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Vibration Analysis of Multilayered beam of Graphite Epoxy, Epoxy E-Glass Composites based on layup sequence, fibre orientation and boundary conditions

Pothuraju Tharun[1], Dr Kalapala Prasad[2]

[1]PG student, Department of Mechanical Engineering, UCEK, JNTU, Kakinada, AP, India
[2]Assistant Professor, Department of Mechanical Engineering, UCEK, JNTU, Kakinada, AP, India

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Abstract - *Beam is a basic structural element that primarily resists loads applied laterally to its axis. Beams have a wide range of engineering applications such as airplane wings, Helicopter blades, robot arm, medical instruments, turbine blades, automotive industries, sports equipment etc. When these beams are made up of laminated composites their strength to weight ratio increases and these can be used in different applications by varying the stacking sequence in the laminate with same weight and dimensions. So, this requires a complete analysis of laminated composite beams. It is important to study modal analysis of composite structures as they operate in complex environmental conditions and are frequently exposed to a variety of dynamic excitations. So, this work aims to study the natural frequencies and mode shapes of four layered composite beam under various stacking sequences, materials and boundary conditions. In this research work Classical beam theory is used for vibration analysis and non-dimensional natural frequencies are calculated by the FEM modal prepared by using 281 shell element which is having 8 nodes with six degrees of freedom at each node in Ansys APDL. Finally, a Mat lab code is developed to validate the results obtained in Ansys. It is observed that as the angle of orientation increases the natural frequency decreases, as the stiffness increases the natural frequency increases.*

***Key Words*: Laminated composite beam, free vibration, Natural frequencies, Finite element analysis**

1.INTRODUCTION

Composite materials have gained many applications in recent decades like in aerospace, automotive, and civil engineering structures due to their many advantages, Such as High strength/rigidity to weight ratio, high stiffness to weight ratio, Corrosion resistant and tuning of fibre angles in different layers to obtain the required properties. The complex structures in various fields of engineering such as Aerospace, Mechanical, Civil, Naval and automobile are made up of simple structural members like beams. So, Evaluation of free Vibration behaviour of a structure is an essential Consideration in the design of a structure. Understanding the fundamental frequency parameter of beams will be helpful in the design of structural members in the initial stages of design. Numerous methods and materials have been developed by various researches to know dynamic behaviour in past decades. Rudy Lukez [1] described about the various applications of Graphite epoxy composites because of their high strength to weight ratio, high stiffness to weight ratio and near-zero coefficient of thermal expansion. Graphite epoxy composite solves the problem with the space environment like radiation, physical demands based on size and weight etc. Ganesh kumar Tirumalasetty [2] discussed about the application of glass-fiber reinforced epoxy composite in manufacturing of train Components with its greater strength and impact resistance. Nitesh Talekara et al [3] described mathematical procedure for the free Vibration analysis of four layered composite cantilever beam using first order shear deformation beam theory by Varying layup sequence and Thickness ratios. They observed natural frequencies of all the modes are highly sensitive to a smaller layup angle than the higher lay up for all the boundary conditions.

