Multiple-crack detection in beam structures using curvature based continuous wavelet transform

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Abstract: Damage identification in beams and plate using curvature mode shape and its has become a research focus of increasing interest during the last few years. Hence this paper presents the numerical and experimental studies for damage detection in beam and plate structure with mode shape curvatures. The purpose of the study is to present the influence of the higher order modes of the beams and plates on damage detection and quantification and location. We observed that detection quality for particular mode shape depends on order of mode shape and it is also demonstrated that the location and quantification of single and multi cracks can be detected by this method. First, the displacement mode shapes obtained from the intact and damaged beams which are converted into mode shape curvatures. In this the first five modes of cantilever beam are considered and the influence of the mode order of beam and plate on the effectiveness of damage detection by the vibrational setup.

Index Terms **- Damage detection healthy, single and multi cracks, curvature mode shape, higher vibration modes, Supports**

I. INTRODUCTION

Vibration based Structural Health Monitoring (SHM) became an interesting research topic in structural mechanics around 30 years ago. It is based on the fact that methods allowing to existence of damage detection and its location at earlier stage become an intensive investigation thought the mechanical, civil and aerospace engineering domain from the last two decades. For this reason, methods making to detection and localization of cracks have been the subject of many researchers. The existence of damage in structure introduces local flexibility that would affect dynamic characteristics of whole structure. It causes in reduction of natural frequencies and mode shapes of structure member. This property leads to detect existence of crack and its location and depth in the structural members

Liew and Wang[1] proposed an application of spatial wavelet theory to damage identification in structures. They calculated the wavelet coefficients along the length of the beam based on the numerical solution for the deflection of the beam, the damage location was then indicated by a peak in the coefficients of the wavelets along the length of the beam. In the investigation of existence of crack and its localization and depth of damage the pioneer of the work **Dimarogonas [2]** the crack was modeled as a local flexibility and the equivalent stiffness was computed using fracture mechanics methods. **Adams and Cawley [3]** developed an experimental technique to estimate the location and depth of a crack from changes in natural frequencies. **Rizos PF [4]** proposed method o identification of crack location and magnitude in a cantilever from fundamental vibration modes. **Pandey A.K., M. Biswas, and M. M. Samman [5]** proposed that fundamental mode shape curvature to be a sensitive parameter for damage localization. Curvature was calculated and utilized for damage localization of a simulated beam discredited into a number of finite elements .**Douka et al[6]**investigated experimental and analytical identification of crack in cantilever beam depending on wavelet analysis. The size and the location of the crack is determined using wavelet transform for fundamental mode of vibration. Due to the rapid changes in the spatial difference of the response, the crack location is determined. **Patil and Maiti [7]** have proposed a method for prediction of location and size of multiple cracks based on measurement of natural frequencies for slender cantilever beams**. Abdel Wahab and De Roeck [8]** apply curvature mode based damage detection methods in a continuous beam by averaged modal-curvature difference arising from pairs of damaged and intact mode shapes. The vibration methods are based on the occurrence that damage in a structure produces a local increase in flexibility which induces changes in the dynamic properties of the structure. The analysis of these changes can be used for damage identification. In recent years, the wavelet transform (WT) has been proposed as a promising mathematical tool for damage detection and localization, in light of its ability to locally analyze a signal. **Q. Wang and X. Deng [9]** applied the WT to spatial problems, specifically to identify cracks in structures: using free vibrations of cracked beams with a local reduction of stiffness, they showed that the wavelet coefficients calculated along the beam presented a maximum precisely at the crack location. Further they dealing with beams, plates or frame structures have validated this technique as a promising research tool. **S.T. Quek, Q. Wang, L. Zhang, K.K. Ang [10]** studied on wavelet transforms in the one-dimensional case is very extensive and applicability of various wavelets in detection of cracks in beams. **Koushik, and Samit Ray [11]** studied the cantilever shear beam, discretized into a large number of elements. It is demonstrated that the change in the fundamental mode shape due to any damage is an excellent indicator of damage localization as it is found to be discontinuous at the location of damage. Further, the change in higher derivatives (i.e., slope and curvature) of the fundamental mode shape is shown to be sensitive enough in damage localization.**Y.F.Xu , W.D.Zhu , J.Liu , Y.M.Shao [12]** proposed two new non-model-based methods that use measured mode shapes to identify embedded horizontal cracks in beams. **M. Rucka, K. Wilde[13]**proposed a method for estimating the damage location in beam and plate structures a Plexiglas cantilever beam and a steel plate with four fixed boundary conditions are tested experimentally by using the one-dimensional continuous wavelet transform. **Chih-Chieh Chang, Lien-Wen Chen [14]** presents a technique for structure damage detection based on the spatially distributed signals without experimental data.**W.L. Bayissa, N. Haritosa, S. Thelandersson [15]** have done work that the wavelet analysis coefficients be employed in the space domain of the structure to detect and localize single as well as multiple damage states and the damage identification results are compared with those obtained from existing and well-established methods. **A.Bagheri, G.GhodratiAmiri, S. A. Seyed Razzaghi[16]** has been employed discrete curvelet transform using unequally-spaced fast Fourier transforms to identify damage location in plate structures. In addition, the performance and sensitivity of the proposed method have been investigated using numerical and experimental data. Mario **Solis, Mario Algaba, Pedro Galvin [18]** presents a new damage detection methodology for analyses the severity threshold of damage in beams by applying continuous wavelet analysis. **F. Bakhtiari-Nejad [19]** presents analytical estimation based on the Rayleigh's method to find out natural frequencies and mode shape for a beam having one or two cracks. In addition that investigates the upper limit of crack depth in which natural frequencies and mode shapes have error less than 5% and 7% respectively obtained by analytical estimation in compare to the exact solution.

