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A Numerical Study on Damage Assessment of RCC Beams

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Abstract—*In recent years, considerable research has been carried out on the use of mode shape based methods to detect structural damage in various types of structures. Damage is identified be comparing the typical dynamic properties of the damage and undamaged structures. In this study, modal flexibility method and modal curvature method are used to detect crack damage in finite element models of plane concrete beams. Any reduction in structural stiffness and increase in damping in the structure may indicate structural damage or degradation. The crack damage is simulated using discontinuing element model method. It is observed that these methods effectively detected the existence of damage and also able to located the position of damage for single and multiple damage scenarios for beams.*

1. INTRODUCTION

Structural health monitoring is gaining high importance in conjunction with damage assessment and safety evaluation of structures .The ultimate goal of Structural health monitoring is to diagnose structural damage at the earliest possible stage so that human life can be protected [1-4].

Every nation is spending millions of Dollars every year for the rehabilitation and maintenance of civil engineering structures. Failure of civil infrastructure to perform at optimum level may affect the gross domestic production of the country. Strength of structures decreases due to continuous loading and impact of environment. Hence, it should be evaluated if the performance of the structure is satisfactorily or not after such deterioration. If structural strength falls down below a certain threshold level, sudden failure is possible which might result in accident and affect the serviceability of the structure. Early detection of damage is of special concern for civil structures. If not identified in time, damage may have serious consequences for safety of occupants. There are several natural events which may affect the strength of structure. It should be ensured that the structure is safe after such natural events. If structures are monitored periodically or continuously, better understanding will be achieved about the behavior of the structure [5-9].

The earlier studies on dynamic response based damage detection used the natural frequency as a parameter by many researchers – (adams et al., 1978; Cowley and adams , T , 1998; zhou et al. 2000) reviewed some of the vibration based detection techniques for identification of delamination in composite structures. Lee and Chung (2000) used the first four frequencies of a simulated cantilever beam to locate a single crack and assess their corresponding effectiveness the crack depth was then approximated iteratively to match the frequency as closely as possible before the location of the crack was finally defined. Chinchalkar (2001) developed a numerical method for determining the crack location in a damaged beam [10-14].

The object of the study is as follows:

- To study different methods of damage assessment
- To model plain concrete beams, with different support conditions, in software as per requirements of study.
- To study variation in dynamic properties of beam, with and without damage.
- Plot mode shapes, both displacement and curvature for different modes.
- To study the change in modal flexibility matrix for different crack sizes.
- Plot of Damage Index using modal strain energy for different damage cases.
- Plot of Curvature Damage Factor for different damage cases.

2. EVALUATION OF DAMAGE DETECTION

A study is made to compare the change in frequencies, obtained due to the presence of a crack in a plane concrete beam with an uncracked beam. The general purpose FEM analysis software SAP 2000 was used in the modal analysis to obtain mode shapes. The finite element analysis was extended to two crack locations with four different crack sizes to obtain the change in frequencies. In the analysis, width and depth of cracks were varied keeping the length constant as the length of beam. The following Damage detection algorithms were used to locate the damage in the beam buy using FE analysis. The modal parameters that change locally are mode shapes, i.e., displacement mode shape and curvature mode shape.

2.1 Modal Based Damage Detection Parameters

Curvature mode shape method:

Mode shape curvature (k) for beam can be estimated numerically from the displacement mode shapes, using central difference approximation (pandey et al. 1991).

$$k = \phi_{ji} = \phi_{(j+1)i} - 2\phi_{ji} + \phi_{(j-1)i} / l^2$$

Where,

i-Mode shape number

j-Node number

l-Distance between the nodes

ϕ_{ji} - modal displacement of the coordinate j at mode i.

Thus the existence and extent of damage can be estimated by measuring the amount of change in the mode shape curvature.

