures are known for their actuating, sensing and the controlling capability of the structural responses. The embedding of the magnetostrictive material with advanced layered composite material effect on structural performance such as bending and strength characteristic significant. The study of the same has been reported by author and the few important of them are reviewed and presented in the next lines.

Noor and Burton [1] investigated the static and dynamic analysis of laminated composite plate by developing a finite element (FE) model based on first order shear deformation theory (FSDT). Anjanappa and Bi [2] established the mathematical model to analysed the vibration response of smart structure embedded with the magnetostrictive mini actuators. Pratt et al. [3] presented the active
vibration control and separation phenomenon for a cantilevered beam embedded with Terfenol-D actuator. Vuksanovic [4] utilized the classical laminate plate theory (CLPT) and FSPT kinematics to examine the static and dynamic response of the laminated structure. Kant and Swaminathan [5] used MPEP Navier’s technique to analyze the composite plates numerically [5]. Huang et al. [6] evaluated the stress and deflection of the composite laminated structure using hybrid stress element numerically. Kumar et al. [7] proposed the FE model to investigate the damping characteristics of the aluminum beam embedded with the layer of magnetostrictive material Terfenol-D. Lee and Reddy [8] presented the static behaviour of magnetostrictive material embedded laminated composite for various uniformly distributed load and sinusoidal load based on the third order kinematics. Park et al. [9] numerically studied the static and dynamic behaviour of both laminated composite plate and shell using four-node element. Zhen et al. [10] proposed a C0 higher-order theory for laminated composite and sandwich plates to determine the natural frequency. The mechanical behaviour of Terfenol-D embedded laminated composite plate is investigated by Kishore et al. [11]. Sahoo and Singh [12] developed the mathematical model of the laminated composite and sandwich plates using a zigzag theory to investigate the structural behaviour. Andakhshideh and Tahani [13] utilized the minimum potential energy principle to evaluate the inter-laminar stress of the laminated plate structure analytically. The static and dynamic response of laminated structure investigated by Rango et al. [14] using a FSDT based mathematical model. Santapuri et al. [14] presented the dynamic analysis of laminated composite stuffed with the Galfenol sheets using a mathematical model based on CLPT [15].

From the survey of the literatures, it is clear that in the past sufficient amount of work have been done for the investigation of bending behaviour of laminated composite structure but for the laminated structure embedded with the magnetostrictive material are less in number. Therefore, the aim of the present work is to investigate the stress as well as deflection behaviour of the laminated structure embedded with an actuating layer of a magnetostrictive material. For the investigation, a simulation model in ANSYS environment has been prepared using APDL code. Further, the computed responses are compared with the responses of published literature. Finally, the versatility of the model has been shown by solving the new numerical example which shows the effect of adding the magnetostrictive material in pure laminate, and geometrical parameter on deflection and strength behaviour of the layered composites plate.

2. Theoretical Formulations

2.1. Displacement model

The mathematical model for the laminated composite plate embedded with magnetostrictive material as shown in figure 1 has been developed in the present investigation. The geometrical configuration of the laminate is defined as length a, width b, and the thickness as h. The laminate is composed of the N number of layer. The displacement kinematic for the same is considered according to FSDT kinematics and presented as:

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

where, u, v and w are the displacements of any point along the x, y and z coordinate axes respectively. \( u_0 \), \( v_0 \) and \( w_0 \) are corresponding displacements of a point on the mid plane and \( \theta_x \), \( \theta_y \) and \( \theta_z \) are the rotations of normal to the mid-surface, i.e., \( z=0 \) about the y and x-axes, respectively.
The magnetic field vector $\{H\}$ can be written in terms of the magnetic field potential as:

$$\{H\} = [Z_M]\{\bar{H}\} \quad (2)$$

The relation of stress and strain for any $k^{th}$ lamina oriented at an arbitrary angle $\phi$ about any arbitrary axes are presented as:

$$\{\sigma\}^k = [\bar{Q}]^k\{\bar{\varepsilon}\} - [\bar{\sigma}]^k\{H\} \quad (3)$$

$$\{B\}^k = [\bar{\varepsilon}]^k\{\varepsilon\} + [\mu]^k\{H\} \quad (4)$$

where $\{\sigma\}, \{\varepsilon\}, \{H\}$ and $\bar{Q}_{ij}$ are stress vector, strain vector, magnetic field intensity and transformed reduced stiffness matrix respectively.

