International Journal of Engineering and Advanced Technology (IJEAT)
ISSN: 2249-8958 (Online), Volume-8 Issue-5, June 2019

Analytical Verification of Applicability of Higher Order Derivatives of Modal Parameters for Damage Prediction in Concrete Beam Structure under Different Crack Lengths

S. Brahma Naidu, Dr. I. Yamini Sreevalli, Dr. K. Muthumani

Abstract: Any engineering structure under various loading and support conditions may damage fully or partially with single or multiple damage locations. Such damage causes reduction in stiffness of member which in turn leads to shortening of serviceability life or safety of a structure. Hence, it is certainly become important to predict the location of damage in structure before assessing the intensity of damage severity. Therefore, in this present research paper damage location in a concrete beam structure was predicted using computational modal analysis (i.e., Mode shapes, Mode shape curvatures and Curvature Damage factor and higher order derivatives)and verified the applicability of higher order modal parameters in determining damage location with required consistency under varying crack lengths.

Index Terms: Mode shapes, Curvature, Stiffness, Damage Factor (CDF), Modal parameters, Safety, Serviceability.

I. INTRODUCTION

Structural members will have significant effect on the vibrational behaviour under dynamic conditions. The reduced stiffness of the structure in turn decreases in natural frequencies and changes in corresponding mode shapes. A mode shape is a specific pattern of vibration executed by a structural system at a specific frequency. Different mode shapes will be associated with different frequencies. In vibrational analysis, modes of vibration are the different types in which the system tries to oscillate naturally, i.e. without any excitation force. The frequency of oscillation is termed as modal frequency (or natural frequency) and the shape made by the system is called mode shape. Therefore, the locations of single or multiple damages can be detected with reference to the fact that any damage in a structure alters its dynamic characteristics or the modal parameters such as natural frequency and its associated mode shapes. The mode shape of the damaged structure may seem to be similar as the mode shape of the undamaged structure. But the derivatives of the mode shapes can clearly define discontinuity at the damaged location. Hence, the present research focuses on effective implementation of curvature mode shapes, difference curvature mode shapes and curvature damage factor as detection tools for better prediction of damage location in Concrete Beam structure and thus verified the fault detection efficiency under varying crack lengths along beam span.

Manuscript published on 30 June 2019.
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II. DISTRESSES IN CONCRETE BEAM

Structural members may be affected by various types of distresses such as, structural deformation under loads, expansion or contraction due to changes in temperature, corrosion, improper design and detailing, and inadequate quality control and also by other causes like floods, fire, vibrations, and earthquakes. Under the influence of one or more such causes, a bridge may be damaged partially or fully. The most common deterioration mechanisms in Concrete beams include alkali aggregate reaction, freeze thaw cycling, creep and shrinkage, and temperature effects etc. In addition to these environmental factors, overloading, poor design, detailing and inadequate inspection and maintenance constitute the other main causes of deterioration and failure of concrete structures. As a result of these different types of deterioration, the safety and serviceability of beams are reduced and their useful service lives are shortened.

III. STAGES OF STRUCTURAL DAMAGE DETECTION

Structural damage detection consists of four different levels (Rytter 1993). The first level determines the presence of damage in the structure. The second level includes locating the damage, while the third level quantifies the severity of the damage. The final level uses the information from the first three steps to predict the remaining service life of the damaged structure. After discovering the damage occurrence, damage localization is more important than damage quantification. In the last years, numerous methodologies have been proposed to accurately locate structural damage using SHM data with the aim to extract features that will be sensitive to the changes occurring in the structure and relatively insensitive to other interfering effects (e.g. operational and environmental effects). The damage location assurance criterion (DLAC) and multiple damage location assurance criterion (MDLAC) based on the changes in natural frequencies have been proposed by Messina *et al*. (1992, 1998).