Curvature Based Damage Detection Method:

The pre and post-damage mode shapes are the basis for damage detection. Mode shape curvature for the beam in the undamaged and damaged condition can then be estimated numerically from the displacement mode shapes. As a matter of fact, curvature mode shape is thesecond derivative of displacement mode shape, so by applying a numerical formulation called“Central Difference Approximation” on displacement mode shapes; curvature mode shapescould be calculated.

For a beam cross section with flexural rigidity *EI*, subjected to a bending moment *M* (*x*), the curvature *κ* (*x*)at location *x* is given by:

$$k(x) = \frac{M(x)}{EI}$$

For the beam with given moment applied to the damaged and undamaged structure, a reduction of stiffness associated with damage will lead to an increase in curvature. Thus the existence and extent of damage can be estimated by measuring the amount of change in the mode shape curvature. Curvatures are often calculated using the central difference approximation:

$$\bar{v}_{i,j} = \frac{\phi_{(i+1),j} - 2\phi_{i,j} + \phi_{(i-1),j}}{h^2}$$

where $v_{i,j}$ represents modal curvature, first subscript *i* represents node number, second subscript *j* represents the corresponding mode number, *h* represents element length as the beam is discredited with elements of equal length and $\phi_{i,j}$represents the mass normalized modal value for the i^{th}node in the j^{th} mode.

The mode shape curvature criterion may be defined as the difference in absolute curvatures (Δ) of the healthy and damaged structures, for each mode, and may be represented as:

$$\Delta = \left| k(x) - k_C(x) \right|$$

At a certain damage location, the value of mode shape curvature is significantly higher than the ones at other locations. Based on the curvature difference values of measured data of damaged and healthy structures the location of damage in the structure can be identified.

II. Experimental Investigations

W In this project an experiment on Al-6061 beam has been performed by using universal vibration apparatus. (COCO 80X). Here cantilever beam of length 400 mm and cross-section 25 x 10 mm^2 was clamped at a vibrating table. Before the experimental study the beams surface has been cleaned and organized for straightness. Subsequently, single transverse cracks is deemed on the beam at 200 mm from fixed end of the beam, the depth of cracks are varied 25% and 75% of height of the beam. During the experiment the cracked and undamaged beams have been vibrated at their 1st and 2nd mode of vibration by using an exciter and a function generator. The vibrations characteristics such as natural frequencies and mode shape (amplitude) of the beams correspond to 1st and 2nd mode of vibration have been recorded by placing frequency analyzer along the length of the beams and displayed on the frequency analyser. It has been observed that the natural frequency of the beam gradually decreases with increase in crack depth and the first two natural frequency results are represents in Fig.1. and schematic block diagram of experimental set-up shown in Fig.1.

