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Damage Detection and Severity Assessment of Composite Rotor Blade Materials using Modal Analysis for SHM

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Abstract: Structural damage detection has gained increasing attention from scientific community since unpredicted major hazards mostly human losses have been reported. Vibration based damage identification has gained a lot of importance in recent years with increasing applications of composite structures in many areas of engineering. Since the modal parameters are related to the physical properties of laminates, changes can be detected when damage occurs in these structures. There have been several studies dealing with detection of damage through modal parameters, especially frequencies and mode shapes. However, not many of them deal with laminated composites. The present work involves damage detection by variation of natural frequency and mode shapes of undamaged and damaged laminated composite cantilever beam (representing static composite rotor blade) using numerical modal analysis. Initially FEA results validation (Static and Modal Analysis) is done with the experimental results of literature "Experimental analysis of thin walled composite rotor blade model from structural health monitoring aspect by Pradip D.Haridasa, Dr. Prashant M. Pawarb", (2017) which focused on the experimental study to obtain natural frequencies at different modes for undamaged and damaged model and their effects on the behavior of a composite rotor blade system. This validated FE modeling is further considered for several damage cases for defining methods to obtain the existence, location and severity of damage. For damage detection (existence of damage), percentage change in natural frequency is considered. For damage location, damage algorithm "curvature mode shape method" is considered. Since deviation in mode shape is insignificant, damage algorithm is used to locate damage. The curvature values are computed from displacement mode shapes obtained from modal analysis. These curvature values are used in the damage algorithm for damage location identification. For damage severity along the model based on damage location, the percentage changes in natural frequencies based on damage locations are compared. This work also involves damage severity assessment based on damage location for different laminated composite materials used in composite wind turbine blades (E-glass/Epoxy, S-glass/Epoxy, Kevlar49/Epoxy, Boron/Epoxy). This is done to obtain the suitable laminated composite material for composite wind turbine blades, which has minimum effect on physical properties due to damage.
Keywords: FEA, composite, laminates, vibration, damage

I. INTRODUCTION

A composite is a structural material that consists of two or more constituents combined at macroscopic level and is not soluble in each other. One constituent is called reinforcing phase (fibers, particles or flakes) and the one in which it is embedded is called matrix (continuous). Examples of composite: Concrete reinforced steel, graphite fibers in epoxy. Advantages of composite: Light in weight, corrosion resistance, flexible, dent resistant, etc. The monitoring and identification of damage in a structure at an early stage is very essential in several engineering applications. Structures are required to work safely during their service life. The common structural defect is the presence of damage in a structure. There is generally loss of local stiffness due to damage which alters the mechanical behavior of the structure. Damages may be due to fatigue under service conditions or initiated in very small size during manufacturing process. Unpredictable occurrence of damage may cause catastrophic failure. Structural damage results in unintentional dynamic response of the structure. Example: Crack in composite wind turbine rotor blade, crack in composite helicopter rotor blade. Therefore, damage detection techniques for Structural Health Monitoring become very important. The experimental methods for damage detection require visibility of the damage and easily accessibility during inspection of the structure. Due to these limitations in the experimental procedures, damage detection is possible only on surface or near structural surface. So, there is a need for damage identification methods which can be used for complex structures for the identification of vibration characteristics changes which are indicative of such damage. Structural damage detection of structural engineering has three main parts i.e. finding the existence, location and severity of damage. It is highly desirable to obtain effective damage detection methods (SHM) for structural failures, to detect, locate and quantify the damage situation at the earliest possible stage. Since the modal parameters (natural frequencies, mode shapes and modal damping) are related to the physical properties (stiffness, mass and damping) of laminates, changes in the modal parameters can be used to detect damage in the structures. Though several studies on cracks in composite laminates have been undertaken using fracture mechanics, use of modal analysis for damage detection has been very limited.

V. B. Dawari1 and G. R. Vesmawala [2] focused on modal curvature difference method which was employed for identifying and locating damage in beam models. Damage is considered as a localized reduction in structural stiffness. From the numerical simulations, it was observed that the absolute changes in modal curvature are localized in the region of damage and hence can be used to detect damage in a structure. This method was found successful for detecting and locating the damage in the beam models with different boundary conditions.

Ramanamurthy E.V.V and Chandrasekaran K [3] focused on changes in natural frequency and damage detection algorithms such as curvature mode shape method based damage detection for single edge crack cantilever beam. The crack was a through thickness one, growing along the breadth of the beam starting from one edge. The location of the crack was also moved from the fixed end to free end along its length.

O. S. Salawu [4] focused on the use of natural frequency as a diagnostic parameter in structural assessment procedures using vibration monitoring. The approach was based on the fact that natural frequencies are sensitive indicators of structural integrity. Thus, an analysis of periodical frequency measurements can be used to monitor structural condition.

A. K. Pandey, M. Biswas and M. M. Samman [5] provides the detail explanation of curvature mode shape method for damage detection using a cantilever and a simply supported analytical beam model.

Though many of the earlier works are related to the detection of damages in structures through non-destructive evaluation procedures, they have concentrated mainly on homogeneous materials and have dealt with one or two specific methods. Extensions of such studies to heterogeneous composite structures have not been many and few works on composites have again focused attention on one or two specific methods. Evaluation of the efficiencies of various damage detection techniques towards arriving at most optimal one for SHM and using this optimal technique to identify safe composite material (least affected by damage) for practical applications such as composite rotor blades (wind turbine rotor blade, helicopter rotor blade) is a gap need to be filled. The present work involves damage detection by variation of natural frequency and mode shapes of undamaged and damaged laminated composite cantilever beam (representing static composite rotor blade) using numerical modal analysis. Initially FEA results validation (Static and Modal Analysis) is done with the experimental results of literature 'Experimental analysis of thin walled composite rotor blade model from structural health monitoring aspect by Pradip D.Haridasa, Dr. Prashant M. Pawarb', (2017) [1] which focused on the experimental study to obtain natural frequencies at different modes for undamaged and damaged model and their effects on the behavior of a composite rotor blade system. This validated FE modeling is further considered for several damage cases for defining methods to obtain the existence, location and severity of damage. For damage detection (existence of damage), percentage change in natural frequency is considered. For damage location, damage algorithm 'curvature mode shape method is considered. Since deviation in mode shape is insignificant, damage algorithm is used to locate damage. The curvature values are computed from displacement mode shapes obtained from modal analysis. These curvature values are used in the damage algorithm for damage location identification. For damage severity along the model based on damage location, the percentage changes in natural frequencies based on damage locations are compared. This work also involves damage severity assessment based on damage location for different laminated composite materials used in composite wind turbine blades (E-glass/Epoxy, S-glass/Epoxy, Kevlar49/Epoxy, Boron/Epoxy). This is done to obtain the suitable laminated composite material for composite wind turbine blades, which has minimum effect on physical properties due to damage and also to assess the materials which has maximum effect due to damage.

II. FE MODEL VALIDATION

A. Overview

This work involves Finite Element Analysis for composite rotor blade for several damage cases for defining methods to obtain the existence, location, severity of damage and also damage severity assessment based on damage location for different laminated composite materials. Initially FEA results validation is done with the experimental results to ensure the accuracy of the FE model of composite rotor blade considered for further study with respect to the actual model used for experimentation, so that the results of studies through FEA represent the results from actual model. The reason for considering FEA over experimentation for further studies is because of its advantage of being less time consuming for performing several iterations compared to time taken for performing experiments.

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B. Details of FE Modeling

For performing FE model validation, both static and modal analysis are performed in ANSYS to validate the deflection and natural frequencies with that of experimental values. The FE model represents carbon epoxy composite rotor blade with 0^o and 90^o plies as considered for the experiment. This is done using SHELL181 element type. The lay-up sequence of the rotor blade is [0-0-90-0-0-90-0-0] (symmetric laminate) having 8 layers geometry with Carbon Fiber Unidirectional Fabric-6 KUD Fabric-360 GSM material properties. The dimensions of the rotor blade are:-

Length = L = 800mm = 0.8m;   Width = W = 57mm = 0.057m; Thickness = T = 4mm = 0.004m

Fig 2.1(a)

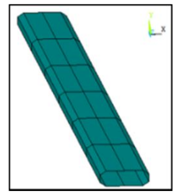


Fig 2.1(b)

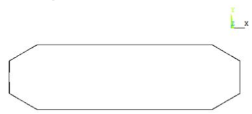


Fig 2.1(c)

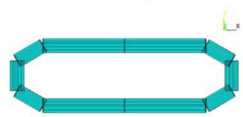
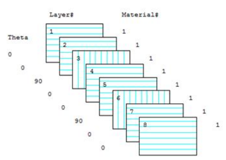


Fig 2.1(d)

Fig 2.1(a) Composite Rotor blade FE model using SHELL181; Fig 2.1(b) FE model mesh;   Fig 2.1(c) Cross-section of FE model; Fig 2.1(d) Cross-section of FE model with /eshape,1,



```
ANSYS 14.5
LAYER STACKING
ELEM    =   0
SECT    =   1
LAYERS :
TOTAL   =   8
SHOWN  :
FROM   1 TO   8
```

```
LIST SECTION ID SETS      1 TO      1 BY      1

 SECTION ID NUMBER:          1
 SHELL SECTION TYPE:
 SHELL SECTION NAME IS:
 SHELL SECTION DATA SUMMARY:
  Number of Layers     =    8
  Total Thickness      =    0.004000
```

