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Studies on Modal Parameters for Identification of Damage in Unreinforced Masonry Panel

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Abstract— Conservation of historical masonry monuments can be fulfilled by adopting damage detection and structural health monitoring methodologies. These methods are the most efficient processes, due to their non-destructive properties and versatility to study the global structural behavior of a system. Modal Analysis was conducted on an unreinforced masonry (URM) panel. Modal parameters such as frequencies and mode shapes which evaluate the structural integrity of a system were extracted by numerical analysis carried out using the Finite Element tool. Inducing damage in a structure alters its dynamic characteristics such as modal frequency and mode shapes. In the present study the cracks were induced in the masonry panel of varying depth. Modal Analysis was performed after each damage state by varying the geometrical properties of the cracks. Damage indicator parameters such a frequency changes, frequency shift, Modal Assurance Criterion, Normalized Modal Difference, Modal Curvature, Curvature Damage Factor, Modal Strain Energy and flexibility based damage indicator were studied. In this paper, a parametric study was conducted based on the changes in the modal properties of an URM panel.

Index Terms— cracks, damage detection, dynamic response, modal analysis, unreinforced masonry panel

1 INTRODUCTION

Engineered structures when subjected to loading during their service life undergo damage or the cracks due to deterioration. Damage is defined as the changes in the material or geometric properties of the structure which adversely affect the current or future performance of these structures. The presence of the cracks in a structural member causes local variations in stiffness, the magnitude of which mainly depends on the location and depth of the crack [1]. To ensure safe operation of structures, it is extremely important to know whether their members are free of the cracks, and if any present to assess their extent. The procedures often used for detection are direct methods such as ultrasound etc. However, these methods have proven to be inoperative and unsuitable in certain cases, since they require expensive and minutely detailed inspections [2].

A number of non-destructive methods such as ultrasonic emission, acoustic emission or X-ray inspection, magnetic field or radiography, eddy currents and thermal field methods etc. were used to detect damage in structures. These non-destructive methods focus on identifying damage in structural elements. But these methods require prior knowledge about the location of damage and access to the area of damage. Nevertheless, there are other non-destructive methods that provide global information of the structure subjected to damage. Global damage detection methods such as vibrational techniques are general based on the changes of dynamic response parameters such as modal frequency, mode shape and modal curvature. Consistent monitoring of changes in the response parameters helps in the assessment of structural integrity, performance and health of the system.

Vibration-based techniques typically involve the entire structural component with its boundary conditions so that an indication of damage can be related to the presence of a defect anywhere within the structure. For example, a local a reduction in stiffness affects the natural frequencies, and in principle can be detected by a single sensor mounted anywhere on the structure under consideration. For this reason, vibration-based techniques are usually considered as a ‘‘global’’ tool. Their global nature, and the relative ease with which modal properties can be extracted through active modal testing or operational modal analysis performed using ambient loads, has promoted the development of several vibration-based techniques for damage identification. Mode shapes, and more importantly, their spatial derivatives, representing quantities such as modal curvatures and power flows, are instead effective at detecting small damages, and at directly providing their location.

2 METHODOLOGY

Unreinforced masonry is an anisotropic material, as they are assemblages of brick and mortar. Joints are the plane of weakness and eventually lead to failure. In this study, an unreinforced masonry panel subjected to shear failure was assumed. The cracks of varying depths were induced along the tension diagonal of the panel as masonry is inherently weak in tension. As the cracks in a structure reduces the stiffness, and a reduction in stiffness is associated with a decrease in the natural frequencies, thus altering the modal properties of a structure. The various parameters are discussed as follows:

2.1 Frequency Change

Among all the modal parameters, natural frequency is widely used as they can be determined easily with high degree of accuracy. The relationship observed between deterioration of structural properties (stiffness and mass) and changes in modal frequencies was a main promoter for developing vibration based damage identification technique [3]. When damage exists in a structure, the stiffness is reduced and consequently decreasing the natural frequencies of the system. Thus, a reduction of the natural frequencies of a structure indicates the presence of damage. The sensitivity of natural frequency to the severity of damage is dependent on the location of the cracks [4].