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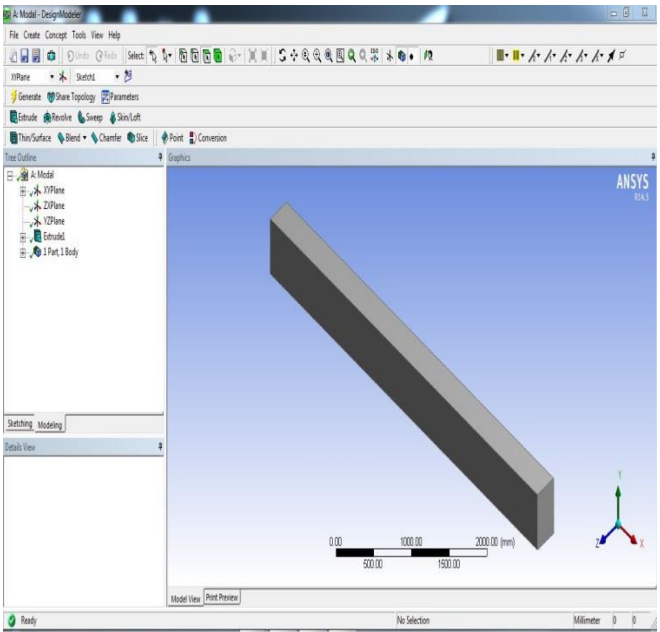
The DLAC and MDLAC criteria are used to locate single and multiple damages, respectively. Damage detection from changes in mode shape curvature has been proposed by Pandey *et al*. (1991). The curvature of mode shapes was investigated as a possible parameter for locating damage in a beam structure. The results showed that the absolute difference in the curvature mode shapes and curvature damage factor are effectively utilized in prediction of damage. It is also verified that under varying crack lengths it is found to be accurate in localization of single or multiple damages.

IV. MODE SHAPE CURVATURE BASED METHODS

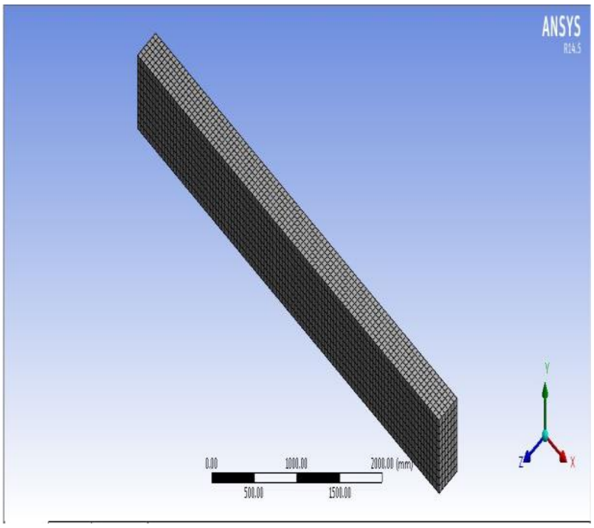
It has been shown by many researchers that the displacement mode shape itself is not very sensitive to small damage, even with high density mode shape measurement. As an effort to enhance the sensitivity of mode shape data to the damage, the mode shape curvature (MSC) is considered as a promising feature for damage identification. It is first noted that for beams, plates and shells there is a direct relationship between curvature and bending strain. The value of curvature at a point in the structure is equal to M/EI, so if the stiffness at a point reduces by damage, the curvature at that point will increase. This can be used to locate damage in the structure. Absolute change in mode shape curvatures can be used as an efficient indicator of damage(s).

V. MODAL ANALYSIS

Initially, an intact concrete beam of span 5000mm, width 300mm and depth 500mm was modelled in Ansys 14.5 work bench with assigning material properties of concrete nonlinear. Then the beam is coarsely meshed with an elemental size of 50mm with fixed support condition at its both ends. Named selection was created with all bottom central node points which would represent the nodal displacements at concerned mode shapes.