Layer	Thickness	Mat ID	Ori. Angle	Num Intg. Pts
1	0.0005	1	0.0000	3
2	0.0005	1	0.0000	3
3	0.0005	1	90.0000	3
4	0.0005	1	0.0000	3
5	0.0005	1	0.0000	3
6	0.0005	1	90.0000	3
7	0.0005	1	0.0000	3
8	0.0005	1	0.0000	3

Shell Section is offset to MID surface of Shell

Fig 2.2 Composite rotor blade FE model lay up[0-0-90-0-0-90-0-0]

Table 2.1 Carbon epoxy rotor blade FE model material properties

LIST MATERIALS 1 TO 1 BY 1
PROPERTY= ALL

MATERIAL NUMBER 1

TEMP	EX	0.1350000E+12
TEMP	EY	0.1000000E+11
TEMP	EZ	0.1000000E+11
TEMP	NUXY	0.1925926E-01
TEMP	NUYZ	0.2600000
TEMP	NUXZ	0.1925926E-01
TEMP	GXY	0.5000000E+10
TEMP	GYZ	0.5000000E+10
TEMP	GXZ	0.5000000E+10
TEMP	DENS	1600.000
TEMP	PRXY	0.2600000
TEMP	PRYZ	0.2600000
TEMP	PRXZ	0.2600000

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C. Static Analysis

Static analysis was performed to validate the deflection values with experimental values for all load cases as done in experiment. This is done to match the mass (m) and stiffness (k) of the FE model to ensure that it represents the actual experimental model accurately. The accurate FE model for composite rotor blade is obtained by following iterations:-

1) Mass matching is done by scaling the density. Since the FE model is obtained by shell modeling and thickness assignment through real constant, there will be unavoidable small difference in the final volume achieved when compared to the actual model. So, in order to achieve accurate mass for the FE model, density is scaled by factor (m1/m2) assuming constant volume.
2) Stiffness matching is done by changing the mesh density. Fine mesh increases the stiffness of the FE model leading to low deflection. Similarly, coarse mesh decreases the stiffness leading to higher deflection. So, in order to achieve accurate stiffness for the FE model several iterations were performed by varying the mesh density till the model with accurate deflection was achieved.

After several iterations by varying the mesh density and density scaling following accurate FE model is achieved. Deflections graph for Experimental Vs FEM values for all the UDL cases are obtained with average percentage difference of 6.15 which is acceptable since percentage difference is within 10 to 15.

Fig 2.3(a)

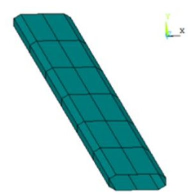


Fig 2.3(b)

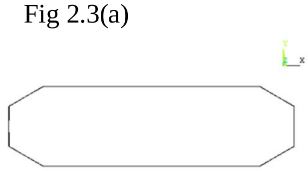


Fig 2.3(c)

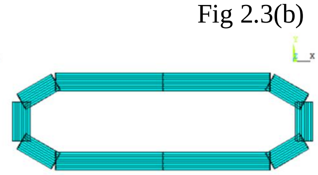


Fig 2.3(d)

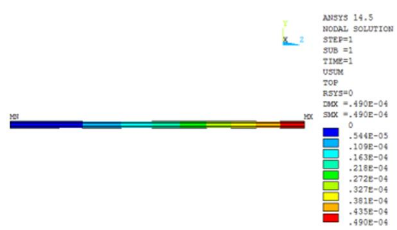
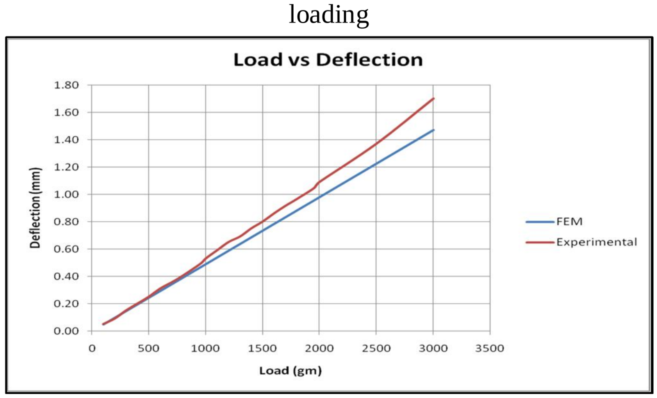


Fig 2.3(e)

Fig 2.3(a) FE model of undamaged composite rotor blade with UDL; Fig 2.3(b) FE model mesh; Fig 2.3(c) Cross-section of FE model; Fig 2.3(d) Cross-section of FE model with /eshape,1, Fig 2.3(e) Result of deflection analysis for 100gm UDL loading



Graph 2.1 Deflection graph for Experimental Vs FEA values

D. Modal Analysis

Modal analysis was performed to validate the natural frequency values with experimental values. Since natural frequency depends only on the stiffness and mass of the model, FE model with accurate mass and stiffness was achieved by the above static analysis (deflection analysis). Following is the FE model considered for undamaged condition and damaged condition of rotor blade.

1) *Natural Frequency of Rotor Blade in Undamaged Condition:* In this the natural frequency obtained by modal analysis is compared with the experimental values for the undamaged rotor blade FE model which was validated in static analysis (deflection analysis).

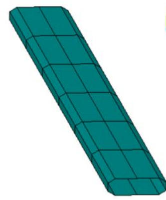
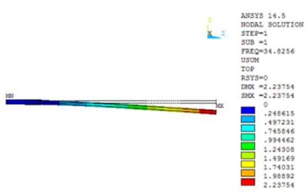


Fig 2.4(a)

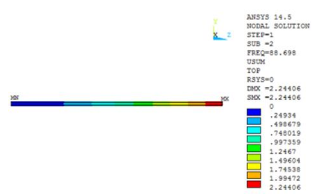
Fig 2.4(b)

Fig 2.4(c)

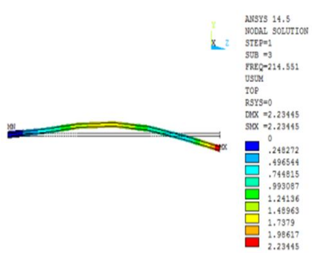
Fig 2.4(a) FE model mesh; Fig 2.4(b) Cross-section of FE model; Fig 2.4(c) Cross-section of FE model with /eshape,1,



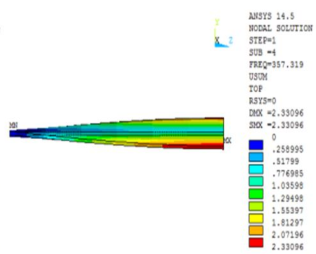
Mode 1



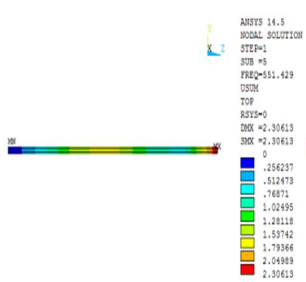
Mode 2



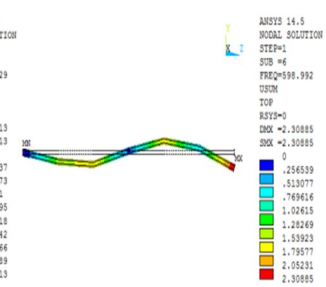
Mode 3



Mode 4

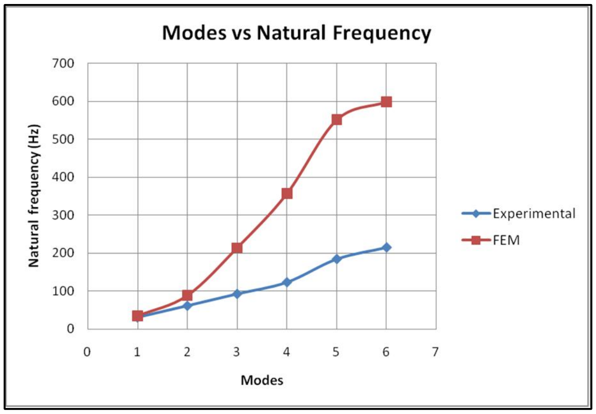


Mode 5



Mode 6

Fig 2.4(d) Resultant mode shapes of modal analysis



Graph 2.2 Natural frequency graph for Experimental Vs FEA values (Undamaged condition)

From the above graph it can be observed that 13.72% difference of natural frequency is obtained for 1st mode between experimental (30.625Hz) and modal analysis (34.826Hz). But at higher modes, the percentage difference of frequency increases. This is because of lack of measured DOFs compared with respect to the FE model. This difference is considerable at higher modes since they reflect local responses of the system, thus the number of measurement points play an important role for the accuracy of the estimation. Since in this experiment only one measurement point is considered that is at the tip of the rotor blade for all the modes (1 to 6), the natural frequency only for the 1st bending mode is most accurate. If the number of measurement points increases, the accuracy of natural frequency at higher modes increases.

Thus, the natural frequency for the 1st mode is most accurate and at higher mode shapes the percentage difference of natural frequency increases. This justifies the accuracy of the FE modeling.

