Damage detection in RC structures for random input signals using jerk-energy curvature diagram

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Abstract: **The present paper proposes, an algorithm for damage detection and its localization for reinforced concrete (RC) structure with ambient vibrations. MATLAB based algorithm was developed for damage detection and localization based on both global and local damage indexes. Damage was localized based on the jerk-energy criterion. A finite element model (FEM) of RC beam was considered to provide evaluation of the proposed algorithm with random vibrations. In second stage, the dynamic responses of a RC four story shear frame subjected to random vibrations at base of the structure were used by simulating continuous ambient vibrations. Finite Element Model of RC beam and shear frame were used to extract the nodal accelerations while considering different damage configurations. Damages in the structure were artificially introduced by local reduction in modulus of elasticity. Results of single and multiple damage cases based on both global and local damage indexes showed that the algorithm can correctly detect and localize the damage in RC structure.**

Keywords: **Concrete structures, Structural Health Monitoring, Ambient Vibrations.**

I. INTRODUCTION

The assessment and monitoring of structural damages in civil infra structures is very crucial issue in order to ensure the human safety. In addition to the natural aging the excessive forces resulting from natural disasters, such as storms and mostly the earthquakes often deteriorate and damage the structures during its service life. These damages have a deep influence on the building safety and without proper monitoring and maintenance the integrity of the structure may be influenced throughout its serviceability and may lead to life losses in the worst case [1]–[2]. Consequently, an accurate detection and localization of damage through an integrated structural health monitoring (SHM) system ensure the safety, performance, and low lifetime operating cost of the structures [3]. SHM is mainly concerned with detection, localization, severity and types of damages in the structure [4].For civil infrastructures, vibration-based damage detection techniques utilizing the dynamic characteristics of a structure are effective in health assessment of the structure on global scale (the whole structure) [5].

Over the recent decades assessment of damages from ambient vibrations under normal operating conditions has been evaluated by focusing on change in the modal parameters e.g. natural frequencies and mode shapes [6]. When structural damages occur the stiffness of the structure is decreased which results in altering the modal parameters [7]. Hence any change in the modal parameters indicate the damage in the structure. Recently a nondestructive technique, Operational Modal Analysis (OMA) has engrossed attention among researchers in assessing the modal parameters of reinforced concrete structures [8]–[9].Various approaches have been investigated in the field of OMA. Change in natural frequencies, very sensitive and easy to implement, are utilized in different perspectives for structural damage detection [10]–[11]. Mode shape correlations such as Modal assurance criterion (MAC) and coordinate modal assurance criteria (COMAC) are used by numerous researchers for damage detection in the structures [12]–[13].

Many other methods and techniques are being explored all over the globe for damage detection and localization in RC structures [14]–[15]. Most of these methods detect the damage of the structure on global scale. Therefore, it remains an area of interest for researchers to detect the damage in RC structures on local scale with practical and improved techniques.
In this study a new methodology for detection and localization of damage in RC structures with ambient vibrations is presented which combine methods based on modal parameters and jerk energy. By applying these methods in a precise order an algorithm was developed in MATLAB and evaluated on a RC beam and a four-story RC shear frame, modelled in Seismostruct software. The final goal of defining this algorithm was to facilitate the integration and implementation of SHM techniques based on both global and local damage indexes into an independent and permanent monitoring system.

II. DAMAGE DETECTION& METHODS

Numerous techniques such as Frequency Domain Decomposition (FDD), Stochastic Subspace Identification Principal Component (SSI-PC) and Canonical Variate Analysis (SSI-CVA) have been set up based on comparison between modal parameters for detection and localization of damage in structures [16]. Frequency Domain Decomposition (FDD) is most common and less time-consuming technique to experimentally calculate the natural frequencies and mode shapes [17]. The FDD algorithm is applied around the peaks of resonance in the Power Spectral Density (PSD) and each peak represent a natural frequency of a specific mode shape.