2.2 Frequency Shift

The measured frequency of a damaged structure can be used for detection and localization of damage in the structure only when the previous history of the structure is known. In other words, the geometrical and mechanical properties of existing and the undamaged structure must be known prior to its detection of damage. But, in many cases, it may not be possible to get the prior information to compare the changes or evaluate the shift in frequencies of an undamaged structure with that of a damaged one. In view of this, a procedure has been adopted in this study where the normalized frequencies of an existing (damaged) structure are used for detection of damage [6]. Thus, the information about the undamaged structure need not be known. In this regard, it is to be mentioned that the frequency ratios (of different modes) are considered as the normalized frequencies. Normalization of frequencies has been carried using the formula given below

$$\omega_{i+1}/\omega_i$$

where ω_i is the frequency of the structure in i^{th} mode.

In this study, normalization has been carried out with respect to first mode frequency (ω_1) to obtain the possible maximum values. It is worthy to mention that this procedure is capable of detecting and localizing the damage when the damage is prominent.

2.3 Modal Assurance Criterion (MAC)

The Modal Assurance Criterion is a statistical indicator that is most sensitive to large differences and relatively insensitive to small differences in the mode shapes [5]. This method is based on the correlation between the two series of mode shapes deducible from the results of two different dynamic investigations executed subsequently, one after the other on the same structure[6]. MAC is bound between the values 0 and 1, MAC=1 means perfect correlation between the two series of mode shapes and MAC=0 means that the mode shapes are not related. The more MAC verges to 0, the more is the damage in the structure.

$$MAC= \frac{[\{\phi_A\}^T\{\phi_B\}][\{\phi_A\}^T\{\phi_B\}]}{(\{\phi_A\}^T\{\phi_A\})(\{\phi_B\}^T\{\phi_B\})}$$

where $\{\phi_A\}$ is the mode shape of undamaged state of structure
$\{\phi_B\}$ is the mode shape of damaged state of structure

2.4 Normalized Modal Difference (NMD)

NMD is an alternative index to assess the mode shape correlation. NMD was proposed by Waters (Waters, 1995) as an adaptation of the MAC index [7].

$$NMD = \sqrt{\frac{1-MAC}{MAC}}$$

The NMD basically represents a close estimation of the average difference between the components of the two modal vectors. It appears much more sensitive to mode shape difference than MAC and, therefore, it is sometimes used to better remark the difference between highly correlated mode shapes. The closer NMD is to zero, the better the correlation is [8].

2.5 Modal Curvature

The presence of the crack or damage in a structure leads to a reduction of flexural stiffness of the structure, hence increasing the curvature of the damaged region of the structure. A change in the magnitude of curvature around the damaged region was used to detect and locate damage in a structure. Mode shape curvatures of undamaged and varied damaged condition were extracted numerically from the displacement mode shapes, obtained from finite element analysis. Finally, the modal curvatures are calculated using central difference approximation [9]

$$u'' = (u_{n+1} - 2u_n + u_{n-1}) / \delta x^2$$

where u_n= displacement mode shape at node n
δx= is the length of the element

The value of mode shape curvature at certain damage state is slightly higher than the other damage states. Based on the curvature difference between the undamaged and damage states, the location of damage in a structure can be determined.

2.6 Curvature Damage Factor (CDF)

CDF is effective in detection of spatial distribution of damage in a structure. This method is considered more accurate than the modal curvature method because it eliminates the problems caused by the damage location in conjunction with certain modes [8]. CDF is the average absolute changes of modal curvature considering several mode shapes. The idea behind this adaptation is that different parts of the structure are activated for different modes. So, if a damaged zone is not strained by a mode, other modes would be able to strain that damaged section [9].