2) *Natural Frequency of Rotor Blade in Damaged Condition:* In this the behavior (trend) of the natural frequency obtained by modal analysis is compared with the behavior of experimental values for the damaged rotor blade. In order to perform this validation, cracks are modeled in the FE model at root, mid and tip as done in the experiment. Since cracks are considered in the FE model, it leads to change in the mesh density thus leading to change in the stiffness of the FE model. So in order to validate the accuracy of the FE model with damage, only the behavior (or trend) of the natural frequencies are compared between experimental and FEA. Here both undamaged and damaged FE models are considered with similar mesh in order to compare the change in behavior of the model due to presence of damage using the previously validated FE model.

The mesh density of FE models (undamaged and damaged condition) considered for the validation is shown below with crack dimensions of length 0.05m, width 0.005m and depth 0.004mm as per the experimental model.

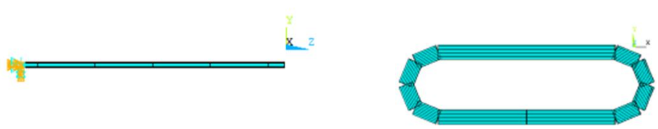


Fig 2.5(a)

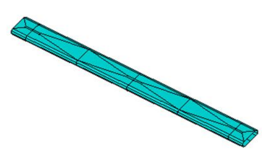
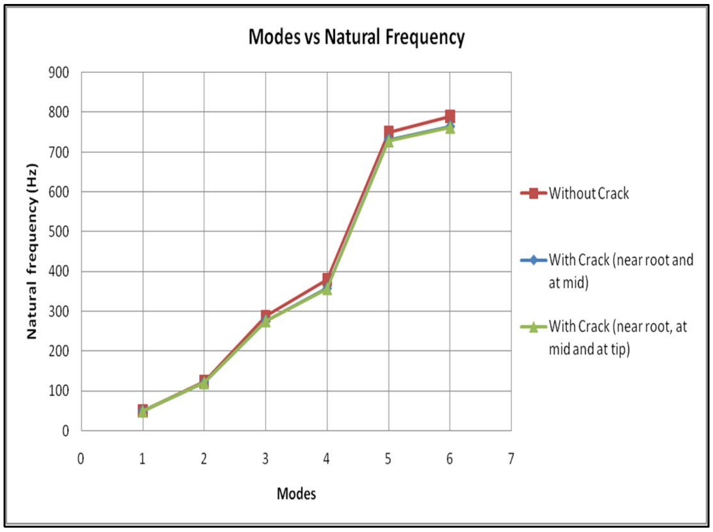
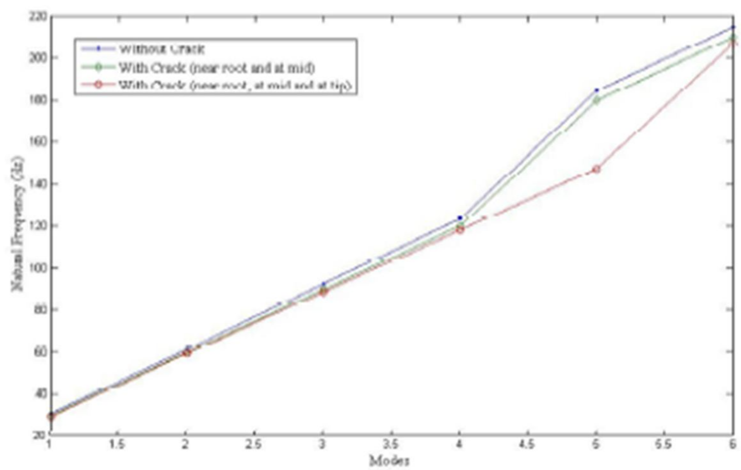


Fig 2.5(b) Fig 2.5(c)

Fig 2.5(a) FE model mesh of damaged composite rotor blade; Fig 2.5(b) Cross-section of FE model; Fig 2.5 (c) Cross-section of FE model with /eshape,1



Graph 2.3(a) Natural frequency FEA values for undamaged and damaged condition



Graph 2.3(b) Natural frequency Experimental values (Courtesy: [1])

Thus, from the above graphs it can be observed that FEA and experimental natural frequency values follow similar behavior (trend).

III. DAMAGE DETECTION AND DAMAGE SEVERITY BY MODAL ANALYSIS

As the accuracy of the FE model is validated by above experimental and FEA correlation, the FE model with mesh as shown in Fig 2.5 will be considered for further studies. This validated FE modeling is considered for modal analysis of several damage cases for defining method to obtain the existence of damage and damage severity depending on damage location. Following cases are considered for FEA:-

1) Undamaged condition
2) Damaged condition with crack at different locations
a) Root (crack center location at length = 0.05m)
b) Mid (crack center location at length = 0.4m)
c) Tip (crack center location at length = 0.75m)
d) Root and Mid
e) Mid and Tip
f) Root and Tip
g) Root, Mid and Tip

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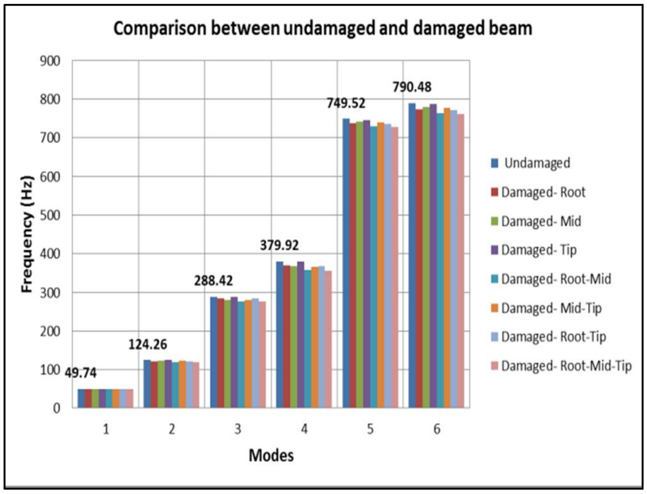
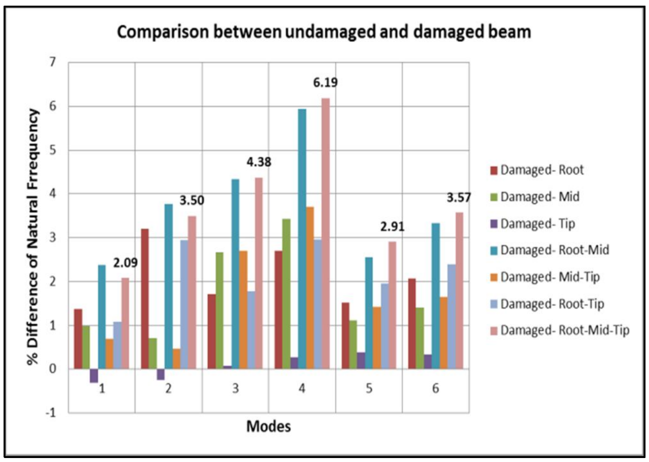
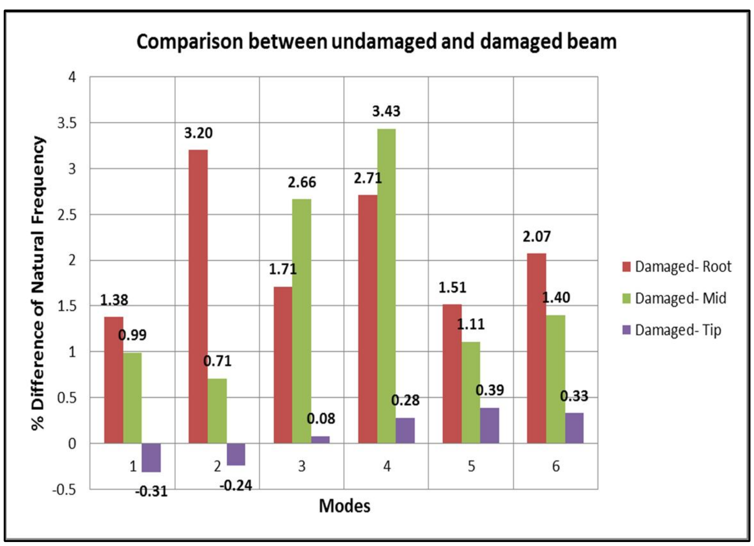
After performing modal analysis for all the above cases, following graphs are plotted to compare the effect of damage.



