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Modal Analysis of Fibre Reinforced Composite Beams with a Transverse Crack Using ANSYS

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Abstract: *In many structures like high speed machineries, aircrafts and light weight structures composite beams and beam like structures are main constituent elements. Cracks induced in these structural elements cause serious failure and monitoring of these cracks is essential. The presence of these cracks influences the dynamic characteristics of the structural elements. Hence the changes in natural frequencies and mode shapes have been the subject of interest of many investigations. In the present work two Fiber- Reinforced Plastic (FRP) materials, Graphite Fibre Reinforced Polyamide and E-Glass Fibre Reinforced Polymer have been selected as beam materials for modal analysis using ANSYS 13.0. The analysis is carried out for these two beams in different ways. Initially the analysis is carried out for different orientation of fibres for two beams. Later the effect of dimensions is analyzed by varying one dimension of the beam at a time by keeping the other two constant. In the next step the analysis is performed for constant dimensions of each beam for same layer orientation and constant volume fraction of fibre by introducing transverse cracks of different depths at various positions along the length of the beam. The results obtained are analyzed.*

Keywords*: ANSYS, Crack, Fibre- Reinforced Composite beams, Modal Analysis, Natural frequency.*

I. Introduction

In the modern decades, different engineering fields like automobile, aerospace, naval, and civil use fiber reinforced composite materials by some means. The various properties of composite materials like high strength, low weight, resistance to corrosion, impact resistance, and high fatigue strength increase their reputation. Fiber-reinforced composite beams include the major collection of structural members, which are extensively used as movable elements, such as robot arms, rotating machine parts, and helicopter and turbine blades. Structural damage recognition has gained increasing deliberation from the scientific society since unexpected major hazards, most with human losses, have been reported. Aircraft crashes and the catastrophic bridge failures are a few illustrations. The cracks can be present in structures due to their limited fatigue strengths or due to the manufacturing processes. These cracks open for a part of the cycle and close when the vibration reverses its direction.

These cracks will grow over time, as the load reversals persist, and may reach a point where they pose a peril to the integrity of the structure. As a consequence, all such structures must be cautiously maintained and more generally, SHM denotes a consistent system with the aptitude to detect and interpret adverse “change” in a structure due to damage or normal operation. This was studied by Ramanamurty[5] . The greatest confront in designing a SHM system is to recognize the emphasize changes due to damage or defect. Lots of damage recognition techniques have been proposed for structural health monitoring. Some of the nondestructive evaluation approaches that exploit technologies such as X-ray imaging, ultrasonic scans, infrared thermograph, and eddy current can recognize damages. However, they are somehow complicated to implement, and some of them are unfeasible in many cases such as in service aircraft testing and in-site space structures. Hence, the vibration-based damage identification method as a global damage recognition technique is developed to surmount these difficulties.

A composite material is defined as a material system which consists of a mixture or combination of two or more specifically dissimilar materials which are insoluble in each other and vary in form or chemical composition. Composite materials of two phase system are classified into two widespread groups. They are particulate composites and fiber-reinforced composites. Particulate composites are those particles having assorted shapes and sizes are dissipated with in a matrix in a random fashion examples are mica flakes reinforced with glass, lead particles in copper alloys and silicon carbon particles in aluminum. Particulate composites are used for electrical applications, welding, machine parts and other purposes.

Fiber-reinforced composite material consists of fibers of significant strength and stiffness embedded in a matrix with perceptible boundaries between them. Both fibers and matrix maintain their physical and chemical characters, as their combination achieves a function which cannot be done by each constituent acting individually. Fibers of fiber-reinforced plastics (FRP) may be short or continuous. FRP'S having continuous fibers appear to be more efficient indeed. According to the type of the matrix used FRP composite materials are classified in to four broad categories. They are polymer matrix composites, metal matrix composites, ceramic composites and carbon/carbon composites. Polymer matrix composites are made of thermo plastics or thermo set resins reinforced with fibers such as glass, carbon or boron. A metal matrix composite consists of a matrix of metals or alloys reinforced with metal fibers such as boron or carbon. Ceramic matrix composites consist of ceramic matrices reinforced with ceramic fibers such as silicon carbide alumina of silicon nitrate. Their applications are more effectual at elevated temperatures.