To summarize the results for all the modes, the curvature damage factor as proposed by Wahab and Roeck (1999) is calculated, which can be written as

$$CDF = \frac{1}{N}\sum_{i=1}^{N} |u''_{oi} - u''_{di}|$$

were N= total number of modes considered
u_{0i}'' = modal curvature of undamaged structure
u_{di}'' = modal curvature of damaged structure

2.7 Modal Strain Energy (MSE)

The elemental the modal strain energy (MSE) is defined as the product of the elemental stiffness matrix and the second power of the mode shape component. The methods based on the modal strain energy of a structure have been commonly used in damage detection [14-16]. Since the mode shape vectors are equivalent to nodal displacements of a vibrating structure, therefore in each element of the structure strain energy is stored. The strain energy of a structure due to mode shape vectors is usually referred to as the modal strain energy (MSE) and can be considered as a valuable parameter for damage identification. MSE before and after the damage is mathematically expressed as [8]

$$MSE = \frac{1}{2}\{ø\}^{T}[K]\{ø\}$$

Where [ø]-is the mass normalized mode shape
[K]-is the stiffness matrix of the element

2.8 Flexibility Based Method

It has been proved that the presence of damage in a structure increases its flexibility. So, any changes observed in the flexibility matrix can be interpreted as a damage indication in the structure and allows one to identify damage [7]. Therefore, another class of damage identification methods is based on using the flexibility matrix. The flexibility matrix *F* is the inverse of the stiffness matrix. Lin [9] has observed that higher modal frequencies contribute to the stiffness matrix, one need to measure all the modes of the structure, especially the high frequency modes. Because of the practical difficulties in experimental instrumentations, it is increasingly difficult to measure higher frequency response data, which makes the accurate extraction of stiffness matrix tougher. While flexibility matrix gives a good estimate as it can be obtained from only a few of the lower frequency modes. On the other hand, the modal contribution to the flexibility matrix a decreases as the frequency increases, i.e. the flexibility matrix converges rapidly with increasing values of frequency. Therefore, from only a few the lower modes, accurate flexibility matrix can be obtained.

$$F = [ø]\,[\Omega]\,[ø]^{T}$$

[ø]-mass normalized mode shape
[Ω]-diagonal matrix that contains the system eigenvalue
$\{[\Omega] = \text{diagonal}\ (\omega^2)\}$

Each column of the flexibility matrix represents the displacement pattern of the structure associated with a unit force applied at the associated DOF. In the damaged vicinity of a uniform structure, an abnormality occurs in the aforementioned displacement shape due to sudden stiffness changes. This abnormality can also be seen in mode shapes; however, flexibility shapes seem to exhibit the damage better, because they make use of frequency information as well as mode shapes.

A Damage Indicator (δ) was calculated as the absolute value of the normalized difference between the diagonal coefficient of the flexibility matrix calculated for the undamaged and damaged condition.

$$[\delta] = \left|\frac{F^{0} - F^{D}}{[illegible]}\right|$$

where, F^0 is the flexibility matrix of undamaged structure
F^D is the flexibility matrix of damaged structure

Damage Indicator associated with flexibility is more sensitive in the lower modes as accurate flexibility matrixes are obtained at the lower modes. Local peaks or abrupt changes in the trend of the damage indicator calculated at different locations in the system were used to localize damage. The method rapidly converges when the number of considered modes increases, however two modes were generally enough to achieve good levels of convergence. This convergence with a reduced number of modes was considered as an advantage because it reduced the concern regarding inaccurate measurements and the effect of non-linear behavior associated with high frequency modes.

3 NUMERICAL SIMULATION

Initially macro and micro-model of an URM panel was being considered. Micro-model specimen gave better results. Hence, micro-model of an unreinforced masonry panel of uniform cross-section, fixed on one surface was implemented for modal analysis.