Modelled undamaged intact Concrete Beam



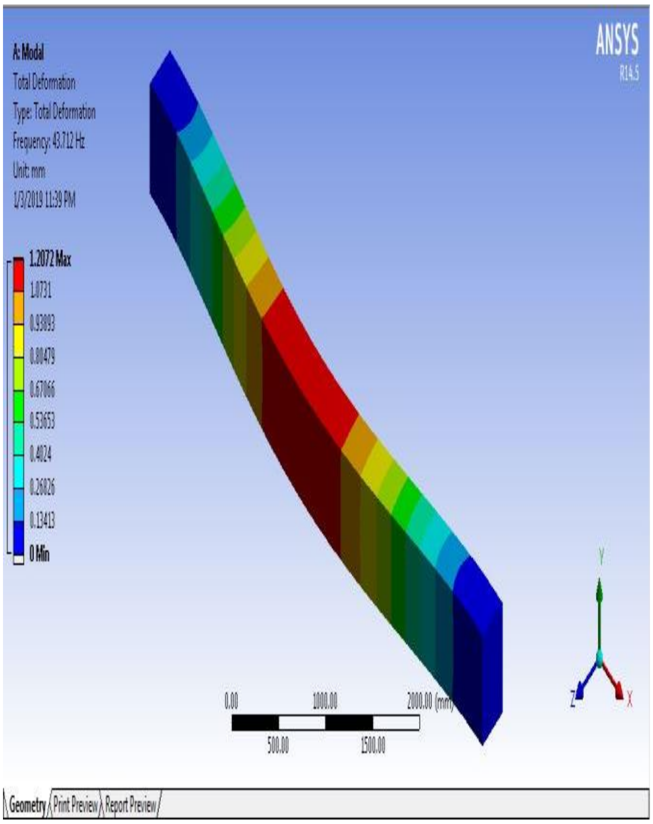
Meshing of Intact Beam

Later, modal analysis is carried out and total mode shape deformations along y axis direction for first three modes were extracted. Mode shape curvatures for respective first three modes are then calculated using central difference approximation as given below.

$$\Phi''_{q,i} = \frac{\Phi_{q-1,i} - 2\Phi_{q,i} + \Phi_{q+1,i}}{l_e^{\,2}}$$

Where *le* is the element length.

Also, Φ*q*,*i*represents the modal displacement for the *ith* mode shape at co-ordinate *q*.



Undamaged Beam, Mode-1

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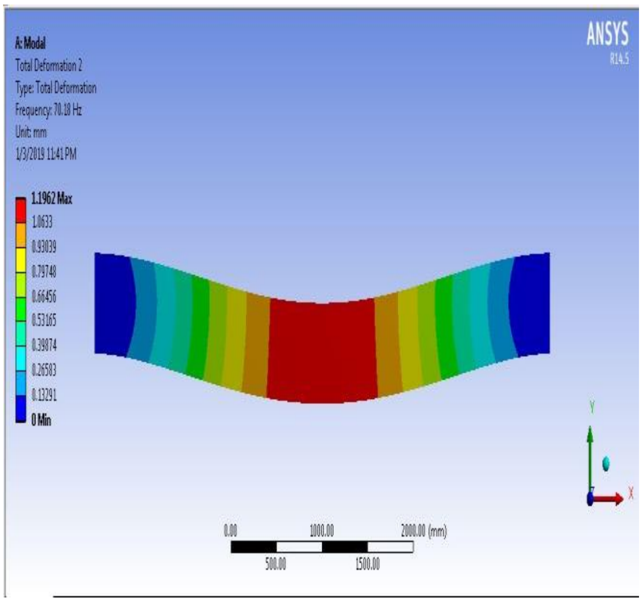
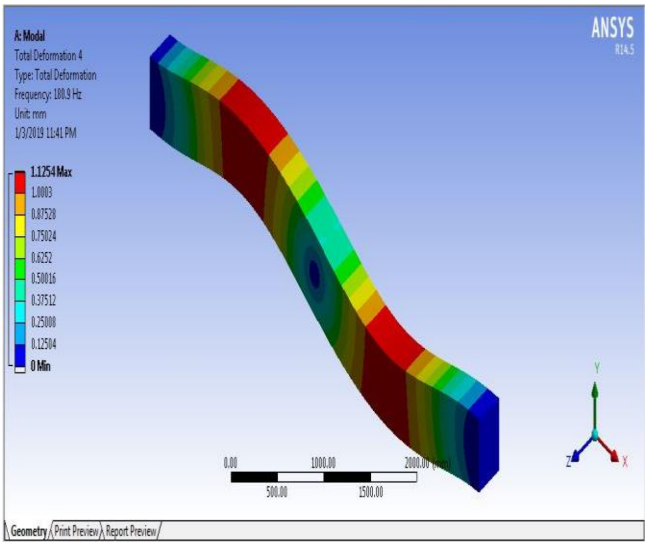
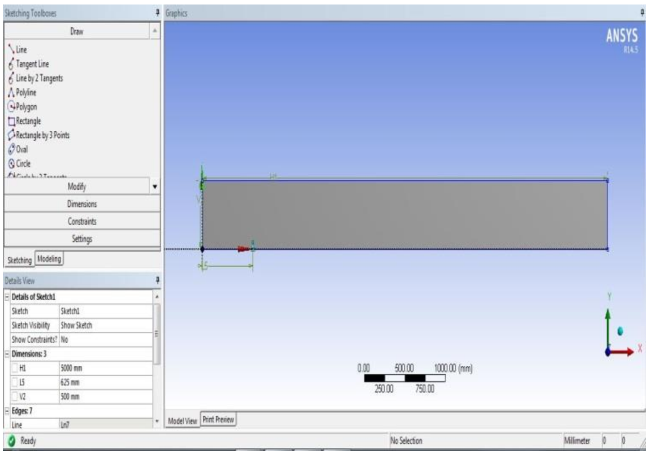