Nikpur and Dimargonas[1] developed the local compliance matrix for unidirectional composite materials. The extent of anisotropy in composites found as a function for increase of interlocking deflection modes were shown in their works. Manivasagam and Chandrasekaran [2] found reduction in fundamental frequency of layered composite materials due to presence of cracks. Krawczuk and Ostachowicz [3] examined Eigen frequencies of a cantilever beam prepared form Graphite Fiber-Reinforced Polyimide with a transverse open crack by generating two models of the beam, the effect of various parameters, the crack location, the crack depth, the volume fraction fibers and fiber's orientation were premeditated upon the deviations of natural frequencies of the beam. Ghoneam [4] investigated the dynamic characteristics of laminated composite beams with an assortment of fiber orientations and dissimilar boundary conditions in non existence and existence of cracks. The possessions of assorted crack depths and positions, boundary conditions were studied both by mathematical development and experimental analysis. The accord among the experimental and theoretical results was established well during analysis.

In the present work modal analysis using ANSYS was carried out for two composite beams of Graphite Fibre- Reinforced Polyamide and E-glass Fibre- Reinforced polymer for the purpose of study by modeling which enables saving of time and cost. Initially by modeling the beams in ANSYS and analyzing them the first three natural frequencies were estimated for different fibre orientations for same volume fraction and then the dependency of the first three natural frequencies of the beams were studied by varying the dimensions of the beams in individual directions. In the next step the variations in the first three natural frequencies due to presence of crack of different depths at various locations on the beam were studied by taking constant volume fraction and constant angle of orientation.

II. Theoretical Analysis

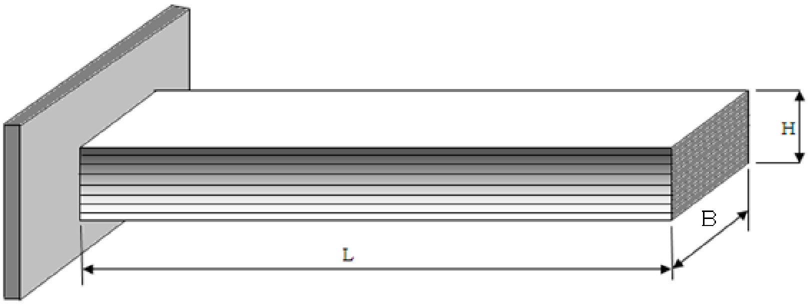
Considering mid –plane symmetry the differential equation of a beam for bending, when there is no bending- stretching coupling and no shear deformation in transverse direction.

$$IS_{11}\frac{d^4\omega}{dx^4} = q(x) \dots\dots\dots\dots..(1)$$

If the beam involves only one layer i.e. isotropic, under the above mentioned conditions.

$$IS_{11} = EI = \frac{Ebh^3}{12} \dots\dots\dots\dots..(2)$$

The Poisson's ratio effects are disregarded for the beam of rectangular cross-section in beam theory.



Length(L)=1000mm, Width(B)= 50mm & Height(H)=25mm
Layer Orientation (0^0,45^0, 60^0,90^0,-45^0,-60^0,-90^0,0^0)

Figure1: Schematic diagram of composite beam of standard dimensions.

The imposed static load is written as force per unit length in "equation1". By applying D' Alembert's principle the inertia force is applied and the "equation 1" becomes

$$IS_{11}\frac{d^4\omega(x,t)}{dx^4} = q(x,t) - \rho F\frac{\partial^2\omega(x,t)}{\partial x^2} \dots\dots\dots\dots..(3)$$

Here ω and q are the functions of time and space and their derivates become partial derivatives ρ is the mass density of the beam material, and F is the cross- sectional area of the beam. The term q(x, t) is spatially varying time-dependent forcing function causing the dynamic response.

For the composite beam of rectangular cross-section having different lamina and different mass densities the above equations are used.

$$\rho F = \rho bh = \sum_{K-1}^{N} \rho b(h_k - h_{K-1}) \dots\dots\dots\dots (4)$$

By the forcing functions the natural frequencies, material properties and geometry of the beam are not affected and therefore the term q(x, t) be zero.

For the mid-plane symmetrical composite beam the natural vibration equation is given as

$$IS_{11}\frac{d^4\omega(x,t)}{dx^4} + \rho F\frac{\partial^2\omega(x,t)}{\partial x^2} = 0 \dots\dots\dots\dots (5)$$

The natural frequency in radians/unit time is prearranged as

$$\omega_n = \alpha^2\sqrt{{IS_{11}}/{\rho F L^4}} \dots\dots\dots\dots (6)$$

Here α^2 is the co- efficient ω_n is the natural frequency in cycles per second (Hertz) is prearranged as

$$f_{n=} {\omega_n}/{2\pi} \dots\dots\dots..(7)$$

In common, the governing equation of the beam for free vibration is expressed as

$$[K] - \omega^2[M]\{q\} = 0 \dots\dots\dots..(8)$$

K= Stiffness matrix, M= Mass matrix and q= degrees of freedom.

