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AN ENERGY-BASED DAMAGE DETECTION ALGORITHM BASED ON MODAL DATA

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ABSTRACT

In recent years, significant efforts have been devoted to developing non-destructive techniques for damage identification in structures. Damage detection techniques based on modal testing rely on the fact that the occurrence of damage or loss of integrity in a structural system leads to changes in the dynamic properties of the structure. In this paper, an energy index based on mode shapes and their derivative is applied to detect damage in reinforced concrete beams isintroduced. The effectiveness of the proposed methods is examined through analytical model on an RC beam. Results illustrate that the energy index is sensitive to damage, and the proposed method is simple and robust in locating single or multiple damages in a structure.

INTRODUCTION

Many civil engineering structures, exposed to various external loads such as earthquakes, traffic and wind during their lifetime, have been suffering damage and deterioration in recent years which seriously affects their performance and may even lead to structural failure. The same phenomena are applicable in aerospace and mechanical engineering. Because of this, structural health monitoring and damage assessment of these structures is becoming increasingly important in order to determine their safety and reliability. Non-destructive inspection techniques, such as ultrasonic and acoustic emission methods, X-ray methods, etc., are generally used to investigate the critical changes experienced by the structural parameters with the purpose of preventing unexpected structural failures. These kinds of experimental techniques are based on a local evaluation ineasily accessible areas and, therefore, they require a certain a priori knowledge of the damage distribution. Furthermore, they are costly and, in order to perform an inspection, the structure needs to be taken out of service.

However, nowadays, techniques based on modal testing(Ewins, 1984) and signal processing constitute a promising nondestructive tool for damage identification in many engineering applications, including civil engineering applications. Using these techniques modal parameters (frequencies, mode shapes and damping ratios) can be extracted easily and cheaply from measurements of vibration-based dynamic tests. Changes in the modal parameters of a structure imply changes in its mass, damping and/or stiffness properties and, therefore, serve as a basis not only for finite-element modal updating (Ren et al., 2004) but also for structural damage detection (Casas and Aparicio, 1994), (Doebling et al., 1998). The comparison between the undamaged and damaged structure makes possible the identification of the location and the severity of damage.

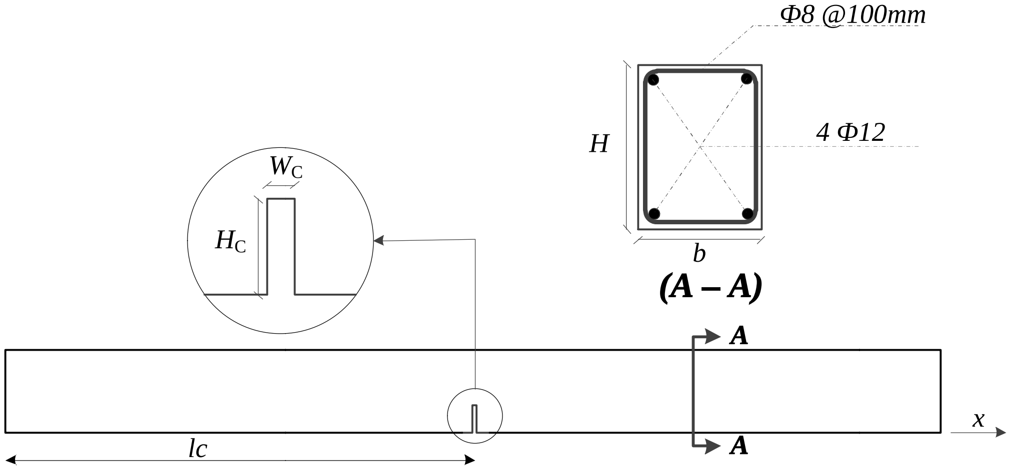
The most simple damage detection methods are those based on changes in resonant frequencies since thisparameter can be determined by measuring at only one point of the structure (Salawu, 1997, Bicanic and Chen, 1997)and are often reliable. However, although changes in natural frequencies give a useful 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 can be used, in principle, for identifying the damage location (Kim et al. 2003). Displacement mode shapes can be obtained by experimental means but an accurate characterization of the damage location from these parameters requires measurements in many locations and, moreover, changes in mode shapes between damaged and undamaged structures can be not very significant (Salawu and Williams, 1995).