Channabasavaradhy Suragimath [4] studied the Vibration analysis of composite beam using mat lab. The study involved finding the natural frequency and mode shapes of structure made up of Glass-epoxy, Carbon epoxy and Graphite fibre reinforced polyamide materials. Euler's Bernoulli beam theory is used for analytical Solution and to construct Mat lab codes. The natural frequency is maximum at the fixed-fixed Condition when compared with all other boundary conditions and higher natural frequencies were found in Carbon-epoxy composites due to higher flexural rigidity (EI) when compared with other composite materials. Graphite - fibre reinforced polyamide Composite has shown higher natural frequencies when compared with glass-epoxy composites. Nitesh Talekar [5] described mathematical procedure for the free Vibration analysis of four layered composite beam using first order shear deformation beam theory by various boundary conditions and effect of poissons ratio. Mahmoud yassin osman et.al [6] discussed about the study of free vibration of rectangle laminated Composite beams by using first order Shear deformation theory. In this paper, formulated the mathematical equations and verified with fem method for Graphite epoxy composite structure for various boundary conditions. The results obtained were compared with previous papers and found in good agreements. Priyadarshini Das and shishir kumar Sahuta [7] discussed about experimental and numerical free Vibration analysis of industry-driven woven fibre laminated glass/epoxy composite beams. The results conclude that the free vibration finite element predictions for glass/epoxy are Sensitive to effects of different boundary conditions and Span-to-thickness ratio. The nature of the supports at the edges influences the free Vibration frequencies. Due to rigid condition at both the ends, fixed-fixed beam shows higher frequencies than other types of beams. Rajesh Kumar and v. Hariharan [8] discussed about free Vibration of Hybrid Composite beams by varying aspect ratio using Ansys 12.0. The natural frequencies are maximum for smaller aspect ratios and it decreases once the aspect ratio increases. Also, the twisting occurs at lower mode number for smaller aspect ratio and occurs at higher mode number for higher aspect ratios. chandrasekhara and Bangera [9] presents the equation of motion for laminated Composite beams based on a higher order plate theory. The natural frequencies for symmetric and unsymmetric laminated beams under various boundary conditions are discussed and suggested that the mode shapes for cross ply clamped-clamped beams indicate that the effects of shear de formation are greater for higher modes. Jun-et al. [10] introduced a dynamic finite element method by first order shear deformation theory for free Vibration Analysis of generally layered Composite beam. Hamilton's principle is used to desire the coupled differential equations which govern the free Vibration of generally layered composite beam. Shi and Lam [11] used third order beam theory for a new finite element formulation for the free vibration analysis of the layered composite beams. The coupling mass matrices and higher order have a negligible effect on the laminated fundamental frequencies, but they have a significant effect on the higher modal frequencies of flexural vibration. Bhimaraddi and Chandrasekhar [12] found the basic equations of the beam theory based on the parabolic Shear de formation theory for the laminated beams by a systemic reduction of the constitute relations of the three-dimensional anisotropic body. Banerjee and williams [13] presented an exact dynamic stiffness matrix for composite beam with the impacts of Shear deformation, rotary inertia and coupling between the bending and torsional deformations.

Table -1: Nomenclature

N_X, N_Y, N_{XY}	In Plane Forces	D_{ij}	Bending stiffness
M_X, M_Y	Bending moment	Q_{IJ}	Transformed elasticity constants
M_{XY}	Twisting moment	$\overline{EI_{YY}}$	Bending stiffness about y-axis
ϵ_X, ϵ_Y, ϵ_{XY}	Mid- plane strains	L	Length of the Beam
K_X, K_Y	Bending curvatures	b	Width of the Beam
K_{XY}	twisting curvature	h	Height of the Beam
A_{ij}	Extensional stiffness	ρ	Density of the Beam
B_{ij}	Coupling stiffness	ɵ	Angle of orientation of the Fiber

2. MATERIALS AND MECHANICAL PROPERTIES

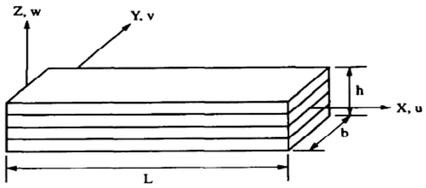
Table -2: Properties of Composite Materials

Material	**Young's Modulus**			**Shear Modulus**			**Poisson's Ratio**		
	E1	E2	E3	G12	G23	G13	µ12	µ23	µ13
Graphite-Epoxy	144.8e9 pa	9.65e9 pa	9.65e9 pa	4.14e9 pa	3.45e9 pa	4.14e9 pa	0.3	0	0
EpoxyE-glass	45e9 pa	10e9 pa	10e9 pa	5e9 pa	5e9 pa	3.84e9 pa	0.3	0.3	0.4

3. METHODOLOGY

3.1. Analytical Method –

Consider a beam of length L, breadth b and total thickness h, which is laminated of a finite number of orthotropic layers of thickness hi with the principal material axes of each layer being oriented with respect to the beam mid-plane.



Fig, 1 Geometry of Laminated Composite Beam

By the classical lamination theory, the constitutive equations of the laminate can be obtained as:

$$\begin{Bmatrix} N_X \\ N_Y \\ N_{XY} \\ M_X \\ M_Y \\ M_{XY} \end{Bmatrix} = \begin{matrix} A_{11} & A_{13} & A_{16} & B_{11} & B_{12} & B_{16} \\ A_{12} & A_{22} & A_{26} & B_{12} & B_{22} & B_{26} \\ A_{16} & A_{26} & A_{66} & B_{16} & B_{26} & B_{66} \\ B_{11} & B_{12} & B_{16} & D_{11} & D_{12} & D_{16} \\ B_{12} & B_{22} & B_{26} & D_{12} & D_{22} & D_{26} \\ B_{16} & B_{26} & B_{66} & D_{16} & D_{26} & D_{66} \end{matrix} \begin{Bmatrix} \epsilon_X^0 \\ \epsilon_Y^0 \\ \epsilon_{XY}^0 \\ K_X \\ K_Y \\ K_{XY} \end{Bmatrix}$$