2.2. Finite element formulation

The displacement fields for the assumed kinematic models are expressed in terms of desired field variables and the models are discretised using suitable FEM steps. The displacement vector $'d'$ at any point within the mid-plane is given by:

$$d = \sum_{i=1}^{4} N_i(x, y) d_i \quad (5)$$

$$\psi = \sum_{i=1}^{4} N_i(x, y) \psi_i \quad (6)$$

where, $\{d_i\} = \{u, v, w, \theta_x, \theta_y\}^T$ is the nodal displacement vector, $\{\psi_i\}$ is the magnetic potential and $N_i$ is the corresponding interpolating function for the $'i^{th}$ node.

The strain vector can be expressed in the matrix form after introducing the FEM steps and conceded as:

$$\{\varepsilon\} = [T]\{\bar{\varepsilon}\} \quad (7)$$
where, \([T]\) is the thickness coordinate matrix and \(\{\varepsilon\}\) is the mid plane strain vector which can be further reduced as:

\[
\{\varepsilon\} = [B_x]\{d\} 
\]

(8)

\[
\{H\} = [B_m]\{\psi\} 
\]

(9)

where, \([B_x]\) is a general strain displacement relation matrix and \([B_m]\) is the magnetostrictive laminate strain displacement matrix.

The total strain energy of the laminate can be expressed as:

\[
U = \frac{1}{2} \int \int \{\varepsilon\}^T \{\sigma\} d\varepsilon d\sigma 
\]

(10)

The total work done due to the externally applied mechanical load \((F)\) is expressed as:

\[
W = \int \{d\}^T \{F\} dA 
\]

(11)

The stiffness matrix \((K)\) can be further expressed as:

\[
[K] = \sum_{k=1}^{n} \int\int [B_k] [D][B_k] 
\]

(12)

2.3. Governing equations

The final form of governing equation for static analysis of flat plate is obtained using minimum potential energy principle:

\[
\delta \Pi = \delta (U - W) = 0 
\]

(13)

where, \(\Pi\) is the total strain energy.

Further, equation (13) is modified by substituting the equations (10) and (11) into equation (13) and expressed as:

\[
[K]\{\delta\} = \{F\} 
\]

(14)

2.4. Boundary condition

To solve the above set of governing equation following boundary conditions are taken in to considerations:

Simply supported

\(v_0 = w_0 = \theta_y = \theta_z = 0\) at \(x=0\) and \(a\);

\(u_0 = w_0 = \theta_x = \theta_z = 0\) at \(y=0\) and \(b\);

Clamped

\(u_0 = v_0 = w_0 = \theta_x = \theta_y = \theta_z = 0\) at \(x=0\) and \(a\); \(y=0\) and \(b\);

Free

\(u_0 \neq v_0 \neq w_0 \neq \theta_x \neq \theta_y \neq \theta_z \neq 0\) at \(x=0\) and \(a\); \(y=0\) and \(b\);

(15)

(16)

(17)
3. Result and discussion

The bending behaviour of the composite plate embedded with the magnetostrictive material layer is analysed by developing a simulation model in ANSYS using APDL code. The model is discretised with the help of four-node shell element shell-181. For the convergence purpose, the central deflection responses of the Graphite/Epoxy laminated plate with Terfenol-D layers is computed for different mesh density. Further, the computed responses are compared with the response of the published literature. Finally, the effect of the magnetostrictive material on deflection and stress value are examined and discussed in detail. The material property used in the analysis has been shown in table 1. The clamped condition is taken for the further investigation in this present article. The equation used for the nondimensional form of the load and deflection are as follows: \[ \bar{P} = q_0 a^2 / E_{xy} h^3, \bar{w} = w / h. \]

3.1 Convergence and validation study.

For the convergence study, static behaviour of clamped square symmetric ten-layer (0°/30°/-30°/30°/-30°), laminated composite plate is analysed under uniformly distributed load for different mesh density and shown in Figure 2. The responses are evaluated using Graphite/Epoxy material property as given in table 1. From the figure, it depicts that the results are converging well for various mesh refinement. Based on that a mesh size of (8×8) is chosen for further analysis. Further the analysis is expended for the validation study. The nondimensional central deflection responses of square ten-layer (m/90°/0°/90°/0°), Graphite/Epoxy layered plate structure embedded with Terfenol-D layers has been investigated. The material property used for the present investigation are shown in table 1. The result is evaluated for two different end condition, compared with Lee and Reddy [8] and Kishore et al. [11] and shown in table 2.

