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2D finite element simulation of air-coupled impact echo testing on concrete slab

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Abstract Impact-echo is an effective method in identifying and detecting delamination in concrete structures. Recently, the contact sensor is replaced with air-coupled sensor due to the interest in rapid testing method. This paper presents a study of the optimum test configuration of air-coupled impact echo and conventional concrete-coupled impact echo tests by means of numerical simulation. Two-dimensional finite element analyses were performed on concrete slab to investigate the effect of impact-to-sensor distance and sensor height from concrete surface. Two concrete slabs, one without delamination and one with delamination, were modelled. For intact concrete, both sensors were effective in detecting concrete thickness at any point within the specified location range. However, for air-coupled IE performed on concrete with 40 mm delamination depth, optimum sensor location is 60 to 100 mm away from impact point at height of 10 mm.

1. Introduction

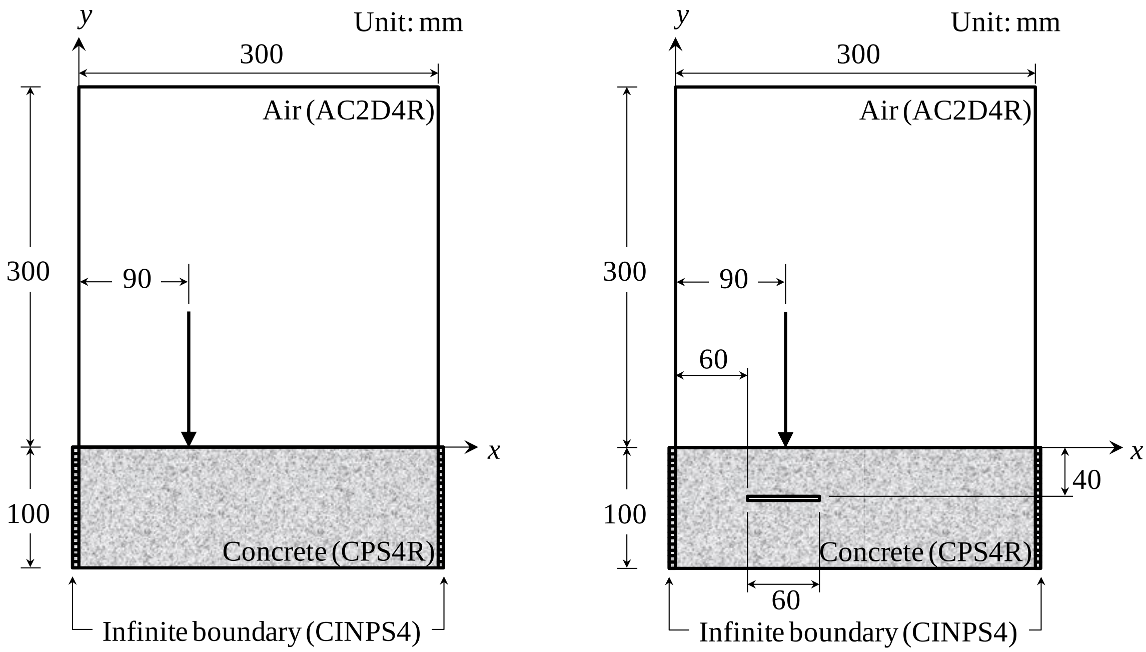
Non-destructive evaluation techniques have become important for the maintenance of existing structures as well as for the construction quality control. Impact-echo is a widely used non-destructive testing method that has been demonstrated to be effective in identifying and detect delamination in concrete structures. Impact-echo is one of the techniques which work on the principle of stress wave propagation that has been introduced since 1980s. It can be used to determine the location of flaw such as cracks, delaminations, estimating the depth of delamination and slab thickness. Impact-echo is a mechanical wave-based NDE technique which transient point load is applied at specimen surface to initiate waves propagation. This impact generates body waves (P-waves and S-waves) and surfaces waves (Rayleigh waves) that simultaneously propagate in the concrete. The resulting transient surface motion which is set up by a vibration resonance through the thickness of the element is detected by a sensor coupled to specimen surface. The transient time response of the solid structure is commonly measured with a contact sensor coupled to the surface at some distance to the impact source. The time domain signal is transformed to the frequency domain where the frequency at the maximum spectral amplitude is obtained. The thickness or depth of delamination, d is related to P-wave velocity V_p and peak frequency, f_{max} of the frequency spectrum by

$$d = \frac{V_p}{2f_{max}} \tag{1}$$

This is the basic equation for determining the thickness of solid concrete structures using the impact-echo method. However, previous research consisting of experiment and numerical simulations has demonstrated there should be a shape factor, β, which is function of the geometry of the tested concrete structure, to convert the P-wave speed from the Equation (1) or the P-wave speed test to the apparent P-wave speed measured in the impact-echo test. For plate-like structure, the shape factor is equal to 0.96 and Equation (1) can be written as

$$d = \frac{\beta V_p}{2f_{max}} \tag{2}$$

The use of an air-coupled sensor was demonstrated to be effective in improving the IE testing speed [1, 2, 3]. In an air-coupled IE testing system, the contact sensor is replaced with a contactless sensor. The basic idea of this test is that waves propagates into the air initiated by the wave motion of the surface can be captured by a microphone, which is an air-coupled sensor. Numerous investigations have demonstrated that air-coupled IE data are consistent, reliable and are equivalent to that collected using conventional contact sensor [3].



