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Dynamic analysis of laminated composite beam using Timoshenko beam theory

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Abstract: ***The uses of laminated composite beams are increasing day by day in many industries. This laminated composite beam has been exposed under different dynamic loadings in mechanical operation. Therefore, the dynamic investigation of laminated composite beams (LCB) is very much necessary to forecast the catastrophe fail of the LCB components. At present, dynamic investigation of the LCB is carried out by the determining of fundamental frequency and mode shape. The special attentions like; in the design of geometry, orientation of fibres, layup of sections and boundary conditions are also analysed with referring the dynamical loadings and industry uses. The analysis procedures and results are validated with the reference results using finite element analysis software. Present research deals with the consequence of different volume fraction, boundary conditions and geometrical variation like aspect ratio, geometric ratio and length of E-glass polyester LCB. By altering different stacking sequences and these effects on mechanical properties as well as natural frequency are also analysed.***

Keywords: Laminated, composite, dynamics, stacking sequences, orientations, geometric ratio, aspect ratio, volume fraction.

I. INTRODUCTION

The mechanical properties of LCB structure are influenced by its constituent materials: fiber and matrix. The variation of volume fraction, geometry and boundary condition of the LCB structure made of same matrix and fiber combination, performs important role in the variation of mechanical properties under different working conditions and loadings according to the necessity. The elastic modulus and strength of the LCB structure depends upon the orientation of fiber layers, height of LCB and boundary conditions. Some of research works using different approaches (analytical, numerical and experimental) have been carried out by past researchers to understand the dynamics of composite structures. Yung et al. [1] have used Newton-Raphson technique and finite element method to examine the transient vibration of LCB with transverse loading. Liou et al. [2] have investigated transient vibration of plate. They have examined the transverse deflection at centre by using impact hammer. Matsunaga [4] has calculated the buckling stress and frequency of cross-ply laminated composite plates considering rotary inertia and shear deformation. They have applied Hamilton's principle and power series expansion.

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Koo [5] has applied finite element method and methods to experimental examine the consequence of layer wise in-plane displacement on natural frequency and damping aptitude of laminated composite plates. Lee and Yhim [6] have investigated on single as well as two-span uninterrupted composite plates under multiple moving loadings. They have applied third order shear deformation principle to study the dynamical actions of the plates. Lee et al. [7] have studied vibrational behavior of multi-ply-folded composite laminated plate by applying higher order plate principle as well as third order shear principle in finite element approach. They have also studied the effects of ply orientations and folding angles by altering different loads and end conditions. Morozov [8] has explained various possessions of textile fabric. Khalili et al. [9] have applied Fourier transformation to study vibration of plate under different loading conditions. They have also used NISA-II coding to obtain the results and validated. Attaran et al. [10] have analysed the effects of sweeping angle; stack order and aspect ratio of laminated composite structures in aero-dynamic condition like flutter speed. They used 2-D FEA model. Davallo et al. [12] have examined the flexural bending test and tensile testing of (0^0 fibre orientation) glass-polyester composites beam. The consequence of beam height on the mechanical property is investigated. Mohammed et al. [13] have used finite element analysis (FEA) and experimental analysis to calculated natural frequency by altering fiber orientations. Majid et al. [14] have studied modal analysis of composite plate like wing by using frequency response function under fixed-free boundary conditions. They have also studied the effects of orientation of ply and height (thickness) of the plate on dynamics properties. Jweeg et al. [15] have fabricated various composite materials by reinforcing different fiber lengths (short, long, powder, and particulate size). They examined elastic modulus of these composite materials by experimentally. Ratnaparkhi and Sarnobat [16] have studied modal analysis beam by using ANSYS and computed natural frequencies in free-free end-conditions. Long et al. [17] given a mathematical model to analysis of free vibration and transient vibration of LCB under any boundary conditions. They have validated the result of mathematical model with the result of experimental and FEA. Jena et al. [18-23] have discussed the dynamics of intact beam considering Euler beam equation, orientation of woven fibres and boundary conditions. They also discussed the dynamic behaviour of beam with pre crack under free vibration condition. They studied effect of woven fiber orientation under different boundary conditions and compared the results of all three characterized methods: theoretical, numerical, and experimental. From the literature it is understood, the fiber layer direction and thickness are governing the strength and modulus of elasticity of LCB.

In the current research work; the effect of LCB length, fiber orientation, volume fraction, geometric ratio and aspect ratio for laminated composite beam (LCB) by altering end conditions are to be calculated.