Derivatives of mode shapes, such as mode shape curvatures, are more sensitive to smallperturbations than modal displacements and, therefore, can be also used to detect damage (Pandey et al., 1991, Ratcliffe, 1997). However, their applicability is minimumsince their estimation from experimental data is difficultand, therefore, they are very uncertain from a statistical point of view. More recently, Stubbs and Kim (1996), Shi et al. (2002) and Ndambi et al. (2002)have directly used the modal strain energy change as a damage indicator.

In this paper, an energy based damage index is proposed to identify location and severity of damage in an analytical model of concrete beam.

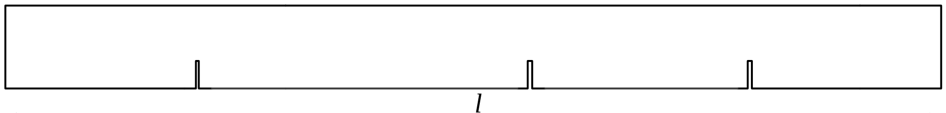
ANALYTICAL MODEL

In this section, a simple example of reinforced concreter damaged beam is given to test the proposed method. The RC beam with dimensions of 150 mm wide, 200 mm high and 2200 mm long is shown in Fig.1 and modeled by ABAQUS software.



a) Single damage

b) Double damage



c) Triple damage

Figure 1. Model of damaged reinforced concrete beam: a) Single, b) Double and c) Triple damage scenario

The flexural reinforcements are two $\Phi12$ bars at the bottom and top of the beam. Stirrups are $\Phi8$ steel bars with center-to-center spacing of 100 mm. The 2D FE model comprised of 528 linear isotropic plane elements (CPE4R) for concrete and 308 truss elements (T2D2) for reinforcements. The mechanical properties for steel and concrete are presented in Table 1.

Table 1.Mechanical properties of materials

Material	Modulus of Elasticity (GPa)	Specific Weight (kg/m^3)	Poisson Ratio	f_c' (MPa)	f_y (MPa)
Concrete	15	2400	0.17	20	- - -
Steel	200	7850	0.3	- - -	400

As shown in Table 2 and 3, Three damage scenarios located at different distances (l_C)from the left edge are considered with crack width W_C =5mm and five types of crack depth (H_C)considered as damage levels h2 to h10.

Table 2.Damage scenarios location

Damage scenario	Type of damage	Damage location (l_C)(mm)
C-0	No damage	- - -
C-1L	Single damage – left	500
C-1m	Single damage – middle	1100
C-1r	Single damage – right	1900
C-2Lr	Double damage – left and right	500, 1900
C-2Lm	Double damage – left and middle	500, 1100
C-2mr	Double damage – middle and right	1100, 1900
C-3mLr	Tripledamage – left, middle and right	500, 1100, 1900

Table 3. Damage level and crack ratio

Damage level	*Undamaged*	*h2*	*h4*	*h6*	*h8*	*h10*
H_C(mm)	0	20	40	60	80	100

Initially, as shown in Fig. 2, the first three modal shapes of a damaged beam are computed using the finite element method.