Damage index method

The damage index method was developed to locate damage in structures given their characteristic mode shapes before and after damage .For a structure that can be represented as a beam, a damage index, β, is developed based on the change in strain energy stored in the structure when it deforms in its particular mode shape. For location jth on the beam this change in the ith mode the damage index β ij was defined as

$$\beta_{ij} = \frac{\left((\varphi_d^{"})_{ij}^2 + \sum_1^{i\max} (\varphi_d^{"})_{ij}^2) * \sum_1^{i\max} (\varphi_{ud}^{"})_{ij}^2 \right)}{\left((\varphi_{ud}^{"})_{ij}^2 + \sum_1^{i\max} (\varphi_{ud}^{"})_{ij}^2) * \sum_1^{i\max} (\varphi_d^{"})_{ij}^2 \right)}$$

Where,

ϕ_d - Curvature in damage state

ϕ_{ud} -Curvature in undamaged state

i- Node location

j- Mode considered

Curvature damage factor

The difference in curvature before and after damage averaged over a number of considered modes is defined as the Curvature damage factor.

$$CDF = \frac{1}{N} \sum_1^{i} | \phi_{ud,i}^{"} - \phi_{d,i}^{"} |$$

Displacement mode shapes

Displacement mode shapes provide vital information regarding response of a structure or structural components. Regarding this analysis all the beams modelled are divided into ‘n’ shell elements. Therefore it is not feasible to take into account all degree of freedom.to overcome this effect joint displacement of shell elements at mid height of section are considered as displacement mode shapes for both damaged and undamaged case.

Modal flexibility matrix

It is defined as the accumulation of the contributions from all available mode shapes and corresponding natural frequencies.

The modal flexibility includes the influence of both the mode shapes and the natural frequencies. The modal flexibility matrix associated with the referenced degrees of freedom can be established from the following equation.

$$[F]=[\phi]\left[\frac{1}{\omega^2}\right][\phi]^T$$

$$\Delta[F] = [F^d] - [F^{ud}]$$

Where,

[F]- Modal flexibility matrix

[ϕ]-Mass normalized modal vectors

ω- Natural frequency

3. MODELING

Three different softwares are used in present analysis. Description of these softwares and their participation in analysis is mentioned below.

SAP 2000 – Modelling and Analysis

Microsoft Excel- Plotting of mode shapes and damage index

Matlab 2007 – Computation of Flexibility matrix

SAP 2000 is used to model plain concrete beams. The analysis of beams is based on Euler-beam theory, i.e., shear deformations are not considered. Area section is used to model beam. Element type is selected such that assumptions of Euler-beam theory are satisfied. Therefore ‘thin shell’ is used to model the beam.

Three different types of beams are selected for the purpose of analysis.

Simply supported beam.

Cantilever beam

‘Grid only’ option is used to create beam models. for all three beams specified above grid is created such that sectional view along the longitudinal axis of beam is divided into 'n' no. of rectangle representing minimum size of crack to be provided.

DIMENSIONS OF BEAM:

For all three cases same cross-section and span length is considered.

Cross section - 230 x 300 mm

Span length - 3000 mm

DIMENSION OF CRACK AND CRACK LOCATION:

Crack sizes-

For all 3 beams mentioned, 4 crack sizes were used mentioned below (fig. 1-3),

30mm x 20mm x 230mm

30mm x 40mm x 230mm

60mm x 20mm x 230mm

60mm x 40mm x 230mm

Crack location-

Crack locations (table 1) for beams with different support conditions are chosen such that, locations where slope of curvature is zero are skipped.

Table 1: Location of crack in different beams

Beam type	Case 1	Case 2	Case 3
Simply supported beam	At L/4	At L/4 & 2L/5	N.A
Fixed beam	At L/4	At L/4 & 2L/5	N.A
Cantilever beam	At L/10	At L/10 & L/2	At L/10, L/2 & 9L/10

SIMPLY SUPPORTED BEAM:

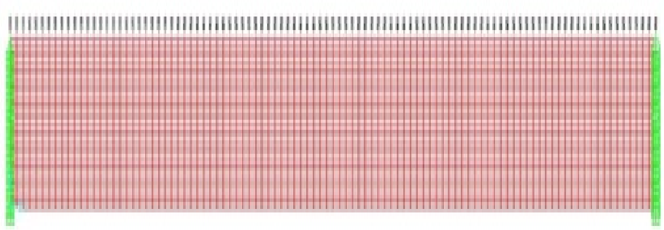


Fig. 1: XZ view of undamaged simply supported beam

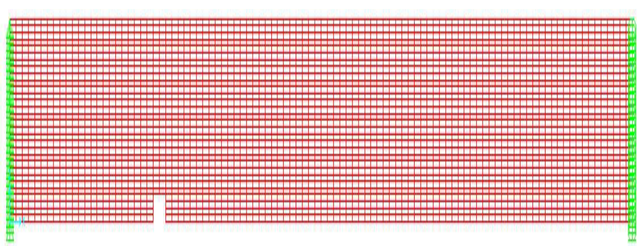


Fig. 2: Crack at L/4 in simply supported beam

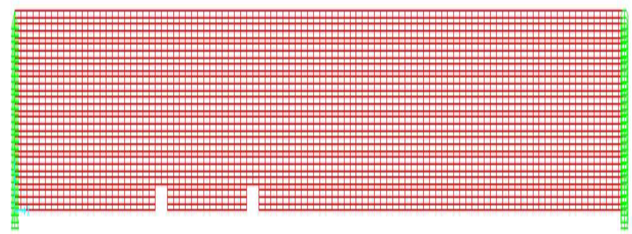


Fig. 3: Crack at L/4 and 2L/5 in simply supported beam

4. RESULTS AND DISCUSSION

As discussed above two damage detection techniques are studied in this analysis, frequency based, mode shape based and modal flexibility based.

Comparative results and plots obtained from both methods are discussed below. And the same can be divided in 3 parts as shown.

Results of time period, frequency and natural frequency are arranged in tabular form.

Plots are shown for displacement mode shape, curvature mode shape, and damage index and curvature damage factor.

Matrices of change in flexibility and a plot to demonstrate it.

Modal analysis results:

Time period:

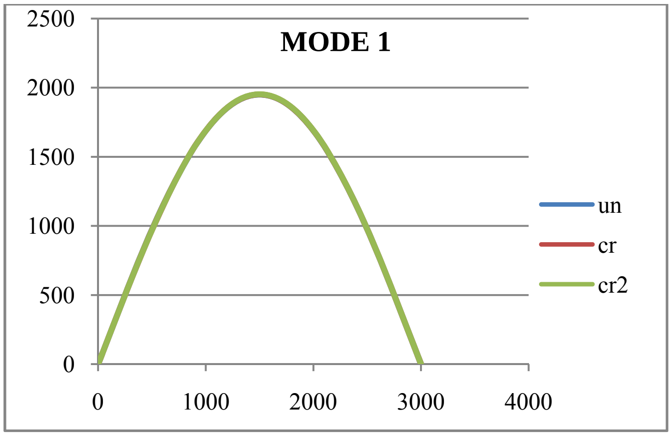
Comparison (table 2) between time periods at different modes for all mentioned beams.

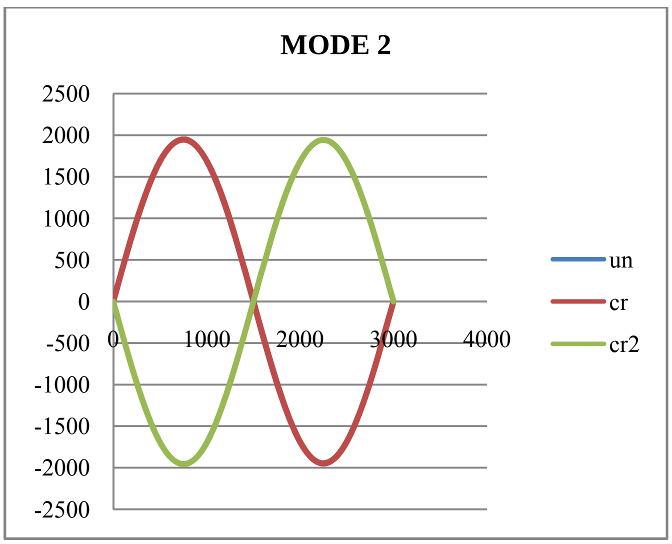
Table 2: Comparison b/w time periods at different modes for simply supported beam