Graph 3.1 Natural frequency Vs Modes (for all damaged and undamaged cases)



Graph 3.2(a) Comparison for all the undamaged and damaged cases



Graph 3.2(b) Comparison for all the single location damaged cases

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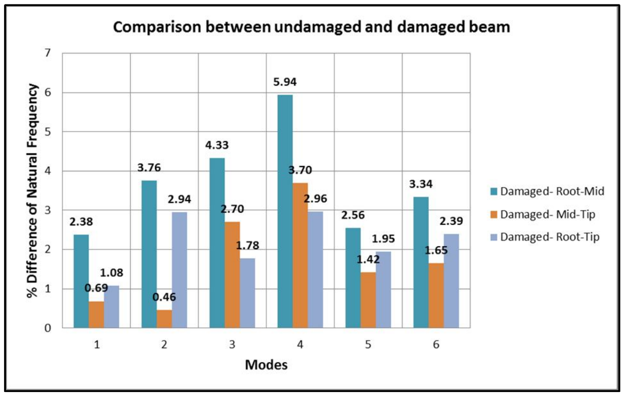
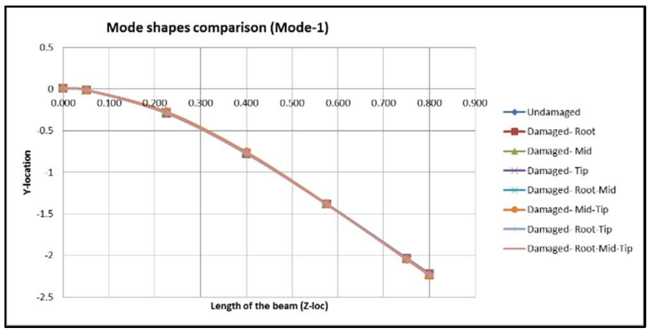
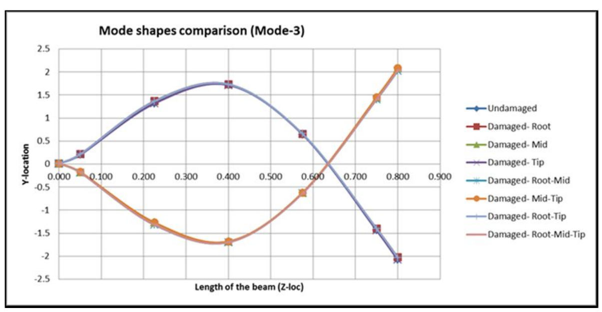


Graph 3.2(c) Comparison for all the double location damage cases

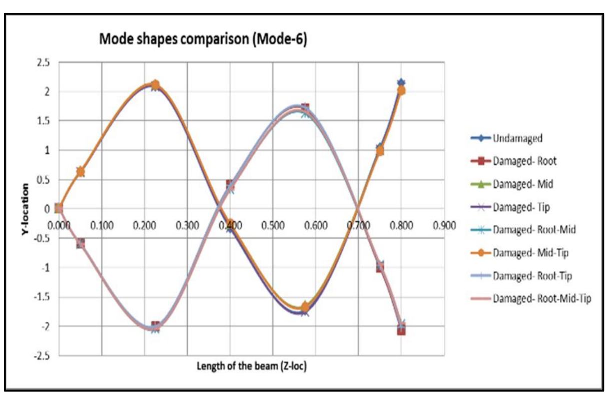
Graph 3.2(a-c) Percentage Difference in Natural frequency Vs Mode (for all damaged cases with respect to undamaged condition)



Graph 3.3(a) Mode-1



Graph 3.3(b) Mode-3



Graph 3.3(c) Mode-6

Graph 3.3(a-c) Displacement mode shapes of bending modes-1, 3 and 6 (for all damaged and undamaged cases)

From the above graphs it was observed that the best method to obtain the existence of damage and damage severity depending on damage location is by percentage difference in frequency of damaged condition with respect to undamaged condition.

Following are the observations obtained from percentage difference in natural frequency Vs modes graphs:-

i) Frequency reduces for damage cases due to reduction in stiffness which gives information about existence of crack

ii) Severity of damage is maximum for maximum number of cracks i.e. at root, mid & tip with maximum percentage difference in natural frequency of 4.38% at mode-3, 6.19% at mode-4, 2.91% at mode-5 and 3.57% at mode-6

iii) Among damage cases for cracks at two locations (i.e. root & mid, mid & tip, root & tip), maximum severity is due to crack at root & mid with maximum percentage difference in natural frequency of 2.38% at mode-1, 3.76% at mode-2, 4.33% at mode-3, 5.94% at mode-4, 2.56% at mode-5 and 3.34% at mode6

iv) Among damage cases for crack at one location (i.e. root, mid, tip), minimum severity is due to crack at tip with minimum percentage difference of natural frequency of 0.08% at mode-3, 0.28% at mode-4, 0.39% at mode-5 and 0.33% at mode-6

IV. DAMAGE LOCATION DETECTION BY MODAL ANALYSIS

The detection of location of damage is based on mode shapes. Since the variation of the displacement mode shapes for damaged cases with respect to undamaged case is not very significant, the changes in the curvature mode shape are comparatively localized in the region of damage. The difference in the curvature mode shapes between the undamaged and damaged case can be used to detect the location of the crack.

Curvature mode shapes are related to the flexural stiffness of beam cross-sections. Curvature at a point is given by

$u'' = M/(EI)$ (4.1)

Where u” is the curvature at a section, M is the bending moment at a section, E is the modulus of elasticity and I is the second moment of the cross-sectional area.

If a crack or other damage is introduced in a structure, it reduces the (EI) of the structure at the cracked section or in the damaged region, which increases the magnitude of curvature at that section of the structure. The changes in the curvature are local in nature and hence can be used to detect and locate a crack or damage in the structure. The change in curvature increases with reduction in the value of (EI), and therefore, the amount of damage can be obtained from the magnitude of change in curvature.

From the displacement mode shapes, obtained from the modal analysis using the FE model as shown in Graph 3.3(a-c), curvature mode shapes were obtained numerically by using a central difference approximation as

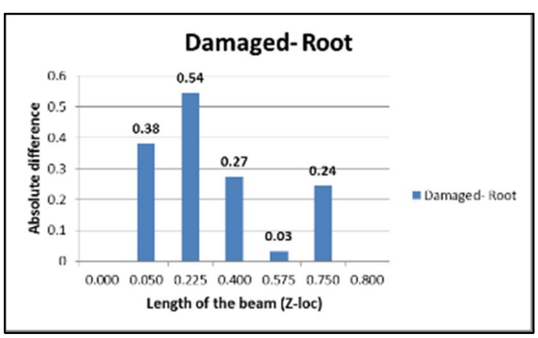
$$\boldsymbol{v_i'' = (v_{i+1} - 2v_i + v_{i-1})/h^2} \quad (4.2)$$

Where ‘h’ is the length of the elements for equal elemental length and ‘i’ is the node. In this study since the FE model has elements of unequal length, ‘h’ is considered as average length of the elements. Here only the translation degree of freedom along the Y axis was considered. This was done because, in any experimental work, in general, rotations are not measured because of difficulty in their measurement. Then the absolute difference in the curvature mode shapes between the undamaged and damaged case is used to detect the location of the crack.

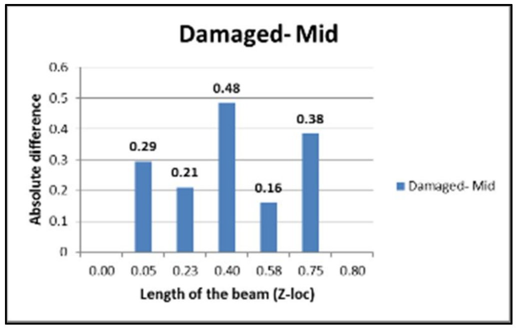
$$\boldsymbol{\Delta v_i'' = \left| v_{ud,i}'' - v_{d,i}'' \right|} \quad (5.3)$$

Where $\boldsymbol{v_{ud,i}''}$ is the curvature mode shape for undamaged condition at node i and $\boldsymbol{v_{d,i}''}$ is the curvature mode shape for damaged condition at node i.

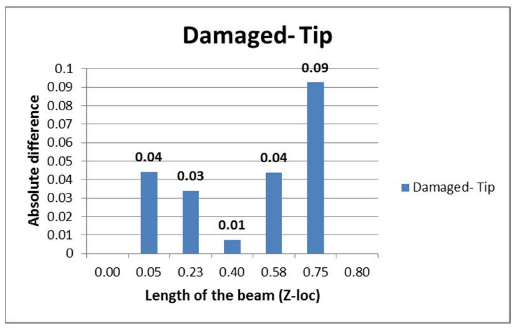
Since here the displacement mode shapes have similar trend only for 1st mode for the undamaged and damaged cases and also at high modes we may get misleading values, damage location detection using curvature mode shape method is applied to only 1st mode as shown below.