II. ANALYTICAL MODEL

In general, the modal study discusses to the determination of fundamental frequencies as well as LCB curvature mode shape. Commonly, bending force is a pre-dominant of beam element. The expression of fundamental frequency of beam elements under bending force is given as;

$$(\omega_{zi}^{B})^2 = \frac{EI_{zz}}{2\pi\rho}\frac{\alpha_{Bi}^4}{L^4} \qquad (1a)$$

However, the fundamental frequency of beam element with shear force is presented as;

$$(\omega_{zi}^{s})^2 = \frac{S_{yy}}{\rho}\frac{\alpha_{zi}^2}{L^4} \qquad (1b)$$

In present research, the analysis is carried out by considering Timoshenko's beam theory and first order shear deformation theory (FSDT). According to the FSDT, it is understood that the cross sections are remains plane before and after bending but sections aren't right angle to the beam axis. The laminated composite beam (LCB) with dimensions L×B×T is considered for mathematical formulation as shown in Figure 1. The expression of fundamental frequency of LCB by FSDT with assumptions the bending and shearing deformation simultaneously is presented as,

$$(\omega_{zi})^2 = \left[\frac{1}{(\omega_{zi}^{B})^2} + \frac{1}{(\omega_{zi}^{S})^2}\right]^{-1} \qquad (1c)$$

where, $\mathrm{Syy} = \frac{5}{6} B \int_{T/2}^{T/2} (q_{ss}\, dy)$, $\mathrm{EIzz} = \frac{1}{a_{xx}}\frac{B^3}{12}$ in N.m²

The super script 'S' and 'B' stands for shearing and bending separately.

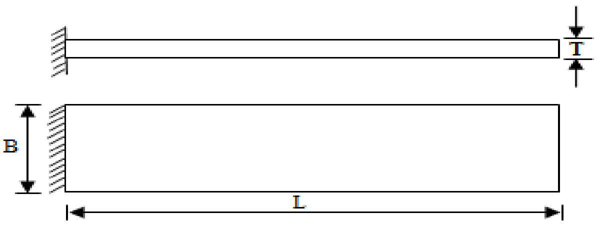

Figure1: Schematically diagram of cantilever beam considered to mathematical formulation.

The mechanical properties of the woven fabric LCB as a function of volume fraction are presented as,

$$U_i = U_f V_f + U_m V_m \qquad (2a)$$

$$V_{\tilde{v}} = 1 - \frac{\left(\frac{W_f}{\rho_f}\right) + \frac{W_c - W_f}{\rho_m}}{\frac{W_c}{\rho_c}} \qquad (2b)$$

$$\rho_c = \rho_f v_f + \rho_m (1 - v_f - v_{\tilde{v}}) \qquad (2c)$$

$$E_x = E_f V_f + E_m V_m \qquad (2d)$$

$$E_y = \left[\frac{E_f \times E_m}{V_f E_m + V_m E_f}\right] \qquad (2e)$$

$$\gamma_{yz} = \gamma_f V_f + \gamma_m (1 - V_f)\left[\frac{1 + \gamma_m - \frac{\gamma_{xy} E_m}{E_{xx}}}{1 - \gamma_m{}^2 + \frac{\gamma_m \gamma_{xy} E_m}{E_{xx}}}\right] \qquad (2f)$$

$$G_{xy} = \frac{G_m G_f}{V_m G_f + V_f G_m} \text{ and } G_{yz} = \frac{E_{yy}}{2(1 + \gamma_{yz})} \qquad (2g)$$

Where U_i: any mechanical property in functional form, the subscript f, m, $\tilde{v}$ and c, presents fiber, matrix void and composite individually. Similarly, ρ, γ, E, G, and V, presents density, poison's ratio, modulus of elasticity and shear modulus and volume fraction fiber and matrix individually.

The mechanical properties constituent materials of composite beam are given in Table1.

Table 1: Properties of Constituent fibre and matrix.

Properties	Fibre	Polyester
E	80GPa	3.5GPa
G	30.3GPa	1.26GPa
ρ	2600 kg/m³	1200kg/m³
γ	0.32	0.38

III. PROBLEM FORMULATION

For the study, polyester-glass laminated composite beams (LCB) are considered. The LCB are stacked six ply layers and kept in symmetric orientation (i.e. lower stacking layers are just opposite to the upper stacking layers). Six different arrangements in orientation like 45˚,30˚and15˚ along with 0°-30°-15° and0°-15°-30° are considered in present analysis. The finite element analysis is carried out by using ANSYS. The LCB is discretized by using 8 node 185solid brick element. In meshing, the length of each element is refined as 3mm to obtain good result. The analysis is considered for all six different kinds of orientations by altering LCB volume fraction, aspect ratio, geometric ratio and length and results are presented. These results are equated with the results obtained from the plies at 0°-0°-0° orientation. The present analysis procedures and results are also validated with the results of Goda et al. [13] and the results are shown in Figure 2.