A. Frequency Shift

The physical properties e.g. stiffness of a structure changes during the damaging event which results in drop of the natural frequencies of the respective modes [18]. More the damage is severe, the greater is frequency drop[19]. Thus, monitoring of natural presents a simple method of SHM for routine health assessment of civil engineering structures[20]. Frequency drop method is very sensitive and easy to implement and can be computed as [19]-[21]:

$$\Delta f = f_i^u - f_i^d \tag{1}$$

where f_i^u and f_i^d denotes the natural frequency of the i^{th} mode in undamaged and damaged state respectively.

The damage can be successfully identified when the frequency drop is 5% or above [19]. Frequency drop below 5% can be described due to some hygrothermal effects [22]-[23].

B. Modal Assurance Criterion

Mode shapes are considered favorable tool for damage detection as it contains spatial information and are less effected by environmental effects than frequencies [24]-[25]. MAC method is based on the correlation between mode shapes of damaged and undamaged state[26]. Incomplete correlation ensures the presence of damage [27]. The MAC matrix is defined as follows:

$$MAC_{j,k} = \frac{(\sum_{i=1}^{n_d}[\varphi_u]_i^j[\varphi_d]_i^k)^2}{\sum_{i=1}^{n_d}([\varphi_u]_i^j)^2([\varphi_d]_i^k)^2} \tag{2}$$

Where $[\varphi_d]$ and $[\varphi_u]$ represents the mode shapes in the damaged and undamaged state respectively.MAC method can identify damage successfully in higher order modes even for the frequency drop less than 5%.

III. JERK ENERGY & DAMAGE LOCALIZATION

Damage localization methods based on jerk energy with pulse excitation are proposed in earlier work for regular tests[14]. Let the sampled points of the acceleration data of a Signal are represented by $a_1, a_2, ,....., a_{n-1}, a_n$, then jerk energy at a particular node i is given by (3),

$$JE_i = \log\sum_{x=1}^{n-1}\left(j_x^i\right)^2 = \log\sum_{x=1}^{n-1}\left(\frac{a_{x+1}-a_x}{\Delta t}\right)^2 \tag{3}$$

Where i represents the number of corresponding node, x represents the respective number of acceleration data point, log denotes the natural logarithm and is the sampling time interval between two data points. By connecting jerk energy values at every node, the jerk energy waveform (JEW) is formed. The curvature of JEW at every node can be computed by. The ‘‘curvature’’ of JEW at every specified node can be computed similarly by (4),

$$C_i = \frac{JE_{i-1} - 2JE_i + JE_{i+1}}{h^2} \tag{4}$$

Where C_i represents the curvature of jerk energy waveform JEW at node i , JE_i is jerk energy computed at node i , h is the distance between two adjacent nodes. The node numbering sequence can be represented by a closed clockwise loop as shown in the Fig. 1 (taking $n_d = 13$ in this study). Thus, curvature of JEW can be computed at all nodes. Consequently, the JEW curvature of 1st and 13th (last) node are computed as $C_1 = \frac{JE_{13} - 2JE_1 + JE_2}{h^2}$ and $C_{13} = \frac{JE_{12} - 2JE_{13} + JE_1}{h^2}$ respectively.

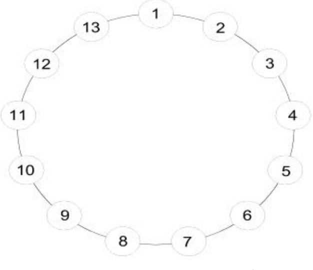


Fig. 1: Node numbering sequence for RC beam

The curvature difference of JEW is computed at a specified node by subtracting JEW curvature values in the damaged state from JEW curvature values in undamaged state as refers in (5).

$$\left(C_{\Delta}^{i}\right)_{rs} = C_{r}^{i} - C_{s}^{i} \qquad (5)$$

A. Damage Index

Mean normalized curvature difference of JEW is used as a damage index $\left(DI_1\right)$ for damage localization. In this method the damage can be localized by normalizing the curvature difference values of JEW at each node and can be observed in (6),

$$\left(C_{\Delta}^{i}\right)_{rs}^{*} = \left(C_{\Delta}^{i}\right)_{rs} / \max\left(C_{\Delta}^{i}\right)_{rs} \qquad (6)$$