III. Modeling And Analysis Of Composite Beam Using ANSYS

Modal analysis of ANSYS is used to determine natural frequencies and mode shapes which are essential parameters in design of a structure for dynamic load conditions. The beam chosen initially is a composite beam of rectangular cross section for the purpose of analysis in two ways. The first one is for the purpose of variation in fiber orientation and the second one is for varying of the dimensions the beam. The two materials considered for compostie beam models are Graphite Fibre-Reinforced Polyamide and E-Glass Fibre-Reinforced Polymer. The orthotropic material properties of the two beams are mentioned in table1.

Table 1: ***Properties Of Compotie Beam Materials***

Graphite Fibre-Reinforced Ployamide	E-Glass Fibre Reinforced Polymer
E_1=129.207 GPa	E_1=57.502 GPa
E_2=E_3= 9.42512 GPa	E_2=E_3= 18.802 GPa
G_{xy} = 5.15658 GPa	G_{xy} = 7.446 GPa
G_{xz}=4.3053 GPa	G_{xz}=7.446 GPa
G_{yz}=2.5414 GPa	G_{yz}=7.239 GPa
ν_{xy}=0.3	ν_{xy}=0.25
ν_{yz}=0.218	ν_{yz}=0.29
ν_{yx}=0.218	ν_{yx}=0.29
ρ=1550.0666 Kg/m3	ρ=1910 Kg/m3

The second model chosen for analysis is a cantilever composite beam of uniform cross-section, having an open transverse crack of depth ‘a’ at position L_1 from fixed end is shown in “Fig.2”.

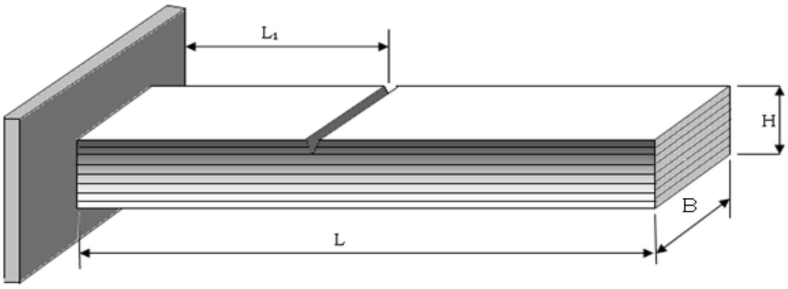


Figure 2: Schematic Diagram of Cantilever Composite Beam with a Transverse Crack.

3.1 Modeling Procedure by ANSYS 13

The ANSYS procedure for any type of problem consist of mainly three stages, namely preprocessing, solution stage and post processing stage. In preprocessing stage the element type, material properties and real constants are specified. In the solution stage the boundary conditions and loads are defined. The ANSYS postprocessor stage provides a powerful tool for viewing results. The flow chart of the ANSYS procedure is represented in “Fig.2”.In the present work “SOLID SHELL190” has been selected. To create layered composites the layer thickness, material, orientation and number of integration points were specified. The beam was then created by using key points and the lines of the beam were obtained by joining these key points. These lines were then joined to obtain area. This area then extruded to get the 3dimensional beam. The boundary conditions were then applied to fix one end of the beam to make it clamped free. Modal analysis was then performed by using Block Lonczos method and the required first three natural frequencies were obtained from general post processor. The same procedure was repeated to obtain the frequencies by changing the dimensions of the composite beams of two materials considered.

The same procedure was adopted for the composite beams with a crack, by modifying the selection of key points in the initial stage to suit the generation of the crack of required dimensions at various locations on the beam.