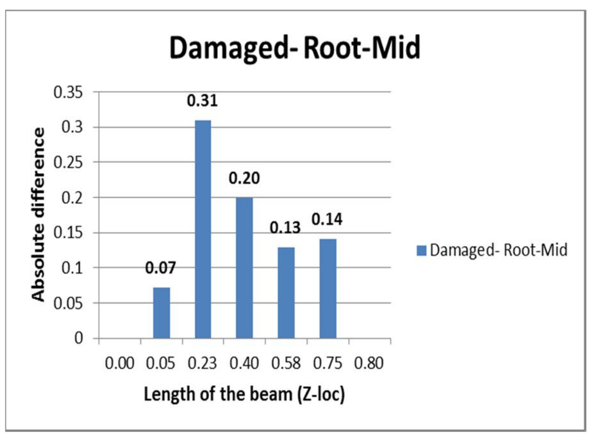
Graph 4.1(a)



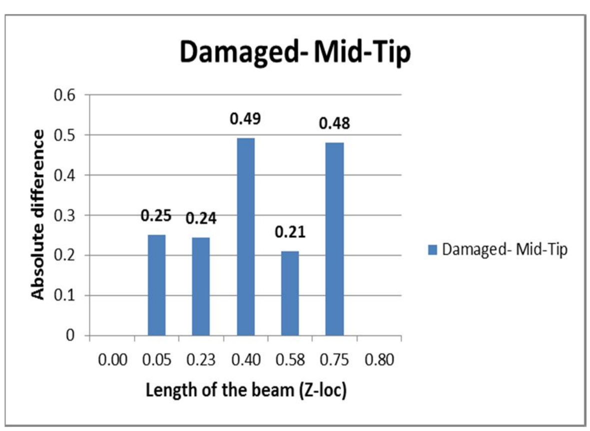
Graph 4.1(b)



Graph 4.1(c)



Graph 4.1(d)



Graph 4.1(e)

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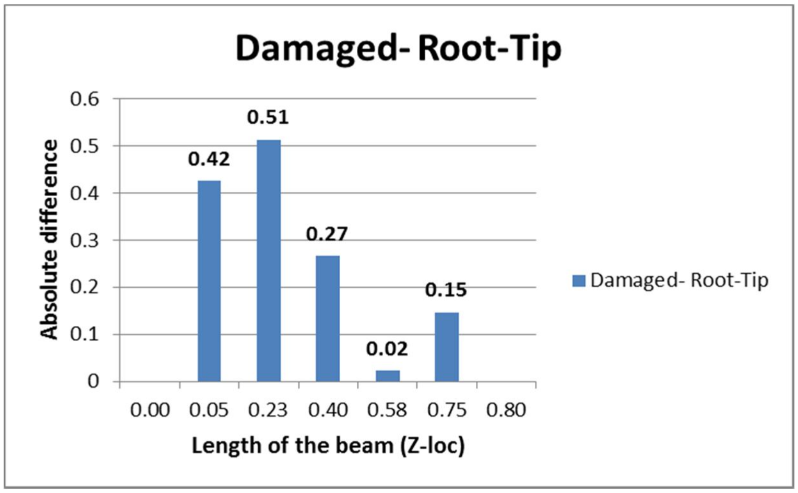
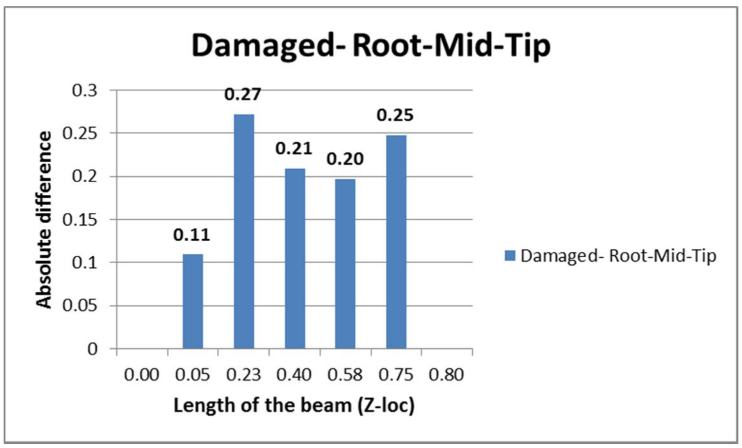


Graph 4.1(f)



Graph 4.1(g)

Graph 4.1(a-g) Absolute difference (damage indicator) of Curvature mode shape Vs Length of the beam for all the damage cases w.r.t undamaged case

From the above graphs it can be observed that this method is most effective to detect damage location for damage cases with single crack in the model with maximum absolute difference of 0.54 for damage at root, 0.48 for damage at mid and 0.09 for damage at tip.

V. DAMAGE LOCATION SEVERITY ASSESSMENT FOR LAMINATED COMPOSITE MATERIALS USED FOR WIND TURBINE BLADES

This work also focuses on determining the suitable laminated composite material for composite wind turbine blades, which has minimum and maximum effect on physical properties due to damage. So, the work also involves damage severity assessment based on damage location for different laminated composite materials used in composite wind turbine blades (Carbon/Epoxy, E-glass/Epoxy, S-glass/Epoxy, Kevlar49/Epoxy, Boron/Epoxy). The lay-up sequence of the blade considered for all the above laminated composite materials is [0-0-90-0-0-90-0-0] (symmetric laminate) having 8 layers geometry as considered for the experimental model.

A. Static Analysis

After calculating the engineering constants, static analysis or deflection analysis is performed for all the load cases for different laminated composites materials used for wind turbine blades (for undamaged FE model used in above static analysis for Carbon/Epoxy composite) and compared the deflections. This is done to assess the stiffness variation of laminated composite rotor blades made up of different materials. Following is the deflection comparison obtained from deflection analysis:-

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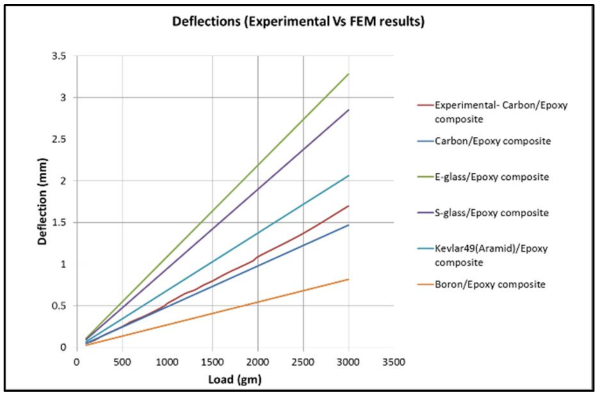


Graph 5.1 Deflection Vs Load for different laminated composite materials

Following are the observations obtained from deflection Vs load graph:-

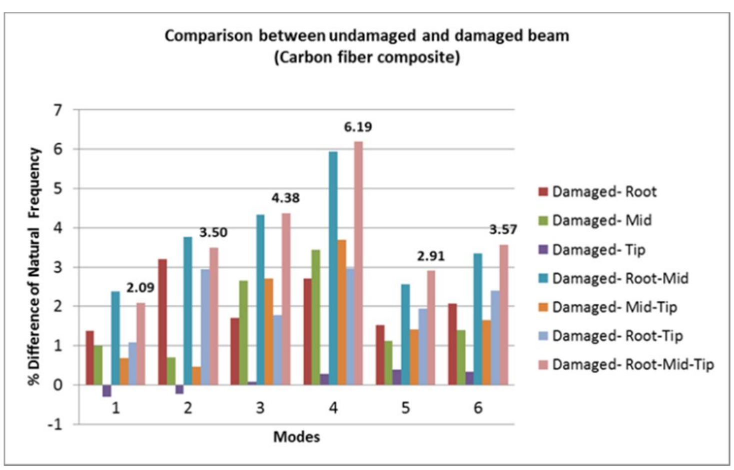
1) Since lesser the deflection higher the stiffness and vice-versa, Boron/Epoxy composite has the maximum stiffness of 35975.39N/m and E-glass/Epoxy composite has the minimum stiffness of 8960.94N/m (Stiffness= Load in Newton / Deflection in Meters)
2) Following are the composite materials arranged according to the descending order of their stiffness values
a) Boron/Epoxy (Stiffness = 35975.39N/m)
b) Carbon/Epoxy (Stiffness = 20023.73N/m)
c) Kevlar-49/Epoxy (Stiffness = 14269.40N/m)
d) S-glass/Epoxy (Stiffness = 10322.31N/m)
e) E-glass/Epoxy (Stiffness = 8960.94N/m)

B. *Modal Analysis*

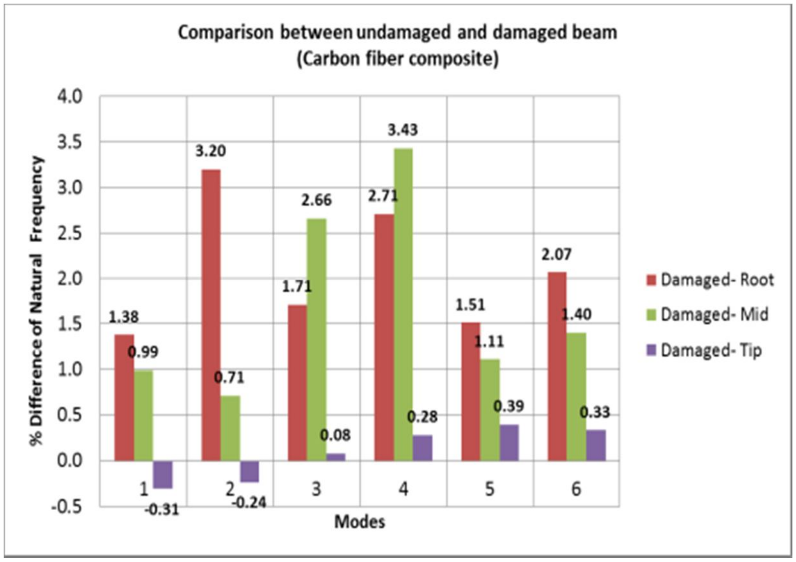
In order to assess the severity of damage based on damage location for different laminated composite materials used in composite wind turbine blades (E-glass/Epoxy, S-glass/Epoxy, Kevlar49/Epoxy, Boron/Epoxy), modal analysis is performed to compare the percentage difference in frequency between undamaged and damaged cases. This is done to obtain the suitable laminated composite material for composite wind turbine blades, which has minimum effect on physical properties due to damage and also to assess the materials which has maximum effect due to damage. Higher the percentage difference in the frequency means higher is the impact or loss of stiffness due to damage. The FE models considered here are same as used for FE model validation by modal analysis of carbon epoxy composite rotor blade in damaged condition.