Where,

N_X, N_Y and N_{XY} are the in-plane forces,

M_X, M_Y and M_{XY} are the bending and twisting moments,

ϵ_X, ϵ_Y, ϵ_{XY} are the mid- plane strains,

K_X, K_Y, K_{XY} are the bending and twisting curvatures.

A_{ij},B_{ij}, and D_{ij}, are the extensional stiffness, coupling stiffness, bending stiffness respectively.

For the case of laminated composite beam:

N_X, N_{XY} and M_Y =0, ϵ_Y, ϵ_{XY} and the curvature K_Y assumed to be non-zero.

Then, equation (1) can be written as:

$$\begin{Bmatrix} N_X \\ M_X \\ M_{XY} \end{Bmatrix} = \begin{matrix} \overline{A}_{11} & \overline{B}_{11} & \overline{B}_{16} \\ \overline{B}_{11} & \overline{D}_{11} & \overline{D}_{16} \\ \overline{B}_{16} & \overline{D}_{16} & \overline{D}_{66} \end{matrix} \begin{Bmatrix} \epsilon_X^0 \\ K_X \\ K_{XY} \end{Bmatrix}$$

Where,

$$A_{ij} = \int_{-h/2}^{h/2} \overline{Q_{IJ}}\, dz, \quad B_{ij} = \int_{-h/2}^{h/2} \overline{Q_{IJ}}\, Z\, dz, \quad D_{ij} = \int_{-h/2}^{h/2} \overline{Q_{IJ}}\, z^2\, dz$$

The transformed reduced stiffness constants Q_{IJ} (i, j = 1, 2, and 6) are given as:

$$\overline{Q}_{11} = (Q_{11}\cos^4\theta + 2(Q_{12} + 2Q_{66})\sin^2\theta\cos^2\theta + Q_{22}\cos^2\theta)$$

$$\overline{Q}_{12} = (Q_{11} + Q_{12} - 4Q_{66})\sin^2\theta\cos^2\theta + Q_{12}(\sin^4\theta + \cos^4\theta)$$

$$\overline{Q}_{22} = (Q_{11}\sin^4\theta + 2(Q_{12} + 2Q_{66})\sin^2\theta\cos^2\theta + Q_{22}\cos^4\theta)$$

$$\overline{Q}_{16} = (Q_{11} - Q_{12} - 2Q_{66})\sin\theta\cos^3\theta + (Q_{12} - Q_{22} + 2Q_{66})\cos\theta\sin^3\theta$$

$$\overline{Q}_{26} = (Q_{11} - Q_{12} - 2Q_{66})\cos\theta\sin^3\theta + (Q_{12} - Q_{22} + 2Q_{66})\sin\theta\cos^3\theta$$

$$\overline{Q}_{66} = (Q_{11} - Q_{12} - 2Q_{66} - 2Q_{12})cos^2\theta\sin^2\theta + Q_{66}(\cos^4\theta + \sin^4\theta)$$

$$Q_{11} = \frac{E_1}{1-\mu_{12}\mu_{21}},\ Q_{12} = \frac{\mu_{21}E_1}{1-\mu_{12}\mu_{21}},\ Q_{22} = \frac{E_2}{1-\mu_{12}\mu_{21}},\ Q_{11=G_{12}}$$

3.2. Bernoulli-Navier Hypothesis –

The Euler Bernoulli beam theory (or classical beam theory - CBT) assumes that straight lines perpendicular to the mid-plane before bending remain straight and perpendicular to the mid-plane after bending. As a result of this assumption, transverse shear strain is neglected.

Vibration in x-z plane is given by:

$$\omega_{yi}^2 = \frac{\overline{EI_{YY}}}{2*\pi*\rho}\frac{\mu^4{}_{Bi}}{L^4}$$

Where

$\overline{EI_{YY}}$ is the bending stiffness about y axis in N.m^2

L is the length of the beam, ρ is the mass per unit length, and $\mu^4{}_{Bi}$ for different boundary conditions is given in table 3.