Undamaged Beam, Mode-2

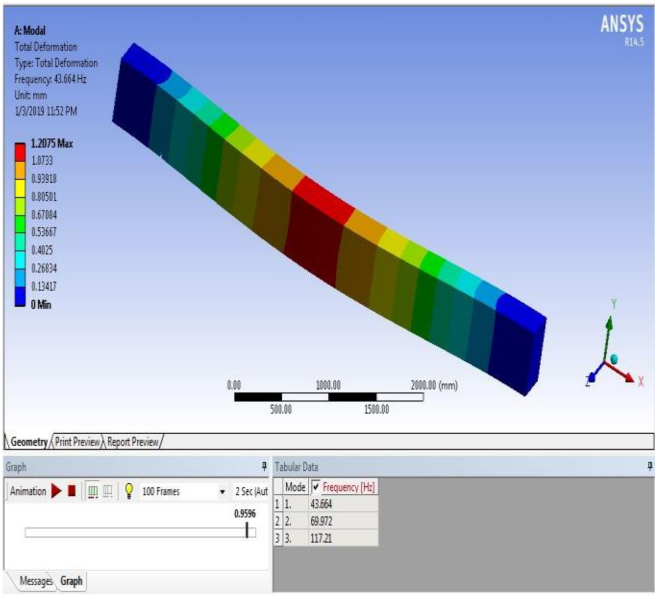


Undamaged Beam, Mode-3

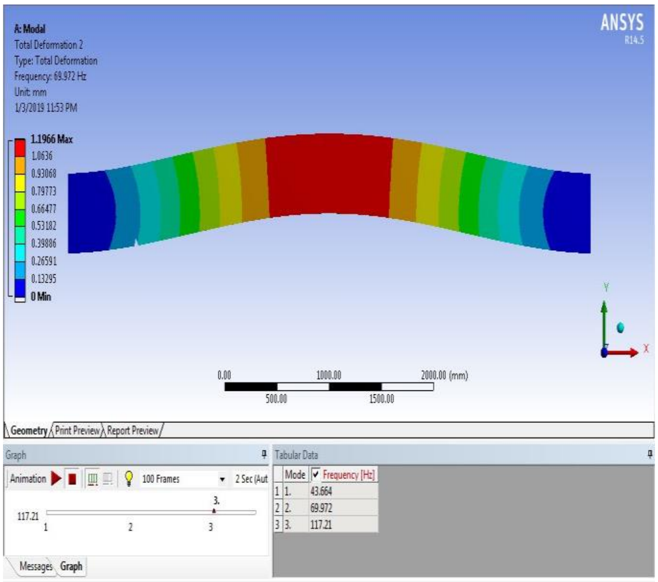
Similarly a damaged concrete beams of same material properties are simulated with a crack of 50mm depth is located at L/8 span and L/4 span(i.e, at 625mm & 1250mm from left fixed support respectively). Modal analysis was conducted and curvature mode shapes for first three modes are calculated.