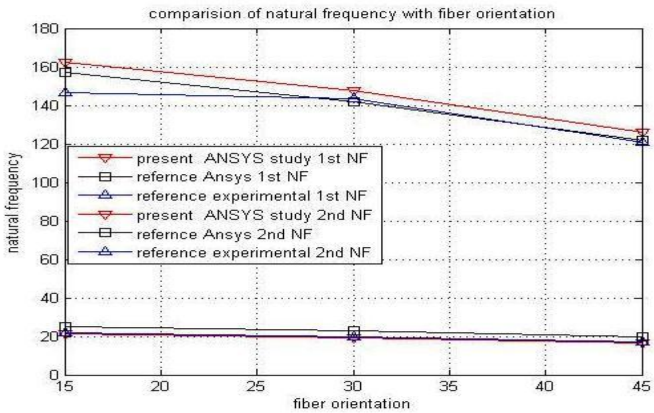

Figure2: present analysis procedures and results are validated with the results of Goda et al. [13].

It is observed that the present analysis (FEA) results are closed to the results of Goda et al. [13] and the present analysis procedures can be validated.

IV. RESULTS AND DISCUSSION

The 1st, 2nd, 3rd, 4th and 5th (observation is taken (at plane bending conditions corresponding mode shapes) natural frequencies (NF) of the fabricated LCB samples are found in FEA (ANSYS) study. This research is mainly focused on such variable parameters as stated as outer fiber orientations, boundary conditions, length, geometric ratio, aspect ratio and volume fraction. Nine combinations of outer fiber orientations of fiber layers to vary the stacking sequences of the composite beam are taken, the orientations taken for the study are ±(0˚-30˚-15˚), ±(30˚-45˚-15˚), ±(45˚-30˚-15˚),±(0˚-15˚-30˚),±(45˚-15˚-30˚),±(30˚-15˚-45˚), ±(15˚-45˚-30˚) and ±(15˚-30˚-45˚) ±(0˚-0˚-0˚). In this study, beam of dimensions (450×50×3.5) mm is taken.

A. Variation of volume fraction

In the current section, the consequence of volume fraction (VF)in NF of LCB is studied. The volume fraction of fiber is varied as 0.3 to 0.6 (step size 0.05). The values of five in-plane-bending NF achieved from FEA by altering volume fraction (VF) of altered stacking sequence of LCB are shown in Figure 3(a) to Figure 3(e).It is clearely observed that the NF increases linearly asfiber volume increased in VF. It can be uderstood the strengthof fiber is greater than matrix and offersadditional strength to the LCB. So by increasingthe volume fraction of fiber increasesstiffness of LCB and natural frequency as well.

