The 2013 World Congress on
Advances in Structural Engineering and Mechanics (ASEM13)
Jeju, Korea, September 8-12, 2013

Identification of Delamination Damages in Concrete Structures Using Impact Response of Delaminated Concrete Section

Sung Woo Shin[1),*], Taekeun Oh[2)], and John S. Popovics[3)]

1) Department of Safety Engineering, Pukyong National University, Busan 608-739, Korea (shinsw@pknu.ac.kr)
2) Department of Safety Engineering, Incheon National University, Incheon 406-772, Korea
3) Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Illinois 61801, USA
[1)] shinsw@pknu.ac.kr

ABSTRACT

The deteriorating national infrastructures demand improved non-destructive evaluation (NDE) methods for detection of defects which reduce the integrity of the structures. Vibration resonance tests offer an efficient NDE method to identify and characterize shallow (near surface) delamination defects in reinforced concrete slabs In this study, we compare the capability to visualize near surface delamination defects in concrete slabs using two testing configurations : modal testing and impact-echo testing. The mode shape obtained from two testing configurations are used to visualize defects in the slab and compared. The effectiveness of air-coupled impact-echo testing configuration for defect visualization is discussed.

1. INTRODUCTION

The dynamic characteristics of a vibrating system are best characterized by modal analysis, using modal parameters such as natural frequency and mode shape sets. Natural frequency characterizes the vibration resonance of a structure while the corresponding mode shape contains geometric (spatial) information of vibration resonance. In the case of a near-surface delamination defect in reinforced concrete structures, accurate determination of frequency and mode shape of the concrete section above the delamination enables effective characterization of that defect, in terms of the location, geometrical shape and areal extent. These modal parameters can be experimentally obtained following established modal testing procedures. However,

---

[1)] Associate Professor
[2)] Assistant Professor
[3)] Associate Professor

these procedures are time and labor intensive, and do not lend themselves to incorporation within a rapid scanning test scheme, for example from a moving test platform above the bridge deck. In contrast, conventional impact-echo (IE) tests (with one grouped set of excitation and detection points) are more readily incorporated in to a rapid scanning test configuration, especially if contactless air-coupled sensors are employed [1].

In this study, we compare the capability to visualize near surface delamination defects in concrete slabs using two testing configurations : modal testing and impact-echo testing. The mode shape obtained from two testing configurations are used to visualize defects in the slab and compared. The effectiveness of air-coupled impact-echo testing configuration for defect visualization is discussed.

2. EXPERIMENTAL SETUP

Conventional modal and the multi-point air-coupled IE tests were carried out on a reinforced concrete slab with two layers of steel bars at 60mm and 200mm depths, respectively. The size of slab is 1.5 m by 2.0 m with 0.25 m thickness. The concrete has a 28-day compressive strength of 42.3 MPa. Ultrasonic pulse velocity measurements (ASTM, 1997), show that the P-wave velocity of the mature concrete is 4,100-4,200 (m/s). Thus we expect an impact echo mode (thickness stretch mode) frequency of around 8.0 kHz for the full thickness of a defect-free slab. This slab contains a variety of embedded artificial delaminations and voids. Double-layered plastic sheets and soft foam blocks simulate artificial delaminations. Figure 1 shows the location of delaminations and grid area that defines test points. Near-surface rectangular (0.4×0.6 m^2), square (0.3×0.3 m^2) and circular (diameter: 0.3m) delamination defects with a depth of 60 mm from the surface were selected for air-coupled impact resonance tests reported here. A 25 mm by 25 mm test point grid was defined in order to provide high spatial resolution if test points, needed to appropriately characterize the shape of the most relevant modes of vibration. At each testing point in the grid only one direction, normal to the concrete surface plane, is considered in the analysis; it follows that the number of DOFs of a delaminated concrete section is equal to the number of testing points. For example, the square delamination has 144-DOFs.

A steel ball with 18mm diameter is used as an impact source in this study. The forcing function associated with the steel ball impact event exhibits consistent and broad spectral content, ranging from DC to 15 kHz for a 18 mm of steel ball diameter [2]. The generated surface vibrations set up by the ball impact event are detected by air pressure sensors. The air pressure sensor is a dynamic vocal microphone which has 1.85 mV/Pa of sensitivity at 1 kHz and 50 Hz to 15 kHz of working frequency range. The same steel ball source was used for all resonance tests. Normally an instrumented hammer is used in conventional modal analysis tests. Since our steel ball source is not instrumented, a contact accelerometer is used as a reference sensor to normalize input forcing function magnitude. First an impact position where multiple modes are effectively excited was determined. Then the loading and reference sensor positions are fixed and a single air-coupled sensor is moved over the test area collecting data from each test point. In this study, the loading and reference sensor positions for the rectangular delamination are at 2/3 of length from center toward two different edges.

For the square and circle delaminations, the reference sensor was placed at 1/2 of length from center toward two edges. For the IE test, both impact source and air-coupled sensor are moved together as a closely spaced set across the testing grid. The reference sensor was not used with the IE tests.