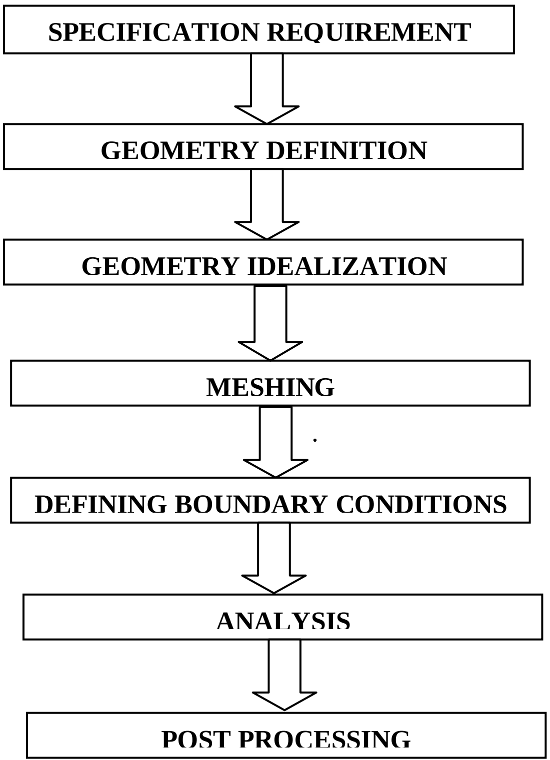


Figure 3: Flow chart representing ANSYS procedure

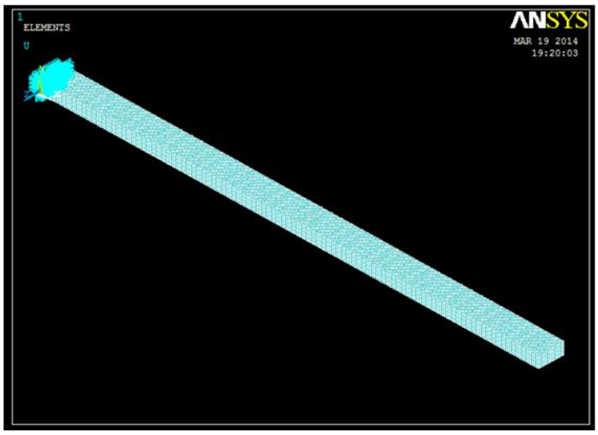


Figure 4: Image of the beam after applying the boundary conditions

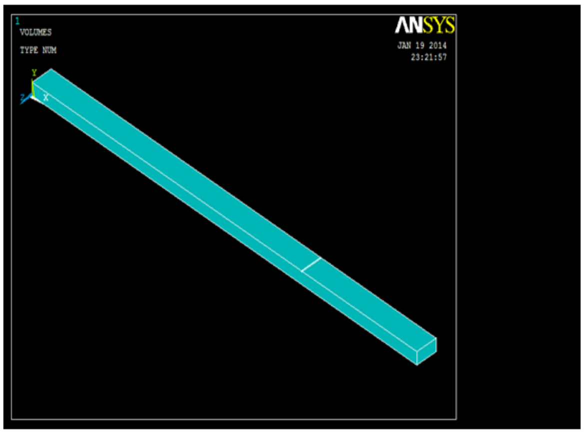


Figure 5: Composite beam with crack in ANSYS

IV. Results And Discussions

Dynamic analysis of composite beams of two different materials of Fibre -reinforced Plastics (FRP) are considered for the purpose of analysis and comparison. One is Graphite Fibre-Reinforced Polyamide and the other one is E-Glass Fibre-Reinforced Polymer. Modal analysis is done using ANSYS13.0 on these beams by generating different models of the beams for the calculation of first three Natural frequencies of the beams. The analysis is carried out for different fibre orientations of the composite beams of same fibre volume fraction of 0.4. Later the analysis is continued by varying the dimensions of the beam in one direction from standard size of the beam (1000mmx50mmx25mm), by keeping the other two constant. This process is done for all three dimensions i.e. for length, width and height of the beam.

In the next step the modal analysis is also carried out for two beams of standard size considered by introducing a transverse crack of certain Crack Depth Ratio (CDR) at a particular Crack Position Ratio (CPR). The process is repeated for different CDRs at various CPRs.When the orientation of the fibres is changed from 0^0 to 90^0 it is observed that the natural frequency decreases with increase in the orientation of the fibres. This is shown in the from “Fig.6”to “Fig.8”. When the fibres are lying along the length of the beam they support maximum share of the load on the beam. Hence the strength of the beam increases, which in turn increases the stiffness of the beam. After 70^0 the change in all these frequencies is unaltered. Therefore it can be concluded that the natural frequencies of a composite beam is a function of angle of fibres.