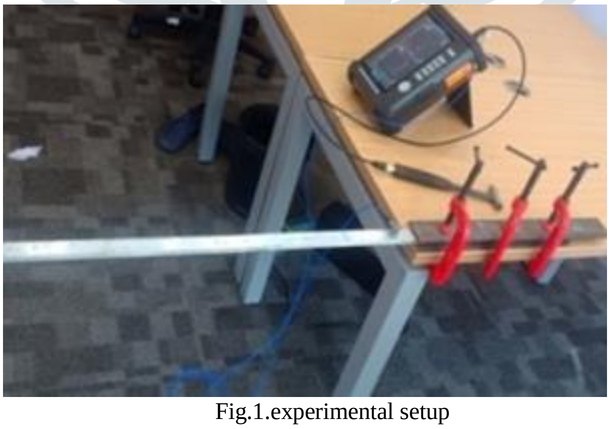


Fig.1.experimental setup

III. FEM SIMULATION

A. Modelling of Crack on Cantilever Beam

The finite element analysis is brought out for the cracked beam (Fixed-free) to locate the mode shape of transverse vibration at different locations and crack depth. The crack modelling has been very important aspect, FEM software package ANSYS has been used to modelled the cracks are deemed on Fixed-Free beam with relative crack location at 25% and 75% of length of the beam from one fixed end and the analysis has been done using general purpose finite element software ANSYS on un-cracked and cracked fixed beam beam to obtain natural frequencies and mode shape of transverse vibration at different locations with different crack depths interval of 25% and 75% crack depth. Properties the cracked beams of the current research have and dimensions mentioned below:

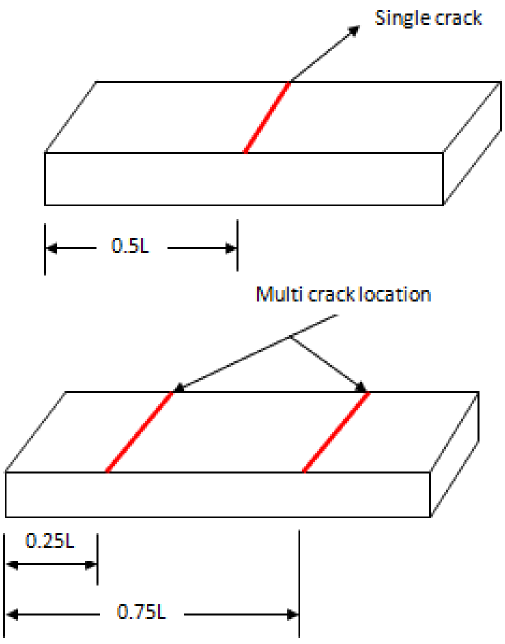
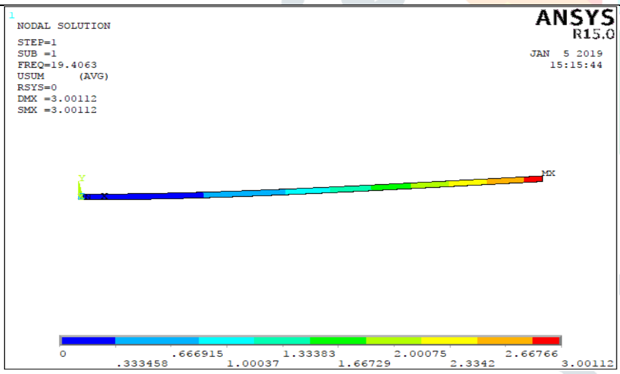
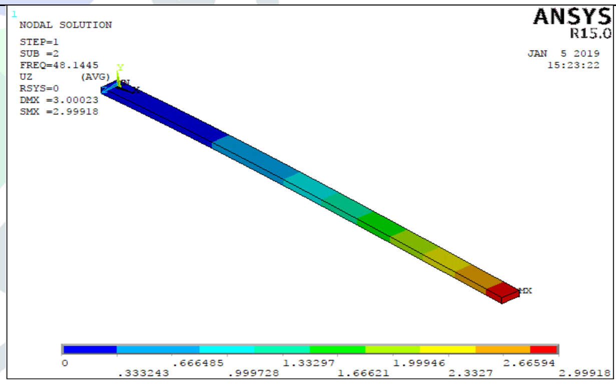


