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Damage Identification of Beam using Structural Dynamic Parameters

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Abstract — *A structural member can suffer varying degrees of damage due to reasons such as over loading, environmental ageing, corrosion, poor quality of construction, fatigue crack growth under cyclic loading, and creep. The changes can be characterized by the changes in the modal parameters, namely modal frequencies, mode shapes and modal damping values. The modal parameters are the functions of physical properties of the structure such as mass, damping and stiffness. Estimation of the magnitude of damage, location and its spread thus plays a crucial role in the repair methodology to be adopted. The study describes different methods for the damage detection of beams based on modal parameters.*

Keywords*- Damage Identification, Cantilever Beam, Fixed Beam, Mode Shapes, Curvature Mode Shapes, Modal residual force*

I. INTRODUCTION

Damage in a structure can be defined as a reduction of its load bearing capacity, which can result from deterioration of its components, connections, or boundaries during its service life. All load-bearing structures continuously accumulate structural damage; early detection, assessment, and monitoring of this damage can avoid catastrophic failures. Failures of structures, particularly aircraft structures, often have tragic consequences. Therefore, damage detection, especially on-line, becomes a very important issue [1].An important application of structural system identification is health monitoring, also referred to as damage detection. This is the practice of conducting non destructive tests or inspection of a structure to determine the existence, location, and extent of damage, and in some cases make a determination as to the remaining life of the system [2].This practice has taken on increased importance in aerospace and civil applications over the last several decades, due to the increased use of aircraft structures and buildings far beyond their original life expectancy [3].Estimation of the magnitude of damage, location and its spread thus plays a crucial role in the repair methodology to be adopted. Also, residual strength and remaining life depends on the magnitude and position of damage. Thus damage identification is a needed procedure in order to make the existing structure safe [4].

F.Magalhaes *et al* [5] describes the strategy that was followed to minimize the effects of environmental and operational factors on the bridge natural frequencies, enabling, in a subsequent stage, the identification of structural anomalies. Static and dynamic regression analysis were conducted.

Ruigen Yao *et al* [6] proposed time-domain regression based algorithms for damage identification are found these methods are computationally efficient and easy to implement, and thus effective for fast damage prognosis.

In this study the finite element models corresponding to healthy and damaged were made. The damage is created by changing the stiffness of selected elements by reducing the depth of the beam section. The main aim is to detect and locate the damage by investigating various techniques using structural dynamic parameters such as frequencies and associated mode shape between healthy and damaged (theoretically simulated) structure.

The paper is structured as follows: Section II provides the methodology of our approach as well as relevant backgrounds. In Section III presents different damage detection techniques to detect damage such as direct natural frequency correlation technique and Modal Assurance Criteria (MAC). In Section IV different damage location techniques are discussed in order to get the exact location of damage. The techniques include Coordinate Modal Assurance criteria

(COMAC), Curvature Mode shapes, Modal residual force method. Section V outlines the results interpreted using these techniques. In Section VI concludes the paper with an overview of the related work.

II.METHODOLOGY

The methodology for detecting, locating the damage in beam is mentioned below**:**

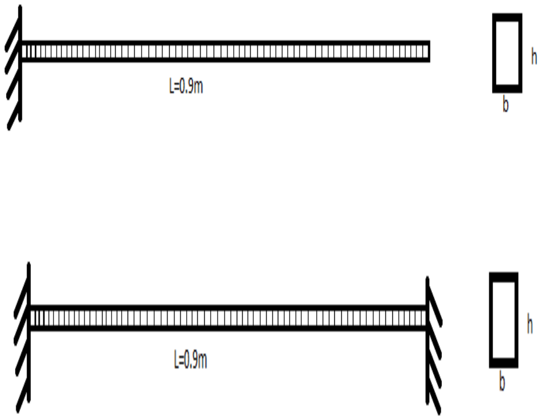


***Figure1: Cantilever and Fixed Beam models with 40 elements**.*

1) A cantilever beam and fixed beam of rectangular cross section is taken as shown above in figure 1.
2) Modeling and analysis –Both healthy state and damaged state are modeled by changing the property of one/more elements. The property used here is depth reduction.
3) Using the frequency and mode shape obtained from both healthy and damaged models-various techniques are used to detect the damage.
4) Locating the damage using different techniques.