Where $\left(C_{\Delta}^{i}\right)_{rs}^{*}$ represents the normalized curvature difference. Therefore, at each node mean of the normalized curvature difference of JEW is taken and recorded as a damage index $\left(DI_1\right)$ as follow:

$$\left(DI_1\right)_i = \frac{1}{RS}\sum_{r=1}^{R}\sum_{s=1}^{S}\left(C_{\Delta}^{i}\right)_{rs}^{*} \qquad (7)$$

Where; R and S denotes the total number of acceleration responses recorded in the undamaged and damage state, respectively. A threshold value (δ) is defined using data of undamaged structure. If the damage index value DI_1 of a specified node is greater than threshold value, then the node is considered as damaged.

$$Damage\ element = \left[\left(DI_1\right)_i \geq \delta\right] \qquad (8)$$

IV. DAMAGE DETECTION ALGORITHM& RESULTS

Considering the SHM levels, a damage detection and localization algorithm combining both global and local scale damage indexes is presented. The algorithm utilizes the methods based on modal parameters and jerk energy in some in a unique order and provides a proficient approach to detect and localize damage in the structure. The proposed damage detection and localization algorithm is presented in Fig. 2.

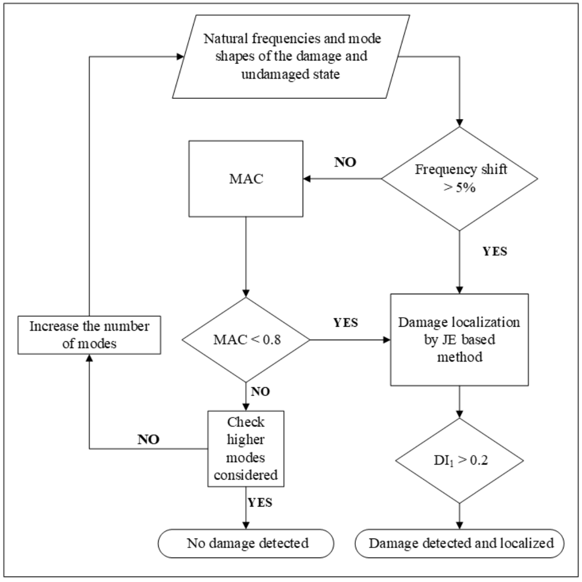
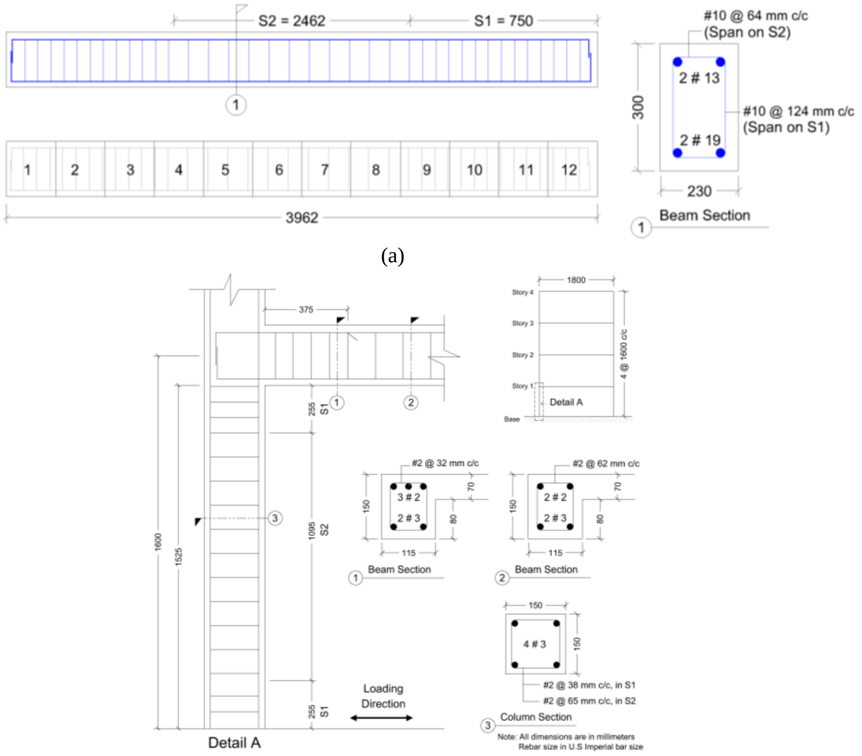