SIMPLY SUPPORTED BEAM				
TIME PERIOD (Sec)				
Crack size (mm)	**Crack location**	**Mode1**	**Mode2**	**Mode3**
UNCRACKED		0.002836	0.001417	0.000945
30 X 20	L/4	0.002836	0.001417	0.000946
	L/4 & 2L/5	0.002835	0.001418	0.000946
30 X 40	L/4	0.002839	0.001416	0.000946
	L/4 & 2L/5	0.002837	0.001418	0.000948
60 X 20	L/4	0.002836	0.001416	0.000946
	L/4 & 2L/5	0.002834	0.001417	0.000946
60 x 40	L/4	0.002838	0.001415	0.000946
	L/4 & 2L/5	0.002835	0.001417	0.000949

Displacement mode shapes

FIXED BEAM





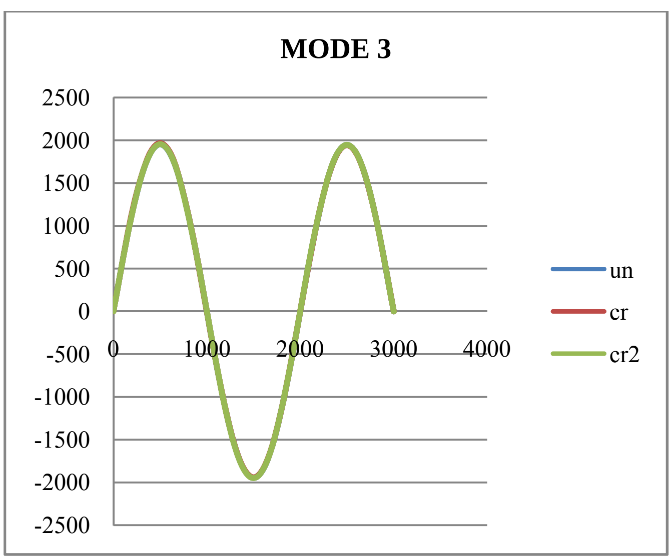


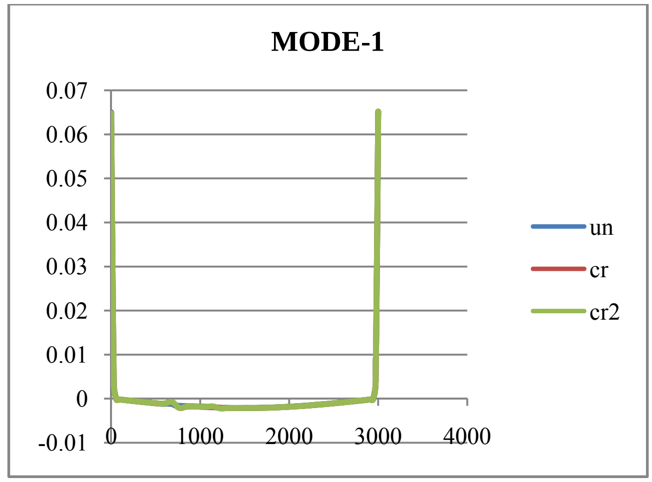
Fig. 4: Showing cracks of 30mm X 20mm at L/4 and 2L/5

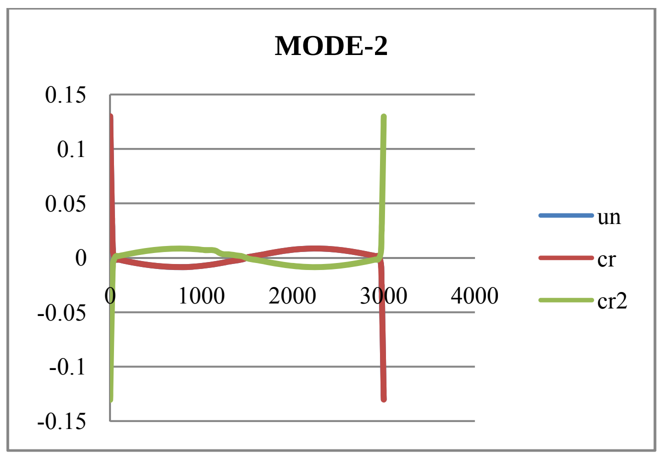
As it can be seen from above plots (fig. 4) that effect of crack is clear only in higher modes of beam.

