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Experimental Investigation on Damage Sensitive Dynamic Responses of a Reinforced Concrete Beam

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Abstract

Reinforced concrete structures are subjected to damage due to environmental loading and operational conditions. Early detection of damages in reinforced concrete structures is very important. However, this becomes difficult because failure at the micro level in the form of minute cracks, develops much earlier than the visual appearance of actual damages resulting out of coalesce of several such micro level damages. Vibration based damage detection techniques, particularly use of modal testing by exciting a structure dynamically and measuring resulting responses is well established in current practice. Still, real experimental investigation involving a full scale reinforced concrete structure is somewhat rare in current literature. In the present investigation, dynamic responses of a 3.3-metre long reinforced concrete beam were measured experimentally before and after damage. Damage in the form of flexural cracks was inflicted by applying quasi-static load using a universal testing machine of capacity 300 kN under the four-point bending configuration. Broadband roving impact excitation was imparted through an impact hammer and the resulting responses were picked up by a single accelerometer. The time signals of both the force and acceleration responses were Fourier transformed using a spectrum analyser to determine the frequency response functions. The modal parameters e.g. frequencies, mode shapes, modal damping factors are found out through curve fitting. The frequency response function at a particular point has also been investigated for all the load increments and gradual changes into the dynamic properties are noted. Comparison of modal parameters between the undamaged and damaged state including their curvatures indicates that they are sensitive to the crack locations. On the other hand, the differences in frequency response functions including their curvatures were sensitive to the damage intensity in turn. The current experimental investigation provides great insight into the application of vibration-based damage detection technique to reinforced concrete structures.

Keywords: Reinforced Concrete, Modal Testing, Frequency Response Function (FRF), Damage Detection

1. Introduction

In Reinforced Concrete (RC) structures, the detection of damage at an early stage is essential so as to repair the structure before it fails. The invisible cracks inside the structure may initiate the structural failure when coalesce and hence the knowledge of damage and its extent is essential for strengthening or rehabilitating the damaged RC structures. There are various local and global damage detection techniques in current engineering practices for detecting different types of damages, applicable to a wide variety of structural forms. Global damage detection techniques depend upon deployment of distributed sensors at limited number of observation points and prescribed excitation of the structure as a whole, through modal testing. Vibration based damage detection methods employing such modal test do not need the damaged site to remain directly accessible. Modal testing provides measurements of dynamic characteristics such as natural frequency, mode shapes and modal damping from measurement of both applied forces and acceleration responses. Damage detection is possible using vibration data because damage alters the physical properties of the structure such as mass, stiffness, and damping, which in turn affect its dynamic characteristics, namely, frequencies, mode shapes and modal damping. Therefore, by analyzing a structure’s dynamic properties from structural vibration, damage can be identified including its location and severity [1]. Casas and Aparicio, [2] conducted dynamic testing on cracked and uncracked RC beams of 1.5-metre length and observed no direct relation between crack growth and increase in damping. Wahab and Roeck [3,4] introduced curvature damage factor and observed it to be promising in detecting the damage location in prestressed concrete bridges. Ren and Roeck [5,6] presented mode-based

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damage identification techniques to predict both the damage location and severity successfully. They observed a reduction of 50% in bending stiffness after the ultimate load is reached. Ndambi et al. [7] observed that the frequencies were affected by loading configuration, with odd modes more affected by the symmetrical configuration and the even modes affected by the asymmetrical configuration. They concluded that the strain energy method was more precise than the standard COMAC (Coordinate Modal Assurance Criteria) factors, or use of flexibility matrix etc. for locating the damage. Neild et al. [8] confirmed a change in nonlinear vibration behavior of a 3-metre long RC beam with damage which is found to be greatest between 5% and 9% of the failure load. A slight reduction in non-linearity after 27% failure load was observed. Morassi et al. [9] proved flexural frequencies showed high sensitivity to damage, which caused nodes of flexural vibration modes to displace towards the damaged area. RC beams with various volumes of construction difficulties, such as honeycombing showed the irregularities in mode shapes around the region of honeycombs [10, 11]. Sampaio et al. [12] have given an account of the frequency response function curvature methods for damage detection. Mondal et. al [13] have investigated damage detection using FRFs at frequencies other than the natural frequencies.