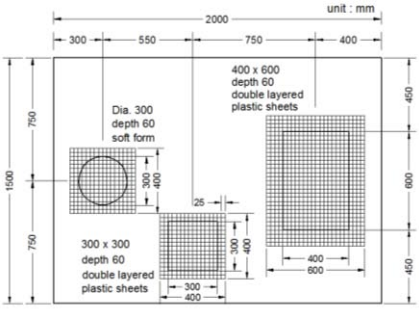

Fig. 1 Plan view of test slab and test grids over three near-surface delamination defects. The depth to each defect is 60 mm.

3. RESULTS AND DISCUSSIONS

The peak picking method [3] was applied to obtain mode shape from IE testing (DPMS) and that from conventional modal testing (TMS). At a given natural frequency, the magnitudes of the frequency spectrum across all test points are plotted on a contour graph to visualize the DPMS and TMS. In the contour graphs, the x and y axes describe the spatial coordinate of the test point and z axis represents the magnitude of the frequency spectrum, representing the contribution of a specific mode. It should be noted that all presented data represent the absolute value of normalized, actual modal displacement. The sign of modal displacement value is not needed to visualize mode shape.

Figures 2 (a) and (b) show the TMS associated with the three dominant flexural modes over the sqaure delamination, obtained by the conventional modal test. The artificial delamination boundaries are indicated with thick dashed lines. This figure clearly indicates that the areal extent of the delamination can be visualized by mode shapes. Figures 2 (c) and (d) show analogous results for the circular shaped defects. We note that the first anti-symmetric modes in square and circular defects do not show expected shape, possibly because the actual constraint condition at the periphery of the defects is not consistent or the artificial delaminations might not be perfectly parallel to the slab surface. Assuming that all boundary conditions are constant along the periphery of the proposed delamination shapes, the mode shapes should be symmetric about the center.

Figure 3 show DPMS obtained from the normalized IE test data over the square and circular delamination defects. Normalization is required for the IE test since the mode shape representation without normalization is poor compared with the results of the conventional modal testing (TMS). The main reason for this is the unknown and varying magnitude of input forcing function from the individual impact events. With conventional modal testing, an external reference sensor was used to normalize the input effect. For the IE tests, the magnitude of negative R-wave peak is utilized for this purpose. As shown in Figure 3, compared to the TMSs obtained from conventional modal testing (Figure 2), the area of the normalized DPMS at each natural frequency are slightly smaller, but nearly equivalent. Most likely, the small discrepancy between TMS and DPMS representations arises from imperfect normalization offered by the negative R-wave peak as compared to that of the contact reference sensor. Nevertheless, the normalized DPMS obtained from IE test successfully identify all pertinent vibration modes of delaminated concrete section and are effectively equivalent to TMS from conventional modal tests.

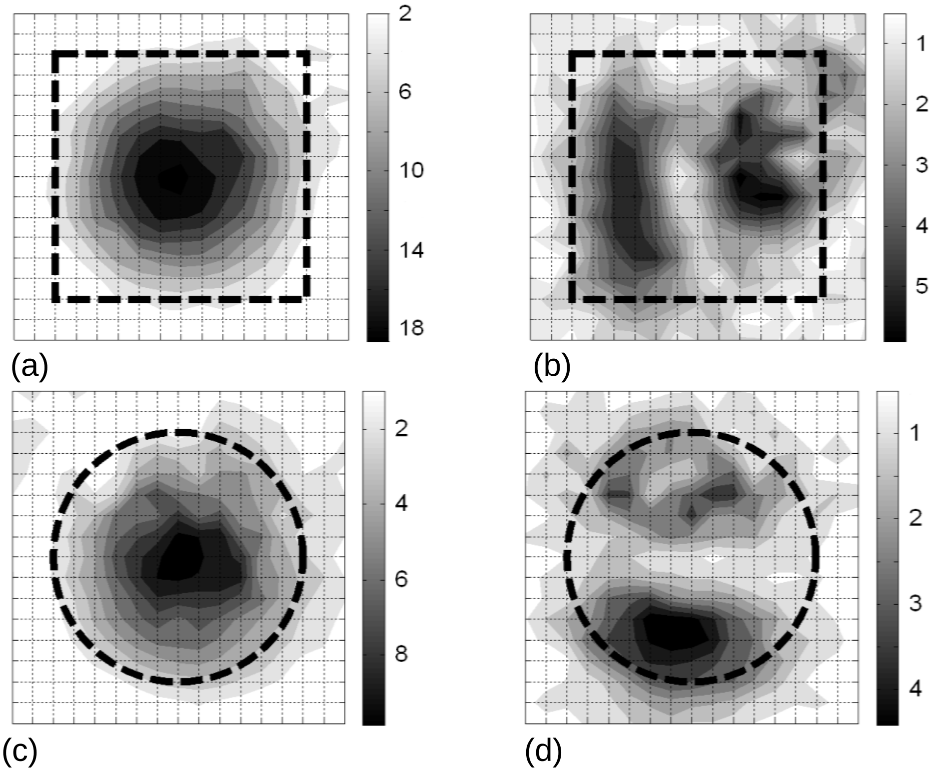

Fig. 2 Mode shapes of the square (a) and (b) and circle (c) and (d) delaminations obtained using the conventional modal testing: (a) at 1st and (b) at 2nd natural frequency and (c) at 1st and (d) at 2nd natural frequency.