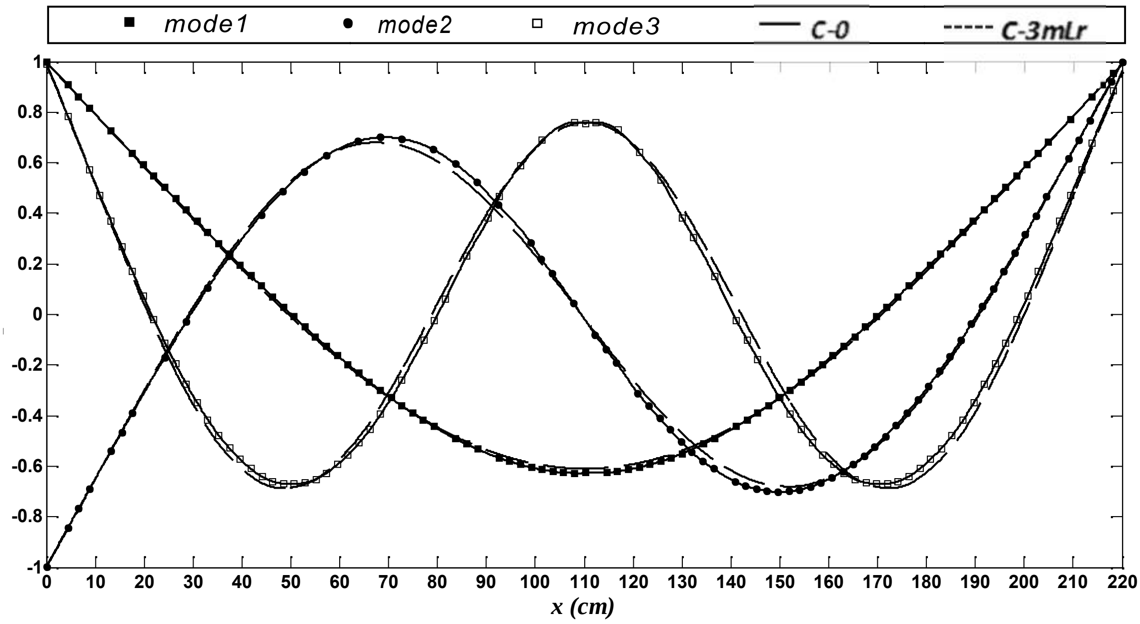


Figure 2.The first three mode shapes of undamaged and last level of damaged beam.

It is well known that it is difficult to detect damages by comparing mode shapes of undamaged and damaged beams when the damage is relatively small. This conclusion can be verified from Fig.2, in which there is no noticeable difference between the curves of the first three mode shapes of the undamaged beam and the cracked beam.

METHOD OF DAMAGE IDENTIFICATION

It has been shown by many researchers that the displacement mode shape itself is not very sensitive to small damage, even with the high density mode shape measurement (Salawu& Williams 1994). Pandey et al. (1991) suggested for the first time that the mode shape curvature, i.e. the 2nd derivatives of mode shape, is highly sensitive to damage and can be used to localize it. The curvature mode shapes are derived using a central difference approximation as follows

$$\copyright_i = (w_{i+1} + w_{i-1} - 2w_i) / h^2 \tag{1}$$

Where h is the sensor spacing.Deriving the mode shape curvature from central difference approximation may have not a smooth tendency and are fluctuating neatly.Obtaining a smooth curve can be achieved by curve fitting methods. Spline functions have been used in this study which creates a polynomial function through the available points. A sample of curve fitting with these functions is shown in Fig.3.