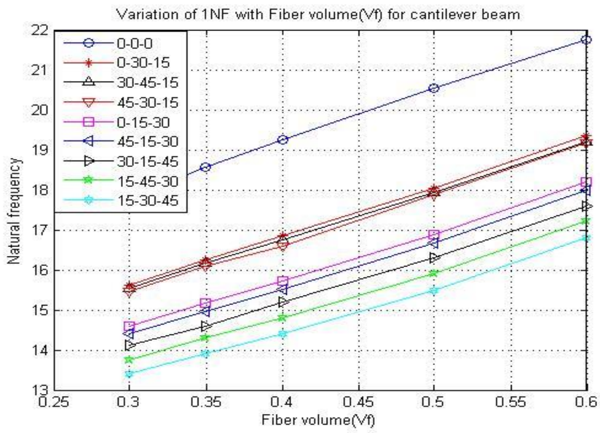

Figure 3(a): variation of 1st NF with VF

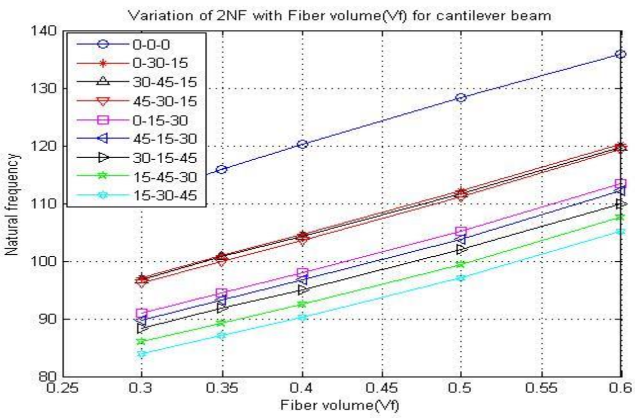

Figure 3(b): variation of 2ndNF with VF

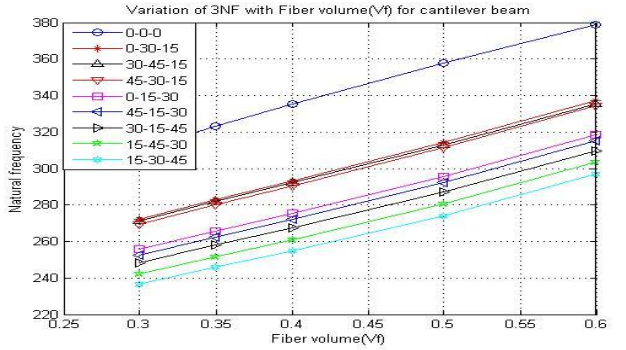

Figure 3(c): variation of 3rd NF with VF

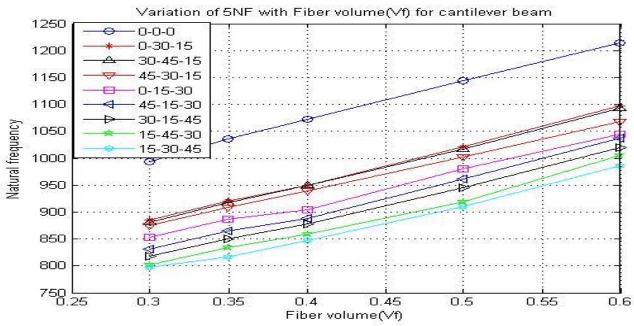

Figure 3(d): variation of 4th NF with VF

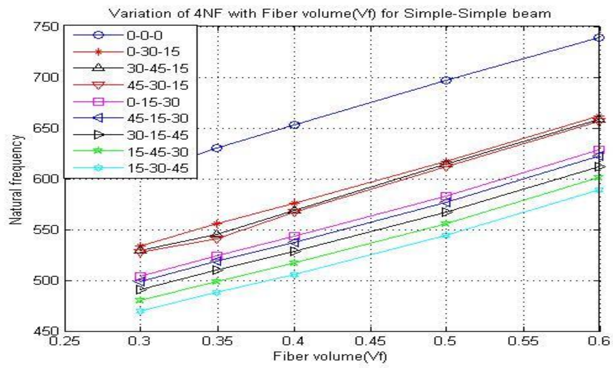

Figure 3(e): variation of 5th NF with

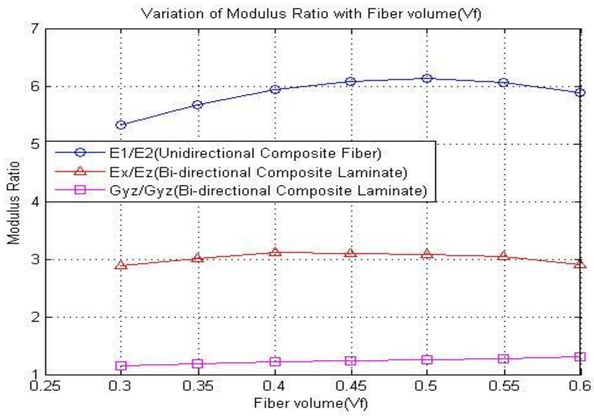

Figure 3(f): variation of modulus of elasticity ratios with VF.

Being fiber mechanical strength is higher than the resin, the natural frequency increases as increase fiber percentage in LCB. As consequence, it increases bending stiffness as well as modulus of elasticity and shear modulus. Figure 3(f) displays the slope among the elastic ratios vs. fiber volume fraction of LCB.

It is observed as by varying fiber volume as 0.3 to 0.6 with 5% increment there is increased in elastic ratios and it gives maximized value at volume fraction is 50% and then decreased.

B.Variation of length

In the study also the effect of variation of length of composite beam for fixed thickness (beam height) and width were studied. For the study the length of a composite cantilever beam were varied gradually up to 450mm for the above said orientations. The thickness and width of the beam is kept fixed as.