![Figure 2: Nondimensional deflection at different mesh size](image-url)
Table 1. Material properties of Graphite/Epoxy and Terfenol-D.

| Properties                                         | Graphite/ Epoxy | Terfenol-D |
|----------------------------------------------------|-----------------|------------|
| Young’s modulus x direction (\(E_x\))              | 138.6GPa        | 26.5GPa    |
| Young’s modulus y direction (\(E_y\))              | 8.27GPa         | 26.5GPa    |
| Young’s modulus z direction (\(E_z\))              | 8.27GPa         | 26.5GPa    |
| Shear modulus (\(G_{xy}\))                        | 4.96GPa         | 13.25GPa   |
| Shear modulus (\(G_{xz}\))                        | 4.12GPa         | 13.25GPa   |
| Shear modulus (\(G_{zy}\))                        | 4.96GPa         | 13.25GPa   |
| Poisson’s ratio (\(\nu_{xy}\))                    | 0.26            | 0.26       |
| Poisson’s ratio (\(\nu_{xz}\))                    | 0.26            | 0.26       |
| Poisson’s ratio (\(\nu_{zy}\))                    | 0.26            | 0.26       |
| Density (\(\rho\))                               | 1824 Kgm\(^{-3}\) | 9250 Kgm\(^{-3}\) |

Table 2: Comparison study of central deflection of ten-layer Graphite/Epoxy laminated composite embedded with Terfenol-D (a/h=10).

| Constraints condition | Load parameter | Present   | Lee and Reddy[8] | Kishore et al.[11] |
|----------------------|----------------|-----------|------------------|-------------------|
| CCCC                 | 1              | 0.004817  | 0.00482          | 0.0043            |
|                      | 5              | 0.024807  | 0.02407          | 0.0215            |
|                      | 30             | 0.14452   | 0.14292          | -                 |
|                      | 60             | 0.28905   | 0.27777          | -                 |
|                      | 100            | 0.48174   | 0.43938          | 0.4301            |
| CCSS                 | 1              | 0.0066438 | 0.00615          | 0.0066            |
|                      | 5              | 0.033179  | 0.03073          | 0.0331            |
|                      | 30             | 0.19103   | 0.18183          | -                 |
|                      | 60             | 0.34815   | 0.3507           | -                 |
|                      | 100            | 0.5072    | 0.549            | 0.6623            |

3.2 Effect of magnetostrictive layer on in-plane normal and shear stresses (\(\sigma_x\), \(\sigma_y\) and \(\tau_{xy}\))

In-plane stresses have been plotted in figure 3-5 for different lamination schemes under uniformly distributed load both for square clamped laminated plate (a/h=10) embedded with and without MS material. From the figure, it has clearly observed that the with the increase in load parameter there is an increase in the stress. In continuation to that, the effect of adding the MS material on stress behaviour is same for the normal stress (\(\sigma_x\)) and shear stress (\(\tau_{xy}\)) i.e. stress is lower in case of adding the MS material. On the other hand the effect on normal stress (\(\sigma_y\)) is opposite to the previous two stresses i.e. stress is higher in case of adding the MS material.
Figure 3: Effect of magnetostrictive layer on in-plane normal stress $\sigma_x$

Figure 4: Effect of magnetostrictive layer on in-plane normal stress $\sigma_y$
3.3 Effect of magnetostrictive layer on in-plane shear stress $\tau_{xy}$

The nondimensional transverse central displacement of the laminated composite plate with and without MS material is investigated in the present illustration. For the computation, square clamped ten-layer with laminated composite ($a/h=10$) with two lamination scheme [(m/30°/-30°/30°/-30°)$_{ls}$ and (m/45°/-45°/45°/-45°)$_{ls}$] has been utilised. The responses are shown in figure 6. The figure shows that deflection parameter increases for both the lamination scheme by adding the MS material. In addition, a contour plot of deflection responses with and without MS material has also been presented in figure 7 and 8.

