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Damage assessment of reinforced concrete beams by modal test

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ABSTRACT: Modal analysis is a popular non destructive method for evaluating the health of structural systems. Damaged as well as intact structures are being used as validation tools. A test program on reinforced concrete beams is set up. Beams are gradually damaged and the changes of the dynamic parameters monitored from the initial to the failure state. A total of 8 reinforced concrete beams with similar dimensions were made using concrete with two different compressive strengths and reinforcement ratios. Static loading was performed with four-point-bending setup in order to generate different damage levels in specimens while dynamic testing was conducted to monitor the changes in dynamic characteristics of the samples. By increasing the damage level in specimens, frequencies of the beams were decreased. Damping prosperities behave in the opposite direction and grew as damage level increased. Modal curvatures turned out to be a good damage indicator.The intensity of the damage level in each specimen affects the shape of its mode as well. Fixed points and curvature of the beams tends to move toward the location of the damage.

1 INTRODUCTION

Reinforced concrete structures are not built for eternity. Service loads, environmental and accidental action may cause damage to structures. Regular inspection and condition assessment of engineering structures are necessary so that early detection of any defect can be made and the safety and reliability of the structure can be determined. Early damage detection and damage location allows maintenance and repair works to be properly programmed, thereby minimising costs.

One of the useful and accurate non-destructive techniques in evaluation of structures is the vibrational modal test. This method is based on the changes in dynamic characteristics due to damages in a structural system. Modal analysis is a recognition test for dynamic characteristics of structures through applying vibration modes. Dynamic characteristics include eigenfrequencies, damping and mode shapes which can be achieved by modal test. The response of a structure for an arbitrary load can be obtained using Equation 1 for any linear dynamic system. Here, $h(t-\tau)$ is the response function of a impulse that includes the characteristics of frequency, damping and mass of a structure (Lynch 2005, Clough & Penzin 1993):

$$U(t) = \int_0^t p(\tau)h(t-\tau)d\tau \tag{1}$$

where, $U(t)$, $p(t)$ and t represent displacement, external load and time, respectively. When $p(\tau)$ is unknown, the solution of the above integration becomes difficult. Fourier transform

moves $p(\tau)$ and $h(t-\tau)$ from time domain to frequency domain. Consequently, the structure response in frequency domain will be achieved by a simpler equation as follow (Lynch 2005, Clough & Penzin 1993):

$$U(\omega) = 2\pi H(\omega) \cdot P(\omega) \tag{2}$$

In the modal test, an electromagnetic vibrator or an impact hammer excites the structure at an assumed degrees of freedom. Accurate sensors measure the response of the structure and the matrix of $H(\omega)$ will be obtained from dividing the response by excitation. This function for a structure with one degree of freedom under the general loading is as follows (Schwarz & Richardson 1999):

$$H(\omega) = \frac{1}{-m\omega^2 + ci\omega + k} \tag{3}$$

$H(\omega)$ and related diagrams represent the behavior of a structure. The response diagram in frequency domain is the plot of $H(\omega)$ with respect to ω. This diagram is called Frequency Response Function (FRF). Experimental modal parameters (frequency, damping and mode shape) are driven from a FRF diagram. This technique has been used for the evaluation of reinforced concrete bridges. Researchers have used this technique for evaluation of damage on specimens made based on real structures (Peeters et al. 1996). Neild, Williams & Mcfadden (2002 & 2003) were also performed valuable research on the non-linear behaviour of concrete bridges. Furthermore, this technique is used for the evaluation of retrofitted structures (Ibarra, Bonfiglioli & Pascale 2001). In this study, several specimens have been made and tested using the modal technique in order to investigate the behaviour of reinforced concrete beams.

2 SPECIMEN DESIGN

In order to match the behavior of specimens with real structural elements, it is important to design the specimens which their main frequencies are equal to the frequency of real structures. Figure 1 illustrates geometrical characteristics and the position of longitudinal and shear reinforcement for specimens. The specifications of each specimen are given in Table 1.

3 TEST PROCIDURE AND INSTRUMENTATION

Static and dynamic tests were performed in this study. The testing procedure can be described as follows: The structure was damaged applying monotonic loading by using four point bending setup with a constant rate of loading. At each prescribed loading step, the structure was unloaded and dynamic test was carried out. Figure 1 shows the location of supports and loading plates. For measuring load and displacement, a Load cell and a LVDT were used and their values were recorded at the mid span throughout each test.