A three dimensional masonry wall of dimension 1.2m x 1.2m x 0.23m was adopted. Young's modulus and mass density of brick masonry and mortar, $E_{masonry}$ =15GPa and 1700kg/m^3, E_{mortar}=1GPa and 1500kg/m^3 respectively and Poisson's ratio=0.3.

In the FEM tool, a solid, deformable, 3D extrusion was used to create part. Micro modelling was done by partitioning the panel based on the brick and mortar dimensions. Corresponding material properties were assigned to the partitioned brick and mortar elements. Boundary condition (i.e. fixed end) was assigned to one surface of the panel. Meshing was done by assigning approximate global size=1. 8-node linear brick, reduced integration, hourglass control element type was used for meshing. Frequencies and modal displacement was obtained as the output from the numerical analysis.

The analysis was carried out using Finite Element software package. The changes in the natural frequencies and mode shapes of first five vibrational modes were examined. The basic procedure adopted was to first determine the modal parameters of a healthy unreinforced masonry panel and then incrementally induce damage states by increasing the depth of the crack and extract the modal parameters for the corresponding damage states.

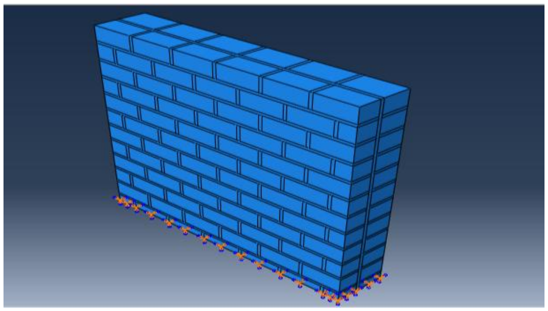

Figure 1: ABAQUS model of undamaged an URM panel

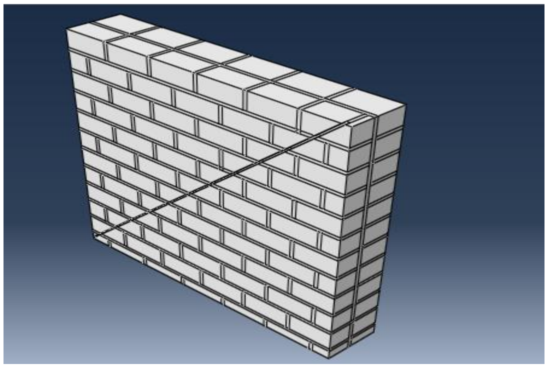

Figure 2: Cracks were induced in an URM panel along the tension diagonal

