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Structural Damage Identification Using Modal Curvature Differences

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***ABSTRACT**: Structural health monitoring is gaining high importance in conjunction with damage assessment and safety evaluation of structures. Vibration based damage identification techniques are global methods that are able to assess the condition of the entire structure at once. These methods are based on the fact that damage in a structure alters dynamic characteristics of the structure. The change is characterized by changes in the eigen parameters that are natural frequency, damping values and the mode shapes associated with each natural frequency. Damage can be identified by comparing the identified dynamic properties of the damage and undamaged structure. Modal-based damage detection methods, have received considerable attention in civil engineering applications. In the present work, method of modal curvature difference is employed for identifying and locating damage in beam models. Damage is considered as a localized reduction in structural stiffness. From the numerical simulations, it is 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. The method is found successful for detecting and locating the damage in the beam models with different boundary conditions.*

***Keywords:** - Damage detection, modal curvature, natural frequency, vibration based methods*

I. INTRODUCTION

Civil Engineering structures are prone to damage and deterioration during their service life. Damage assessment attempts to determine whether structural damage has occurred as well as the location and extent of the damage. The information produced by a damage assessment process can play a vital role in the development of economical repair and retrofit programme.

In the most general terms, damage can be defined as changes introduced into a system that adversely affects its current or future performance. Damage can be identified by making comparison between two different states of the system, one of which is assumed to represent the initial and often undamaged state [1].

In the light of current developments in modal testing and signal processing, the vibration-based methods have become the most promising non-destructive damage detection technique [2]. Among the vibration-based methods, modal-based damage detection methods, have received considerable attention in civil engineering applications [3]. Changes in the modal parameters of a structure imply changes in its mass, damping and/or stiffness properties and, therefore, serve as a basis for structural damage detection. The comparison between the modal parameters such as natural frequency, mode shapes of undamaged and damaged structure makes possible the identification of the location and the severity of damage.

Over the past three decades, intensive research has been undertaken in the field of vibration based damage detection, and many algorithms have been developed. Most of the work carried out use modal data such as modal frequencies and mode shapes, mode shape derivatives, modal strain energy etc.

Among the above said modal properties, natural frequency is widely used as it can be easily measurable [4, 5]. The state of damage can be detected from a decrease in natural frequencies and an increase in damping. Although changes in natural frequencies give a useful indication of the existence of damage, they cannot provide sufficient information to locate the damage since they are global properties of the system.

To overcome this drawback, mode shapes have been used for identifying the damage location [6]. Changes in mode shapes are more sensitive to local damage when compared to changes in natural frequencies. However, using mode shapes also has some drawbacks. First, damage is a local phenomenon and may not significantly influence mode shapes of the lower modes that are measured from the vibration tests of a large structure. Second, the extracted mode shapes are affected by environmental noise from ambient loads or inconsistent sensor positions. Also, an accurate characterization of the damage location the displacement mode shapes requires measurements in many locations [7].

Derivatives of mode shapes, such as mode shape curvatures, are more sensitive to small perturbations than modal displacements and, therefore, can be also used to detect damage [7-10].

The emphasis of this paper is to demonstrate the effectiveness of modal curvature difference method for determining location of the damage in beam structure. In the present study, basics of modal curvature difference method are discussed and the patterns of curvature difference for different damage scenarios for beams are presented.

II. MODAL CURVATURE BASED DAMAGE DETECTION METHOD

The pre and post-damage eigenvectors 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.

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:

$$\kappa(x) = \frac{M(x)}{EI} \qquad (1)$$

For the beam with given moment applied to the damaged (shown with *) 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 [7]:

$$\kappa = \frac{\varphi(j+1)i - 2\varphi ji + \varphi(j-1)i}{l^2} \qquad (2)$$

With *i* being mode shape number, *j* the node number, φij is the modal displacement of the coordinate *j* at mode *i*. *l* is distance between the nodes.

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:

$$\Delta = \kappa^*(x) - \kappa(x) \qquad (3)$$

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.

III. NUMERICAL IMPLEMENTATION

To study the effect of damage on the modal curvature differences, a numerical study using finite element model of simply supported and cantilever beam structures is conducted. ISMB 250 steel section is used for the numerical study. The dimensions of the simply supported beam are shown in Fig. 1. The cantilever beam model is also of the same dimension.