The subscript i= 1, 2…., indicates the first, second and so forth modes.

For symmetric orthotropic laminated beam:

The bending stiffness about y axis EI_{YY} can be obtained by using the relation

$EI_{YY} = \frac{b}{d_{11}}$ in N.m^2

Where d_{11} is the element 1-1 of the laminate bending compliance matrix (1/Nm.)

Table 3 The constants μ_{Bi} for different boundary conditions are:

Boundary Condition	Mode 1	Mode 2	Mode 3
Fixed-free	1.87	4.694	7.85
Fixed-fixed	4.73	7.85	10.99
Fixed-pinned	3.92	7.068	10.2102

4. RESULTS

The theoretical formulation in the previous section is applied to compute the natural frequencies and mode shapes of generally layered composite beam. The validation of numerical results is done by using ANSYS APDL software.

The following are the three boundary conditions:

1. Clamped- Clamped (C-C)
2. Clamped- Simply supported (C-S)
3. Clamped- Free (C-F)

Table4.Represents the Fundamental natural frequency of [**θ/-θ/-θ/θ**] orientation beam for varying boundary conditions. Graphite epoxy has the following material properties: E1= 144.8 * 10^9 Pa, E2= E3= 9.65 * 10^9 Pa, G12=G13= 4.14 * 10^9 Pa, G23= 3.45 * 10^9 Pa. µ12=0.3, ρ= 1389.23 kg/m3, L=0.381m, b=0.0254m, h=0.0254m

Table -4: Fundamental natural frequency (Hz) of [θ/-θ/-θ/θ] orientation of Graphite Epoxy Composite beam

BC's	0		15		30		45		60		75		90	
	Ansys	Ref	Ansys	Ref	Ansys	Ref	Ansys	Ref	Ansys	Ref	Ansys	Ref	Ansys	Ref
C-C	1376.7	1384.3	1130.4	1125.7	824.63	818.3	564.06	548.4	468.74	475.1	457.04	460.9	459.19	463.7
C-S	1058.6	1090.5	838.72	856.1	593	592.4	390.19	386.3	325.21	323.2	318.84	321	320.65	320.6
C-F	278.23	278.4	209.8	207.2	140.09	137.9	90.903	89.3	75.285	74.7	73.781	73.7	74	74.2

Table-5 Represents the Fundamental natural frequency of [**θ/-θ/-θ/θ**] orientation beam for varying boundary conditions. Epoxy E-Glass has the following material properties: E1= 45* 10^9 Pa, E2= E3= 10 * 10^9 Pa, G12=5 * 10^9 Pa, G13= 3.84 * 10^9 Pa, G23= 5 * 10^9 Pa. µ12=0.3, ρ= 2000 kg/m3, L=0.381m, b=0.0254m, h=0.0254m

Table-5. Fundamental natural frequency (Hz) of [θ/-θ/-θ/θ] orientation of Epoxy E-Glass Composite beam

BCs		**0**	**15**	**30**	**45**	**60**	**75**	**90**
Clamped-clamped(C-C)	present	778.65	702.79	571.64	464.75	410.22	393.32	390.5
Clamped-SS(C-S)	present	557.51	499.89	401.86	324.07	285.74	274.26	272.4
Clamped-Free(C-F)	Present	132.8	117.98	93.814	75.177	66.166	63.426	62.996

Table6. Represents the natural frequency of [**θ/-θ/θ/-θ**] orientation beam for varying boundary conditions. Graphite epoxy has the following material properties: E1= 144.8 * 10^9 Pa, E2= E3= 9.65 * 10^9 Pa, G12=G13= 4.14 * 10^9 Pa, G23= 3.45 * 10^9 Pa. µ12=0.3, ρ= 1389.23 kg/m3, L=0.381m, b=0.0254m, h=0.0254m

Table-6. Natural frequencies (Hz) of [θ/-θ/θ/-θ] orientation of Graphite Epoxy Composite beam