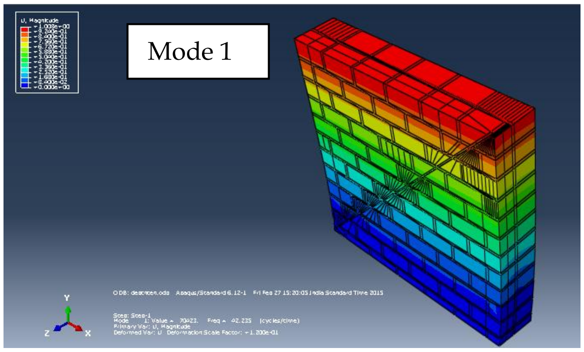

Figure 3: Mode shape of URM panel with depth of crack = 100mm

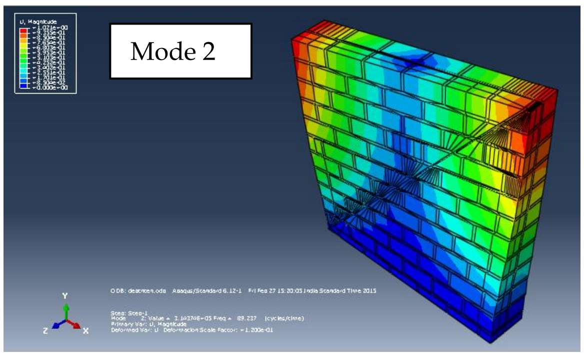

Figure 4: Mode shape URM panel with depth of crack = 100mm

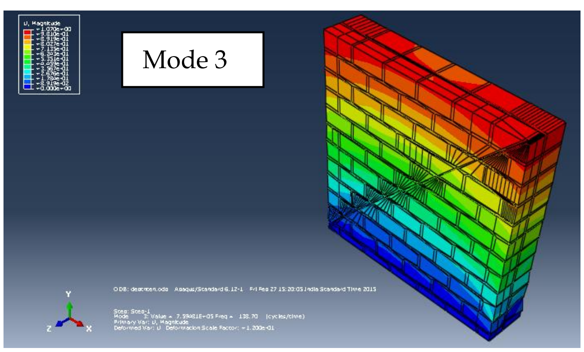

Figure 5: Mode shape of URM panel with depth of crack = 100mm

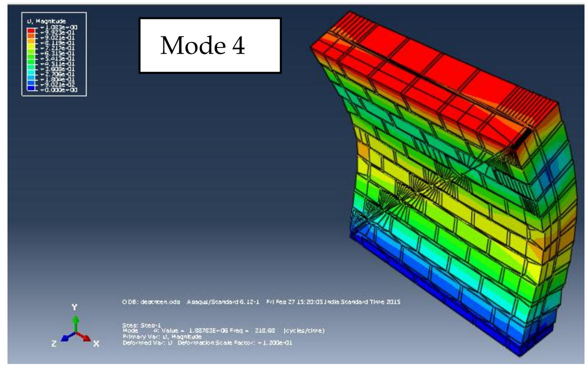

Figure 6: Mode shape of URM panel with depth of crack = 100mm

4 RESULTS & DISCUSSIONS

4.1 Frequency Change

Table 1 contains the natural frequencies of the undamaged and the damaged structure for the first five mode shapes

Depth of crack (mm)	MODE 1 (Hz)	MODE 2 (Hz)	MODE 3 (Hz)	MODE 4 (Hz)	MODE 5 (Hz)
0	50.62	104.21	162.35	262.21	342.10
20	42.235	89.237	138.70	218.68	311.80
40	41.553	86.499	138.35	214.17	300.08
60	40.670	84.897	136.76	212.98	306.25
80	39.420	81.067	135.63	206.42	289.98
100	38.674	75.368	137.35	208.32	261.80
120	28.476	61.160	133.33	195.57	234.38
140	25.875	59.014	129.29	194.05	229.57
160	24.555	58.134	127.21	193.47	223.85
180	21.252	56.628	121.72	191.05	216.07
200	24.27	57.243	116.28	186.03	215.57
220	22.075	55.891	113.97	181.49	207.97
230	1.0407	8.1319	20.287	67.969	91.557

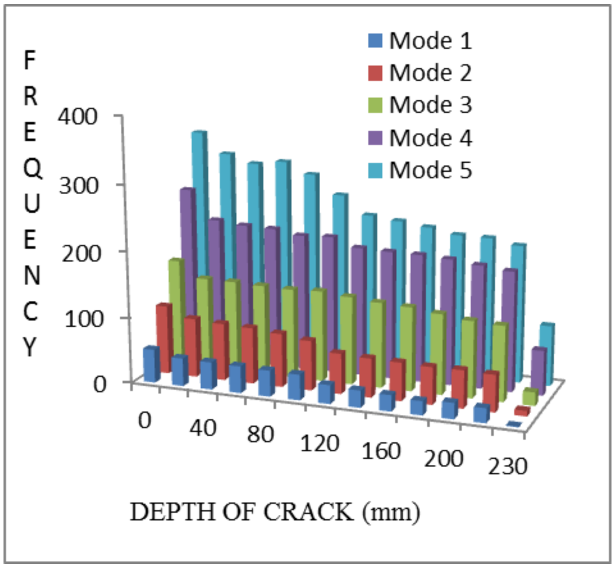

Figure 7: Frequency changes as the depth of the crack increases in an URM panel

Table 1 and figure 7 indicates a decrease in the natural frequencies as the depth of crack increases, this is basically due to reduction in the stiffness caused due to crack being induced in the URM panel.