Fig. 2: Jerk Energy Based Algorithm

This is a two-level algorithm: (a) detection and (b) localization.Damage is detected if frequency drop of first two mode shapes is greater than 5%, after which the algorithm initiates the localization phase. If frequency drop is less than 5% then the algorithm run the MAC method for damage detection. Damage is detected by the MAC method if any value in the diagonal of MAC matrix is less than 0.8 otherwise, the number of modes is increased and the algorithm restart on the same procedure from the beginning.In the localization phase, the jerk energy-based damage localization methodis applied for localization of the damage. The structure is considered undamaged if the detection and localization conditions are not satisfied and higher modes are used already.

A. Implementation of Algorithm

The proposed algorithm is evaluated on a RC beam and RC shear frame model constructed in Seismostruct. The RC beam, length 3.962 m, is divided into 12 elements and 13 nodes.The RC shear frame is a one-bay, four story with story height of 1.60 m. In order to reduce the computational cost, the RC shear frame is modelled to half scale. The selected scale ratio was 1:2. The reinforcement and dimensions of the RC beam and shear frame model are presented in Fig. 3(a) and 3(b) respectively. Columns and beams of the structure are modelled by inelastic force-based plastic hinge frame element type-infrmFBPH. This is the force-based 3-Dimensional column-beam element type and generally space frame members with geometric and material nonlinearities are modelled with it. The inelasticity is fully distributed across the depth of section and along the fixed length of element.



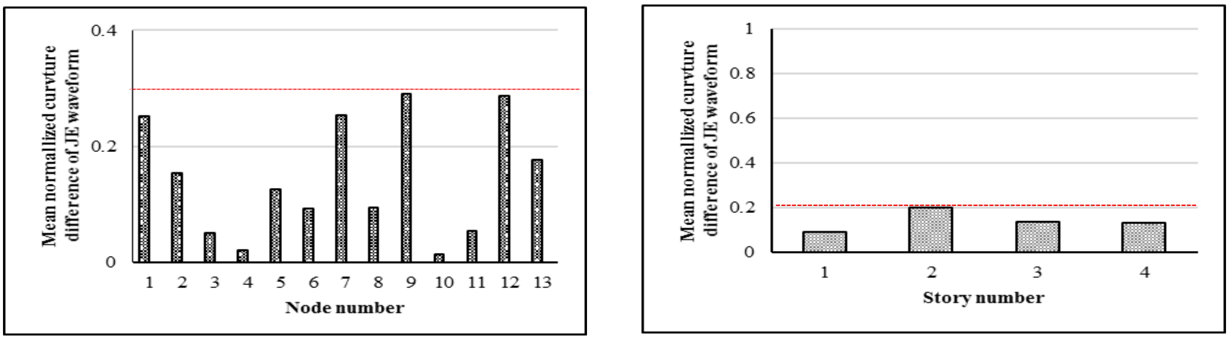
(a)

(b)

Fig. 3: Reinforcement details(a) RC beam (b) Shear frame

The modulus of elasticity (E) and yielding strength of the reinforcement steel are assumed to be 200000 MPa and 415 MPa, respectively. The value of E and 28-days cylinder compressive strength of the concrete are taken as 21393 MPa and 20.71 MPa, respectively.

In case of each unique structure, a threshold values must be selected for damage localization index. The thresholdwas determined based on the two sets of acceleration data from the undamaged structure. In Fig.4(a) and 4(b) it is shown that the highest value of damage localization indexes for RC beam and shear frame are 0.291 and 0.198, respectively. Hence, the threshold values selected are 0.3 and 0.2, respectively.