Fig.2 (a) Location of single crack (b) Location multi-crack



(a)



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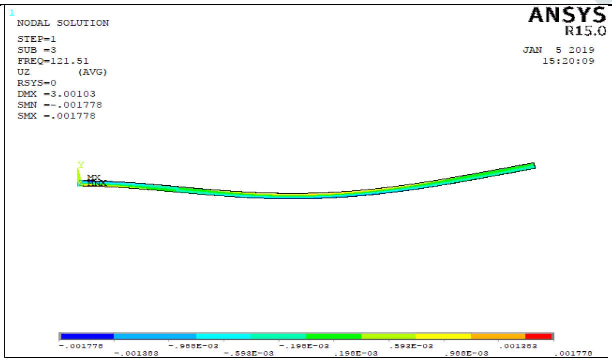

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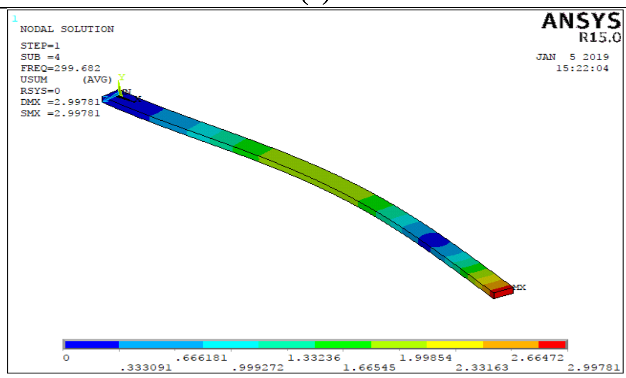

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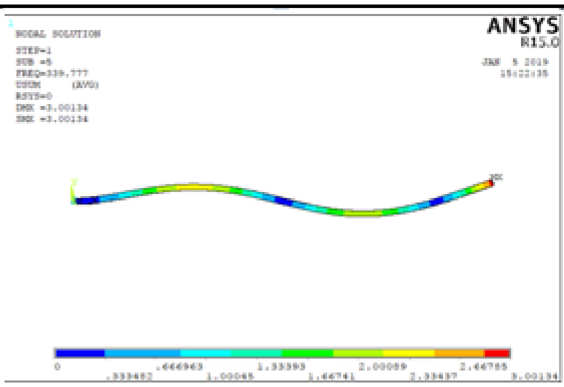


(e)

Fig. 3 Shows first mode shapes for Intact single and multi crack beam

Table.1.Natural frequency and frequency residuals of single cracked beam in EMA&FEMA

Mode No.		After Damage (single crack)	
		EMA (Hz)	FEMA (Hz)
1	15.6250	16.258	
2	20.0000	21.3040	
3	115.6250	115.2980	
4	305.0000	304.1200	
5	318.1250	318.6900	

Table.2.Natural frequency and frequency residuals of damaged beam(multy crack) in EMA&FEMA

Mode No.	After Damage (multi-crack)	
	EMA (Hz)	FEMA (Hz)
1	15.1250	15.1009
2	19.0000	21.2721
3	114.8750	117.2116
4	300.0000	311.3741
5	318.1500	320.1318

Table.3.Natural frequency and frequency residuals of intact beam (EMA&FEMA)

Mode No	Healthy beam	
	Before EMA (Hz)	Damage FEMA (Hz)
1	16.2500	17.6250
2	21.8750	22.2115
3	116.0000	118.2215
4	316.0000	319.1240
5	320.7500	323.4500

IV. Specifications

The dimensions and the material constant for the uniform fixed-free beam investigated in this paper are:

Material of Beam= Al-6061

Total Length = 400mm

Width of Beam =25mm

Height of Beam =10mm

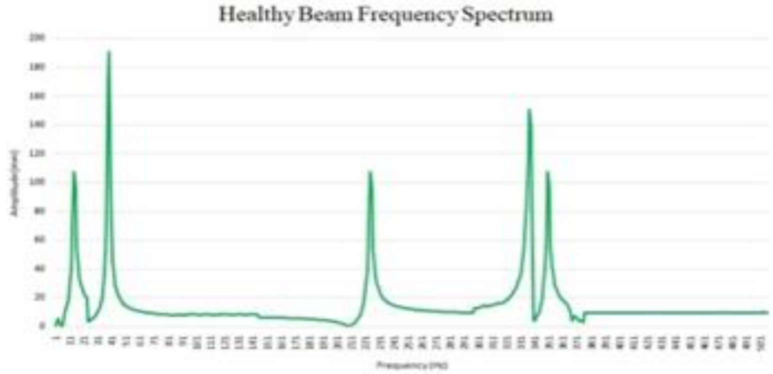
Moment of Inertia(I)=2.0833x10^{-09} m^4

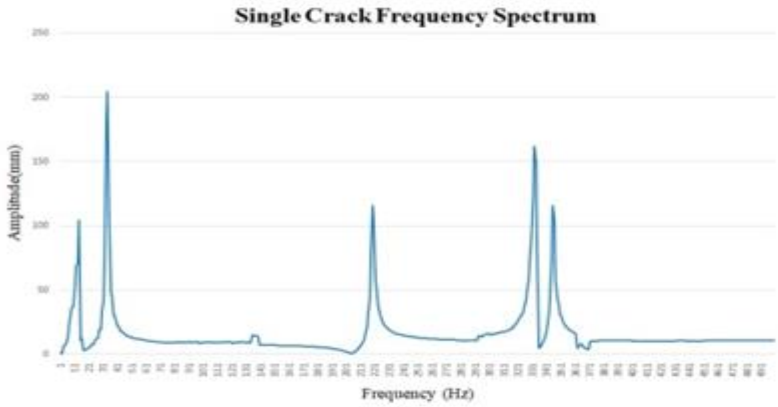
Density Of Material= 2770 kg/m^3

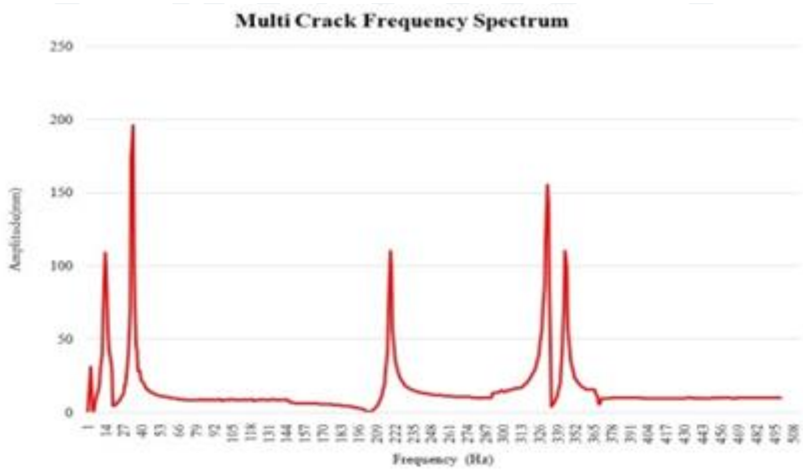
Cross-Section Of Beam= 10*25 mm^2

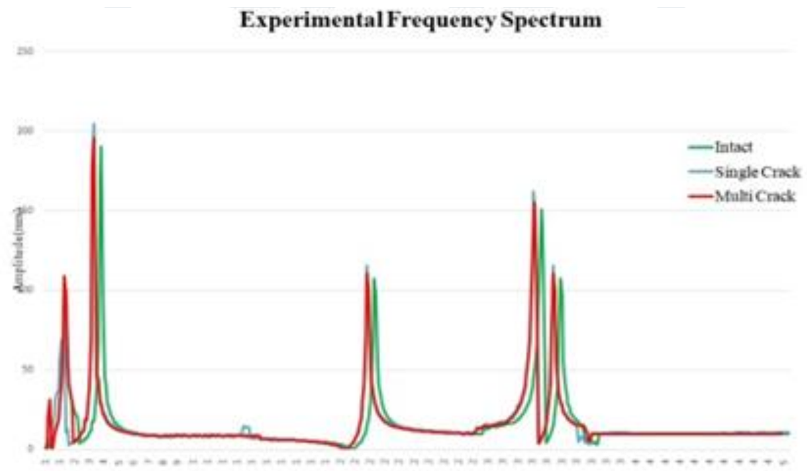
Young's Modulus Of Elasticity= 70 GPa

Poission's ratio=0.33


Healthy Beam Frequency Spectrum


Single Crack Frequency Spectrum
Amplitude(mm)
Frequency (Hz)