The FE model of the beam has been created in ANSYS 12, FEA commercial software. The FE model consists of 32 equal length two dimensional beam elements. Each element consists of three degrees of freedom at each node: translations along X and Y directions and rotation along Z direction. The material considered to be linear isotropic with Modulus of elasticity, *E* =200 GPa; Poisson’s ratio = 0.3; Mass density = 7850 kg/m^3.

Using modal analysis, first three natural frequencies and corresponding flexural mode shapes were obtained for the intact beam. Damage in structure affects the stiffness matrix and not the inertia matrix [7]. The change in stiffness was modeled by reduction in the modulus of elasticity, *E* of the section. The degree of damage was related to extent of reduction in modulus of elasticity, *E*.

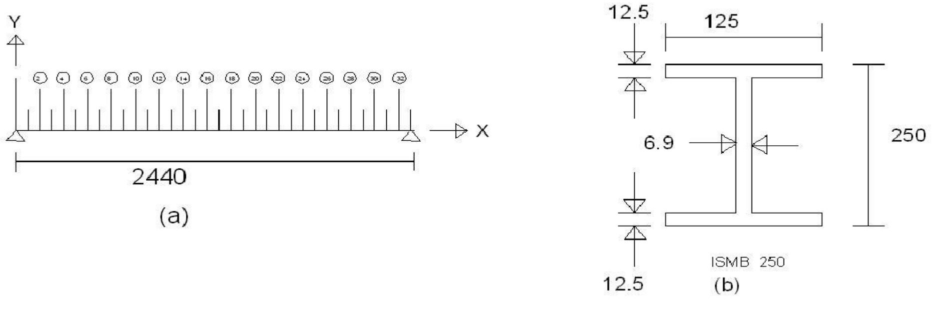


Fig. 1. (a) finite element model; (b) cross section of the beam; (all dimensions in mm)

A study is conducted with simulation of damage in terms of 50% reduction in turn in modulus of elasticity, at locations *L*/8, *L*/4, 3*L*/8 and *L*/2 where *L* is span of the beam. A further study has been carried out in which damage was prescribed at *L*/4 of each beam. The intensity of damage was varied by changing the modulus of elasticity by 10% to 90% with the increment of 20%. Damage of 60% has been imposed at locations *L*/4 and 3*L*/4 at a time so as to simulate case of multiple damages.

Modal analysis is repeated for each damage location and first three natural frequencies and corresponding mode shapes are obtained for the damaged beam. The curvature difference between the damaged and intact case are obtained by using a newly developed MATLAB code with modal data obtained from finite element analysis using ANSYS 12.0 as input.

IV. RESULTS AND DISCUSSION

Table 1 and 2 compare first three natural frequencies for the intact case and two of the typical damage locations (50% reduction in *E* at element *L*/8 and *L*/2 respectively) of simply supported and cantilever beam respectively. From the changes in the natural frequencies existence of damage can be identified but the location of the damage is not evident.

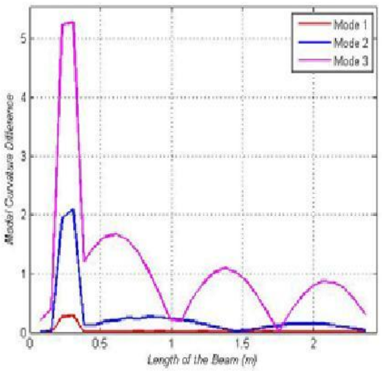
The absolute differences between the curvature mode shapes of the intact and the damaged simply supported and cantilever beams respectively are plotted in Fig. 2 and Fig. 4. The maximum difference for each curvature mode shape occurs in the damaged region, the differences in the curvature mode shapes are localized near the damaged zone, i.e., it is much smaller outside the damaged region.

Fig. 3(a-c) and Fig. 5(a-c) show the results of absolute difference between the curvature mode shapes for mode 1, 2 and 3 resp. of the intact and the damaged beam for increased damage intensities for simply supported and cantilever beams respectively. The maximum difference for each of the damaged cases occurs in damaged zone. The maximum difference increases with increase in damage intensity (reduction in stiffness) of the damaged zone. The higher modes give the better results in terms of location of damage.