(a)

(b)

Fig. 4: Threshold values(a) RC beam (b) Shear frame

B. Application to RC beam

Two different artificial damage scenarios were made to evaluate the performance of the proposed algorithm in case of severe and low damages. Modulus of elasticity of different beam elements was reduced to introduce damage in the beam. The reduction was implemented by reduction in the reduction in the material properties:

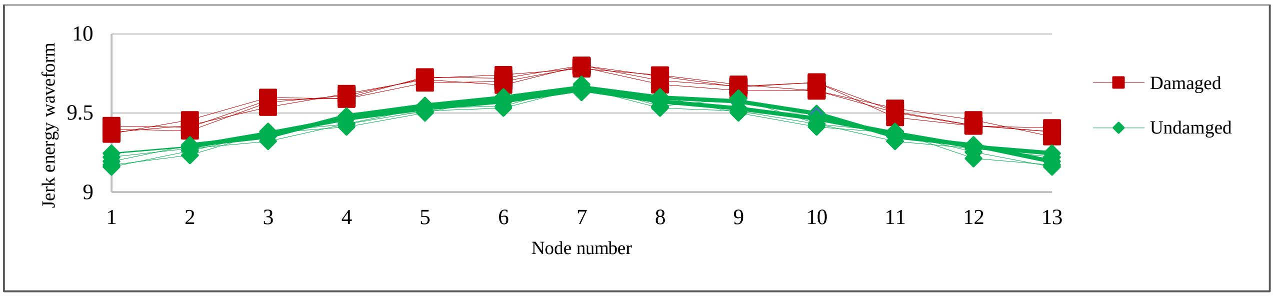
- First damage scenario: 30% reduction in modulus of elasticity in 3rd and 9th element (from left side)
- Second damage scenario: 15% reduction in modulus of elasticity in 3rd and 9th element (from left side)

In first damage scenario, the damage was introduced at the 3rd element (between node 3 and 4) and 9th element (between node 9 and 10) by reducing the modulus of elasticity 30% that of undamaged concrete. The natural frequencies determined by FDD technique are shown in Table 1. The damage was detected due to frequency drop of 12.20% (higher than 5%) in the first mode shape. As the damage is detected by the frequency drop method so the MAC method is not triggered, and the algorithm initiated the localization phase.

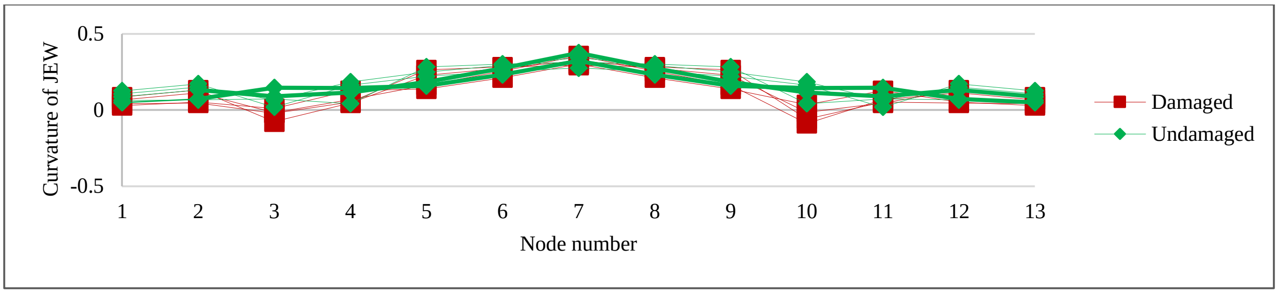
Table 1: Frequency drop by 30% reduction in modulus of elasticity for RC beam

Damage case	**Modes shapes**	**Frequency (undamaged)**	**Frequency (damaged)**	**Frequency drop %**
1st damage scenario	1st	75.31	66.12	12.20
	2nd	96.03	90.20	6.07
2nd damage scenario	1st	75.31	71.94	4.47
	2nd	96.03	92.43	3.74

In the localization phase the damage was located at 3rd and 10th node by the jerk energy-based method. The damage localization process is illustrated in Fig. 5(a) and 5(b). Fig. 5(a) shows JEW before and after damage with ambient base vibrations. Fig. 5(b) shows that values of JEW curvature decreased after damage.