Multi Crack Frequency Spectrum
250
200
150
100
50
0
Amplitude(mm)
Frequency (Hz)


Experimental Frequency Spectrum
Intact
Single Crack
Multi Crack

V. RESULTS AND DISCUSSION

For that first two natural frequencies of the cracked and un-cracked beam have been obtained experimentally. The effect of the crack on natural frequency of a cantilever beam were investigated for various crack depths is plotted in figures Fig.2.(a and b). And it was observed that in all the cases the modal natural frequencies decrease with increase in crack depth.

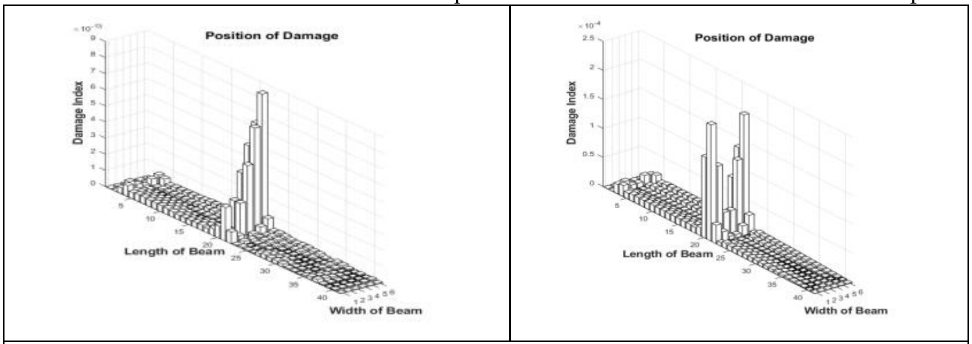


Fig 4: Damage(single crack) Identification in First & Second Modes

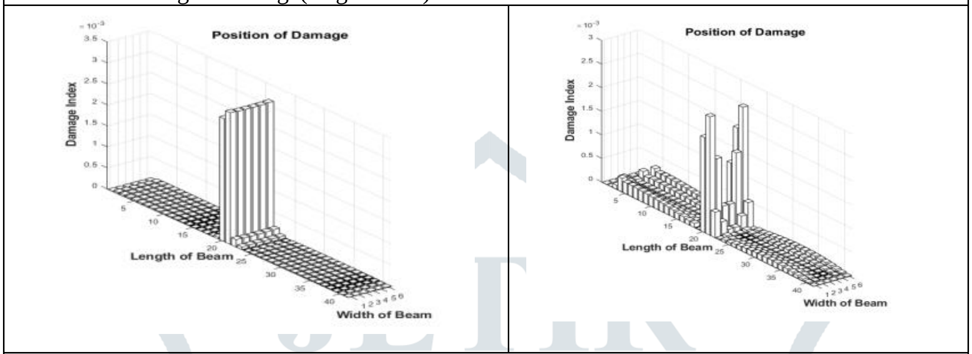


Fig 5: Damage(single crack) Identification in Third & Fourth Modes

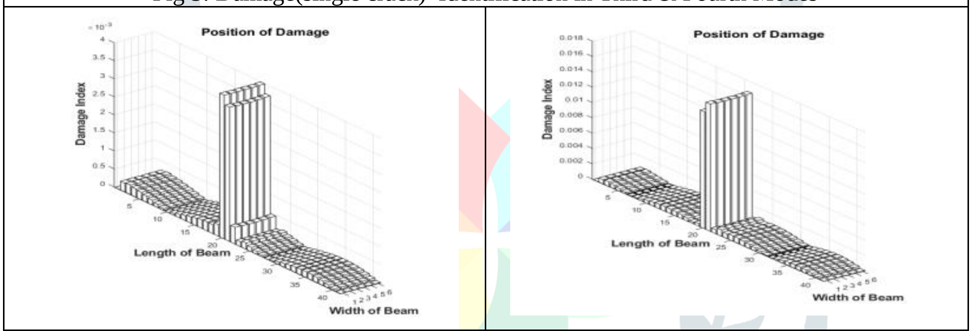


Fig 6: Damage(single crack) Identification in Fifth & Sixth Modes

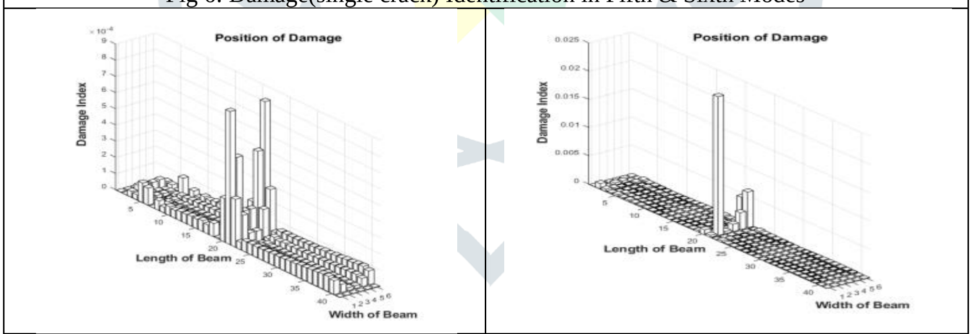


Fig 7: Damage(single crack) Identification in Seventh and Eight Modes

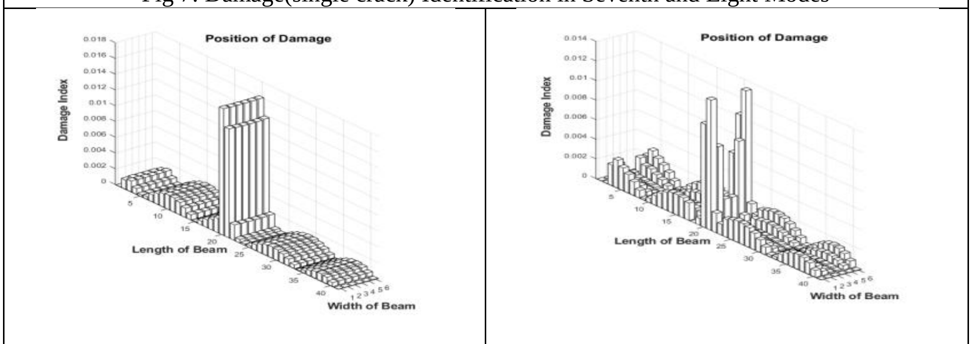


Fig 8: Damage(single crack) Identification in Ninth and Tenth Modes

However, natural frequency changes alone may not be sufficient for a unique identification of the location of structural damage and this change in natural frequency less sensitivity to small cracks. After extensive study of vibration analysis on damaged structural members, only few practical techniques found for small damaged identification. Therefore, the curvature mode shapes and wavelet analysis are utilized as base parameters for damage identification and assessment technique in the present study. The changes of the curvature mode shapes are localized in the region of the damage and consequently the estimated mode shapes of the beam are analysed by continuous wavelet transform may be used effectively to identify damage location and quantification in structures. Successfully determine the natural frequencys of healthy, single and multi cracks for Al-6061 beam. From the results less natural frequency is observed from multi crack compared to single crack and healthy beam.

VI. CONCLUSION

Identify the natural frequencys using numerical and experimental studies for damage detection in beam and plate structure with mode shape curvatures. We noticed the diffrent natural frequencys in healthy, single and multi cracks in beams and plate of Al-6061. In this the first five modes of cantilever beam are considered and the influence of the mode order of beam and plate on the effectiveness of damage detection by the vibrational setup.

Natural frequency is significantly decreased for multi crack beam and plate compared single crack and healthy. We observed that detection quality for particular mode shape depends on order of mode shape and it is also demonstrated that the location and quantification of single and multi cracks can be detected by this method.

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