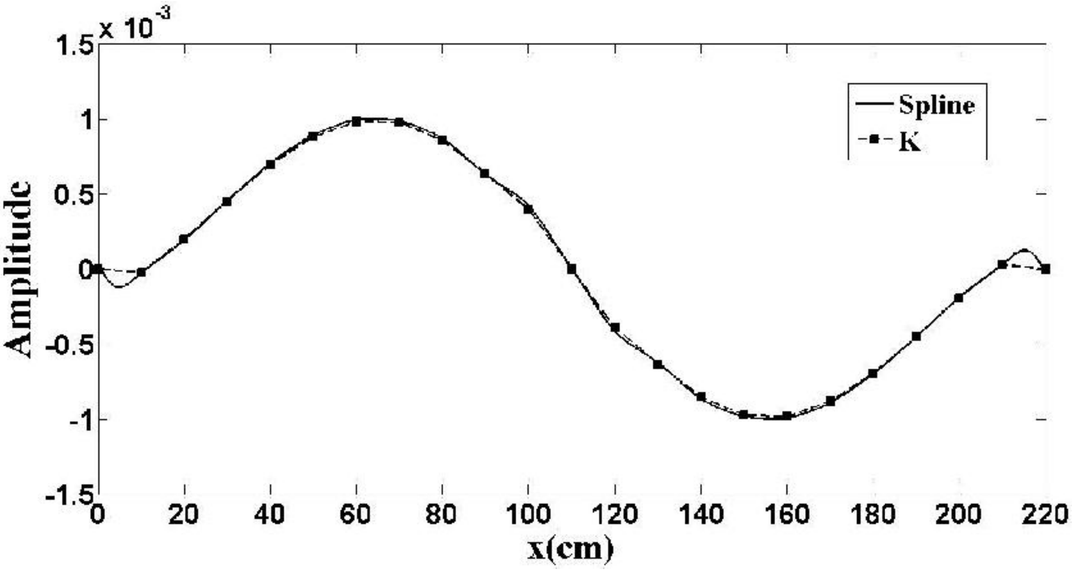


Figure 3. Curve fitting with spline functions.

As a result, in this study, modal strains are considered as inputting data in damage detection system.

In order to quantify the damages, an energy damage index is proposed. Energy of a vector S(k) at its points or degrees of freedom (k = 1,2, …) can be calculated by (Wei et al, 2004)

$$U = |S(k)|^2 \tag{2}$$

In practical projects, location of damage defined in degrees of freedom. So, the energy of the vector in j^{th} degree of freedom is modified as below

$$U_j = \sum_{k=(j-1)/2}^{(j+1)/2} |S(k)|^2 \tag{3}$$

In this paper, number of degrees of freedom are considered as beam length (j =1 to 2200). Considering the modal strains as an inputting vector, an energy damage index, *EI*, is proposed as

$$EI_j = \frac{U_j^d - U_j^0}{\max \; (U_j^0)} \tag{4}$$

In Eq. (4), U_k^0 and U_k^d corresponds to energy of modal strain vector in a healthy and damaged conditions, respectively. The first three modal strain vectors are introduced to energy damage index for damage scenarios at several damage levels (h2 to h10). For instance, the results of damage index for triple damage scenario are presented in Fig.4 to Fig. 6.

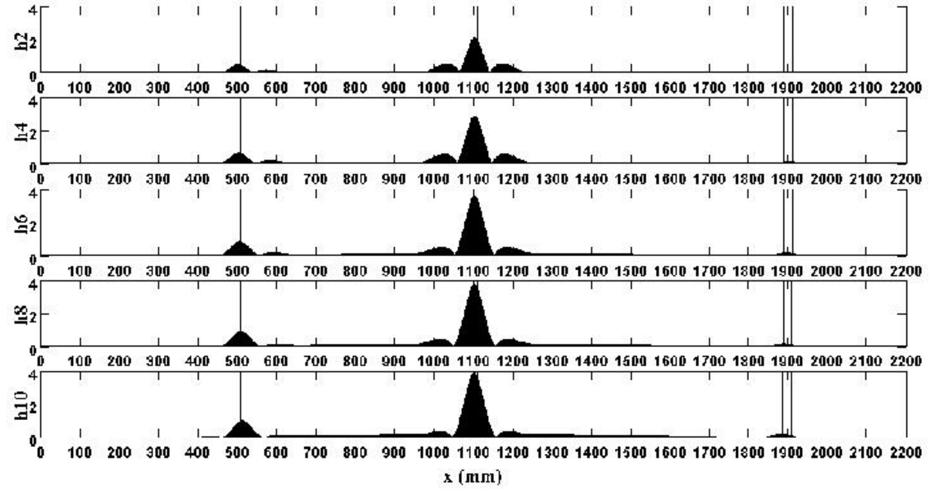


Figure 4.Energy damage index, *EI*, results for triple damage scenario offirst modal strain

According to Figure 4, left and middle defect locations of triple damage scenario are detected well using the energy damage index, EI,but the right damage is not properly identified. Also, besides of damage locations, increasing damage severity at different levels of damage from h2 to h10 (crack depth from 20mm to 100mm), is properly detected with the proposed index.