A limited literature is available for the damage sensitive dynamic response of reinforced concrete structures, especially FRF's involving real experiments. In the present investigation, Modal testing was carried out on a 3.3-metre long reinforced concrete beam before failure (intact stage) and after failure (damaged stage). Relationship between mode shape derivatives and frequency response functions (FRFs) with the damage location in the damaged RC beam is investigated.

2. Experimental Program

2.1. Design of RC Beam

Coarse aggregate of maximum size 20 mm and Portland slag cement of a nominal mix of 1:1.5:3 with a water cement ratio of 0.45 were used to cast a 3.3-meter-long reinforced concrete beam with an effective span of 3.0 m. after deploying in simply supported boundary condition. The rectangular cross section was having width of 0.15m and depth of 0.25m. There were three reinforcement bars of 10 mm diameter placed on the tension side (corresponding to a reinforcement ratio of 0.717%) and two 6 mm diameter hanger bars on the top of beam. Vertical stirrups of 6 mm diameter were placed in an equal interval of 150 mm c/c as shown in Figure 1. The beam is under-reinforced.

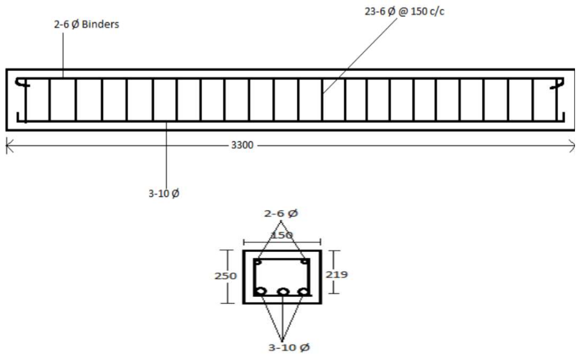

Figure 1: Reinforcement detailing of RC Beam

Figure 2: Static and Dynamic Testing of RC Beam

Six cubes of dimension 150×150×150 mm and six cylinders with height of 300 mm & diameter of 150 mm were also cast for compressive strength test.

2.2. Experimental Modal Testing of RC Beam

The dynamic testing conducted in RC beam with rollers at both ends over a rigid metal supporting platform. A Universal Testing Machine (UTM) of capacity 3000 kN was used for four-point static loading to create cracks due to flexure mainly. Dial gauges were placed at L/3, L/2 & 2L/3 locations (L= Total length of the beam) to record displacement in the vertical direction. Figure 2 shows the configurations of the static and dynamic testing of RC beam. Figure 3 shows the load versus displacement curve from the UTM and Load versus deflection curve from the dial gauges. Dynamic testing is conducted using modal testing setup, containing the excitation mechanism with impact hammer, response measurements using accelerometers and a spectrum analyser for Fourier transform and finding the FRFs.

The beam was divided into 30 equidistant points at an interval of 100 mm along the central line of the beam and the accelerometer was fixed at point 27. The first-hand information collected from modal testing, are the frequency response functions (FRFs), which are the ratio of output (acceleration, velocity or displacement) versus input (force) after Fourier transformation of both the acceleration and force time responses

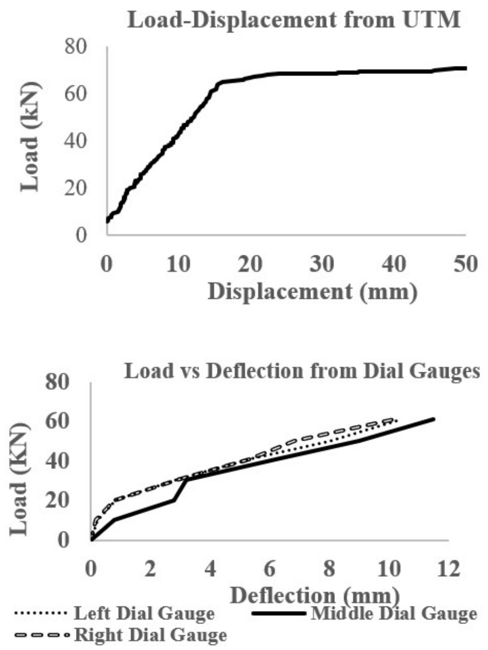

Figure 3: Load vs Deflection from UTM and Dial Gauges

using a spectrum analyser (OROS system). The FRFs are then curve fitted using modal analysis software (ME Scope) to obtain the natural frequencies, mode shapes and modal damping factors.

The 28 days Cube compressive strength was found to be 44.13 MPa whereas, the Cylinder compressive strength was 28.92 MPa. Table 1 shows the frequency and damping of the intact and the damaged RC beams. Figure 4 shows the normalized mode shapes of the RC beam.

