Evaluating the dynamic characteristics of reinforced concrete beams

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ABSTRACT: This experimental study aims to investigate the relationship between the damage and changes in dynamic characteristics of reinforced concrete structures strengthened with Carbon Fiber Reinforced Polymer (CFRP). Modal analysis is a popular non-destructive method for evaluating health of structural systems. A total of eight reinforced concrete beams with similar dimensions are made using concrete with two different compressive strengths and reinforcement ratios. Monotonic loading is applied with four-point-bending setup in order to generate different damage levels in specimens while dynamic testing is conducted to monitor changes in dynamic characteristics of the specimens. In order to study the effect of CFRP on static and dynamic properties of specimens, some of beams are loaded to half of their ultimate load carrying capacity and then are retrofitted using composite laminates with different configuration. Retrofitted specimens demonstrate elevated load carrying capacity, higher flexural stiffness and lower displacement ductility. By increasing the damage level in specimens, frequencies of beams are decreased, while having strengthened these values, they improve significantly. The intensity of the damage level in each specimen affects the shape of its mode as well. Fixed points and curvatures of mode shapes of beams tend to move toward the location of the damage in each case.

1 INTRODUCTION

The strengthening of existing structures may be required for several reasons. Lack of durability of construction materials, overload, corrosion of reinforcement and other factors can gradually damage structural members. Therefore, the regular inspection and health evaluation of structures are essential. As a result, if the damage was detected in advance, safety and longevity of the member would be guaranteed. When damage in structural members is hidden and located inside the member, detection and finding its exact position is impossible through visual inspection. One of the useful and accurate non-destructive techniques in evaluation of structures is the vibrational modal test. This method is based on 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 characteristics of frequency, damping and mass of a structure (Lynch 2005, Clough & Penzin 1993):

$$U(t) = \int_0^t p(\tau)h(t-\tau)d\tau \qquad (1)$$

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 would be difficult. Fourier transform transfers $p(\tau)$ 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 follows (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 assumed degrees of freedom. Accurate sensors measure the response of the structure and the matrix of $H(\omega)$ will be obtained by dividing the response through 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 based on real structures (Peeters et al. 1996). Neild, Williams & Mcfadden (2002 & 2003) 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 study the behaviour of reinforced concrete beams retrofitted by CFRP laminates.

2 SPECIMEN DESIGN

In order to match the behavior of specimens with real structural elements, it is important to design specimens whose 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. Specifications of each specimen are given in Table 1.

3 TEST PROCEDURE AND INSTRUMENTATION

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

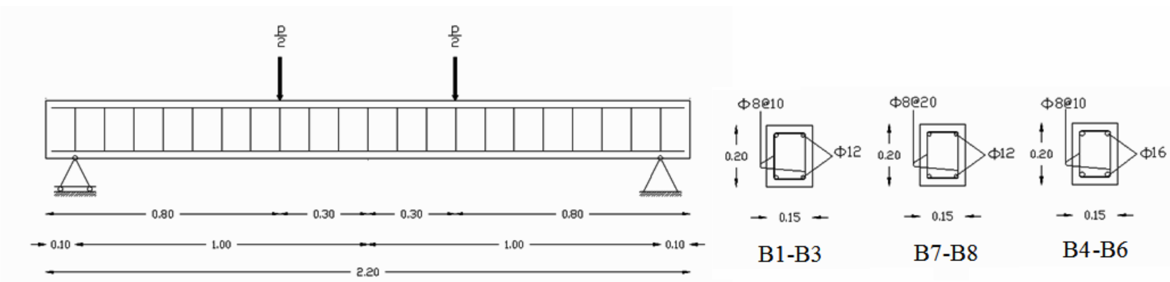

Figure 1. Specimens (Dimensions are in meter).

4 STATIC LOADING

Loading steps are defined with a consideration of the cracking load and the ultimate load carrying capacity of beams. Before strengthening a specimen, loading is applied to the half of the calculated ultimate capacity of unstrengthened beam and a modal test is performed. Then, the beam is strengthened and another modal test is performed in order to compare results before and after strengthening. Afterwards, loading is continued similar the previous step until the beam reaches its ultimate capacity. 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_st (mm^2)	A_s (mm^2)	No. of CFRP Layer
B1-12D-0L	15.43	226	226	0
B2-12D-2L-w	15.43	226	226	2
B3-12D-2L	15.43	226	226	2
B4-16D-0L	15.43	402	402	0
B5-16D-2L-w	15.43	402	402	2
B6-16D-2L	15.43	402	402	2
B7-12D-1L	48.31	226	226	1
B8-12D-1L	15.43	226	226	1

Figure 2. Static loading setup.