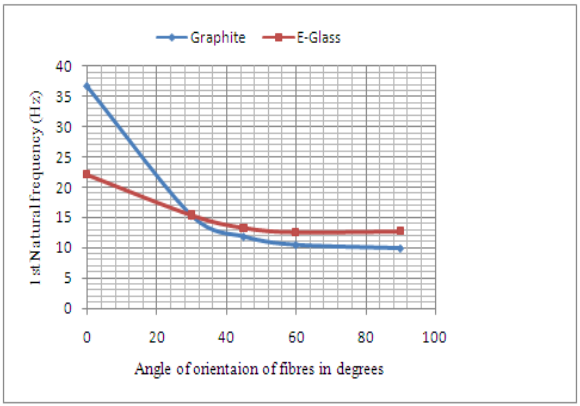


Figure 6: Variation of 1st natural frequency with angle of orientation of fibres

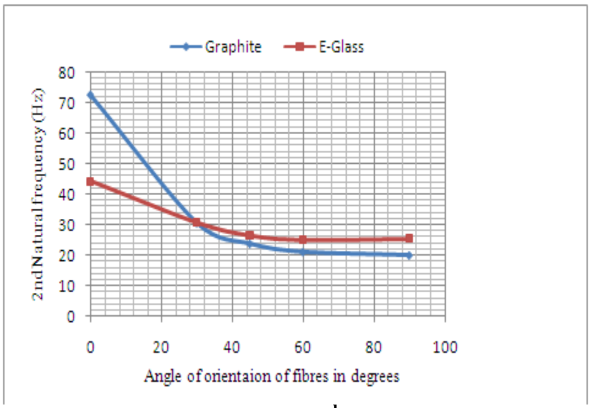


Figure 7: Variation of 2nd natural frequency with angle of orientation of fibres

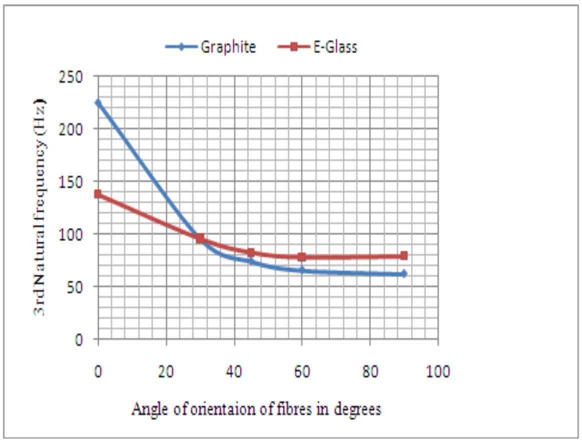


Figure 8: Variation of 3rd natural frequency with angle of orientation of fibres

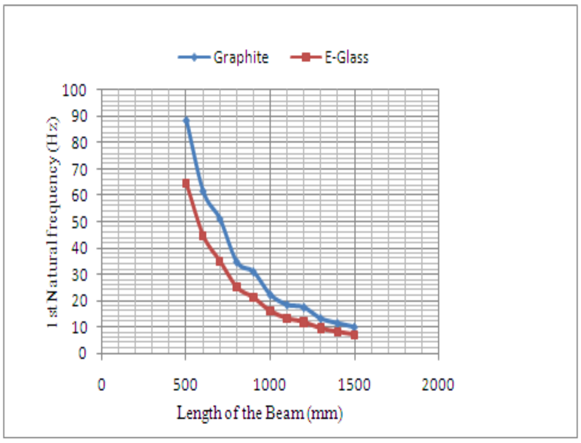


Figure 9: Variation of 1st natural frequency with length of the beam

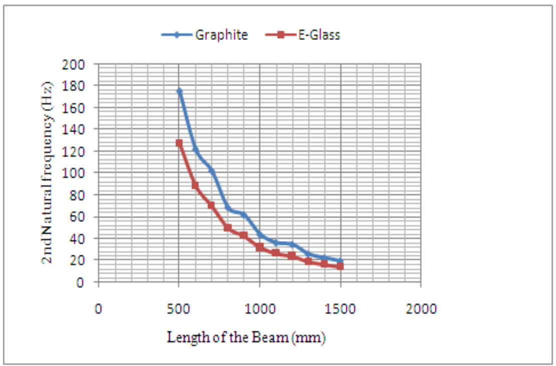


Figure 10: Variation of 2nd natural frequency with length of the beam

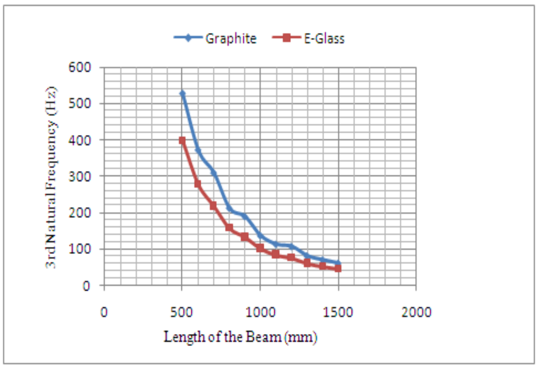