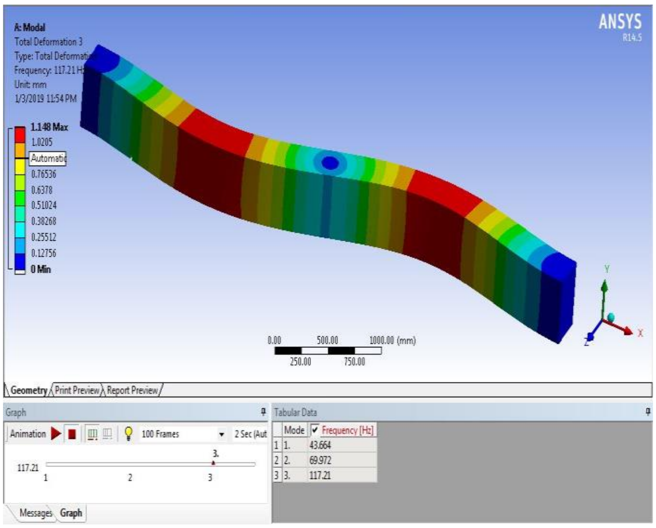
Cracked Beam @ 625mm



Cracked Beam @ 625mm, Mode-1



Cracked Beam @ 625mm, Mode-2



Cracked Beam @625mm, Mode-3

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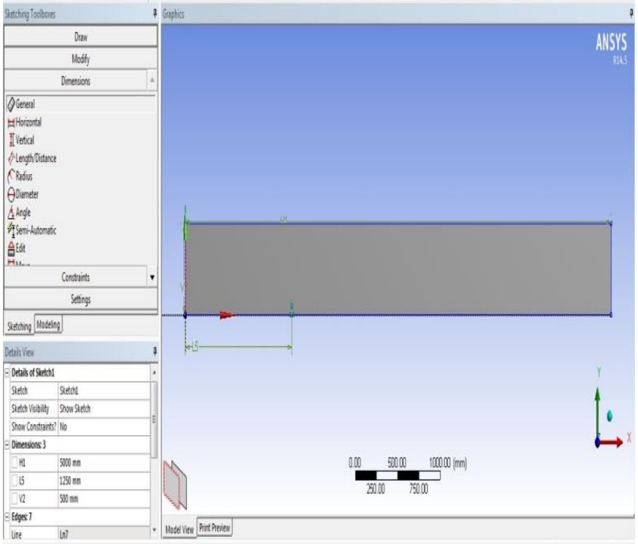
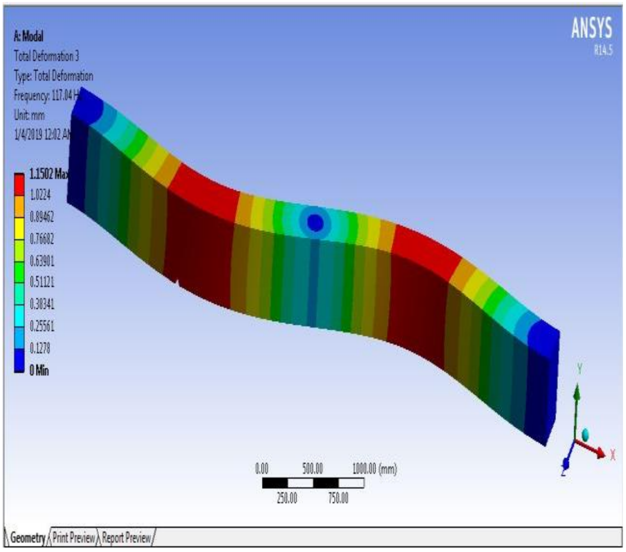
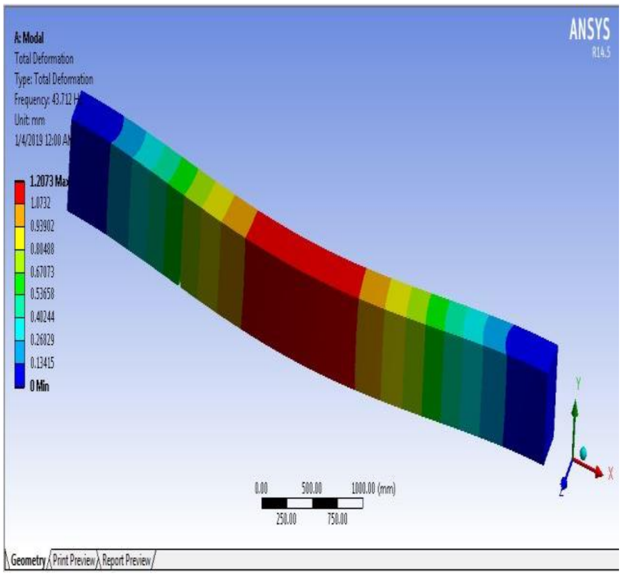