5 STATIC TEST RESULTS

Static tests are performed on all eight control and strengthened specimens. A typical load-displacement diagram and the mode of failure for beam B2 are given in Figures 3 and 4. Loading is applied to structure as previously determined steps. In order to perform dynamic test at the end of each step, the specimen is unloaded.

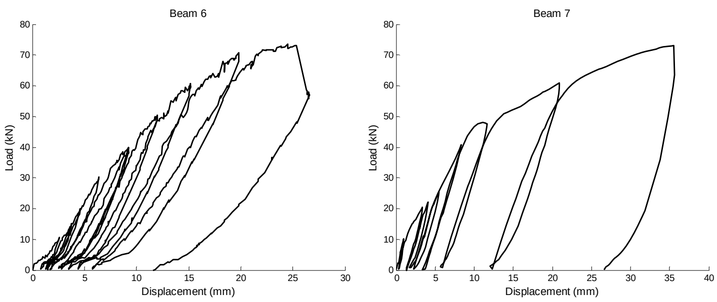

Figure 3. Load-displacement diagram for beams B6-16D-2L and B7-12D-1L.

Figure 4. Failed beam B2-12D-2L-W.

6 DYNAMIC TESTS

Modal test is performed after each unloading. In order to avoid influences of supports on responses of structure, specimens are tested in the suspended state by hanging specimens using elastic cables with a proper stiffness (Figure 5).

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

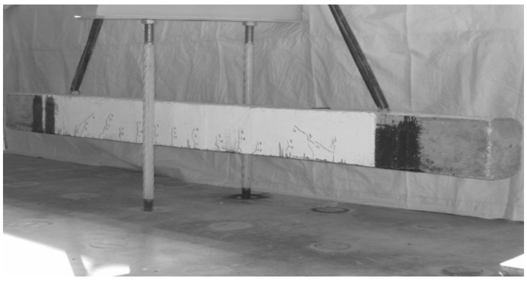

Figure 5. Beam in the hanging state.

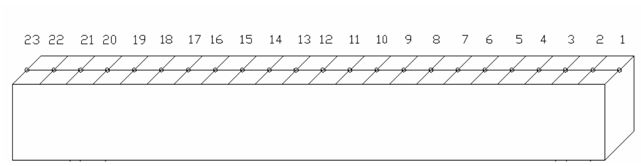

Figure 6. The number and location of degrees of freedom.

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

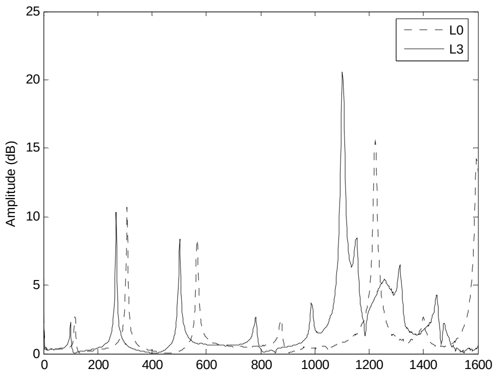

Figure 7. FRF diagram for beam B2 in steps L0 and L3.

6.1 *Frequencies*

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, frequencies are continuously decreasing due to gradual load increment. As it is mentioned, while performing the strengthening stage and reaching the half of the capacity, specimens are unloaded and FRP laminates are installed. The waiting period for CFRP laminates to be completely cured and adhesion to the concrete is more than seven days. Consequently, there is a week (up to ten days) interval between two steps (before and after strengthening). After this period and performing further modal test (without any additional loading), it is observed that, in all modes, the frequency decreases for all of specimens compare to their previous states. This phenomenon has been observed in the work of previous researches as well (Peeters et al. 1996). Specimen B7 that displays higher frequencies is an exception. This phenomenon is most likely related to the creep of concrete. Therefore, more experiments are needed to be performed to understand this behaviour.

Table 2. Frequencies of beam B1 (Hz)

Mode	Before Strengthening				After Strengthening					
Step	L0	L1	L2	L3	L4	L5	L6	L7	L8	L9
Load(kN)	0	10	15	20	0	20	25	30	35	40
1	111.19	97.38	93.59	91.74	87.68	89.81	88.87	85.67	78.27	75.33
2	293.64	261.78	250.92	274.1	244	246.76	244.75	240.45	227.14	220.56
3	541.45	490.96	469.82	461	464.64	470.32	470.11	446.39	431.35	406.41
4	842	776.37	743.55	728.6	715.7	719.32	717.76	702.4	645.17	622.19
5	1.18K	1.09K	1.05K	1.03K	1.01K	1.02K	1.01K	988	930	902

Diagrams shown in Figure 8 display the relative changes in frequencies due to the damage level and the strengthening at various loading steps. The first mode is more sensitive to changes in the damage level and strengthening. It is observed that the first step of loading (associated with cracking load) causes a large decrease in frequencies of all modes. In consequent steps, this reduction in frequencies grows smaller until the yielding of the rebars. The rate of reduction for frequency increases when rebars start to yield and continue up to failure load. The behaviour of specimens, which are not retrofitted, is similar to control specimens and could be used as additional control specimens. At the first step after strengthening stage, frequency reduction in beam is observed (without any additional loading). The increase in frequencies shows the effect of strengthening after retrofitting. 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.