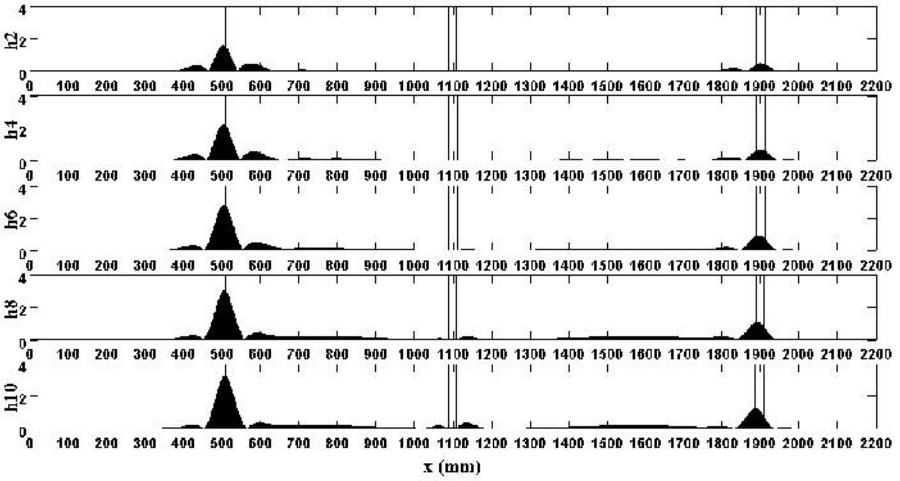


Figure 5.Energy damage index, *EI*, results for triple damage scenario ofsecond modal strain

Fig. 5 shows that the second modal strain, as an inputting vector in proposed damage index, *EI*, can only detect the left and right damage locations.

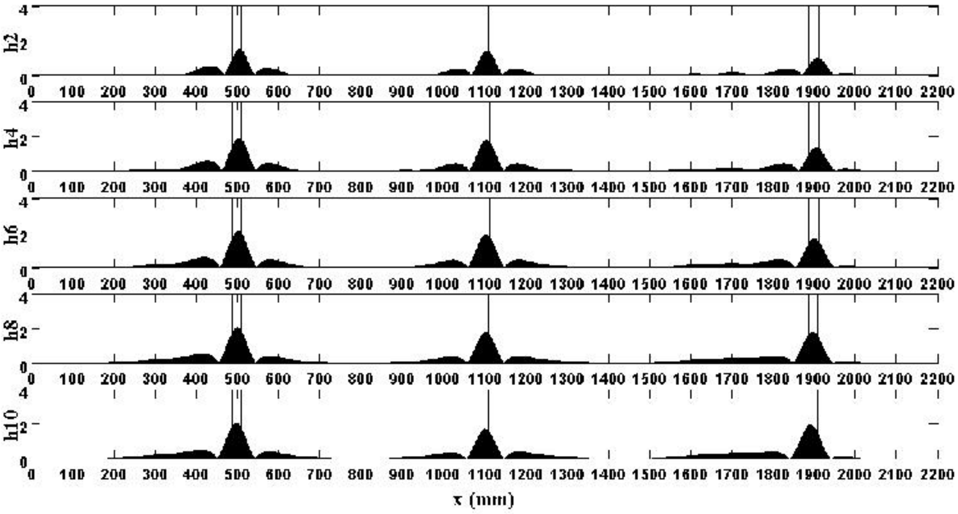


Figure 6.Energy damage index, *EI*, results for triple damage scenario ofthird modal strain

The proposed energy damage index for the third modal strain, as shown in Fig. 6, detects all left, middle and right locations of damage in triple damage scenario.