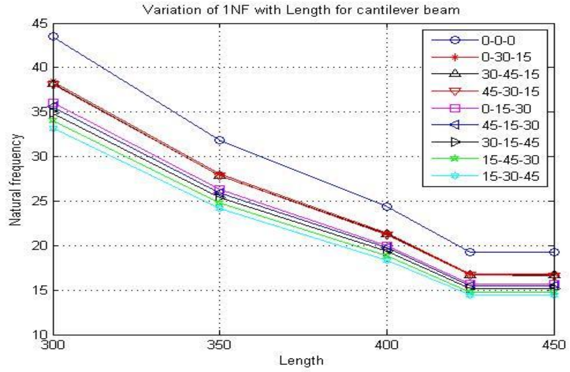

Figure 4(a): 1st NF vs. length of LCB

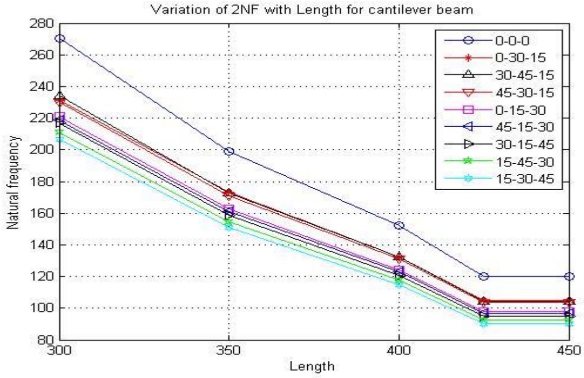

Figure 4(b): 2nd NF vs. length of LCB

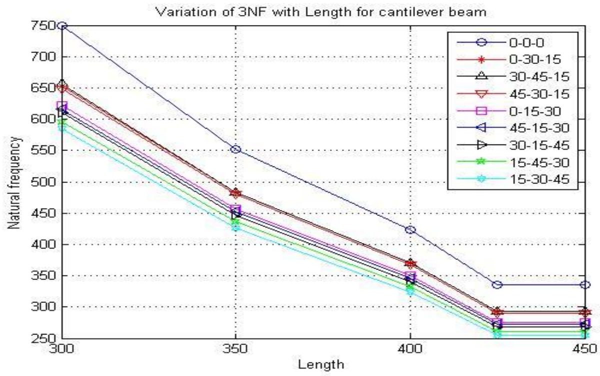

Figure 4(c): 3rdNF vs. length of LCB

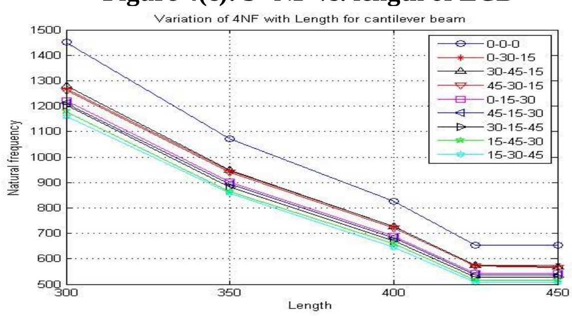

Figure 4(d): 4th NF vs. length of LCB

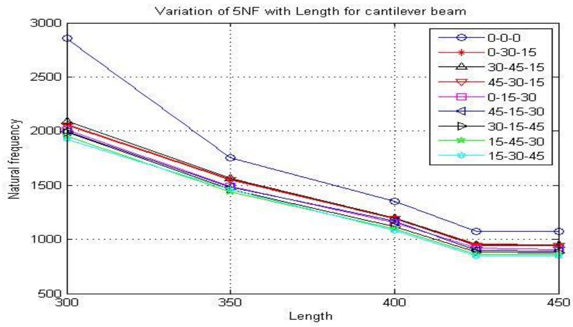

Figure 4(e): 5th NF vs. length of LCB

The study as represented in Figures 4(a) - 4(e), it is quite clear that by increasing the length of the cantilever beam, there is a decrease in natural frequency. It is assumed that by increasing the length the weight of the structure increases though there is a decrease of the bending stiffness as well. The same trends of variation of natural frequencies are found to be true for other type of boundary conditions also.

C. Variation of Geometric Ratio

In this section, the effects of geometric ratio (GR) in natural frequency of LCB as shown in Figure 5(a) to 5(e) are discussed. It is experimental that the frequency risesgraduallyas increases in GR. This trend is observed upto a limit of GR=0.111.At above the GR=0.111, it tends to be sameregardless of orienations of outer fiber. Keeping same length; It is understoodasby increasingthe width of LCB, the contact surface area of the LCB also increases. This surface area offerssufficient strength to carry the aditional mass densityofLCB. Therefore, the stiffness and rigidity of the the LCBcome to bepractically constant of a LCBfor same material and mass density. It is also observed same trends of variation of natural frequencies in different boundary conditions of LCBregardless of orientations of outer fiber.

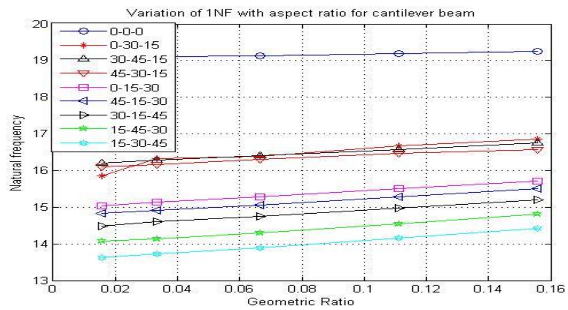

Figure 5(a): Variation of 1stNF with GR.

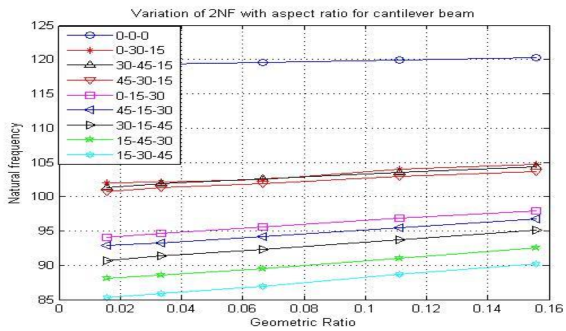

Figure 5(b): Variation of 2ndNF with GR.