III.DAMAGE IDENTIFICATION TECHNIQUES

Before moving to damage identification one must know whether the structure is having a varying dynamic property compared to the healthy state. For this the dynamic data need to be correlated from the finite element model corresponding to healthy state and the measured modal characteristics such as frequencies and mode shape of the damaged structure. The most often used correlation or identification techniques are natural frequency correlation and mode shape correlation.

A.Direct Natural Frequency Correlation
One of the easiest and common approach to correlate two models is the direct comparison of the natural frequencies by taking the percentage difference between natural frequencies of both models.
The equation used for the above detection is,

$$\varepsilon_{fj} = \frac{|fr_{hj} - fr_{dj}|}{fr_{hj}} \times 100 \qquad (1)$$

B.Modal Assurance Criteria (MAC)
The modal assurance criterion is a statistical indicator, just like ordinary coherence, which can be very powerful when used correctly but very misleading when used incorrectly. The function of the ***modal assurance criterion (MAC)*** is to provide a measure of consistency (degree of linearity) between estimates of a modal vector. The modal assurance criterion takes on values from zero, representing no consistent correspondence, to one, representing a consistent correspondence. In this manner, if the modal vectors under consideration truly exhibit a consistent, linear relationship, the modal assurance criterion should approach unity and the value
of the modal scale factor can be considered to be reasonable.

$$MAC_j = \frac{(\phi_{hj}{}^T \phi_{dj})^2}{(\phi_{hj}{}^T \phi_{hj})(\phi_{dj}{}^T \phi_{dj})} \qquad (2)$$

where Φ_{hj} is the healthy eigen mode that has been paired with the *j*-th damaged mode Φ_{dj} .

IV.DAMAGE LOCATION TECHNIQUES

A.Coordinate Modal Assurance Criteria(COMAC)

An extension of the modal assurance criterion is the coordinate modal assurance criterion (COMAC). The COMAC is calculated over a set of mode pairs, analytical versus analytical, experimental versus experimental or experimental versus analytical.

The two modal vectors in each mode pair represents the same modal vector but the set of mode pairs represents all modes of interest in a given frequency range. For two sets of modes that are to be compared, there will be a value of COMAC computed for each (measurement) degree-of-freedom.

$$\text{COMAC}_j = \frac{\left|\sum_{r=1}^{m_s} (\phi_h)_{jr} (\phi_d)_{jr}\right|^2}{\sum_{r=1}^{m_s} (\phi_h)_{jr}^2 \sum_{r=1}^{m_s} (\phi_d)_{jr}^2} \qquad (3)$$

B. Curvature Mode shape.

Mode shapes to obtain the spatial location of damage is an alternative by utilising the mode shape derivatives, such as curvatures. The technique is known as curvature mode shape. There is a direct relationship between curvature and bending strain. Mode shape curvatures which can be estimated numerically from derivatives of the displacement mode shapes have also been used for damage detection purposes. The use of mode shape curvatures in damage identification is based on the assumption that the changes in the curvatures of mode shapes are highly localized to the region of damage and that they are more pronounced than changes in the displacement mode shapes.

Curvature mode shapes are related to the flexural stiffness of beam cross sections. The curvature at location x along the length of the beam, $v''(x)$, is

$$v''(x) = \frac{M(x)}{EI} \qquad (4)$$

where $M(x)$ is the bending moment at x, E is the modulus of elasticity, and I is the second moment of the cross sectional area.

C. Modal Residual force method

In this method the residual force mode-by-mode and by taking all the modes together are computed using equation (5). where F_i is the applied harmonic force error distribution, applied at frequency $(\lambda^{1/2}{}_i)_e$ which is necessary to cause the analytical mode to vibrate with mode shape $\{\Phi_e\}$.These methods do not indicate the absolute magnitudes of the error but they do indicate where modeling differences in the structure exist between the healthy model and the damaged model.

$$\{F_i\} = [K_d]\{\Phi_h{}^i\} - (\lambda_i)_h [M_d]\{\Phi_h{}^i\} \qquad (5)$$

V.RESULTS AND DISCUSSIONS

A. Results of Cantilever beam

Four cases of damages are studied with the cantilever beam. Case 1 is the damage at element 3; case 2 is the damage at element 20; case 3 represents the damage in element 30, case 4 represents the damages in elements 3,2,30. All the four cases are studied with a reduction of 50 percent in depth of the beam. From the natural frequency correlation method there seems to a change in frequency between the healthy to the damage cases, which can define the damage is detectable, but there is no indication of the location of damage without further analysis. The table shows below depicts that damage is detectable, but location is not predictable from these methods.