Figure 11: Variation of 3rd natural frequency with length of the beam

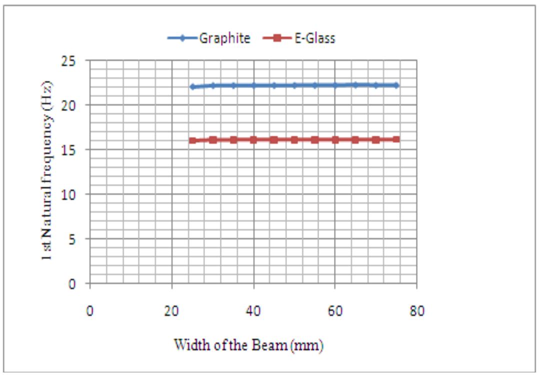


Figure 12: Variation of 1st natural frequency with width of the beam

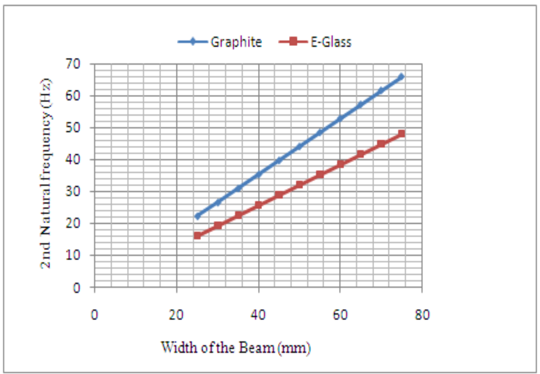


Figure 13: Variation of 2nd natural frequency with width of the beam

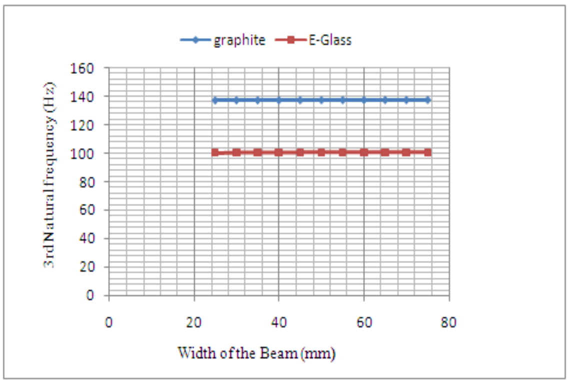


Figure 14: Variation of 3rd natural frequency with width of the beam

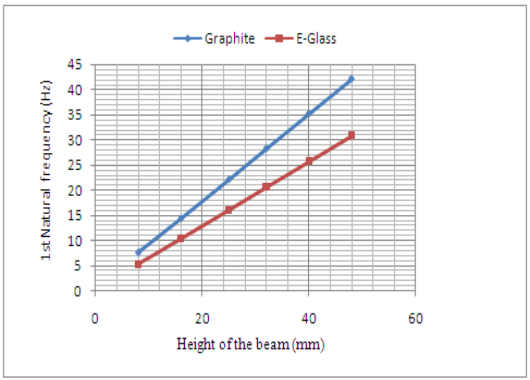


Figure 15: Variation of 1st natural frequency with height of the beam

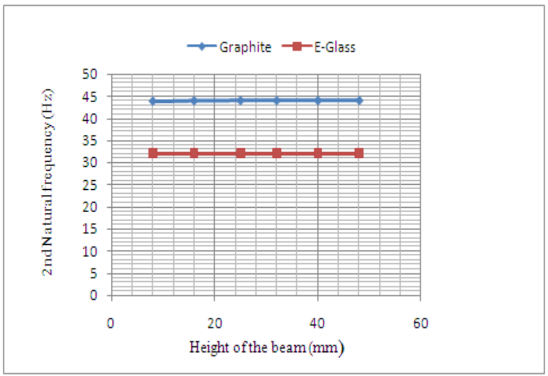


Figure 16: Variation of 2nd natural frequency with height of the beam

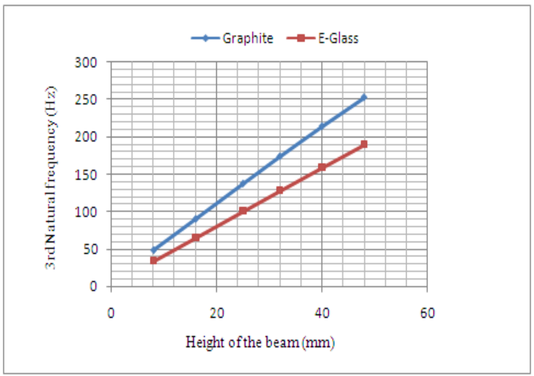