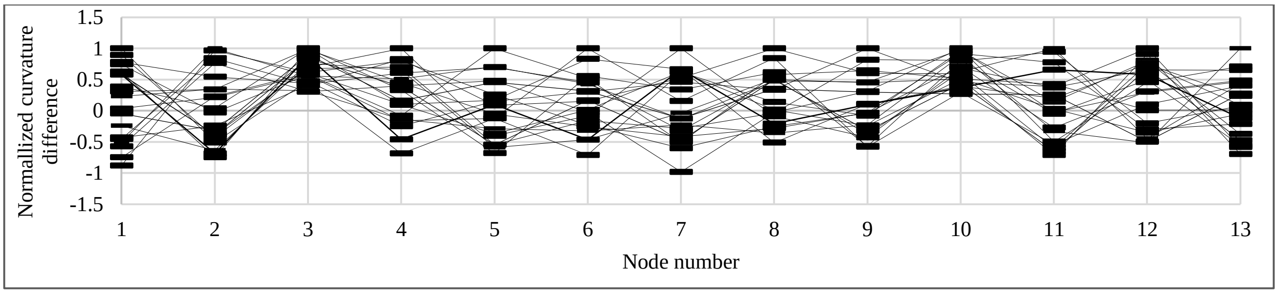
(a)



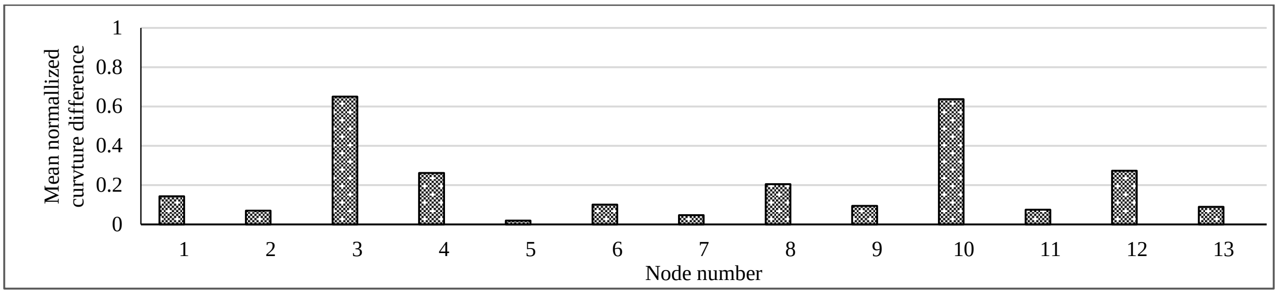
(b)

Fig. 5: (a) Jerk energy waveform (b) JE curvature

Figure 6(a) and 6(b) shows normalized values of JEW curvature difference and mean normalized curvature difference, respectively. The normalized values of curvature difference are always positive and mostly greater than the others at the 3rd and 10th node. The rest of normalized values of curvature difference are sometimes negative sometimes positive. The damage localization index (mean normalized curvature difference) values at 3rd and 10th node is greater than the threshold value, representing that the 3rd and 9th element is damaged.



(a)



(b)

Fig. 6: (a) Normalized values of curvature difference (30% reduction in E-values) (b) Mean normalized values curvature difference (30% reduction in E-values

In second damage scenario, the damage was introduced at by local reduction of 15% in modulus of elasticity, damage was introduced at the same elements (3rd and 9th). Frequencies drop in this case is less than 5% as shown in the Table 1. Thus,damage is successfully detected by MAC method as illustrated in Fig.7. The MAC matrix shows that there is incomplete correlation of mode shapes at the 4th mode which corresponds to, a value 0.742, less than 0.8. Fig. 8 shows the damage localization index values at 3rd and 10th node are greater than the threshold value.