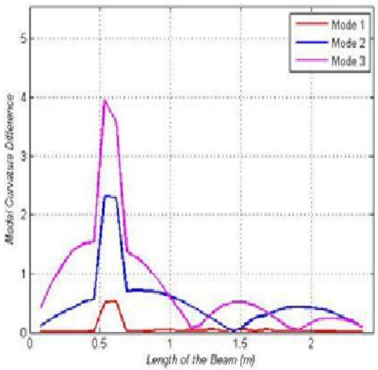
Even for the multiple damage scenario (Fig. 3(d) and 5(d)), the location of the damage have been satisfactorily predicted by the modal curvature method.

Table 1: Natural frequencies for the intact and damaged simply supported beams

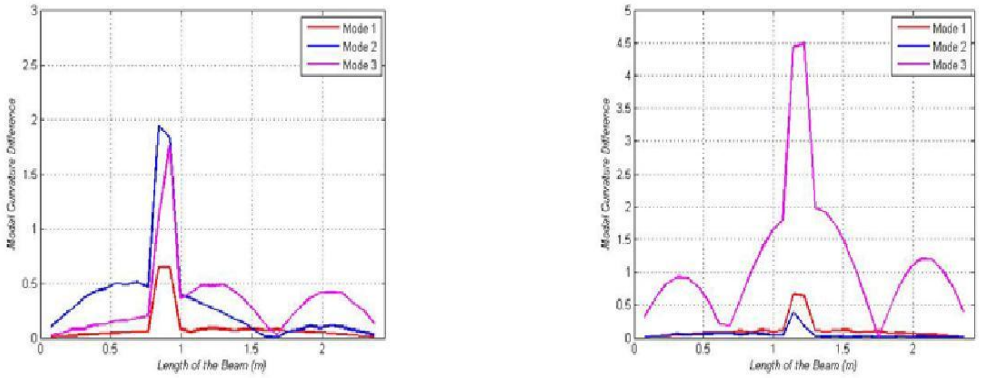
Mode no.	Natural Frequency (Hz)			% Drop in frequency	
	Intact	Damage at L/8	Damage at element L/2	Damage at L/8	Damage at element L/2
1	137.18	136.69	133.09	0.36	2.98
2	534.78	528.08	534.57	1.25	0.04
3	1155.9	1130.1	1123.7	2.23	2.79



(a) 50% Damage at *L*/8



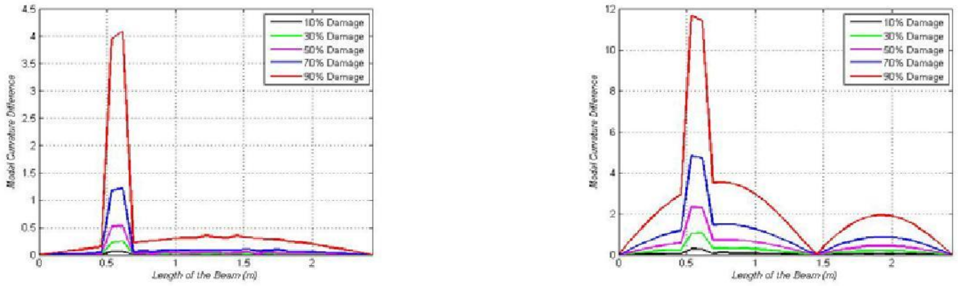
(b) 50% Damage at *L*/4



(d) 50% Damage at *L*/2

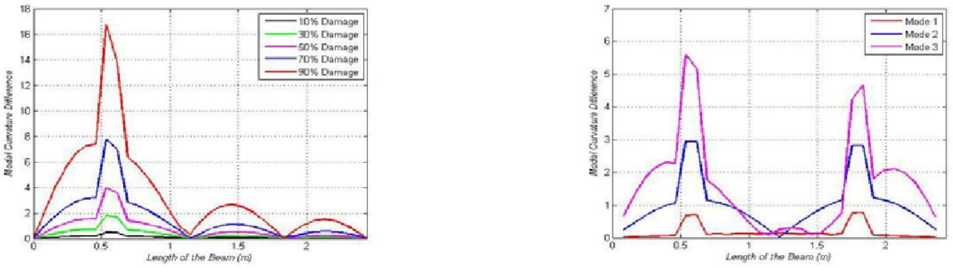
(c) 50% Damage at 3*L*/8

Fig. 2: Modal Curvature Method for damage identification when 50% damage is imposed at locations (a) *L*/8 (b) *L*/4 and (c) 3 *L*/8 and (d) *L* /2 of simply supported beam