4.2 Frequency Shift

Table 2 contains the frequency shift of the damaged URM structure

Depth of crack (mm)	ω_2/ω_1	ω_3/ω_1	ω_4/ω_1	ω_5/ω_1
20	2.1128	3.2840	5.1776	7.3846
40	2.0816	3.3294	5.1541	7.2216
60	2.0875	3.3626	5.2367	7.5301
80	2.0565	3.4406	5.2364	7.3562
100	1.9488	3.5515	5.3866	6.7694
120	2.1477	4.6822	6.8678	8.2307
140	2.2807	4.9967	7.4995	8.8723
160	2.3675	5.1806	7.8790	9.1163
180	2.6646	5.7275	8.9897	10.1670
200	2.3586	4.7911	7.6650	8.8822
220	2.5319	5.1629	8.2215	9.4211
230	7.8138	19.4936	65.3108	87.9764

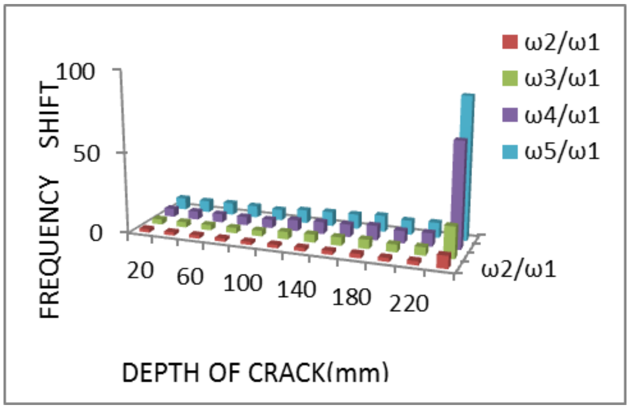

Figure 8: Frequency shift for the various damage states considered in an URM panel

Table 2 and figure 8 indicates the frequency shift of the damaged structure. The peak of frequency shift is maximum at higher level of damage. Thus the presence and location of damage was indicated by frequency shift which does not require the natural frequency of the intact structure.

4.3 MAC

Table 3 shows the modal assurance criterion for the crack of increasing depth in an URM panel

Crack Depth(mm)	MAC
0	1
20	0.9784
40	0.9822
60	0.9784
80	0.9850
100	0.9804
120	0.9451
140	0.9321
160	0.9587
180	0.9299
200	0.8873
220	0.8787
230	0.8234

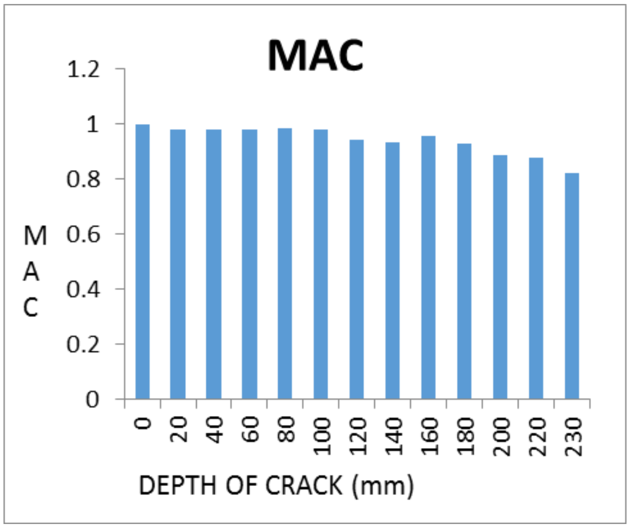

Figure 9: MAC index for corresponding damage state in an URM panel

Table 3 and figure 9 indicates the MAC index for increasing damage state of the URM panel. The MAC value decreases as the damage increases, thus indicating the presence of damage in the structure.