After performing modal analysis for composite rotor blade with different materials for all the damage cases using the calculated engineering constants, following percentage difference of natural frequency Vs mode graphs are plotted for all the materials.

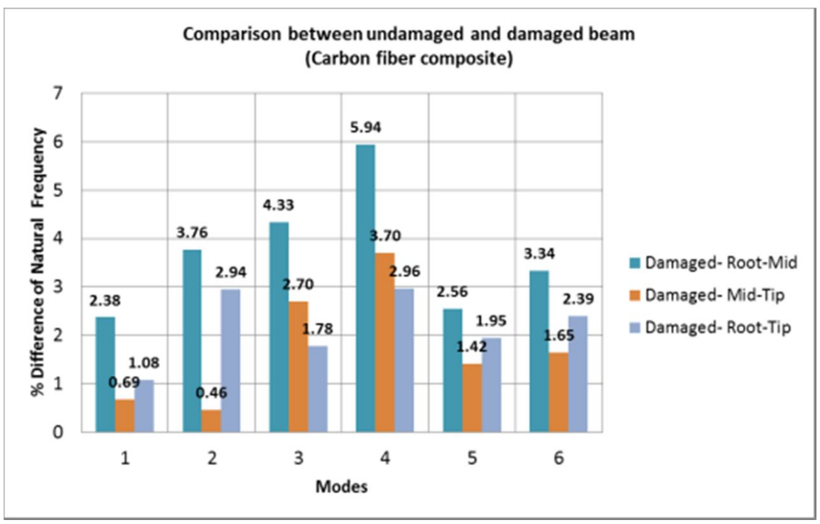
1) Carbon/Epoxy



Graph 5.2(a)



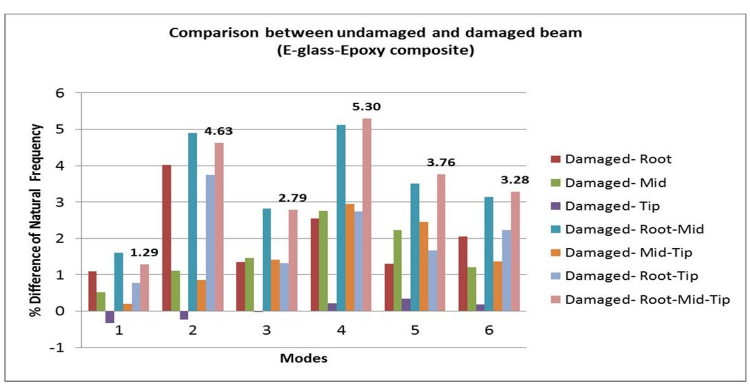
Graph 5.2(b)



Graph 5.2(c)

Graph 5.2(a-c) Percentage difference in Natural Frequency Vs Modes for Carbon/Epoxy laminated composite for all damage cases

2) E-glass/Epoxy



Graph 5.3(a)

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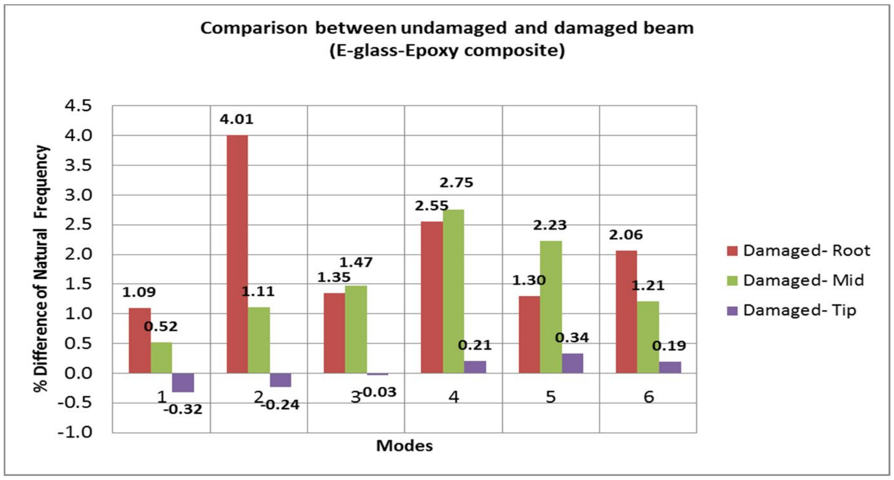
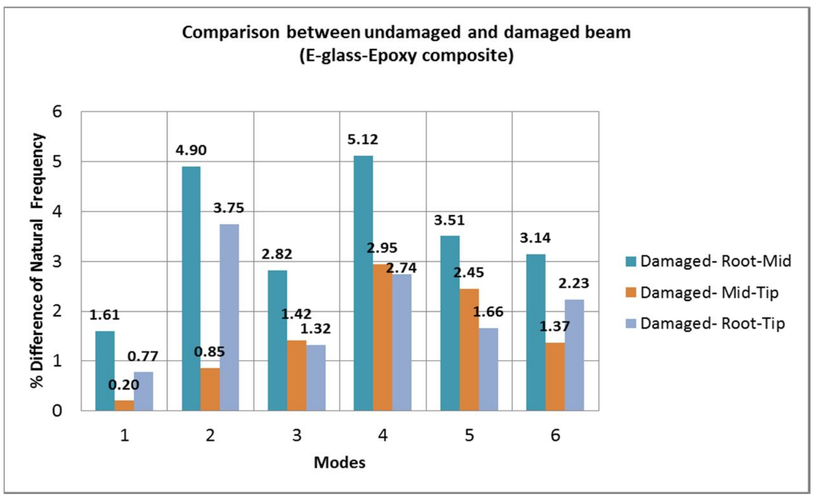


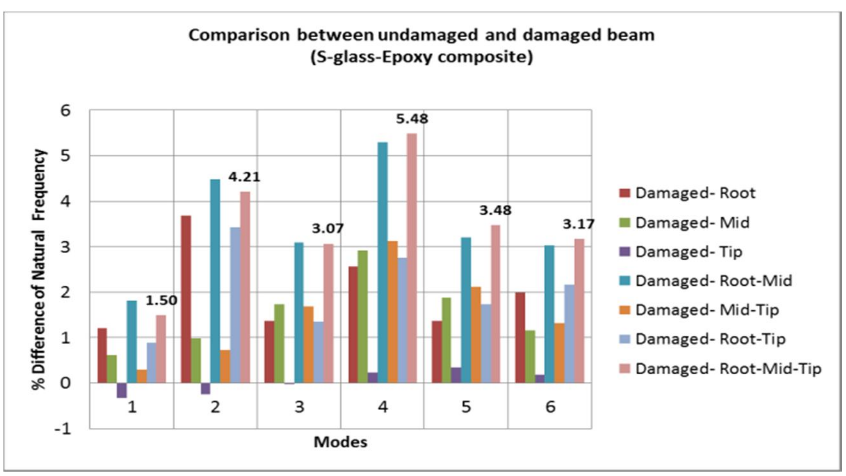
Graph 5.3(b)



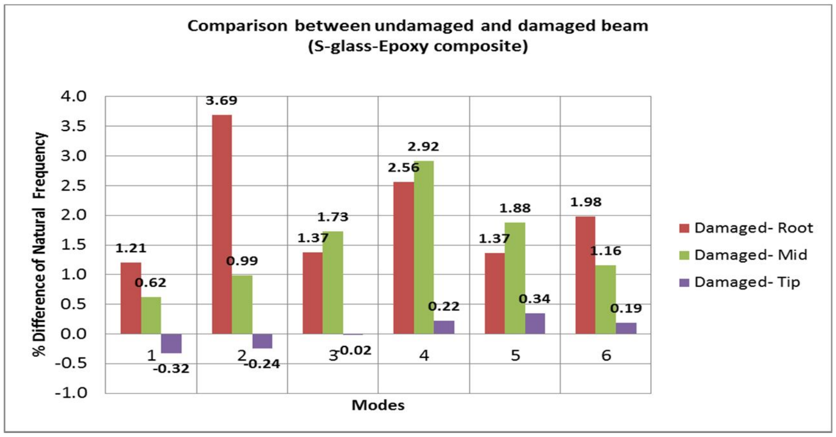
Graph 5.3(c)

Graph 5.3(a-c) Percentage difference in Natural Frequency Vs Modes for E-glass/Epoxy laminated composite for all damage cases