(a) mode 1

(b) mode 2



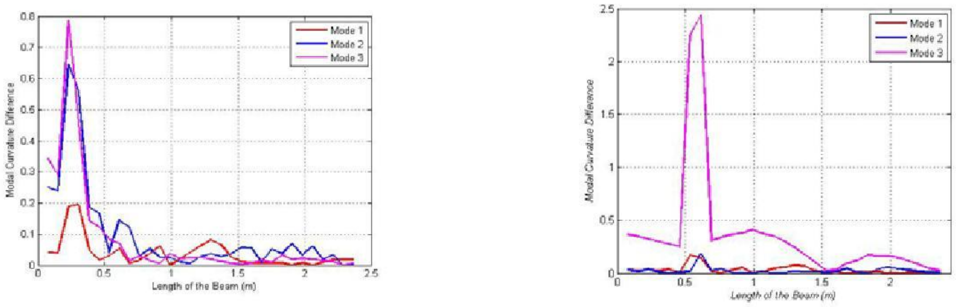
(c) mode 3

(d)

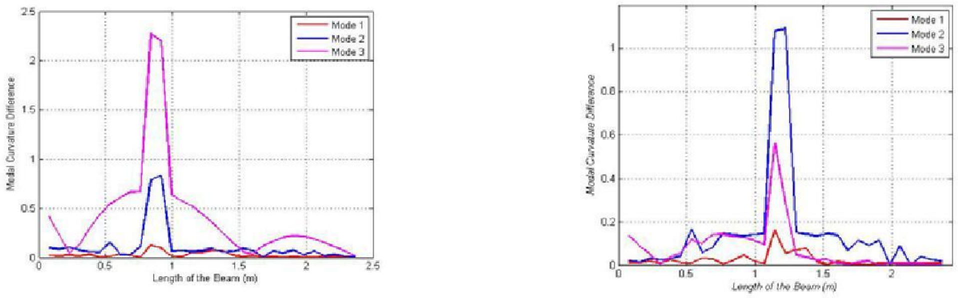
Fig. 3(a-c): Modal Curvature Method for damage identification with different damage severities imposed at *L*/4 of simply supported beam (d) multiple damage identification in simply supported beam

Table 2: Natural frequencies for the intact and damaged cantilever beams

Mode no.	Natural Frequency (Hz)			% Drop in frequency	
	Intact	Damage at L/8	Damage at element L/2	Damage at L/8	Damage at element L/2
1	49.097	47.025	48.705	4.22	0.80
2	300.27	296.35	291.58	1.31	2.89
3	810.25	808.65	809.67	0.20	0.07