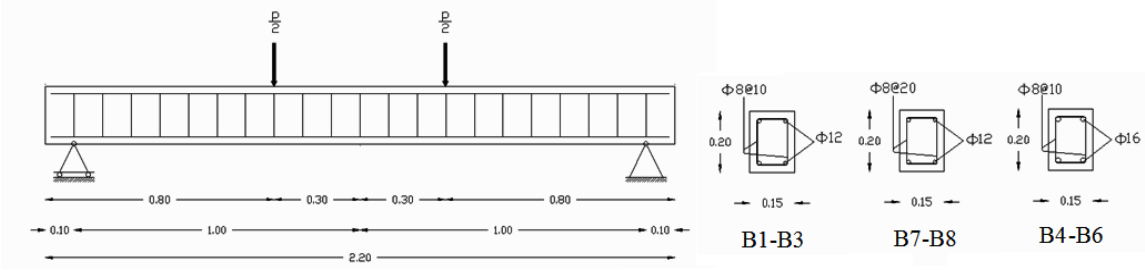

Figure 1. Specimens (Dimensions are in meter).

4 STATIC LOADING

Static and dynamic tests were conducted in parallel. The same simply supported at two ends with two cantilever arms configuration was used for both static and dynamic test, with the scope to evaluate the beams under the real bearing conditions. To reproduce the in-service status of the beams, flexural and shear cracks were induced by means of static loading cycles with increasing amplitude. In this manner investigation of various characteristics of a structure would be possible. Figure 2 illustrates static testing setup.

Table 1. Details of testing specimens

Beams	f'c (MPa)	$A_s t$ (mm^2)	A_s (mm^2)
B1-12D-0L	15.43	226	226
B2-12D-2L-w	15.43	226	226
B3-12D-2L	15.43	226	226
B4-16D-0L	15.43	402	402
B5-16D-2L-w	15.43	402	402
B6-16D-2L	15.43	402	402
B7-12D-1L	48.31	226	226
B8-12D-1L	15.43	226	226

Figure 2. Static loading setup.

5 STATIC TEST RESULTS

Static tests were performed on all eight specimens. A typical load-displacement diagram and the mode of failure for beam B1 are given in Figures 3 and 4. The mode of failure of beams was yielding of tension steel followed by crushing of the concrete in compression zone. Loading was applied to structure as previously determined steps. In order to perform dynamic test at the end of each step, the specimen was unloaded.

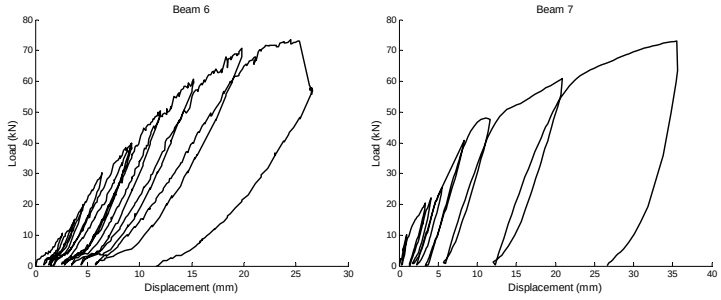

Figure 3. Load-displacement diagram for beams B6-16D-2L and B7-12D-1L.

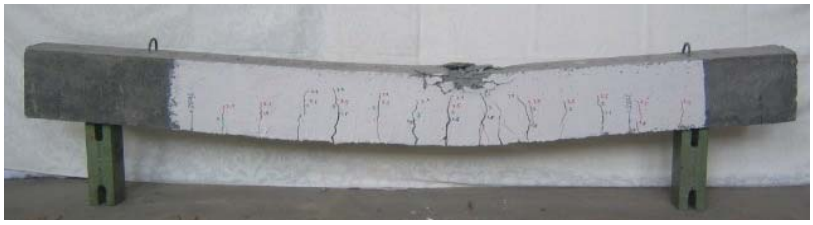

Figure 4. Failed beam B1-12D-0L.

6 DYNAMIC TESTS

A series of dynamic tests were performed on the beams in their virgin state and after each cycle of static loading. In order to avoid the influences of supports on the responses of structure, the specimens were tested in the suspended state by hanging the specimens using elastic cables with a proper stiffness (Figure 5).