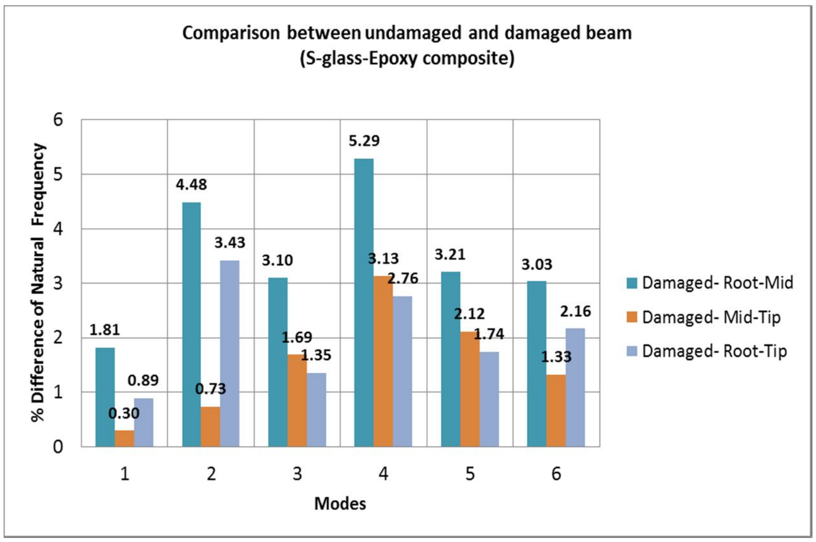
3) S-glass/Epoxy



Graph 5.4(a)



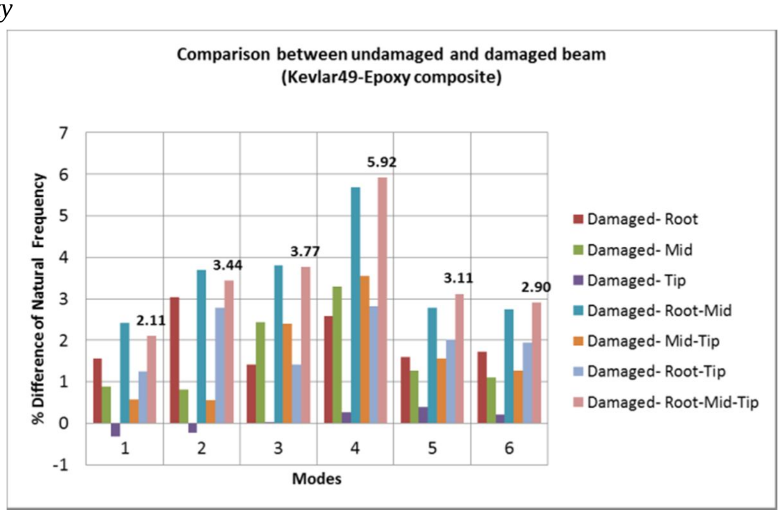
Graph 5.4(b)



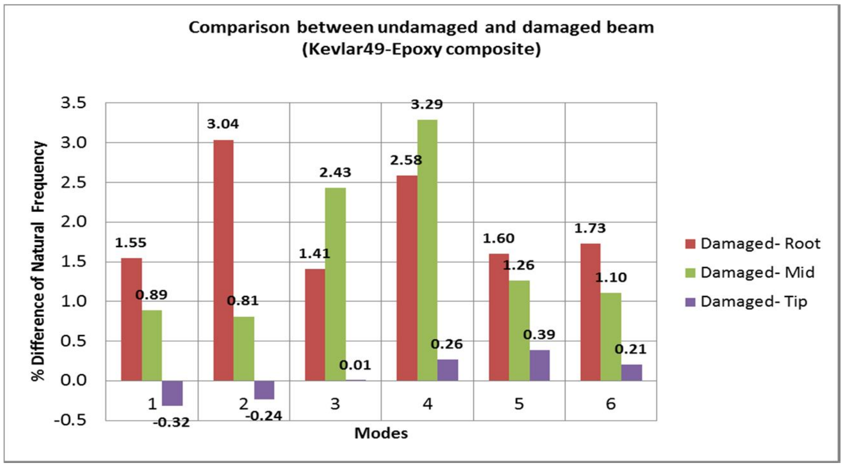
Graph 5.4(c)

Graph 5.4(a-c) Percentage difference in Natural Frequency Vs Modes for S-glass/Epoxy laminated composite for all damage cases

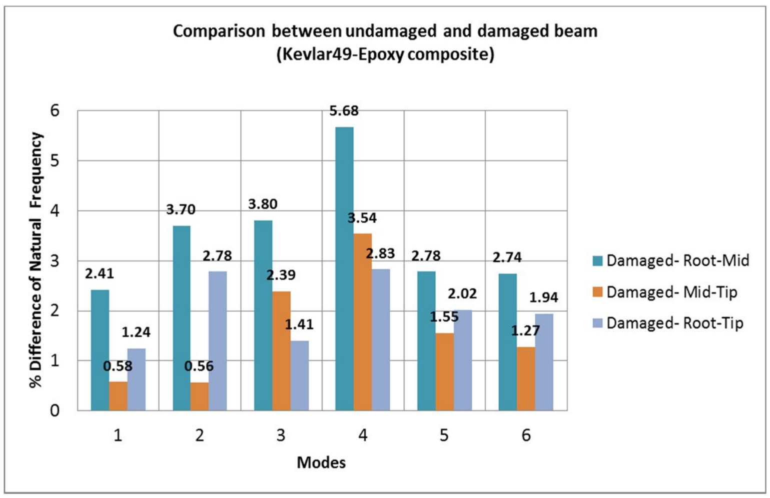
4) Kevlar-49(Aramid)/Epoxy



Graph 5.5(a)



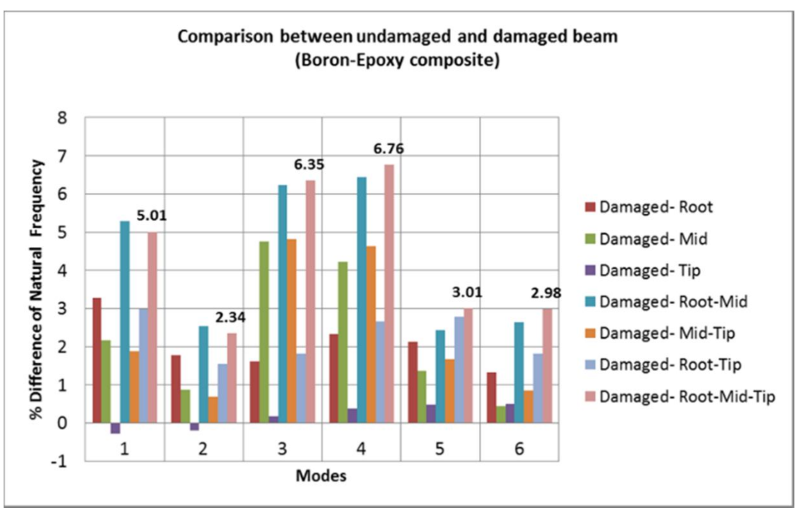
Graph 5.5(b)



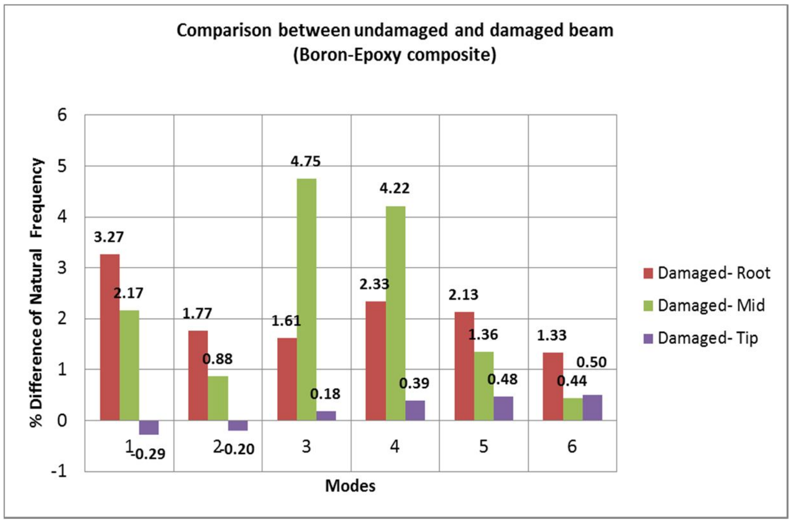
Graph 5.5(c)

Graph 5.5(a-c) Percentage difference in Natural Frequency Vs Modes for Kevlar49/Epoxy laminated composite for all damage cases

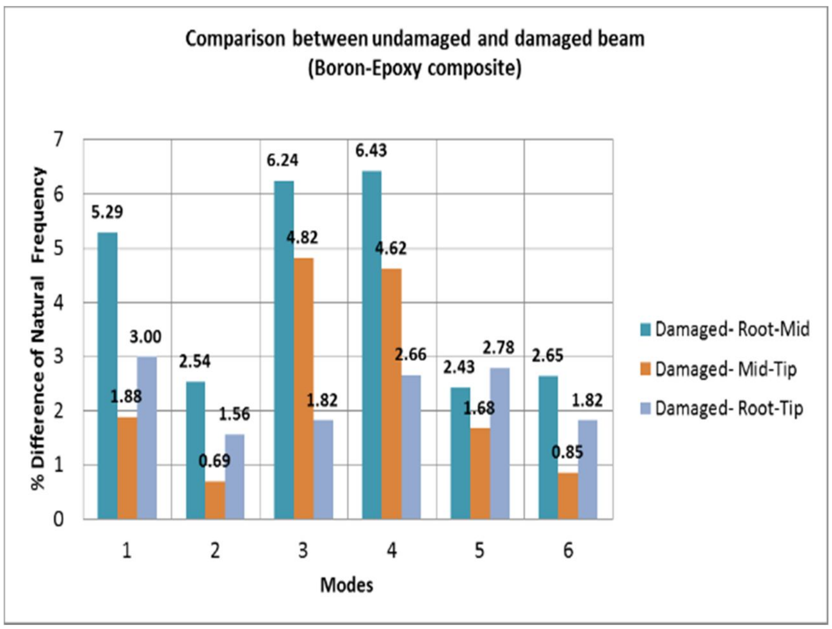
5) Boron/Epoxy



Graph 5.6(a)