3. Damage Sensitive Behavior of RC Beam from Mode Shapes

Damage sensitive behavior is expressed in terms of damage index (DI). Here, damage index similar to the curvature damage factor [3] has been adopted for identifying the damage location. The DI is defined as average summation of curvature difference considering all modes and normalised with respect to the largest value of each mode.

$$\mathrm{DI} = \left(\frac{1}{N}\sum_{i=1}^{N}\frac{\mathrm{MSCd}}{\mathrm{abs\,max(MSCd)}}\right) \qquad (1)$$

where, MSCd is the absolute difference in curvature of the undamaged and damaged state. It is computed as:

$$[\Delta\psi = \psi_{i,u} - \psi_{i,d}] \qquad (2)$$

Here, ψ denotes the mode shape curvature vector of the i^{th} mode, 'u' and 'd' denote the intact and damaged state respectively. Curvature is computed using the central difference formula.

$$\Psi_{ij} = \frac{\psi_{i+1,j} - 2\psi_{i,j} + \psi_{i-1,j}}{h^2} \qquad (3)$$

Here, 'h' is a constant distance that separates two consecutive nodes.

Table 1: Natural Frequencies and Modal Damping Factors of the RC Beam

Mode	Frequency (Hz)			Damping		
	Intact	Damage	Drop	Intact	Damage	Increase
1	42.18	27.441	34.94%	4.21	7.79	45.95%
2	274.70	238.82	13.06%	3.69	3.396	-8.65%
3	488.23	323.9	33.65%	0.71	0.898	20.93%
4	758.56	513	32.37%	0.62	0.81	23.45%