CURVATURE MODE SHAPE BASED PARAMETERS:

Curvature Mode Shape

FIXED BEAM





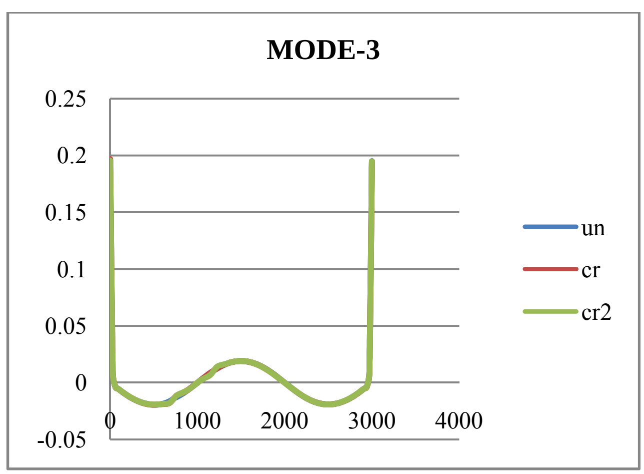


Fig. 5: Showing cracks of 30mm X 20mm at L/4 and 2L/5

Curvature mode shapes are better parameters to identify crack locations than displacement mode shapes as they are obtained from double derivation (fig. 5). Therefore even in smaller modes crack location can be identified.