Table 1: Natural frequency and MAC values of the first five modes of healthy and damaged cantilever for Case 1 damage.

Mode	Healthy	Damaged	Difference in frequencies(%)	MAC(%)
1	6.09	4.83	20.65	0.99
2	38.16	34.56	9.50	0.99
3	106.77	102.03	4.43	0.99
4	208.99	205.38	1.72	0.99
5	345.01	343.58	0.41	0.99

Table 2: Natural frequency and MAC values of the first five modes of healthy and damaged cantilever for Case 2 damage.

Mode	Healthy	Damaged	Difference in frequencies(%)	MAC(%)
1	6.09	5.85	3.94	0.99
2	38.16	33.70	11.67	0.99
3	106.7	106.6	0.08	0.99
4	208.99	190.4	8.88	0.98
5	345.01	343.5	0.42	0.99

***Table 3: Natural frequency and MAC values of the first five modes of healthy and damaged cantilever for Case 3 damage*.**

Mode	Healthy	Damaged	Difference in frequencies (%)	MAC(%)
1	6.09	6.13	0.62	0.99
2	38.1	35.70	6.41	0.99
3	106.70	93.20	12.61	0.97
4	208.90	194.80	6.78	0.97
5	345.00	342.90	0.59	0.97

Table 4: Natural frequency and MAC values of the first five modes of healthy and damaged cantilever for Case 4 damage

Mode	Healthy	Damaged	Difference in frequencies (%)	MAC(%)
1	6.09	4.76	21.86	0.99
2	38.10	28.88	24.31	0.99
3	106.70	88.11	17.47	0.97
4	208.90	171.37	18.00	0.96
5	345.00	171.37	50.37	0.96

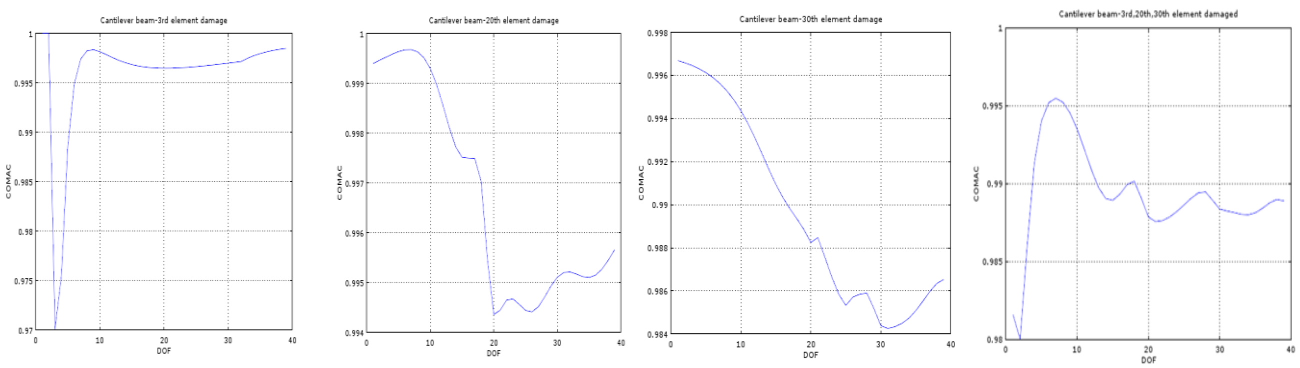


Figure 2: COMAC values of the healthy and damaged cantilever beam for the four different damage cases; case (a) damage at element 3; case (b) damage at element 20; case (c) damage at element 30, (d) damage at elements 3,20,30.