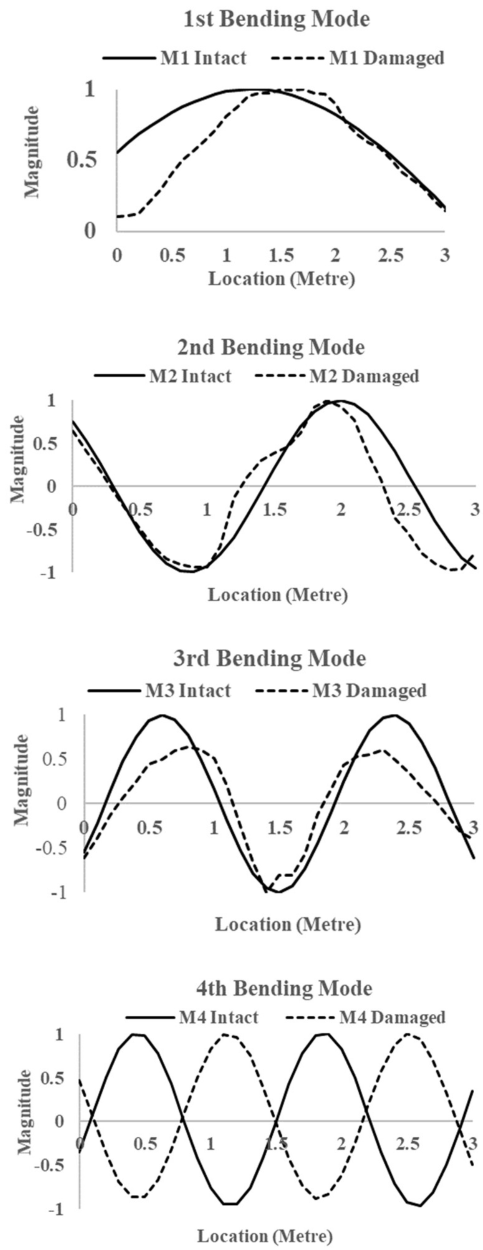

Figure 4: Normalized Mode Shapes of Intact and Damaged RC Beam

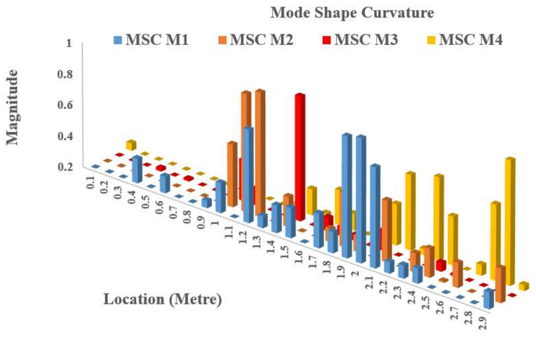

Figure 5: Mode Shape Curvature of All Modes

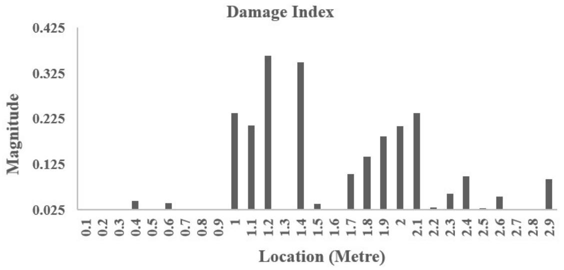

Figure 6: Damage Index of RC Beam

Figure 5 shows the mode shape curvature of all the four modes and Figure 6 represents the damage index calculated on the basis of first three modes only. It was observed that the first three mode shape curvature represented the actual damage location (i.e. 1.0m, 1.1m, 1.2m, 1.4m, 1.7m, 1.8m, 2.0m and 2.1m along the length of beam) more accurately. Previous studies from literature also suggested to neglecting the higher modes of vibration [3]. Extra peaks in the figure represent the noise in the form of unmeasured input during the experimental investigation.

4. Damage Sensitive Behavior of RC Beam from Frequency Response Function (FRF)

For an intact or damaged beam of given dimensions, the natural frequency of vibration is mainly related to the equivalent modulus of elasticity or stiffness of the system. Hence, the equivalent modulus of elasticity of a material can be related to the measurement of the natural frequency of vibration. Based on this point, shifts in natural frequencies are considered as damage indicators. Figure 7 shows the shifting of FRFs at 0.3m, 1.2m, 1.5m and 2.1 metre. Shift in FRF peaks can be observed clearly at 1.2 metre and 2.1 metre.

The modal testing was also carried out to measure the FRFs at a distance of 2.7 metre from one end at an interval of loading of every10kN up to the ultimate load i.e. 70 kN. Figure 8 shows the shifting of frequencies in FRFs on incremental loading at point 27 in the range of 20Hz to 300Hz.

Since the natural frequency of vibration is mainly related to the stiffness of the system, the shift in FRFs on incremental loading, shows the reduction in stiffness due to increased load. In figure 8, the shifting of FRF is shown by 0-1’, 1’-2’, 2’-3’, 3’-4’ from the undamaged state to 20kN, 20kN to 40kN, 40kN to 60kN and 60kN to70kN load respectively. In static testing, the visible cracks were observed at 40kN load and in Figure 8, after 40kN load, no clear peaks were observed indicating the loss of stiffness.