BCs		**0**	**15**	**30**	**45**	**60**	**75**	**90**
Clamped-clamped(C-C)	ω1	1376.7	1135	855.54	572.93	469.74	457.17	459.19
	ω2	1403.5	1462.1	1020.2	630.58	532.12	520.33	524.28
	ω3	2083.3	2239.4	2014.3	1475	1243.5	1213.4	1217.9
	ω4	3075	2503.5	2272.5	1720	1451.0	1410.6	1399
Clamped-SS(C-S)	ω1	1058	879.29	625.27	398.06	325.74	318.89	320.65
	ω2	1397.6	1452.9	1016.3	628.42	529.57	517.33	519.50
	ω3	2078.8	2175.1	1774.7	1223.9	1022.9	1002.9	1007.9
	ω4	2826.1	2319.1	2193	1714.1	1444.2	1402.3	1385.1
Clamped-Free(C-F)	ω1	278.47	233.66	154.86	93.326	75.443	73.792	74

	ω2	281.34	248.47	161.58	98.737	83.769	82.552	84.331
	ω3	1039.2	1080.2	874.88	563.29	462.29	452.69	455.16
	ω4	1468.4	1216.9	997.56	614.24	521.11	512.04	518.72

Table7. Represents the natural frequency of [**θ/-θ/θ/-θ**] orientation beam for varying boundary conditions. Epoxy E-Glass has the following material properties: E1= 45* 10^9 Pa, E2= E3= 10 * 10^9 Pa, G12=5 * 10^9 Pa, G13= 3.84 * 10^9 Pa, G23= 5 * 10^9 Pa. μ12=0.3, ρ= 2000 kg/m3, L=0.381m, b=0.0254m, h=0.0254m

Table-7. Natural frequencies (Hz) of [θ/-θ/θ/-θ] orientation of Epoxy E-Glass Composite beam

BCs		0	15	30	45	60	75	90
Clamped-clamped(C-C)	ω1	759.84	701.86	586.80	473.65	413.35	395.62	392.96
	ω2	809.92	774.98	655.53	525.22	471.79	457.82	454.56
	ω3	1776.2	1731.2	1485.4	1239.4	1099.5	1057.4	1051.3
	ω4	1869.7	1814	1749.7	1418.8	1275.8	1232	1217.2
Clamped-SS(C-S)	ω1	549.41	506.21	416.62	330.81	287.47	275.19	273.37
	ω2	806.10	771.07	652.19	522.60	468.53	453.76	449.97
	ω3	1620.5	1497	1261.1	1029.3	905.81	870.27	865.09
	ω4	1772.7	1804	1739	1411.2	1266.7	1220.5	1204
Clamped-Free(C-F)	ω1	132.43	121.66	98.615	77.030	66.447	63.480	63.035
	ω2	137.69	128.16	105.19	83.389	74.970	73.090	72.8941
	ω3	773.50	712.70	588.40	468.69	408.15	390.91	388.35
	ω4	817.41	773.87	646.92	516.26	464.23	451.62	449.21

Table8. Represents the natural frequency of [**θ/θ/θ/θ**] orientation beam for varying boundary conditions. Graphite epoxy has the following material properties: E1= 144.8 * 10^9 Pa, E2= E3= 9.65 * 10^9 Pa, G12=G13= 4.14 * 10^9 Pa, G23= 3.45 * 10^9 Pa. μ12=0.3, ρ= 1389.23 kg/m3, L=0.381m, b=0.0254m, h=0.0254m

Table-8. Natural frequencies (Hz) of [θ/θ/θ/θ] orientation of Graphite Epoxy Composite beam

BCs		0	15	30	45	60	75	90
Clamped-clamped(C-C)	ω1	1376.7	969.32	642.52	510.03	463.49	455.85	459.19
	ω2	1403.5	1047.0	709.62	574.01	530.22	522.78	524.28
	ω3	2083.3	2329.8	1654.5	1342.9	1230.3	1212.5	1217.9
	ω4	3075	2568.7	1904.9	1553.5	1430.1	1399.7	1399
Clamped-SS(C-S)	ω1	1058	697.42	449.02	354.03	322.69	318.75	320.65
	ω2	1397.6	1043.4	706.29	570.89	526.46	517.99	519.50
	ω3	2078.8	1951.3	1369.5	1106.2	1014.7	1002.5	1007.9
	ω4	2826.1	2542.3	1896.0	1545.3	1420.3	1386.9	1385.1
Clamped-Free(C-F)	ω1	278.47	166.58	103.94	81.875	74.66	73.757	74

	ω2	281.34	169.32	105.35	82.801	75.515	74.630	84.331
	ω3	1039.2	952.35	627.15	500.60	458	452.47	455.16
	ω4	1468.4	1004.8	648.52	513.08	467.36	460.02	518.72