As it can be seen in Figure 6, on the upper surface and along centerline of the beam, degrees of freedom were defined at each 10 cm interval. An accelerometer was placed in a particular degree of freedom in which first five modes have a vibrational motion. In all 23 degrees of freedom, the excitation was applied by an impact hammer. FRF and Coherence diagrams were constructed by a double channel analyser. Then, these diagrams were transformed into STAR software through GPIB board and after curve fitting was done on each set of data.

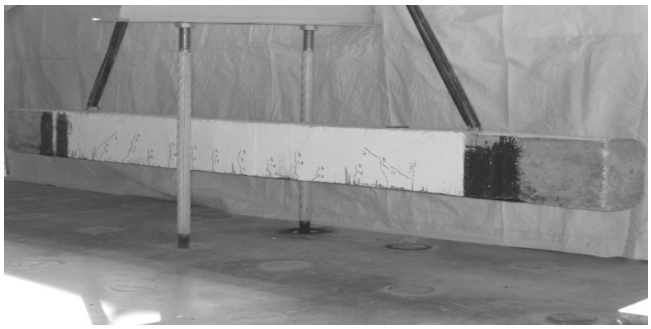

Figure 5. Beam in the hanging state.

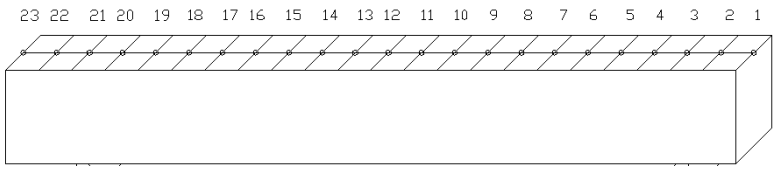

Figure 6. The number and location of degrees of freedom.

Figure 7 illustrates the FRF diagrams for beam B2 in two different steps. As it is shown, the diagrams have display a little noise and five existing peaks in the diagrams demonstrate five initial modes of motion which are separable.

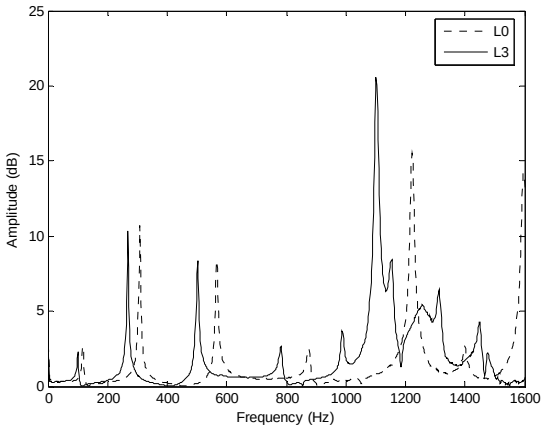

Figure 7. FRF diagram for beam B2 in steps L0 and L3.

6.1 Frequencies

The frequencies of various modes in each step can be obtained by the excitation of an arbitrary degree of freedom and receiving the response at the same degree of freedom for the entire structure. Table 2 displays the values of frequencies for beam B3 in different loading steps. In this specimen, the frequencies were continuously decreasing due to gradual load increment.

Table 2. Frequencies of beam B1 (Hz)

Step	L0	L1	L2	L3
Load(kN)	0	10	15	20
1	111.19	97.38	93.59	91.74
2	293.64	261.78	250.92	274.1
3	541.45	490.96	469.82	461
4	842	776.37	743.55	728.6
5	1.18K	1.09K	1.05K	1.03K

Diagrams shown in Figure 8 display the relative changes in frequencies due to damage level at various loading steps. The first mode is more sensitive to the changes in damage level and strengthening. It is observed that the first step of loading (associated with cracking load) caused a large decrease in the frequencies of all modes. In the consequent steps, this reduction in frequencies became smaller until the yielding of the rebars. The rate of reduction for frequency increased when the rebars started to yield and continued up to failure load. In addition, it can be observed that under equal loading, frequency reduction is less in beams with more longitudinal reinforcements and with higher compressive strengths.

6.2 Mode shapes

The mode shapes were determined by curve fitting of the peaks of the magnitudes of the Fast Fourier Transform (FFT) of the impact acceleration response. Changes in mode shapes and frequencies could be used as a damage indication. After curve fitting FRF diagrams with STAR, all mode shapes were drawn in various damage steps. Changes in the mode shapes at each step show that the nodes have a tendency to move toward the location of the damage. Consequently, it is possible to predict the location of a damage through monitoring of changes in the curvature of mode

shapes and location of nodes at different loading steps. For example, the changes in mode shapes for beam B5 in various steps of loading are given in Figure 9. At few steps before failure, the curvature of the mode shape was changed at the eighth degree of freedom and nodes were also moved to that degree of freedom and finally, the specimen failed at the vicinity of that node.