Figure 17: Variation of 3rd natural frequency with height of the beam

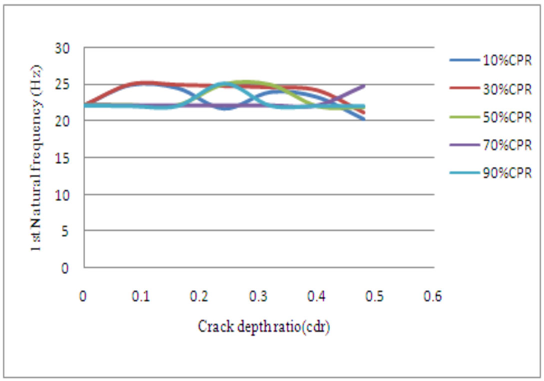


Figure18: CDR Vs 1st natural frequency for various crack positions (graphite)

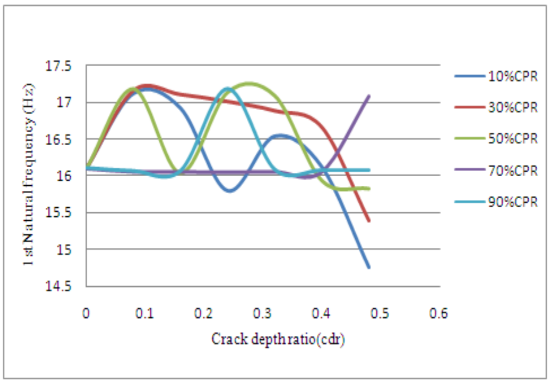


Figure19: CDR Vs 1st natural frequency for various crack positions (E-glass)

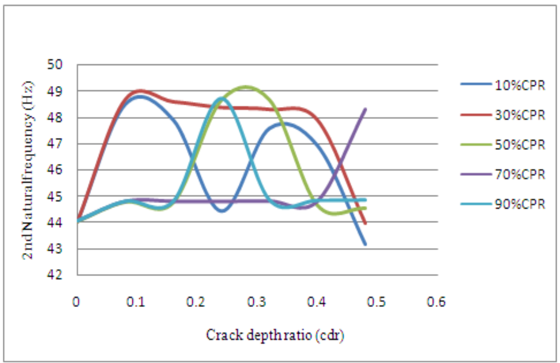


Figure20: CDR Vs 2nd natural frequency for various crack positions (graphite)

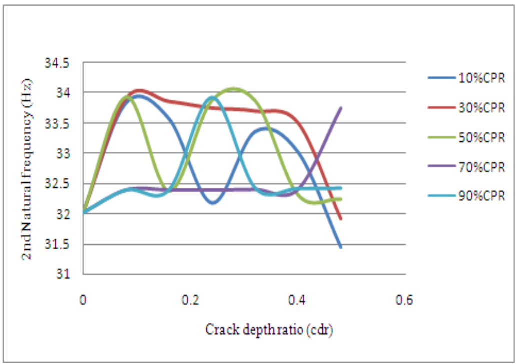


Figure21: CDR Vs 2nd natural frequency for various crack positions (E-glass)

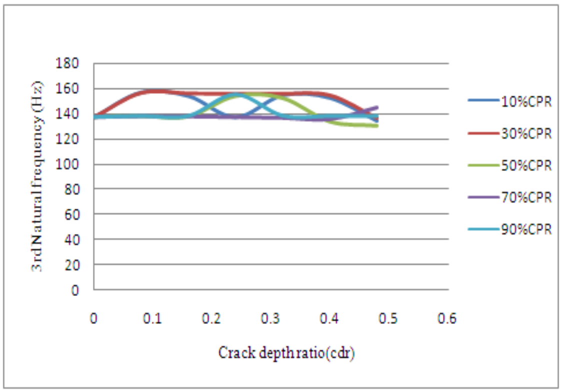


Figure22: CDR Vs 3rd natural frequency for various crack positions (graphite)