Table9. Represents the natural frequency of [**θ/θ/θ/θ**] orientation beam for varying boundary conditions. Epoxy E-Glass has the following material properties: E1= 45* 10^9 Pa, E2= E3= 10 * 10^9 Pa, G12=5 * 10^9 Pa, G13= 3.84 * 10^9 Pa, G23= 5 * 10^9 Pa. μ12=0.3, ρ= 2000 kg/m3, L=0.381m, b=0.0254m, h=0.0254m

Table-9. Natural frequencies (Hz) of [θ/θ/θ/θ] orientation of Epoxy E-Glass Composite beam

BCs		**0**	**15**	**30**	**45**	**60**	**75**	**90**
Clamped-clamped(C-C)	ω1	759.84	676.49	533.5	447.02	407.15	393.16	392.96
	ω2	809.92	774.98	655.53	525.22	471.79	457.82	454.56
	ω3	1776.2	1731.2	1485.4	1239.4	1099.5	1057.4	1051.3
	ω4	1869.7	1814	1749.7	1418.8	1275.8	1232	1217.2
Clamped-SS(C-S)	ω1	549.41	479.98	373.65	311.64	283.64	274.15	273.37
	ω2	806.10	771.07	652.19	522.60	468.53	453.76	449.97
	ω3	1620.5	1497	1261.1	1029.3	905.81	870.27	865.09
	ω4	1772.7	1804	1739	1411.2	1266.7	1220.5	1204
Clamped-Free(C-F)	ω1	132.43	112.59	86.525	72.036	65.581	63.397	63.035
	ω2	137.69	128.16	105.19	83.389	74.970	73.090	72.8941
	ω3	773.50	712.70	588.40	468.69	408.15	390.91	388.35
	ω4	817.41	773.87	646.92	516.26	464.23	451.62	449.21

Table10. Represents the natural frequency obtained from Euler Bernoulli's Equation and Ansys APDL for Graphite Epoxy Composite Beam

Boundary Conditions	**Numerical**	**Ansys APDL**
Clamped-Clamped (C-C)	1513.12	1376.7
Clamped-Simply supported (C-S)	829.231	1058.6
Clamped-Free (C-F)	295.735	278.23

Table11. Represents the natural frequency obtained from Euler Bernoulli's Equation and Ansys APDL for E-Glass Epoxy Composite Beam

Boundary Conditions	**Numerical**	**Ansys APDL**
Clamped-Clamped (C-C)	985.38	778.65
Clamped-Simply supported (C-S)	538.5	557.51
Clamped-Free (C-F)	165.091	132.8

Chart -1: Natural frequency Vs Orientations of Clamped- Clamped Boundary Condition for Graphite Composite Beam

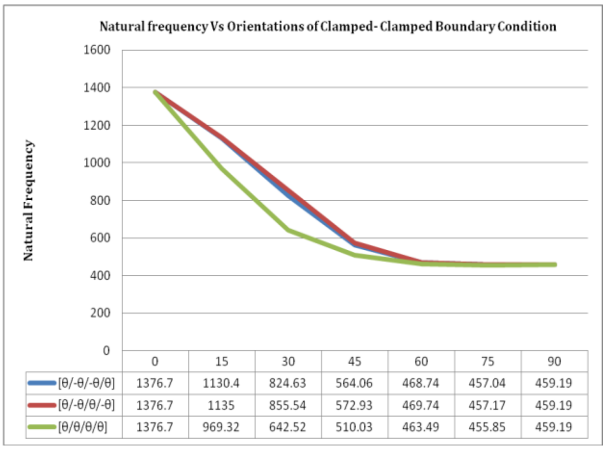


Chart-2: Natural frequency Vs Orientations of Clamped-Clamped Boundary Condition for E-Glass Epoxy Epoxy Composite beam