Graph 5.6(b)



Graph 5.6(c)

Graph 5.6(a-c) Percentage difference in Natural Frequency Vs Modes for Boron/Epoxy laminated composite for all damage cases

Table 5.1 FEA Average percentage difference in Natural Frequency for different laminated composite materials

Laminated Composite	Average % Difference in Natural Frequency		
	Damage-Root	Damage-Mid	Damage-Tip
Carbon/Epoxy	2.10	1.72	0.09
E-glass/Epoxy	2.06	1.548	0.02
S-glass/Epoxy	2.03	1.549	0.03
Kevlar49/Epoxy	1.98	1.63	0.05
Boron/Epoxy	2.07	2.30	0.18

Laminated Composite	Average % Difference in Natural Frequency			
	Damage-Root-Mid	Damage-Mid-Tip	Damage-Root-Tip	Damage-Root-Mid-Tip
Carbon/ Epoxy	3.72	1.77	2.19	3.77
E-glass /Epoxy	3.52	1.54	2.08	3.51
S-glass/ Epoxy	3.49	1.55	2.06	3.48
Kevlar49/ Epoxy	3.52	1.65	2.04	3.54
Boron/ Epoxy	4.26	2.43	2.27	4.41

Following are the observations from the above plotted graphs and table:-

a) The following pairs of laminated composite materials exhibit similar behavior:-

i) Carbon/Epoxy and Kevlar-49/Epoxy

ii) E-glass/Epoxy and S-glass/Epoxy

iii) Boron/Epoxy behaves in a completely different manner

b) Effect on physical properties (stiffness) due to existence of damage:-

i) Boron/Epoxy has the maximum stiffness and also has maximum effect due to multiple damages (maximum percentage difference in frequency due to damage)

ii) E-glass/Epoxy has the minimum stiffness and also has minimum effect due to multiple damages (minimum percentage difference in frequency due to damage)

Since from the structural health perspective it is very essential that the properties of structures are least affected due to the presence of damage, it can be concluded that E-glass/Epoxy laminated composite material with layup [0-0-90-0-0-90-0-0] for composite rotor blade is safe as its physical property (stiffness) is least affected due to multiple damages compared to other materials. Whereas, Boron/Epoxy laminated composite material with layup [0-0-90-0-0-90-0-0] cannot be considered safe for composite rotor blade as its physical property (stiffness) is affected maximum due to multiple damages compared to other materials.

VI. CONCLUSION

Following are conclusions obtained from the present work for Structural Health Monitoring system (SHM) of composite rotor blade:-

1) The best method to determine the existence of damage and severity of damage based on location is by percentage difference of frequency of damaged case with respect to undamaged case. This also lead to following observations

a) Frequency reduces for damage cases due to reduction in stiffness which gives information about existence of crack

b) Severity of damage is maximum for maximum number of cracks i.e. at root, mid & tip with maximum percentage difference in natural frequency of 6.19% at mode-4

c) Among damage cases for cracks at two locations (i.e. root & mid, mid & tip, root & tip), maximum severity is due to crack at root & mid with maximum percentage difference in natural frequency of 5.94% at mode-4

d) Among damage cases for crack at one location (i.e. root, mid, tip), minimum severity is due to crack at tip with minimum percentage difference of natural frequency of 0.08% at mode-3

2) Curvature mode shape method is most effective to detect damage location for damage cases with single crack in the model with maximum absolute difference of 0.54 for damage at root, 0.48 for damage at mid and 0.09 for damage at tip

3) Boron/Epoxy composite has the maximum stiffness of 35975.39N/m and E-glass/Epoxy composite has the minimum stiffness of 8960.94N/m compared to other laminated composite materials used for Wind Turbine Blades such as Carbon/Epoxy, S-glass/Epoxy, Kevlar-49/Epoxy.

4) Physical properties (stiffness) of various laminated composite materials used for Wind Turbine Blades are affected as follows due to existence of damage:-

a) Boron/Epoxy has the maximum stiffness and also has maximum effect due to damage (maximum percentage difference in frequency due to damage)

b) E-glass/Epoxy has the minimum stiffness and also has minimum effect due to damage (minimum percentage difference in frequency due to damage)

Since from the structural health perspective it is very essential that the properties of structures are least affected due to the presence of damage, it can be concluded that E-glass/Epoxy laminated composite material is safer, whereas Boron/Epoxy laminated composite material is maximum affected due to multiple damages with layup [0-0-90-0-0-90-0-0] compared to other materials used for composite wind turbine rotor blade.

The analysis of the present work is limited to only composite rotor blade (cantilever beam). Further research is required for different types of beams depending on various practical applications of composite beams with different boundary conditions.

Applying these damage detection techniques to the structures fabricated with new materials to identify and quantify the damage. Reliability in FEA results and validation is also required.

Finally, the research should be focused on FEA of real complex structures including their operating conditions. These types of research are required for the industry in the field of damage identification and structural health monitoring.

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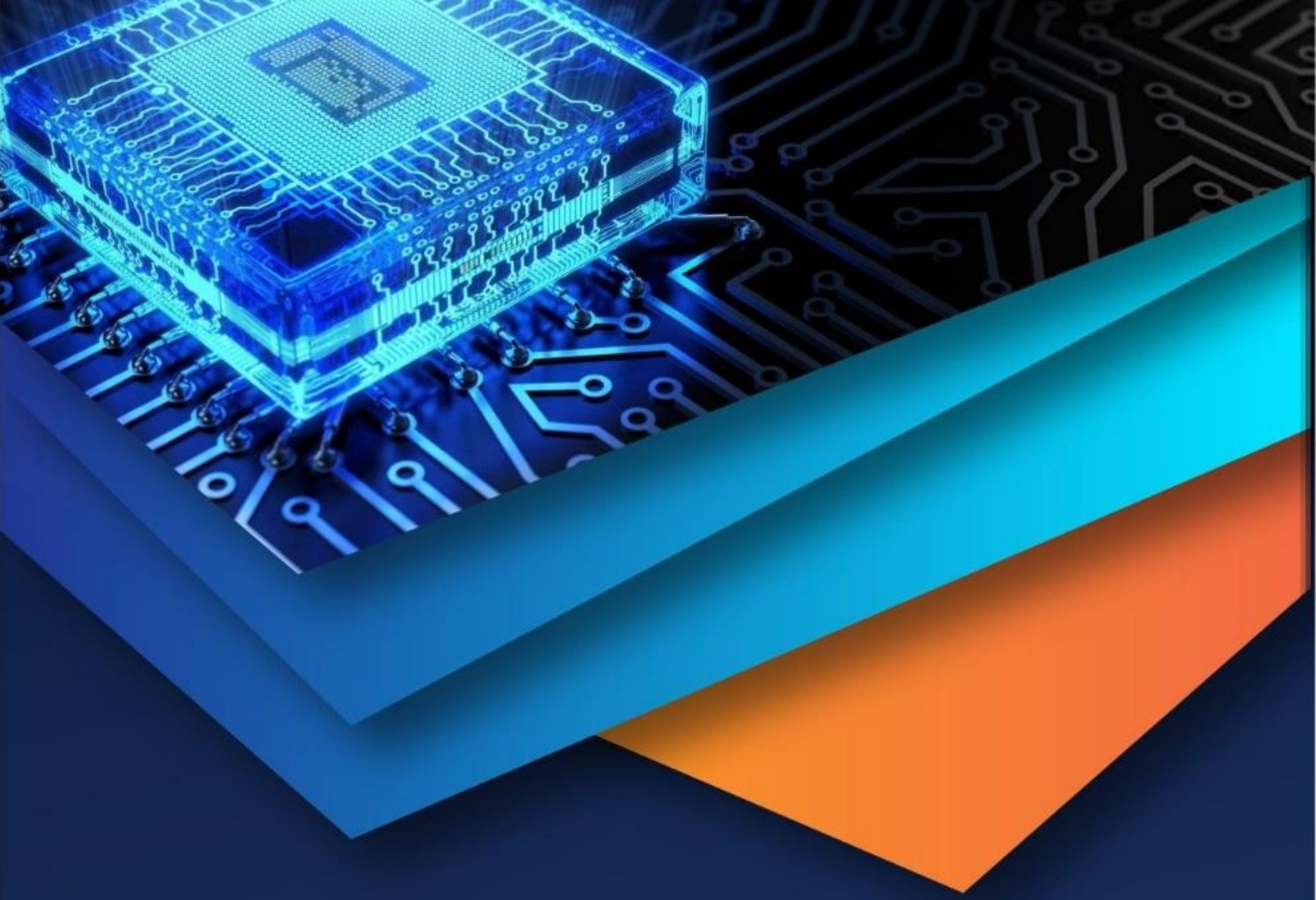

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