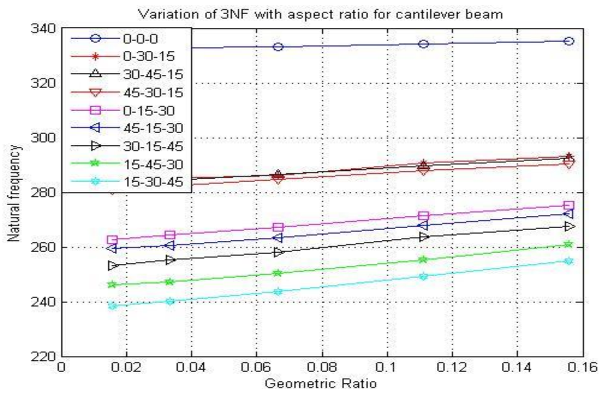

Figure 5(c): Variation of 3rd NF with GR.

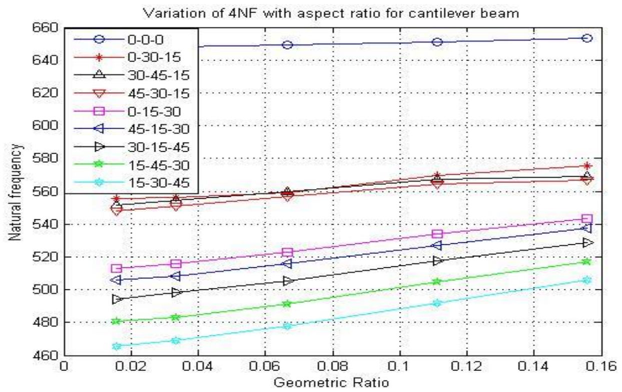

Figure 5(d): Variation of 4th NF with GR.

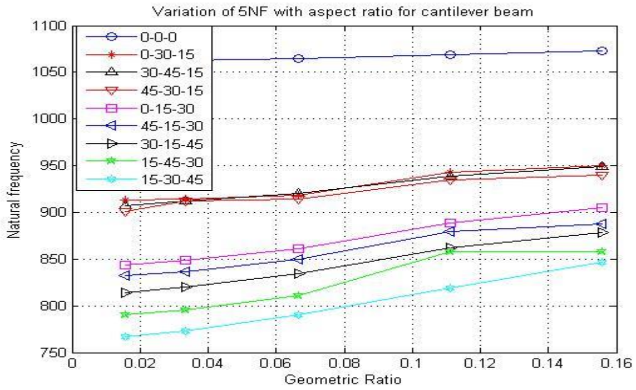

Figure 5(e): Variation of 5th NF with GR.

D. Variation of aspect ratio (AR)

The effect of the aspect ratio (AR) on natural frequency of the cantilever beam is shown in Figure6 (a) to 6(e). From the Figure 6, it is observed as the of natural frequency changes with increasing the aspect ratio of LCB. It is also observed that the natural frequency vs.

aspect ratio curve is varied linearly. Hence, the significance of the increased aspect ratio is increased the stiffness of the corresponding LCB specimen.

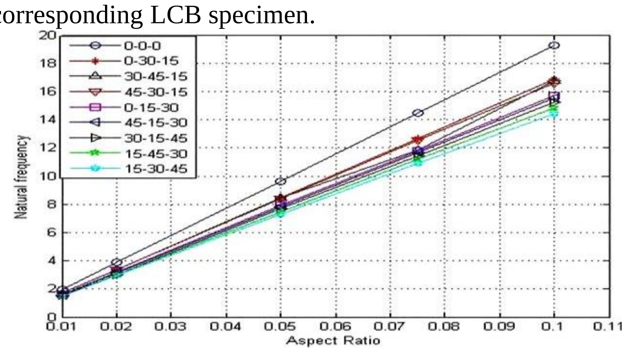

Figure 6(a): 1st NF vs. AR.

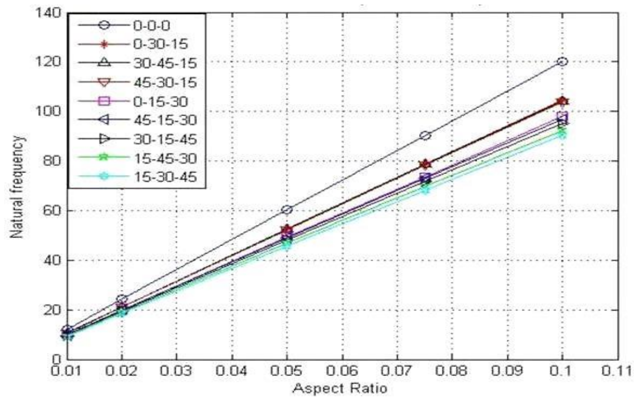

Figure 6(b): 2nd NF vs. AR

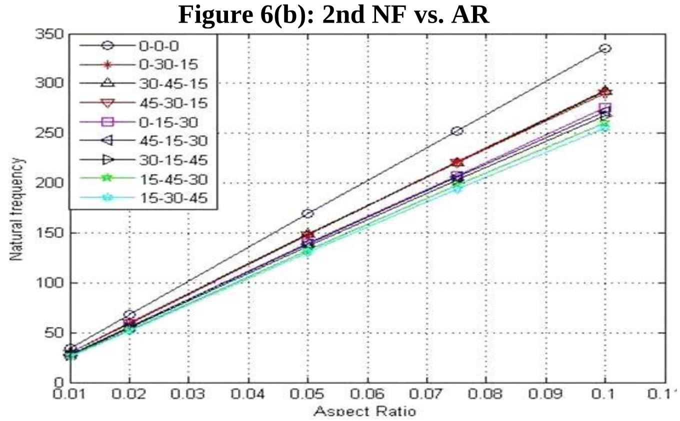

Figure 6(c): 3rd NF vs. AR.