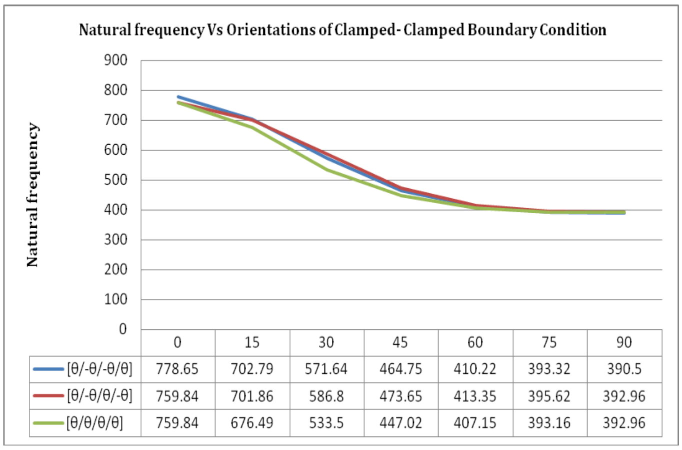
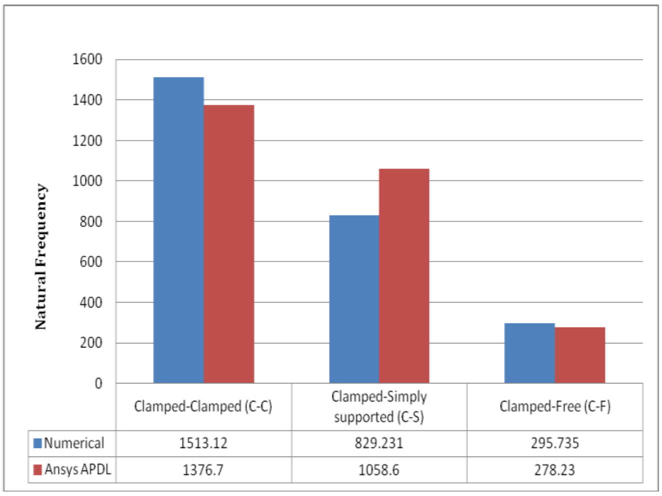
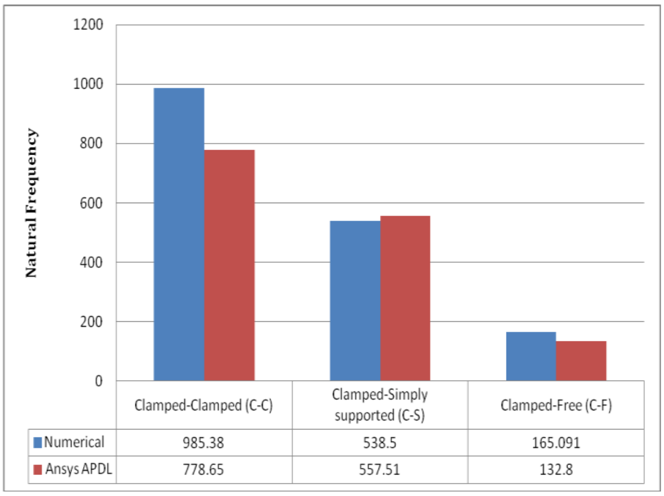


Chart -3: Bar chart representing variation between and Ansys APDL results of Graphite epoxy beam



3.

Chart -4: Bar chart representing variation numerical between numerical and Ansys APDL results of E-Glass epoxy beam



CONCLUSIONS

The finite element model for the free vibration characteristic of the composite beam is analysed in this paper. The impact of lay-up angle and boundary conditions on the natural frequencies of laminated composite beams are investigated for Graphite Epoxy and E-Glass Epoxy composites. It is shown that the natural frequencies obtained with Ansys and numerical are similar to each other. Natural frequency of all the modes is observed to be highly sensitive to a smaller layup angle than a higher lay up for all the boundary conditions.

The following observations have been made:

1. From the graphs it is clear that as angle of orientation increases, the natural frequency of the beam decreases.
2. From the graphs it is clear that as stiffness of the plate increases, the natural frequency increases.
3. The stiffness is more for Clamped- Clamped(C-C) and less for Clamped-Free(C-F) Boundary Conditions.

4. The increasing beam stiffness order and natural frequency values for the boundary conditions considered in the analysis is:

   Clamped-Free < Clamped-pinned < Clamped-Clamped

5. From the chart 1 and 2 it is clear that [θ/-θ/θ/-θ] has the highest natural frequency in between 0 to 90 degrees compared to [θ/-θ/-θ/θ] and [θ/θ/θ/θ] orientations.

6. From the chart 1 and 2 it is clear that [θ/-θ/-θ/θ] has the more natural frequency in between 0 to 90 degrees than [θ/θ/θ/θ] orientations.

7. From the bar chart 3 & 4 it is clear that the numerical and Ansys results hold well with fewer variations.

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