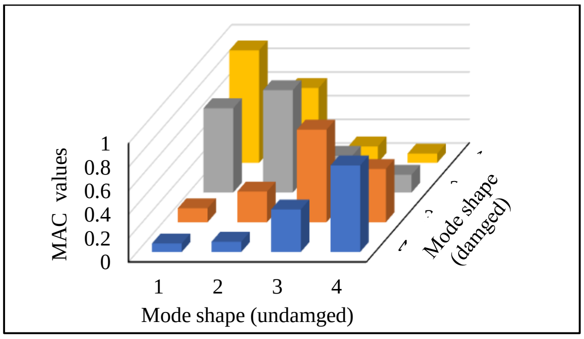


Fig. 7: Modal Assurance Criteria

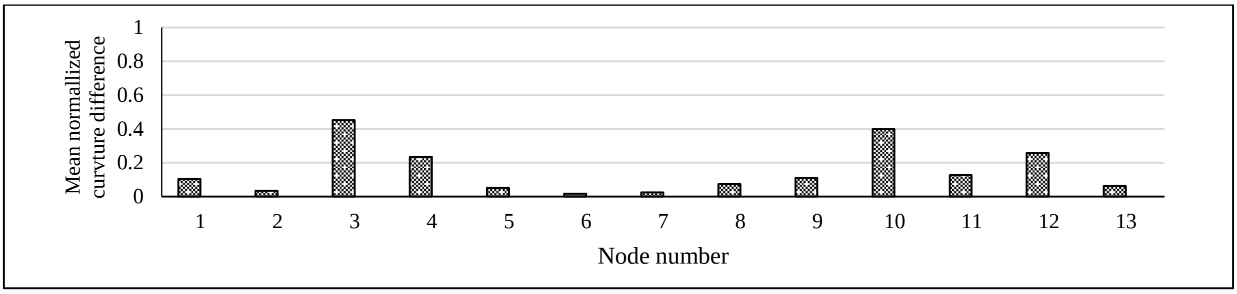


Fig. 8:Mean normalized values curvature difference (30% reduction in E-values

C. *Application to RC shear frame model*

The performance of the proposed algorithm was also evaluated on a shear frame model. Damages were introduced by 30% reduction in modulus of elasticity at 2nd and 4th story. The reduction in modulus of elasticity was accomplished by reduction in the E - value of corresponding story’s columns. The natural frequencies determined by FDD technique are shown in Table 2. The damage was detected due to frequency drop of 6.48% (higher than 5%) in the first mode shape.Fig.9 shows the results of damage localization using the jerk energy-based method.

Table 2: Frequency drop by 30% reduction in modulus of elasticity for RC shear frame

Damage case	**Modes shapes**	**Frequency (undamaged)**	**Frequency (damaged)**	**Frequency drop %**
1st damage scenario	1st	2.393 HZ	2.237 HZ	6.48
	2nd	5.176 HZ	4.946 HZ	4.44

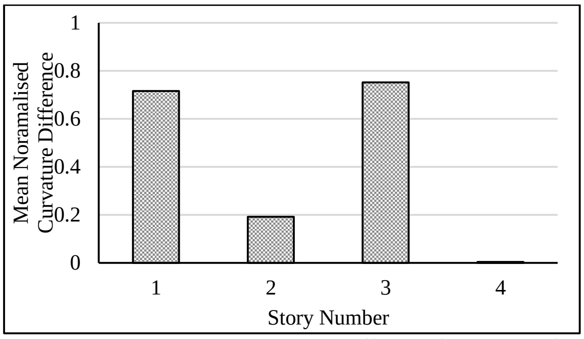


Fig. 9: Mean normalized values curvature difference for RC shear frame

D. Rule of damage localization

As seen from fig 8, in case of RC frame structure, if a story is damaged, the resulting values of mean normalized curvature difference of JEW are always greater than threshold values at node before the damaged node (damaged story) in the clockwise closed loop model. Keeping this rule in mind, it's easy to find correct damage locations

V.CONCLUSIONS

This research work proposed an algorithm for detection and localization of damage in RC structure. The proposed work is a simple, fast and efficient method based on both global and local damage indexes. Following are the conclusions:

- By successfully detecting and localizing the damage with ambient base vibrations this algorithm helps the health assessment of civil engineering structures.
- As for the detection phase is concerned, damage is successfully detected if frequency drop is greater than 5% using jerk-energy method while in case of frequency drop less than 5%, the MAC method for damage detection is successfully applied.
- The algorithm results show a good consistency for both case of high and low severity damage scenario in RC beam. Also, the algorithm successfully detected and localized the damage according to the damages artificially made in 2nd and 4th story of RC shear frame structure.

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