4.4 NMD

Table 4 contains the NMD index for the damage state considered in an URM panel

Crack Depth(mm)	NMD
0	0
20	0.1486
40	0.1346
60	0.1485
80	0.1196
100	0.1414
120	0.2410
140	0.2699
160	0.2076
180	0.2746
200	0.3564
220	0.3715
230	0.4631

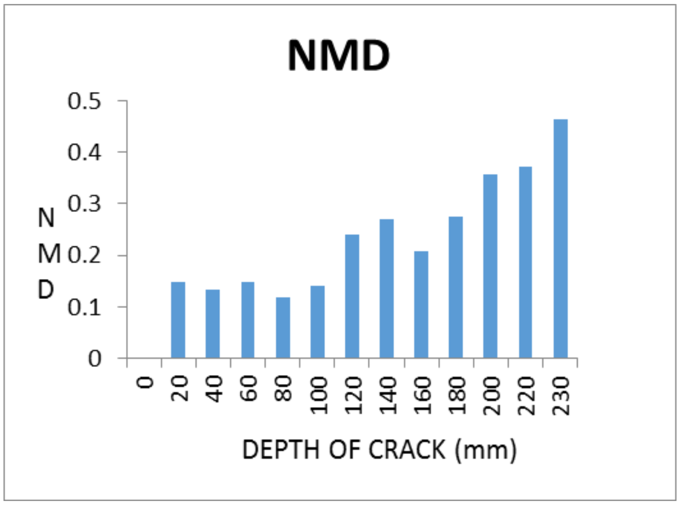

Figure 10: NMD values for corresponding damage in an URM panel

Table 4 and figure 10 represents the NMD values of an URM panel for increasing damage conditions. The MAC value gives a clear indication of damage unlike MAC. Therefore, NMD is much more sensitive to damage than MAC index.

4.5 Modal Curvature

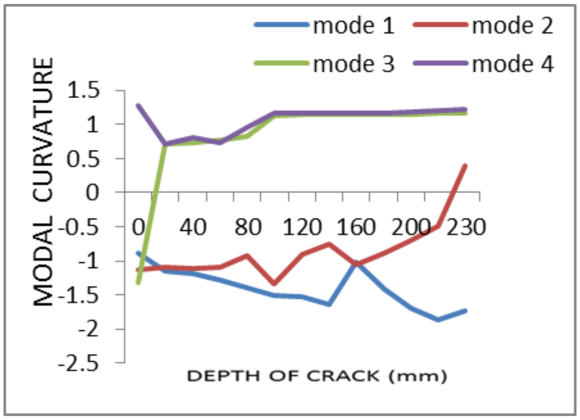

Figure 11: Modal curvature of an URM panel for increasing the crack depths

Figure 11 represents the modal curvature of the URM panel subjected to increasing damage state. Modal curvature is maximum at higher level of damage condition for all the modes due to the magnitude of curvature increasing around the damaged region.

4.6 CDF

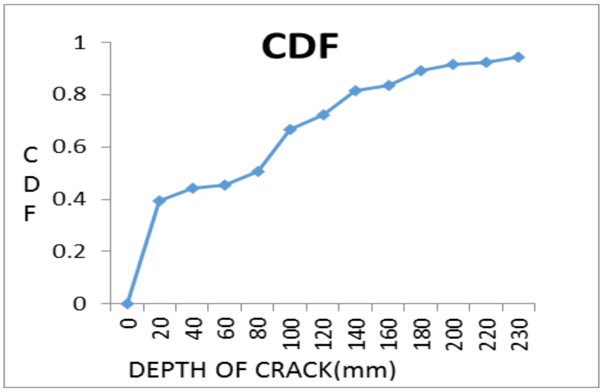

Figure 12: Curvature Damage Factor of an URM panel for increasing the crack depths

Figure 12 represents the curvature damage factor of an URM panel subjected damage of increasing magnitude. The peak of CDF graph represents the location of damage in the structure.