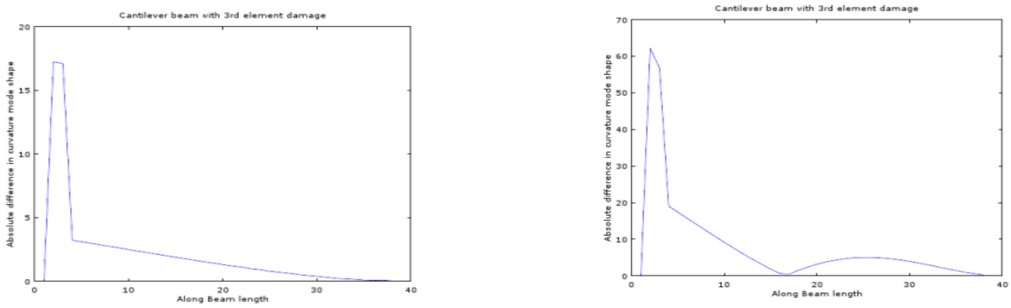


Figure 3: Mode Shape Curvature difference for damaged cantilever (element 3);(a) mode 1;(b) mode 2

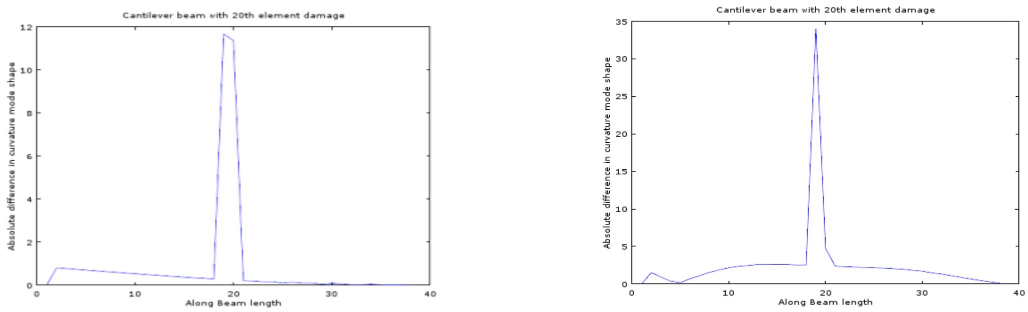


Figure 4: Mode Shape Curvature difference for damaged cantilever (element 20);(a) mode 1;(b) mode 2;

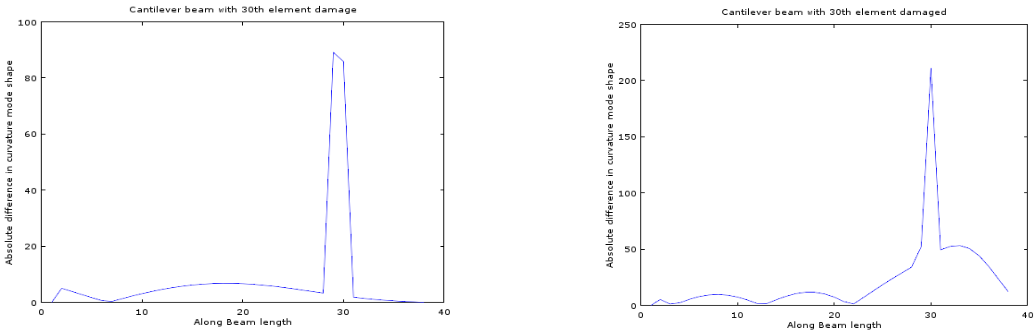


Figure 5: Mode Shape Curvature difference for damage cantilever (element 30);(a) mode 1;(b) mode 2.

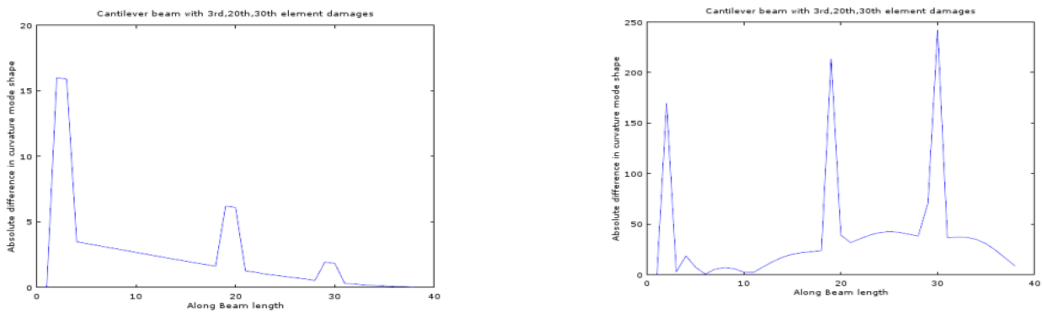


Figure 6: Mode Shape Curvature difference for damaged cantilever (element 3,20 ,30);(a) mode 1;(b) mode 2.