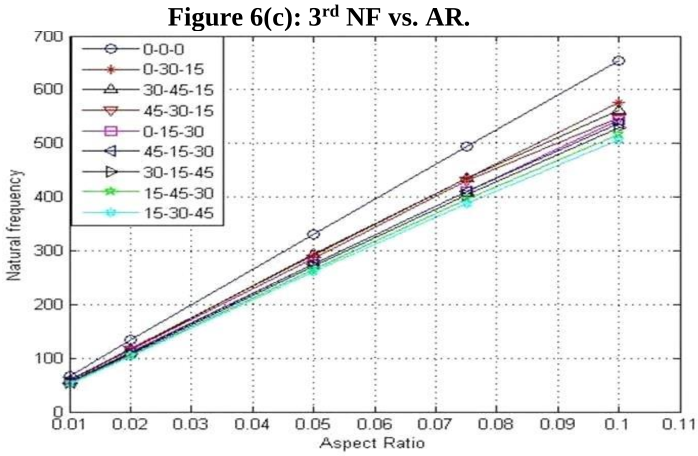

Figure 6(d): 4th NF vs. AR.

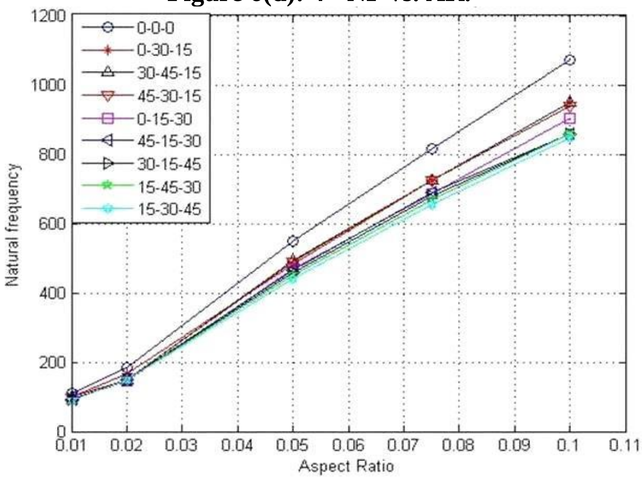

Figure 6(e): 5th NF vs. AR.

The variation of frequency vs. mode number of the LCB specimen at aspect ratio of R=0.01 is shown in Figure7(a) to 7(d).The Figure 7 shows nine curves in lieu of nine orientations of outer fiber. It is observed that curves are varied in same trend regardless of orientation. It is also observed that the LCB specimen of orientation±(0˚-0˚-0˚)2s is exhibited maximum frequency where as ±(15˚-30˚-45˚)2s is produced minimum frequency in the different boundary conditions. Figure 8 is shown for variation of 1stNF ratio (NFR) with variation of different dimension ratios of LCB with AR=0.01 in clamped-free conditions.

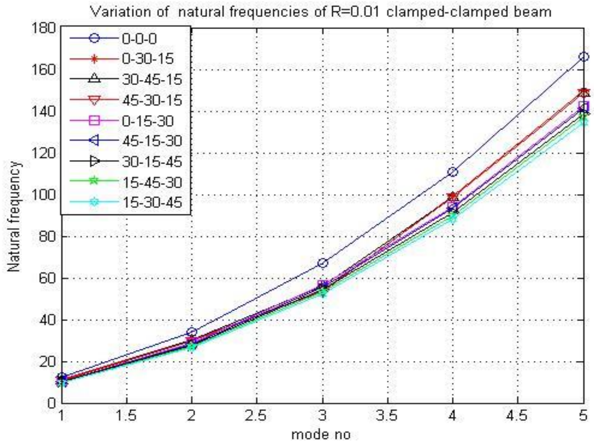

Figure 7(a): Mode number vs. natural frequency with AR=0.01 for clamped-clamped LCB.

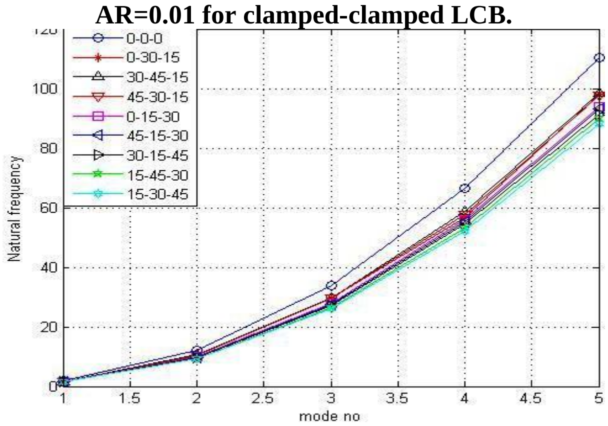

Figure 7(b): Mode number vs. Natural frequency with AR=0.01 for clamped-free support LCB.