From the above analysis, the index values of modal strains can be considered as a proper index to illustrate damage locations in some modal strains for some specified location. Thus, it can be concluded that in order to identify damage location using suggested method, utilizing some modal strains seems to be essential and decision making based on a particular modal strain would not be applicable. In this paper, superposition of results is considered to improve identifying damage locations. Considering *M*, as the number of inputting modal strains, the modified damage index,*MEI*, is proposed as

$$MEI_j = \sum_{i=1}^{M} \left| \frac{U_j^d - U_j^0}{\max \ (U_j^0)} \right| \tag{5}$$

The first three modal strain vectors (i =1, 2, 3) are introduced to modified energy damage index for damage scenarios at several damage levels (h2 to h10). The results of damage index for triple damage scenario are presented in Fig.7.

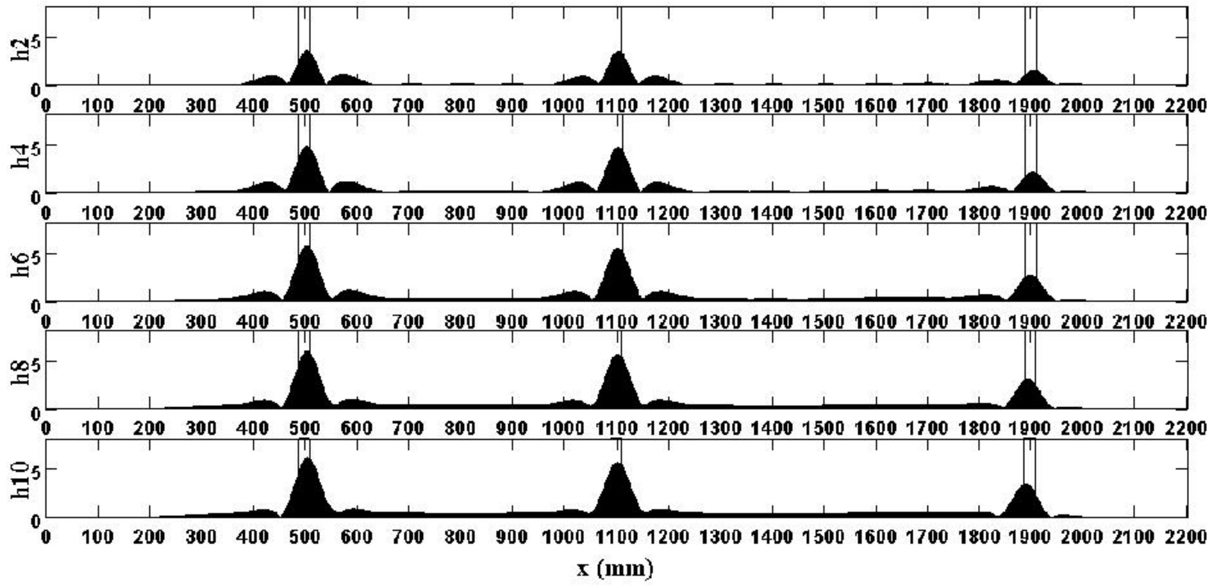


Figure 7.Modified energy damage index, *MEI*, results for triple damage scenario of modal strains

According to Fig.7, the results of modified energy damage index, *MEI*, for first three modal strains indicate the left, middle and right defect locations of triple damage scenario. The damaged areas detected by the proposed method coincide well with the damage scenarios. Also, besides of damage locations, increasing damage severity at different levels of damage from h2 to h10 (crack depth from 20mm to 100mm), is properly detected with the proposed index. From this analysis, the maximum values of proposed method results for modal strains can be considered as a proper index to illustrate damage locations and their severities.

CONCLUSIONS

This paper presented an energy based damage identification approach for beam like structures. To verify the efficiency and practicability of the proposed method, three damage scenarios with different locations have been studied. The modal strains of the beam were obtained and used as inputting vector of damage index. As occurs with other damage detection methods, the new approach needs a baseline as reference which is modal parameters of healthy structure. The numerical results show that in order to identify damage location using suggested method, utilizing some modal strains seems to be essential and decision making based on a particular modal strain would not be applicable. The identified damage regions with proposed method coincide well to artificial damage scenarios.

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