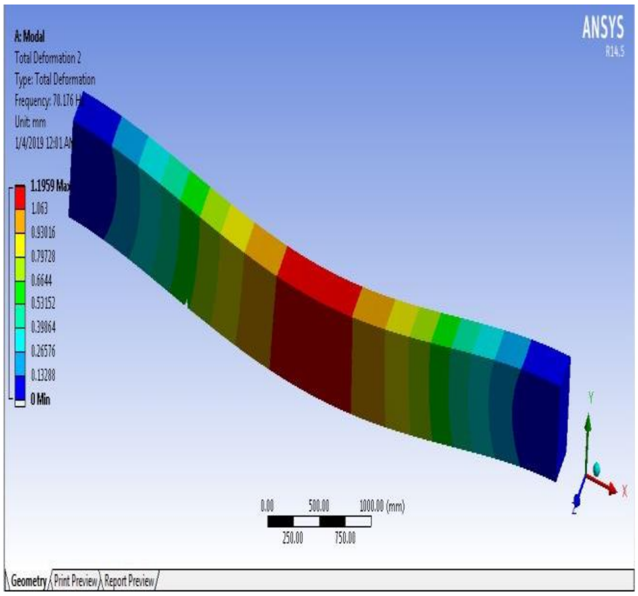
Cracked Beam @ 1250mm



Cracked Beam @ 1250mm, Mode-3



Cracked Beam @ 1250mm, Mode-1

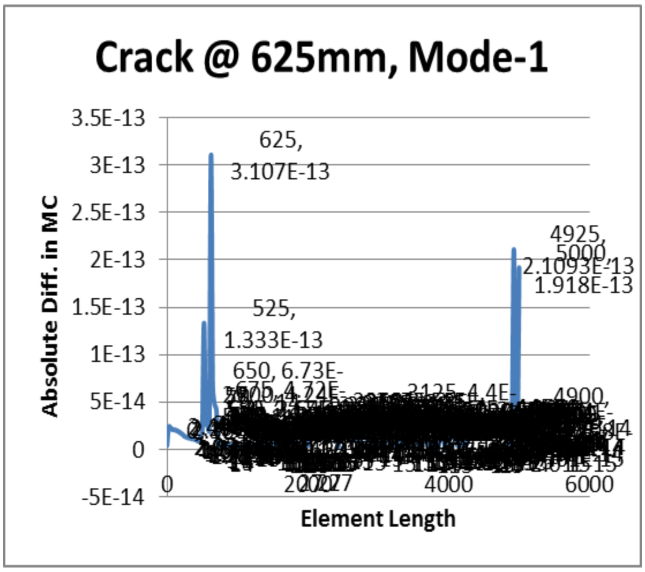


Cracked Beam @ 1250mm, Mode-2

Further, Absolute difference in curvature mode shapes are computed as shown below

$$MSC_q = \sum_{i=1}^{nm} \left| (\Phi_{q,i}^{damaged})'' - (\Phi_{q,i}^{undamaged})'' \right|$$

Plots were made for Absolute difference in curvature mode shapes against element length for all three modes at both cracked cases as shown below



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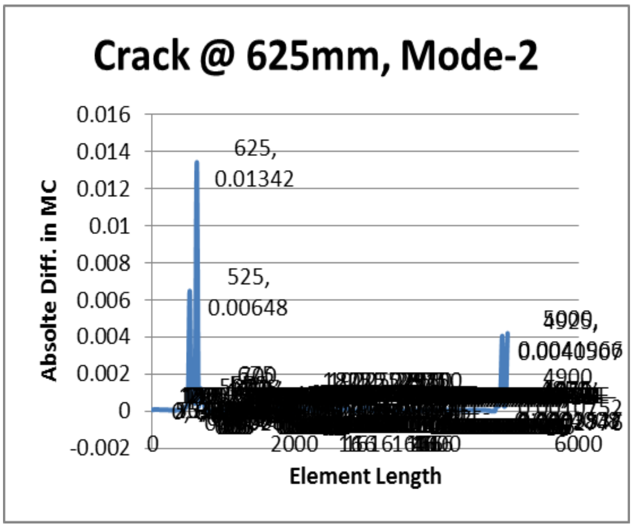