Damage Index

CANTILEVER BEAM

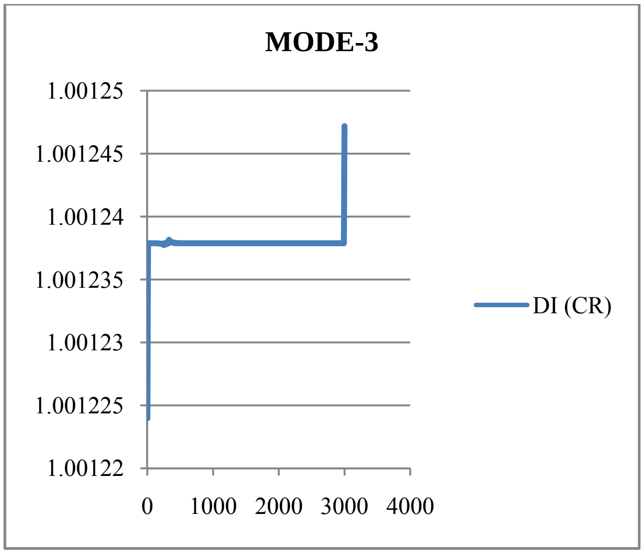


Fig. 6: Showing cracks of 30mm X 20mm at L/10

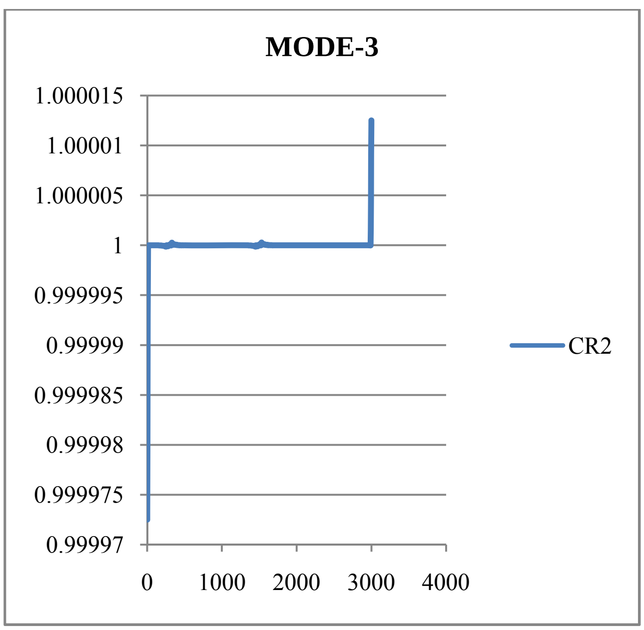


Fig. 7: Showing cracks of 30mm X 20mm at L/10 and L/2

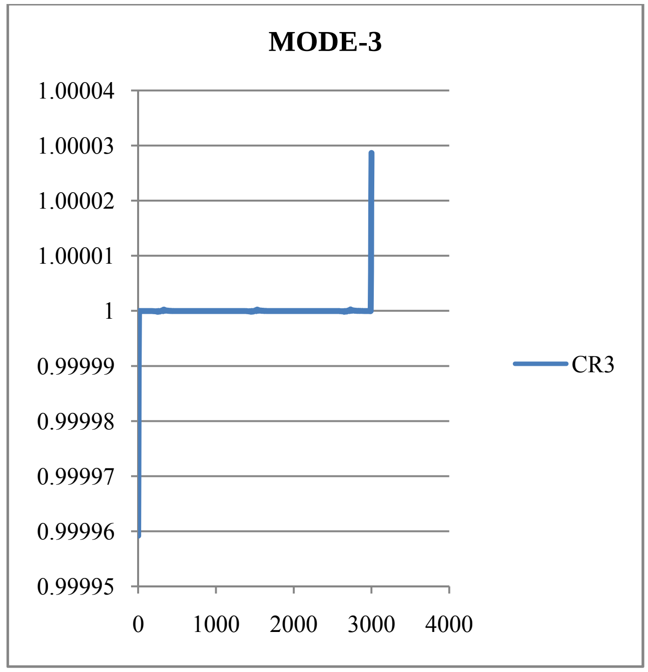


Fig. 8: Showing cracks of 30mm X 20mm at L/10, L/2 and 9L/10

Curvature Damage Factor

FIXED BEAM

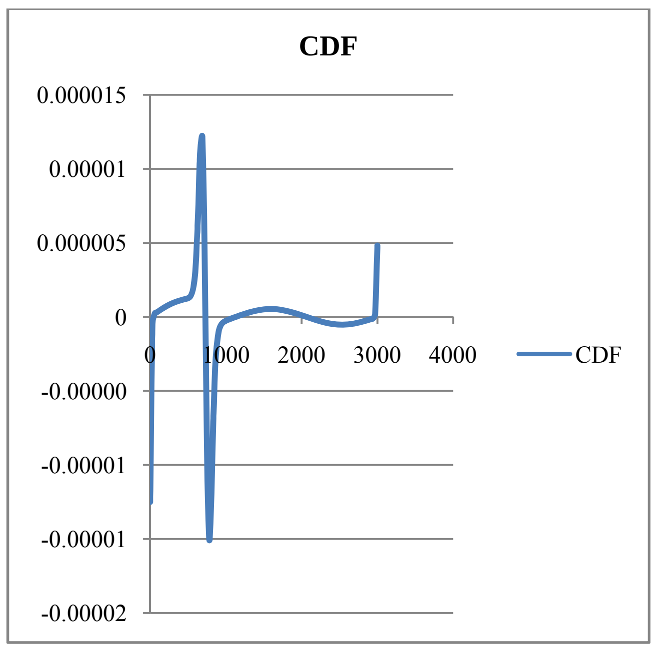


Fig. 9. Showing crack of 30mm X 20mm at L/4

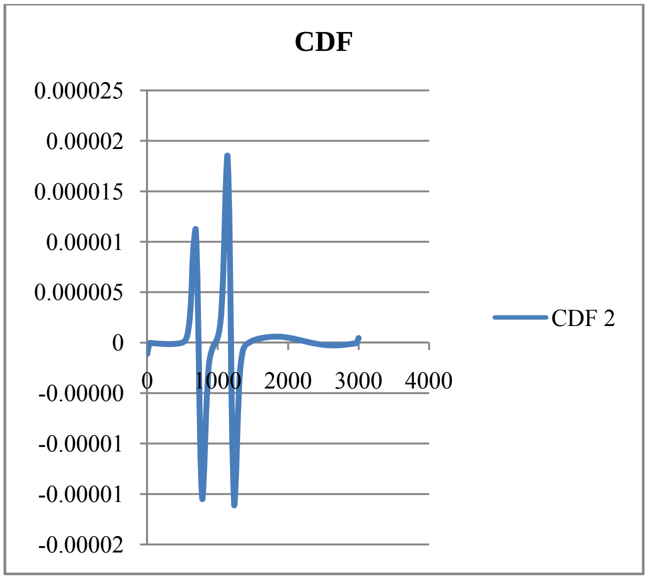


Fig. 10: Showing crack of 30mm X 20mm at L/4 and 2L/5

MODAL FLEXIBILITY MATRIX

FIXED BEAM

Crack size 30mm X 20mm at L/4

Plot of change in flexibility versus node number for crack case of 60 mm X 40mm where crack is provided at 2 locations.

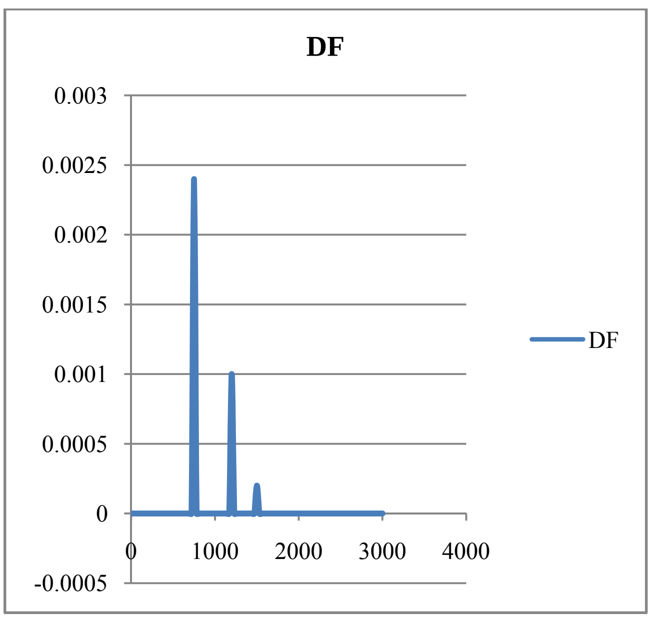


Fig. 11: Change in flexibility versus node number for crack case of 60 mm X 40mm

The above plot shows increase in flexibility at damage locations. It is because stiffness at these locations is reduced by cracks. A very slight peak is visible at mid span of beam where crack is not present; it may be because this location is close to the position of crack (fig. 6-11).

5. CONCLUSIONS

In this paper, two damage localization techniques (1) frequency based and (2) mode shape based evaluated from the modal parameters to assess the state of health of beams with different end conditions. Changes in modal flexibility matrix and damage index between the undamaged and damaged structure provide a basis for identification of localized damage. By applying the damage indices method using strain energy, to the beams, it is observed that the single or multiple damages can be confidently located with no localization error. The same can be said for curvature damage factor.

As modal flexibility method is considered, information for damage localization is not very clear from matrices showing change in flexibility. The implementation of this approach

Is more time consuming than approach for modal strain energy, as to obtain flexibility matrices long programming is done on matlab.

Modal parameters such as time period, natural frequency and frequency don't show significant changes in undamaged and damaged state. These parameters are helpful only in determining the state of beams that if crack is present or not. Once it is clarified any mode shape based method can be used to determine its location.

Strain energy method appears to be more sensitive, precise and convenient to determine than the modal flexibility matrix. As crack locations detected by the prior mentioned method are much clear.

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