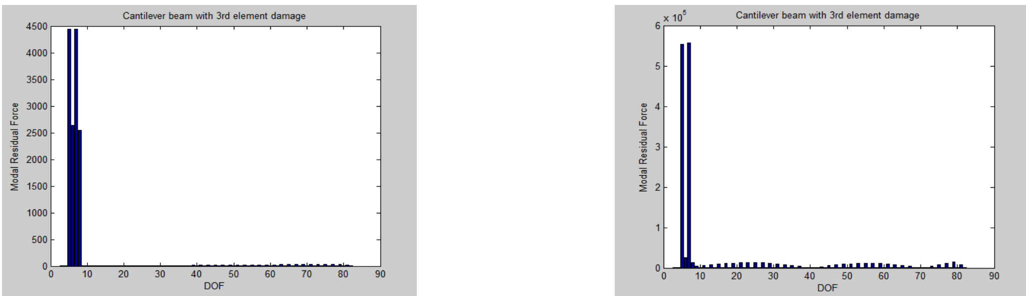


Figure 7: Residual force results for damaged cantilever (element 3);(a) for mode 1;(b) for mode 2

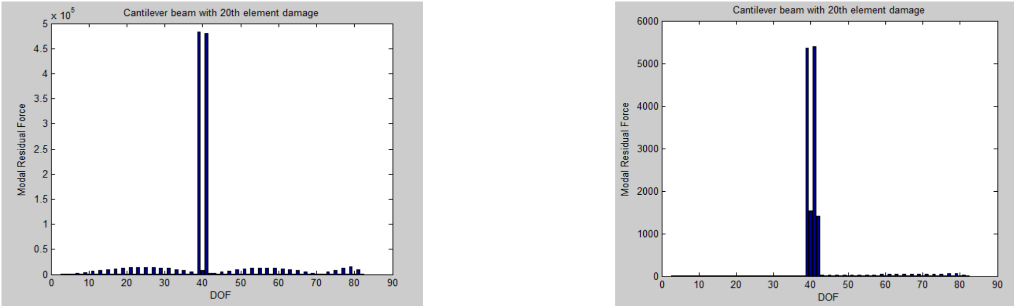


Figure 8: Residual force results for damaged cantilever (element 20);(a) for mode 1;(b) for mode 2

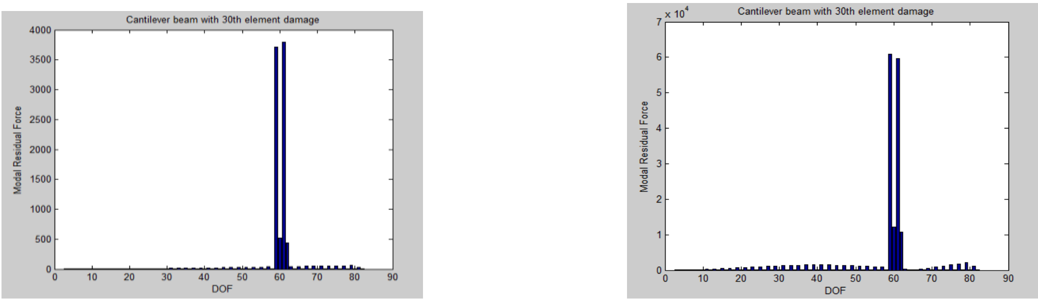


Figure 9: Residual force results for damaged cantilever (element 30);(a) for mode 1;(b) for mode 2