Figure 5: Effect of magnetostrictive layer on in-plane shear stress $\tau_{xy}$

Figure 6: Effect of magnetostrictive layer on central deflection
3.4 Effect of aspect ratio on deflection

Nondimensional central deflection of clamped square symmetric (m/45°/-45°/45°/-45°) laminated composite plate (a/h=10) embedded with MS material is plotted for different aspect ratio and shown in figure 9. From the figure, it depicts that, with increasing the aspect ratio nondimensional deflection response increases irrespective of the loading.
3.5 Effect of thickness ratio on deflection

In this illustration effect of aspect ratio of layered composite embedded with MS material have been examined. For the computation purpose, square clamped laminated composite plate embedded with MS material has been considered and analysed for four thickness ratio (b/a=10,20,50 and100). The results are evaluated using simulation model and presented in figure 10. It is observed from the figure that, with the increase in the aspect value there is a decrease in the nondimensional static deflection of the plate. It is worthy to mention that, the nondimensional form of the load is a function of the thickness ratio which decreases with increasing the thickness ratio.
4. Conclusion

In the present analysis a simulation model of laminated composite plate stuffed with MS material have been developed in ANSYS environment using the APDL code to analyse the stress and deflection behaviour. The model is discretised with the help of four-noded element shell-181 from the ANSYS element library. The convergence and the comparison study have been conducted to check the stability and accuracy of the present model. Finally, the effect of adding the MS material and design parameter have been analysed by solving different illustrations and discussed in detail. On the basis of the outcome of the numerical illustrations few important conclusion has been made. The deflection parameter increases with adding the Terfenol-D layer. The normal ($\sigma_x$) and shear stress ($\tau_{xy}$) decreases while normal stress ($\sigma_y$) increases by embedding the MS layer.

References

[1] Noor A K & Burton W S 1989 Stress and Free Vibration Analyses of Multilayered Composite Plates Composite Structures 11 183-204
[2] Anjanappa M and Bi J 1994 Magnetostrictive mini actuators for smart structure applications Smart Material Structure 3 383-390
[3] Pratt J, R, Shafic, S and Alu H 1999 Terfenol-D Nonlinear Vibration Absorber Journal of Intelligent Material Systems and Structures 10 29
[4] Vuksanovic D 2000 Linear analysis of laminated composite plates using single layer higher-order discrete models Composite Structures 48 205-211
[5] Kant T and Swaminathan K 2002 Analytical solutions for the static analysis of laminated composite and sandwich plates based on a higher order refined theory Composite Structures 56 329–344
[6] Huang Y, Di S, Wu C and Sun H 2002 Bending analysis of composite laminated plates using a partially hybrid stress element with interlaminar continuity Computers and Structures 80 403–410
[7] Kumar J S, Ganesan N, Swarnamani S and Padmanabhan C 2003 Active control of beam with magnetostrictive layer Computers and Structures 81 1375–1382
[8] Lee S J and Reddy J N 2004 Nonlinear deflection control of laminated plates using third-order shear deformation theory International Journal of Mechanics and Materials in Design 1 33-61
[9] Parka T, Kimb K and Han S 2006 Linear static and dynamic analysis of laminated composite plates and shells using a 4-node quasi-conforming shell element Composites: Part B 37 237–248
[10] Zhen W, Wanj C and Xiao Hui R 2010 An accurate higher-order theory and C0 finite element for free vibration analysis of laminated composite and sandwich plates Composite Structures 92 1299–1307
[11] Kishore M D V H, Singh B N and Pandit M K 2011 Nonlinear static analysis of smart laminated composite plate Aerospace Science and Technology 15 224–235
[12] Sahoo R and Singh B N 2013 A new shear deformation theory for the static analysis of laminated composite and sandwich plates International Journal of Mechanical Sciences 75 324–336
[13] Andakhshideh A and Tahani M 2013 Interlaminar stresses in general thick rectangular laminated plates under in-plane loads Composites: Part B 47 58–69
[14] Rango R F, Nallim L G and Oller S 2013 Static and dynamic analysis of thick laminated plates using enriched macroelements Composite Structures 101 94–103
[15] Santapuri S, Scheidler J J and Dapino M J 2015 Two-dimensional dynamic model for composite laminates with embedded magnetostrictive materials Composite Structures 132 737–745