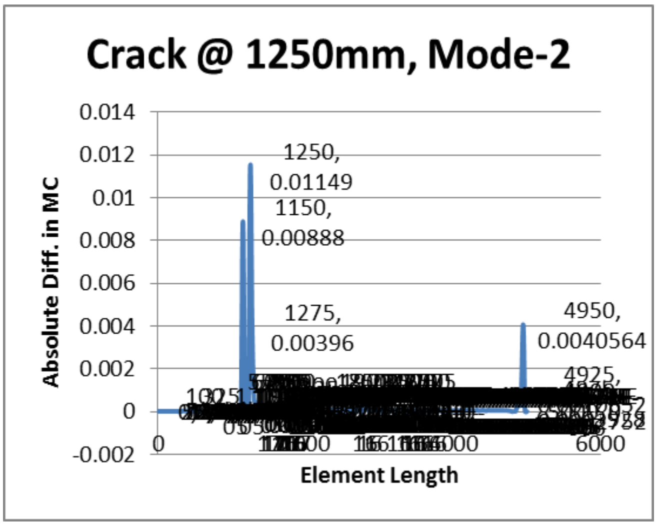

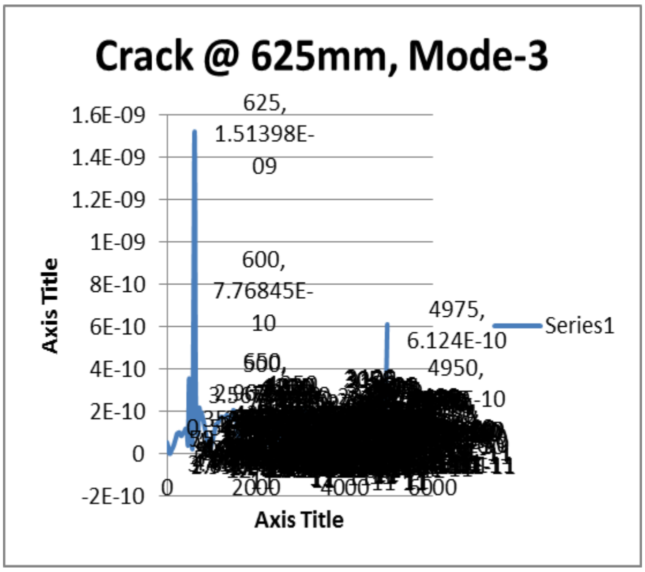

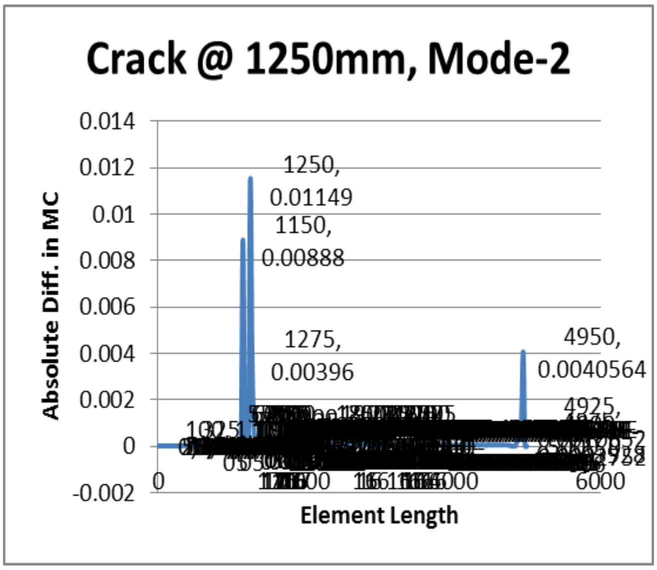

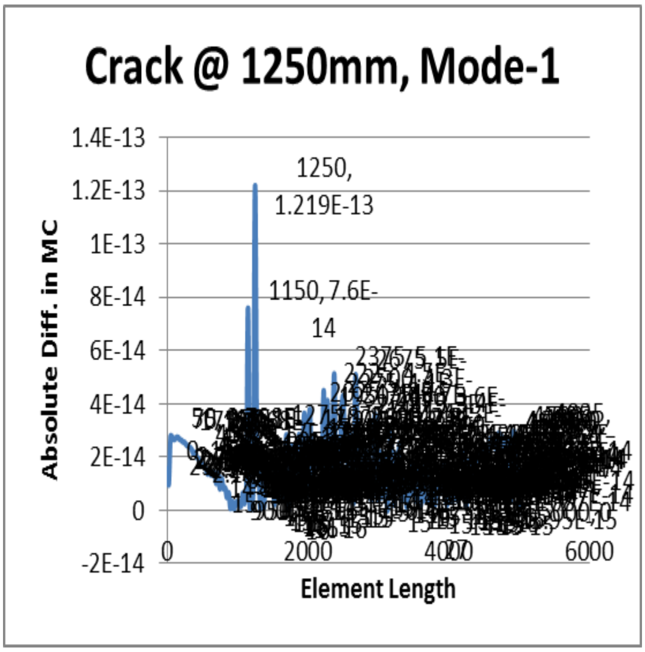

Moreover, for considering the effect of higher modes of a structure, Curvature damage factor (CDF) is then derived by average of Mode shape curvature difference of three modes with the expression given below.

$$CDF_q = \frac{1}{nm}\sum_{i=1}^{nm}\left|\left(\Phi_{q,i}^{\text{damaged}}\right)'' - \left(\Phi_{q,i}^{\text{undamaged}}\right)''\right|$$

Where *nm* is the number of modes to be considered.

Similar to earlier plots, Graphs are thus drawn for CDF and elemental lengths which accurately located the damage at 625mm and 1250mm from left end of the beam respectively.

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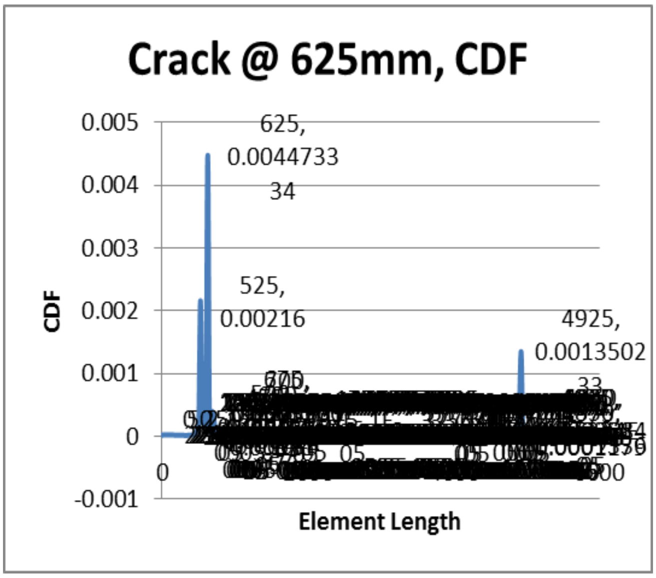

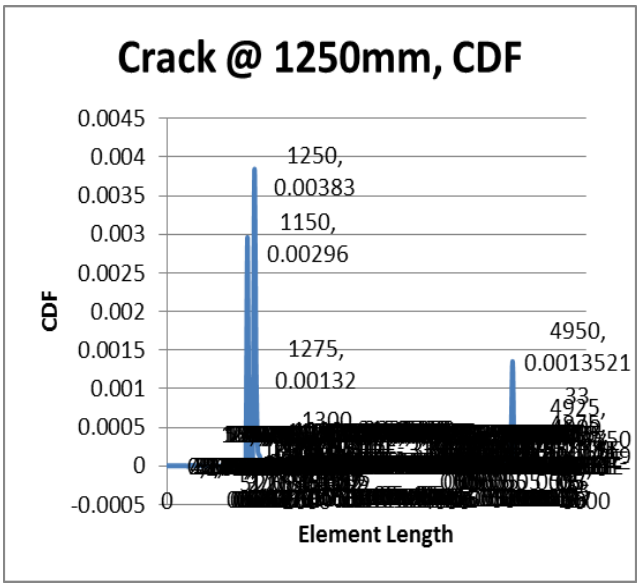

VI. CONCLUSION

The following conclusions are drawn based on the computation modal analysis conducted

- From the plots drawn between Absolute difference in curvature mode shapes and element length, it found that higher derivatives of mode shape are quite efficient in locating the damage with distinct peaks in graphical curves.
- It is also observed Curvature Damage Factor (CDF) was appropriately suitable to minimize the error of locating the damage because of lower order modes are not very sensitive to minor damages and considered for better prediction of Crack Location.
- It is also verified that by varying the crack length from L/8 to L/4 (i.e., from 625mm to1250mm) curvature damage factor found to be effective in accurate detection of crack location.
- With the above obtained results it is verified that higher order derivatives of modal parameters can be applied for effective localization of single or multiple damages in a structure.

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