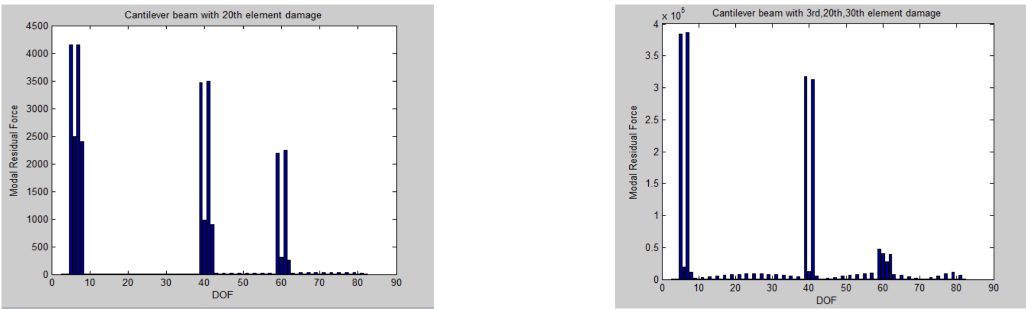


Figure 10: Residual force results for damaged cantilever (element 3,20,30);(a) for mode 1;(b) for mode 2

B.Results of Fixed beam

Analysis of similar type with typical cases of damage was also done with the fixed beam .Case 1 damage in the middle element (20^{th} element).Case 2 damage at three different locations same as that of case 4 of cantilever beam. The percentage change in frequency, MAC is listed in Table 5 .Response due to this method is same as that of cantilever beam, it cannot locate the damage but it can detect the presence of damage in the system.

***Table 5: Natural frequency and MAC values of the first five modes of healthy and damaged fixed for Case 1 damage*.**

Mode	Healthy	Damaged	Difference in frequencies(%)	MAC(%)
1	38.75	35.72	7.82	0.99
2	106.74	106.59	0.001	0.99
3	209.05	190.183	0.090	0.98
4	345.12	343.68	0.419	0.99
5	514.75	479.89	6.72	0.97

Table 6: Natural frequency and MAC values of the first five modes of healthy and damaged fixed for Case 2 damage.

Mode	Healthy	Damaged	Difference in frequencies(%)	MAC(%)
1	38.75	32.14	17.05	0.99
2	106.74	94.11	11.83	0.98
3	209.05	174.00	16.76	0.98
4	345.12	340.60	1.30	0.99
5	514.75	471.29	8.44	0.98

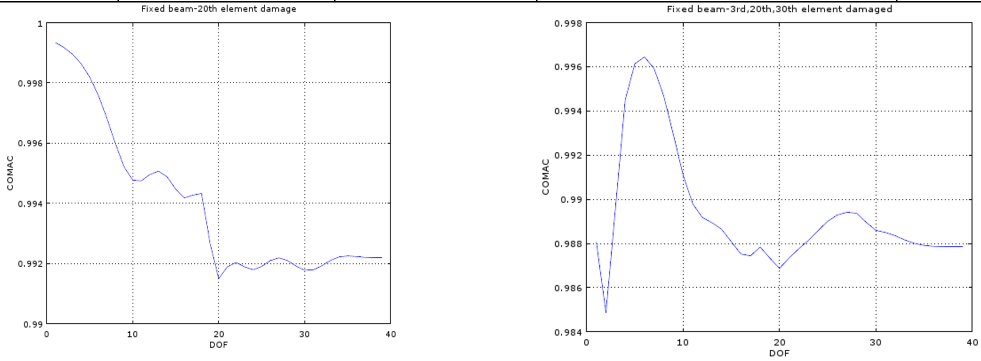


Figure 11: COMAC values of the healthy and damaged fixed beam for the two typical damage cases; case (a) damage at element 20(middle element); case (b) damage at elements 3,20,30.

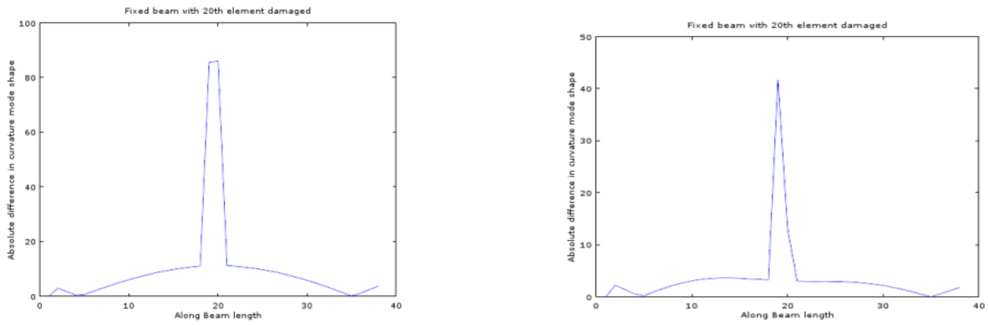


Figure 12: Mode Shape Curvature difference for damage fixed (element 20);(a) for mode 1;(b) for mode 2