4.7 Modal Strain Energy

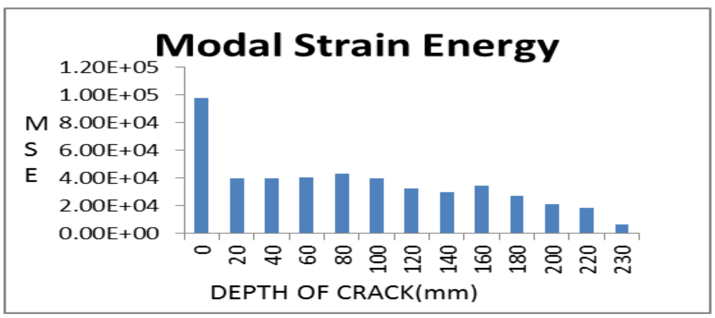

Figure 13: Modal strain energy of an URM panel for the cracks of increasing depths.

Figure 13 indicates the drastic reduction in the modal strain energy as the depth of crack increases. As damage increases the stiffness of the structure decreases leading to a reduction in the modal strain energy of the URM panel.

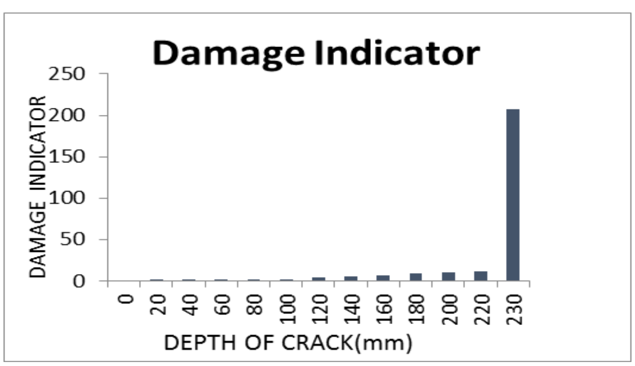

Figure 14: Flexibility based damage indicator of an URM panel for the cracks of increasing depths.

Flexibility based damage indicator indicates the location of damage when the magnitude of damage is severe or prominent.

5 CONCLUSION

In this present paper, a study was carried out for the extraction of modal parameters of an URM panel when subjected to damage by the introduction of the cracks of varying depths. From the numerical analysis it was observed that the displacement mode shapes are more prominent for the cracks of larger the crack depths when compared to the cracks of shallow depths.
The following conclusions can be drawn from numerical analysis of an URM panel:

- Statistically significant a reduction in modal frequencies of structure subjected to damage may be used to detect damage at an early stage.
- It has been observed that the natural frequency depends on the size of the cracks induced in a structure.
- Frequency shift does not require any prior information of the structure, hence making its application feasible during practical implementation. But it can be used only when the intensity of damage is prominent.
- MAC index demonstrated to be an efficient damage indicator for an URM panel. NMD index showed a better behaviour to MAC, hence is more efficient.
- Although MAC index can provide a good correlation between two modes and indicate damage in a structure, but it cannot locate the damage.
- It was observed that the modal curvature was higher at the region of maximum damage (i.e. depth of the crack=230mm).
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- CDF allows a clear detection of damage location in a structure. CDF is maximum at the location of highest the crack depths. The peaks of the plot correspond to the location of the crack. With the help of this factor, the location of the crack can be precisely identified. But accurate mode shape measurement is recommended to avoid errors.
- Damage affects the stiffness matrix of the structure, hence altering the modal strain energy of the structure.
- The modal strain energy a decreases with the increasing the depth of the crack, hence indicating the presence and location of damage.
- Flexibility matrix is accurate because it is calculated using the natural frequency and modal displacement of the structure.
- Flexibility based damage indicator gives an exact indication of the presence and location of damage. It is the most efficient damage detection method.

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