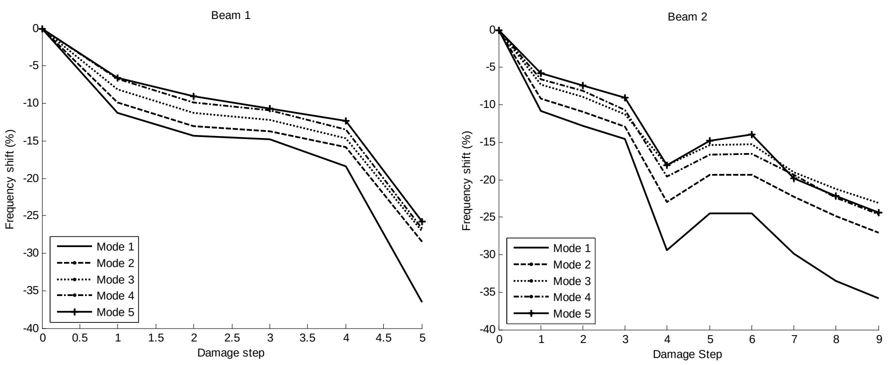

Figure 8. Diagrams of frequency changes in various steps.

6.2 *Mode shapes*

Changes in mode shapes and frequencies could be used as a damage indication. The shape of the i th mode is obtained by linking peaks of the i th mode in FRF diagrams for all degrees of freedom. After curve fitting FRF diagrams with STAR, all mode shapes are drawn in various damage steps. Changes in mode shapes at each step show that nodes have a tendency to move towards the location of the damage. Consequently, it is possible to predict the location of a damage through monitoring changes in the curvature of mode shapes and location of nodes at different loading steps. For example, 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 is changed at the eighth degree of freedom and nodes are also moved to that degree of freedom and finally, the specimen fails at the vicinity of that node.

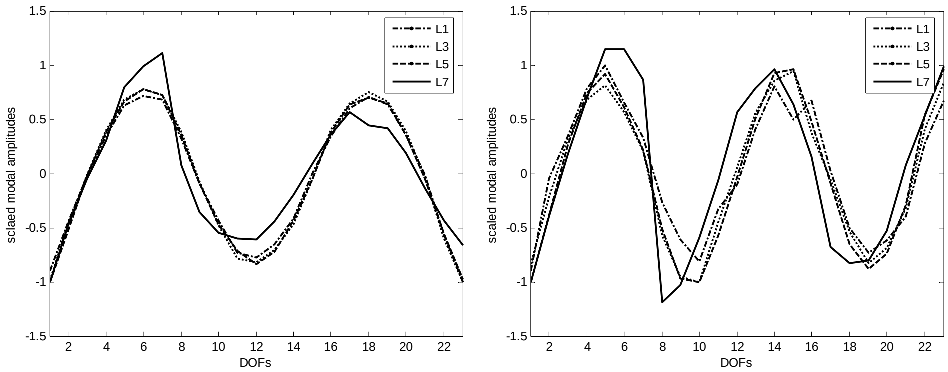

Figure 9. The third and the fourth mode shapes of beam B5-16D-2L-W in various steps.

7 CONCLUSIONS

In order to investigate the relationship among the damage, strengthening of structure and changes in dynamic properties of a structural system, eight reinforced concrete beams are tested. Damage level is increased in specimens through loading which causes cracking and a decrease in frequencies. This reduction is more observed at the beginning of cracking and yielding of re-bars. To evaluate the effect of strengthening, a modal test is carried out before and after strengthening. Beam with CFRP displays higher frequencies. Results display a good perform-ance of beams strengthened with CFRP. Changes of mode shapes in various damage steps indi-cate the location of damaged areas. Therefore, by considering changes in mode shapes the loca-tion of damaged area can be detected. The ultimate load of the strengthened beams, which are retrofitted by CFRP and reinforced with 12 mm rebars, increases between 34 % and 42 % with respect to the control specimen. This ratio is between 9 and 23 percent for strengthened beams retrofitted by CFRP and reinforced with 16 mm rebars. It can be concluded that the decrease in the amount of reinforcements can increase the effect of CFRP on the capacity.

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