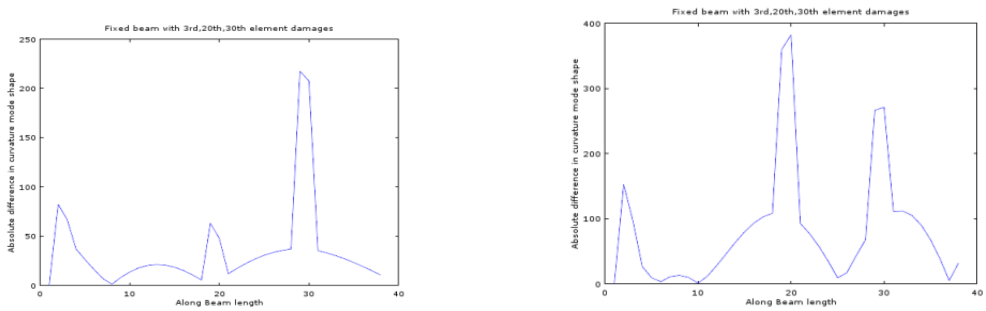


Figure 13: Mode Shape Curvature difference for damage fixed (element3, 20,30);(a) for mode 1;(b) for mode 2

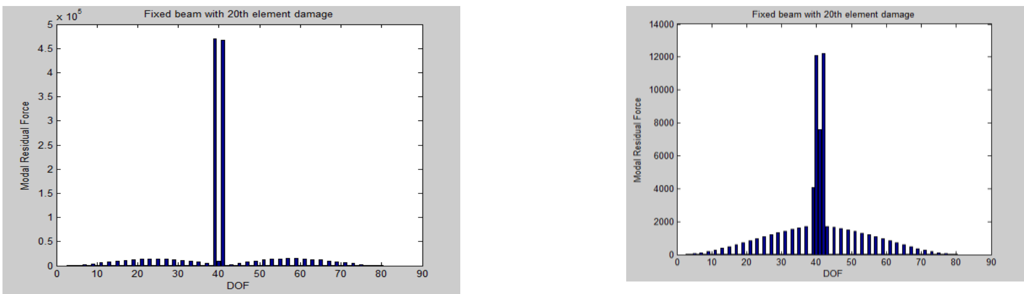
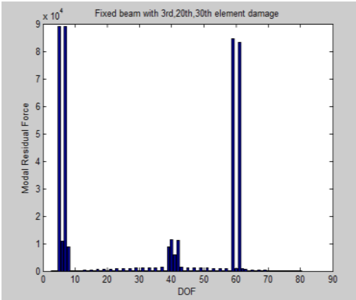


Figure 14: Residual force results for damaged fixed (element 20);(a) for mode 1;(b) for mode 2



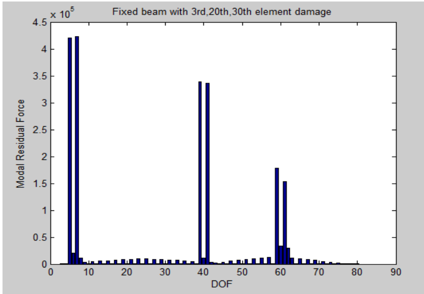


Figure ***10: Residual force results for damaged fixed (element 3,20,30);(a) for mode 1;(b) for mode 2.***

VI. CONCLUSION

The results obtained from cantilever beam model and the fixed beam model demonstrate the effectiveness of the different damage detection methods. Frequency and mode shape based damage detection technique is an efficient method to detect damage in beam like structures. But from the above studies it have revealed that changes in frequencies and MAC alone may not provide enough information for damage detection. It just ensures there is some damage occurred globally. COMAC locates the damage. It is an effective parameter for determining the damage location. Mode shape curvature is a better option to detect the damage and its location since it accurately locates the damage .Modal residual force plots also shows convincing results and the damage is exactly located but limited for practical applications in detection and location of damage.

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