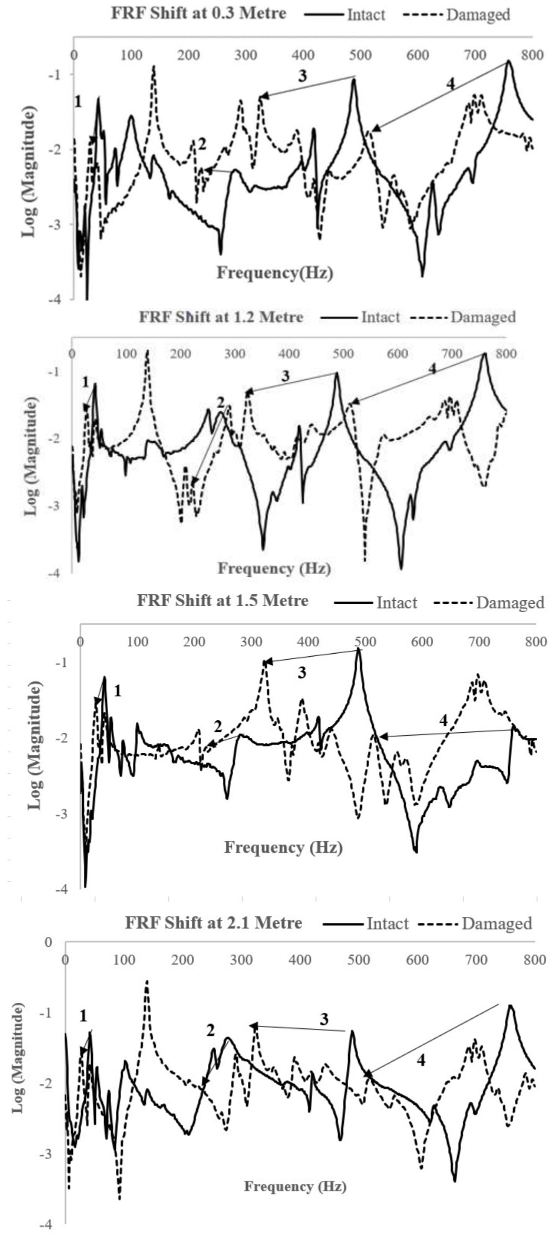

Figure 7: FRF Shift at 0.3m, 1.2m, 1.5m and 2.1m

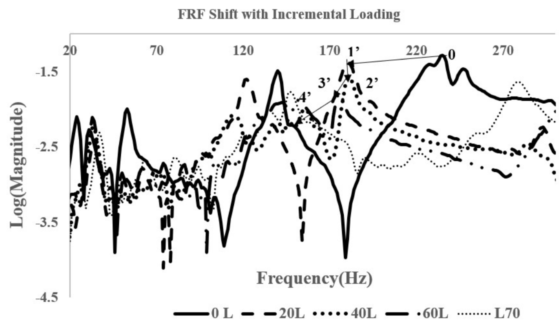

Figure 8: FRF Shift on Incremental Loading at 2.7 metre

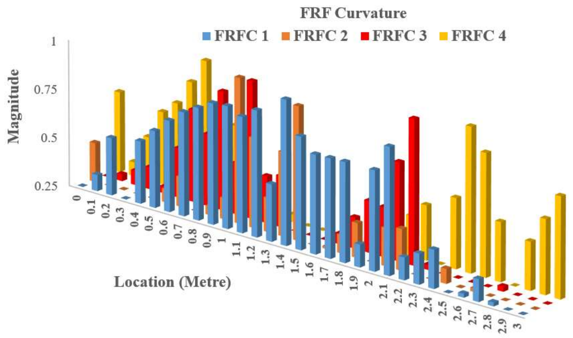

Figure 9: FRF Curvature for all Frequencies

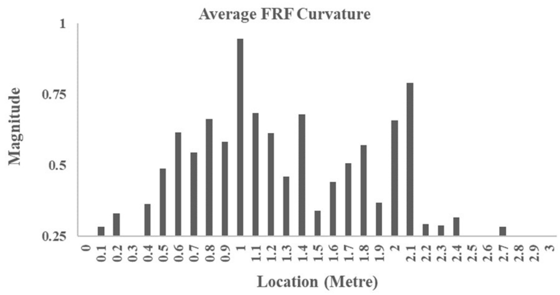

Figure 10: Average FRF Curvature

Frequency response function curvature using central difference formula was plotted using equation 4, as shown in Figure 9.

$$H_{ij} = \frac{H_{i+1,j} - 2H_{i,j} + H_{i-1,j}}{h^2} \quad (4)$$

$$\text{Average FRF Curvature} = \left(\frac{1}{N}\sum_{i=1}^{N}(\Delta H)\right) \quad (5)$$

$$[\Delta H = H_{i,u} - H_{i,d}] \quad (6)$$

Here, H denotes the FRF curvature of the i^{th} frequency, 'u' and 'd' denotes the intact and damaged beam respectively. It was observed that FRF curvature for 4^{th} frequency was not representing the damage case and hence was not considered in average of FRF curvature as shown in Figure 10. Thus, the process of damage detection cannot be fully automatic but interactive.

5. Conclusions

An experimental investigation was carried out to study the damage sensitive dynamic response of a RC beam. Four-Point loading was used to create the flexural cracks in the RC beam. The natural frequencies were reduced in all the flexural modes of vibration. Damping was eventually increased as a result of increased dissipation mechanism, however no clear pattern was observed for any particular mode. For this particular investigation, damage index using mode shape curvature of the first three modes represented the damage location clearly. However, due to the inevitable experimental noise in a fully functional laboratory, some extra peaks were also observed. There was shift in FRF's on incremental loading, indicating the loss of stiffness and hence the vibration characteristics can be studied immediately after the commencement of crack. Average FRF Curvature factor represented the correct damage intensity in the RC beam. In the present investigation, fourth mode shape curvature and frequency response function curvature started losing its representative behavior as a damage indicator, suggesting exclusion of the higher modes for effective damage detection. Further experimental investigation should be carried out using various structural configurations to learn more about the most optimum sets of modal properties to study for damage detection in reinforced concrete beams.

Disclosures

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