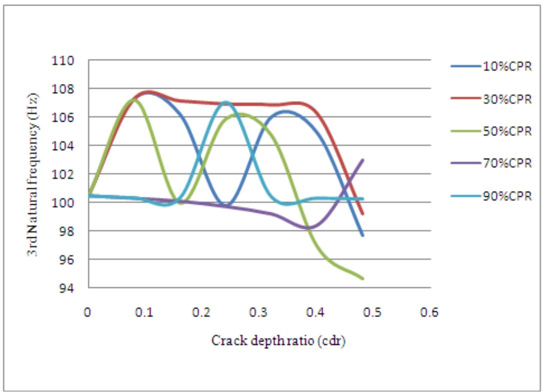


Figure23: CDR Vs 3rd natural frequency for various crack positions (E-glass)

The next analysis is carried out for variation of natural frequencies for length of the beam. It is observed that as the length of the composite beam increases the 1st three natural frequencies decreases. This is because the natural frequency is directly proportional to square root of stiffness of the beam and the stiffness of the beam is inversely proportional to cube of length. These variations are shown form “Fig. 9” to “Fig.11”.

It is observed from the first three natural frequencies obtained, the variation in natural frequency with width of the composite beams shows similar pattern for 1st and 3rd and another same pattern for 2nd natural frequencies. These variations are shown in from “Fig.12” to “Fig14”. The natural frequency is proportional to square root of stiffness of the beam and the stiffness is directly proportional to the width of the beam. The variation of the pattern may be due to different fibre orientation. As the height of the composite beam increases the first three natural frequencies increase. As height increases for constant length and width, the stiffness of the beam increases and in turn results in increase of natural frequency as stiffness is directly proportional to the cube of the height of the beam. In the second natural frequency this variation is not that much significant and fibre orientation may be one of the reasons.

There is no significant change in variation of the natural frequencies for intact and cracked beam when the crack depth ratio (CDR) is small. In general for a beam of uniform cross section of same material as the crack depth increases the natural frequency decreases and as the position of crack of constant depth shifts from fixed to free end the natural frequency increases. But in composite beams considered here interestingly a variety of pattern is observed. In both Graphite Fibre-Reinforced Polyamide and E-Glass Fibre-Reinforced Polymer beams when the crack is located nearer to clamped end (at 30% CPR) and when the position of crack is at free end (at 70% CPR), the patterns obtained are similar i.e. the frequencies decrease with increase in depth of crack and when the CDR crosses 0.4 they exhibit opposite nature with same type of variation. When the crack is located very nearer to clamped end (at 10% CPR), in the mid way of the beams (at 50%CPR) and at the end of the beam (at 90% CPR) the variation of natural frequencies with crack positions follows a wavy nature depending upon its depth. These variations are shown from the “Fig.18” to “Fig.23”. The pattern obtained follows a systematic way for each position of the crack. This may be due to variation in the flexibility of the beam. The non-uniformity of material of the beam and the different orientation of the fibres may cause another reason. These variations can be used to identify the presence of cracks in composite beams. This can be applied to various composite beams of various fibre volumes fractions with various fibre orientations.

V. Conclusions

The following conclusions can be drawn from the present investigations of the composite beam having transverse open crack. The in-plane bending frequencies decrease, in general, as the fiber angle increases; the maximum frequency occurs at $\alpha = 0°$and decrease gradually with increasing the fibre angle up to a minimum value obtained for $\alpha = 90°$. It is found that all the first three natural frequencies of composite beams of the two materials decrease as the length of the beam increases. It is observed from the first three natural frequencies obtained, the variation in natural frequency with width of the composite beams shows similar pattern for 1st and 3rd and another same pattern for 2nd natural frequency and the variation is linear.

It is also found that the height of the composite beam increases the first three natural frequencies increases. The effect of cracks is more pronounced near the fixed end than at far free end. It is concluded that the first three natural frequencies are most affected when the crack is located nearer to the fixed end, the middle of the beam and the free end, respectively.

The analysis can be used to identify the presence of cracks in various composite beams by analyzing the first three frequency patterns of intact and cracked composite beams.

The analysis can be carried out for different volume fractions of fibres and different boundary conditions of composite beams. The mode shapes can be extracted and the analysis of the mode shapes can be used to locate the intensity of depth and location of the crack. Various other types of analysis can be carried out using MATLAB. The vibration results obtained using ANSYS 13 can be verified by conducting experiments on composite beams using FFT analyzer for various boundary conditions.

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