In general, the location, shape and dimensions of actual delamination defects in a structure are normally not known in advance. The advantage of IE testing based defect visualization is that it does not require the information on the location of defects in advance since it enables moving forward-scanning using a set of excitation-sensor set. However, in modal testing based defect visualization procedures, the location and shape of the delamination must be known in advance since loading and reference measurement points must be positioned at certain locations of the vibrating body.

3. CONCLUSIONS

Based on the results presented in this paper, the following conclusions are drawn:

(1) Air-coupled impact resonance tests, using both IE test and conventional modal test configurations, can be used to characterize delamination defects within concrete structures with high accuracy.

(2) Each point of IE data can be self-normalized using the R-wave characteristics in the time signal. The set of normalized IE data can be used to obtain spectral mode shape data that equivalent to those from a conventional modal test configuration.

(3) The IE testing configuration offers significant advantages for field application: it enables moving forward-scanning for damage detection using a set of excitation-sensor set and does not require that the location of defects be known in advance.

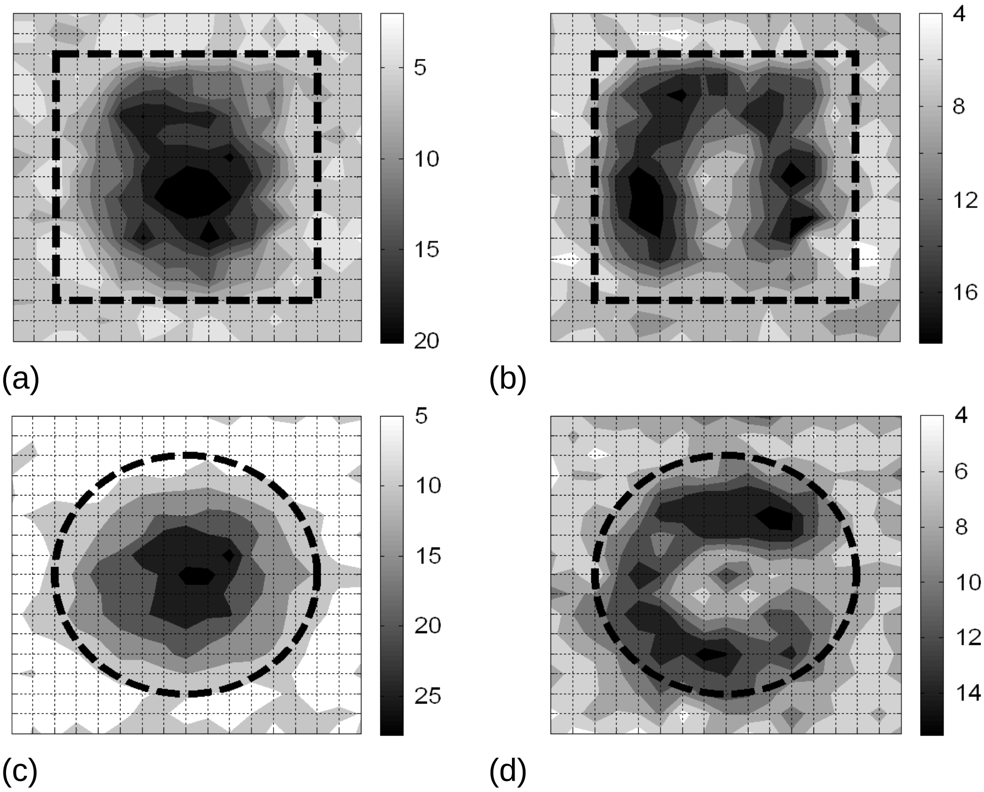

Fig. 3 Mode shapes of the square (a) and (b) and circle (c) and (d) delaminations obtained using the IE testing: (a) at 1st and (b) at 2nd natural frequency and (c) at 1st and (d) at 2nd natural frequency.

REFERENCES

(1) Zhu, J. and Popovics, J.S., Imaging concrete structures using air-coupled impact-echo, Journal of Engineering Mechanics, Volume 133(6), 2007, pp. 628-640

(2) Sansalone, M.J. and Streett, W.B., Impact-Echo: Nondestructive Evaluation for Concrete and Masonry, 1997, Bullbrier Press, Ithaca, New York, USA

(3) Ewin, D.J., Modal Testing, 2000, Research Studies Press, Hertfordshire, UK.