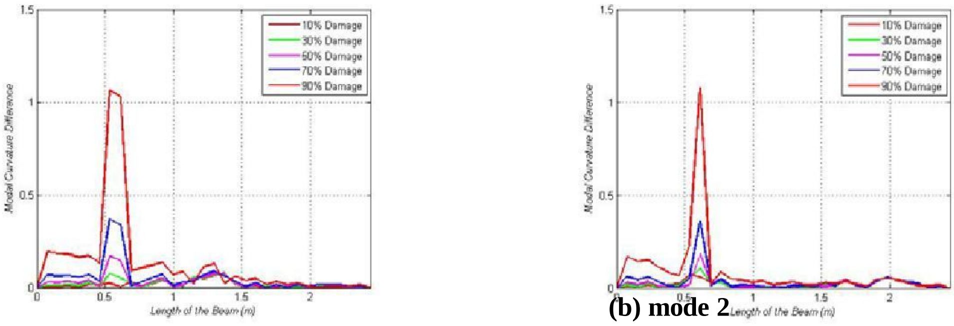


(a) 50% Damage at *L*/8 **(b) 50% Damage at *L*/4**



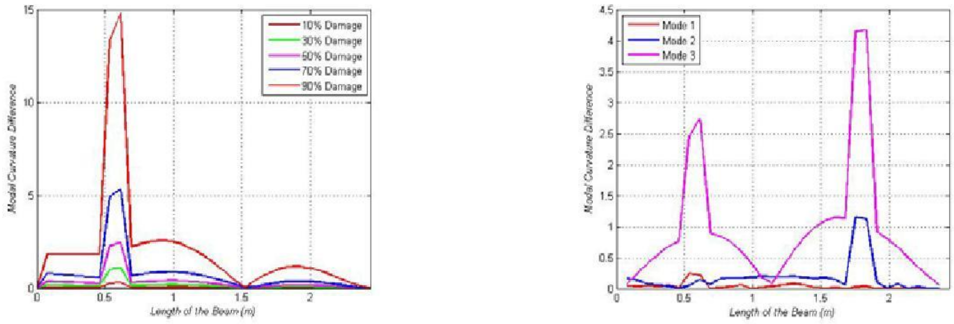
(c) 50% Damage at 3*L*/8 **(d) 50% Damage at *L*/2**

Fig. 4: Modal Curvature Method for damage identification when 50% damage is imposed at locations (a) *L*/8 (b) *L*/4 and (c) 3 *L*/8 and (d) *L* /2 of cantilever beam



(b) mode 2

(a) mode 1



(c) mode 3 **(d)**

Fig. 5(a-c): Modal Curvature Method for damage identification with different damage severities imposed at *L*/4 of cantilever beam (d) multiple damage identification in cantilever beam

V. CONCLUSION

The method of modal curvature is applied to simply supported and cantilever beam models. The numerical results demonstrate the effectiveness of the method in locating single and multiple damage scenarios in beams. Mode shape curvatures changes are observed to be highly localized to the region of damage. The absolute difference between the curvature mode shapes of the intact and the damaged beam increase with increase in the damage severity.

REFERENCES

[1] C.R. Farrar, H. Sohn and A.N. Robertson, Applications of nonlinear system identification to structural health monitoring, *Proc. of the 2nd European Workshop on Structural Health Monitoring*, Forum am Deutshcen Museum, Munich, Germany, 2004, 59– 67.

[2] M. Cao, L. Ye, L. Zhou, Z. Su and R. Bai, Sensitivity of fundamental mode shape and static deflection for damage identification in cantilever beams, *Mechanical Systems and Signal Processing*, 25, 2011, 630–643.

[3] B.H. Kim, H. J. Joo and T. Park, Damage evaluation of an axially loaded beam using modal flexibility, *KSCE Journal of Civil Engineering*, 11(2), 2007, 101-110.

[4] P. Cawley, and R.D. Adams, The location of defects in structures from measurements of natural frequencies, *Journal of Strain Analysis*, 14(2), 1979, 49-57.

[5] O.S. Salawu, Detection of structural damage through changes in frequency: a review", *Engineering Structures*, 19(9), 1997, 718–723.

[6] J.T. Kim and N. Stubbs, Crack detection in beam-type structures using frequency data, *Journal of Sound and Vibration*, 259(1), 2003, 145-160.

[7] A.K. Pandey, M. Biswas and M.M. Samman, Damage detection from changes in curvature mode shapes, *Journal of sound and vibration*, 145(2), 1991, 321-332.

[8] J. Maeck, M.A. Wahab, B. Peeters, G.D. Roeck, J.D. Visschere, W.P. Wilde, J.M. Ndambi and J. Vantomme, Damage identification in reinforced concrete structures by dynamic stiffness determinaition, *Engineering Structures*, 22, 2000, 1339-1349.

[9] Z.Y. Shi, S.S. Law and L.M. Zhang, Improved damage quantification from elemental modal strain energy change, *Journal of Engineering Mechanics*, 128(5), (2002), 521-529.

[10] J.M. Ndambi, J. Vantomme and K. Harri, Damage assessment in reinforced concrete beams using eigen frequencies and mode shape derivatives", *Engineering Structures*, 24, 2002, 501-515.