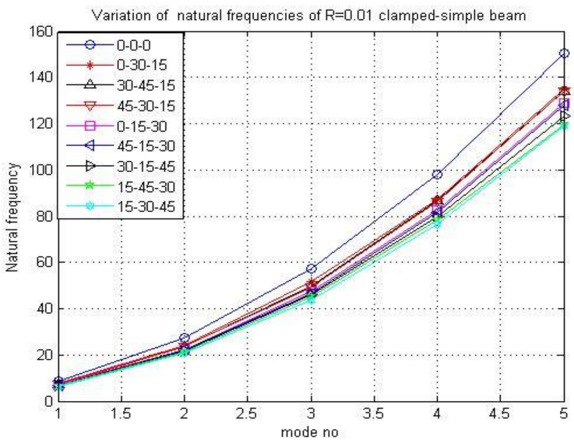

Figure 7(c): Mode number vs natural frequency with AR=0.01 for clamped-simple supported LCB.

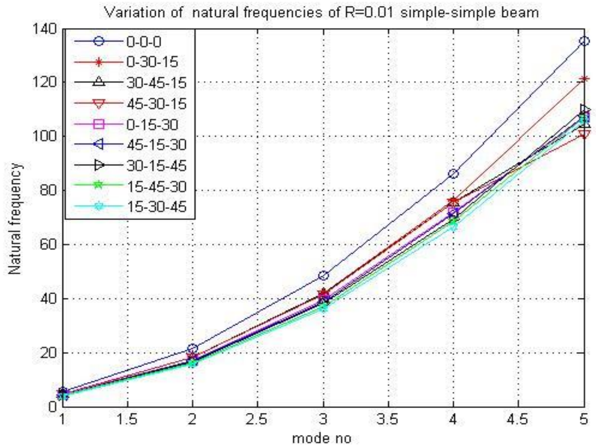

Figure 7(d): Mode number vs. natural frequency with AR=0.01 for simple-simple supported LCB.

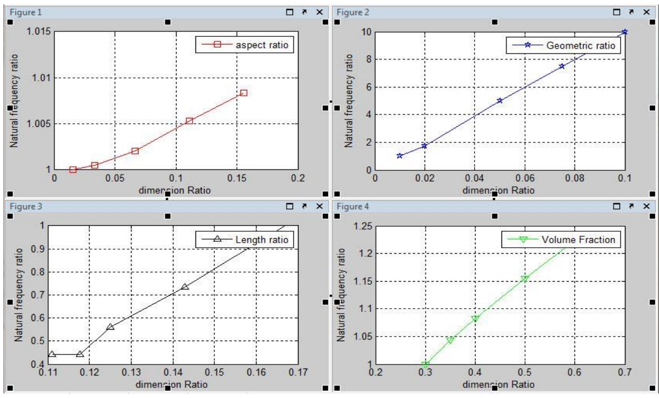

Figure 8: Variation of 1stNFR with variation of different Dimension ratios for cantilever LCB with AR=0.01.

V. CONCLUSIONS

The mechanical property of LCB depends on the property constituent matrix and fiber. It is also true that the orientation of fiber, volume fraction, geometric ratio, length and aspect ratio affect the mechanical property of LCB such as strength and stiffness.The consequences of fiber percentage in volume fraction are observed (Figure 8).

By increased/decreased fiber percentage in volume fraction, it is studied that the slope of natural frequency linearly changes as presented in Figure 8. However the variation of elastic ratios with fiber volume fraction is not linear. From the experimentation, It is observed that the choice of fiber volume fraction should be within the range 0.4 - 0.55 and 0.45 is suitable volume fraction provides better results as shown in Figure3(f). It is also studied that by increasing the aspect ratio, geometric ratios and length of beam, the natural frequency increases, it is to be understood that due to the increase in geometrical dimension, the mass of the beam for same and constant rigidity or stiffness of the LCB increases, as well as it increases the natural frequency as shown in Figure8. Figure7 represents the variation of first natural frequency ratio i.e. $\frac{\omega_i}{\omega_0}$ where ω_0 and ω_i are the natural frequency of ± (0˚-0˚-0˚) orientation and other proposed orientations in fixed-free boundary conditions respectively.

It is also studied that LCB of ± (0˚-0˚-0˚) orientation gives greater natural frequency and ± (15˚-30˚-45˚) orientation gives least natural frequency among all the proposed orientations and end condition. Also the consequence of aspect ratio and change in length is studied and found that by increasing the aspect ratio and length the natural frequencies increases.

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