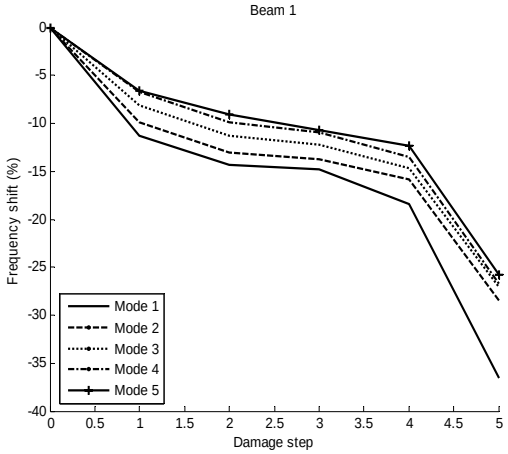

Figure 8. Diagrams of frequency changes in various steps.

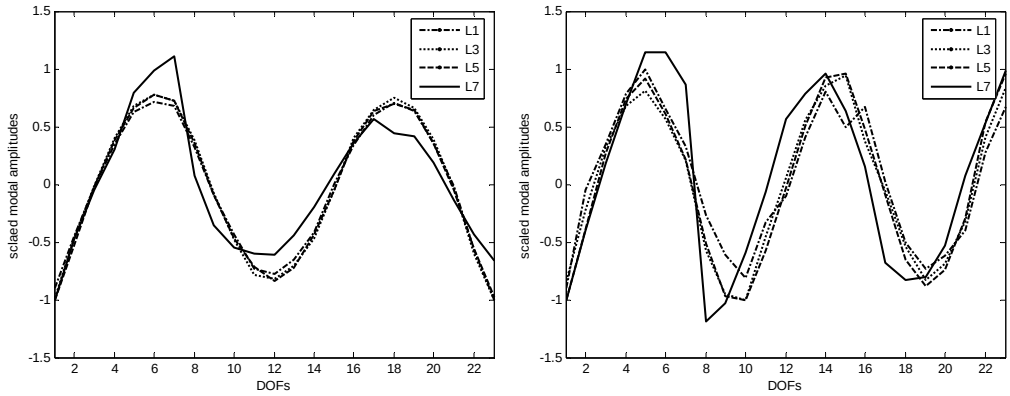

Figure 9. The third and the fourth mode shapes of beam B5-16D-2L-W in various steps.

7 CONCLUSIONS

In order to investigate the relationship between the damage and changes in dynamic properties of a structural system, 8 reinforced concrete beams were tested. Damage level was increased in specimens through loading and it caused cracking and decrease in frequencies. This reduction was more pronounced at the beginning of cracking and yielding of rebars. Changes of mode shapes in various damage steps indicate the location of damaged area. Therefore, through considering the changes in mode shapes the location of damaged area can be detected.

8 REFERENCES

Clough, R., and Penzin, J. 1993. Dynamic of Structures, Mc Graw-Hill Inc.

Ibarra, J., Bonfiglioli, B., and Pascale, G. 2001. Assessment of reinforced concrete beams damaged and repaired with externally bonded FRP sheets. Univ. of Bologna, Bologna, Italy.

Lynch, J. P. 2005. CEE810(CEE619)-Advanced Structural Dynamics and Smart Structures (3 Credits). Michigan University.

Neild, S.A., Williams, M.S., and Mcfadden, P.D. 2002. Nonlinear behavior of reinforced, concrete beams under low- amplitude cyclic and vibration loading. Eng. Struct., 24, 707-718.

Neild, S.A, Williams, M.S., and Mcfadden, P.D. 2003. Nonlinear Vibration Characteristics of Damaged Concrete Beams. Journal of Structural Engineering, 129(2), 260-267.

Peeters, B., Abdel Wahab, M., and De Roeck, G. 1996. Evaluation of structural damage by dynamic system identification. Proceedings of ISMA 21, the 21th Int. Seminar on Modal Analysis, Belgium.

Schwarz, B. J., and Richardson, M. H. 1999. Experimental Modal Analysis. , CSI Reliability Week, Orlando.