(a) (b)

Figure 1. 2D model for an air-concrete systems (a) concrete slab without delamination and (b) concrete slab with 60mm-long delamination at depth of 40mm.

In IE test, the distance between impact point and sensor is important. However, not much consideration was made in deciding the location of sensor relative to source location. If the distance is too large, the response will not dominated by the reflected P-wave, and the simple relationships expressed by Equations. (1) and (2) are not applicable. If the distance is too small, the response is dominated by the effect of the surface wave [4]. [5] suggest that spacing from 0.2 to 0.5 of delamnation depth or concrete thickness was found to give acceptable results based on a series of analytical studies. [6] recommend a spacing of less than 0.4 of the concrete thickness. When the source is impacted to concrete surface, stress waves generated in the air and concrete, and later, waves in the concrete radiated into air nearby air-concrete interface. For air-coupled IE test, [7] setup the microphone at 20 mm above concrete surface and at 0.5 of concrete thickness distance from impact point. The test results agree well with numerical simulation. [8] performed air-coupled IE with MEM microphone array as a transducer. The transducer was placed 30 mm above concrete surface and concluded that zero mode resonance causing a surface displacement that is coherent in an area around the impact location with the radius approximately as the concrete thickness. Therefore, [8] suggested that transducer should be located not less than the concrete thickness from impact point. Microphone height was set closer to concrete surface by [9] at 10 mm. Summary of previous study/suggestion on impact echo test configurations are shown in Table 1.

Table 1. Previous studies on IE test configurations.

	Impact-to-sensor distance, *x*	**Sensor height, y (mm)**
Groschup (2015)	*x > d*	*30*
Shin et al (2012)	-	*10*
Tsai & Zhu (2012)	*x = 0.5d*	*20*
Sansalone & Street (1997)	*x > 0.4d*	-
Carino (1986)	*0.2d < x < 0.5d*	-

**d = concrete thickness/flaw depth*

2. Finite element simulation

Finite element models were modelled to represent the air-solid system using ABAQUS software [10]. 2D planar models were employed to stimulate an impact point source applied on the surface of a solid specimen. Model parameters should be selected properly so that the wave propagation in the air-solid system could be accurately simulated.

Table 2. Material Properties.

Material	**Acoustic-wave Velocity (m/s)**	**S-wave Velocity (m/s)**	**P-wave Velocity (m/s)**	**Density (kg/m3)**	**Poisson's Ratio**
Concrete	-	2510	4100	2500	0.2
Air	343	-	-	1.204	-
Void	-	-	-	-	-

2.1. Model parameters

A 2D model consisting of a solid and air sections was built to represent air-concrete slab system as presented in Figure 1. A 300 mm by 100 mm solid section representing concrete slab is seeded with 4-node bilinear plane stress quadrilateral element (CPS4R). The air part is represented by a 300 mm by 300 mm section seeded with 4-node linear 2-D acoustic quadrilateral elements (AC2D4R). To diminish reflections of stress waves from the left and right boundaries, low-reflecting boundaries were specified on both left and right sides of the concrete plate. A layer of infinite elements (CINPS4) were utilized along the both edge of solid section. Material properties for the solid and air are listed in the Table 2. A maximum impact force of 1 N was used, with contact duration of 30 μs. This impact is similar to that produced by steel sphere 7 mm in diameter, which is a common size use in impact-echo testing. Meshing the model geometry is the last step to complete prior to computing. For transient analysis, a sufficiently fine mesh should be used to resolve the waveforms of the smallest wavelength of interest. Element size of 2 mm is used uniformly throughout the model and an incremental time step of 1 μs is used for internal stability of the finite element analysis.

2.2. Test configurations
Ten contact sensors were coupled to the concrete surface at every 10 mm away from impact point. While air-coupled sensors located at three different lift-offs line parallel to concrete surface which are 10, 20 and 30 mm. At every height, ten contactless sensors placed at every 10 mm starting from impact location. Impact point is aligned with the centre of concrete delamination. The location of impact are maintained for both model. Location for sensors is the same form both sound and defected models. In total, 40 sensors involved in each simulation. Therefore, analyzing each frequency spectra automatically would be beneficial to speed up data reduction process.

2.3. Maximum frequency search
Analyzing many data sets manually requires much time and effort. An algorithm for rapid search of peak frequency in frequency domain is developed as shown in Figure 2. The algorithm is implemented in MATLAB software. All data collected in the simulation were processed using this algorithm.

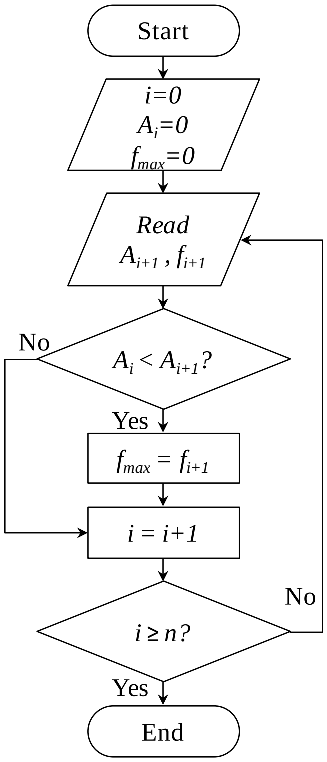


Figure 2. Global peak frequency search algorithm.

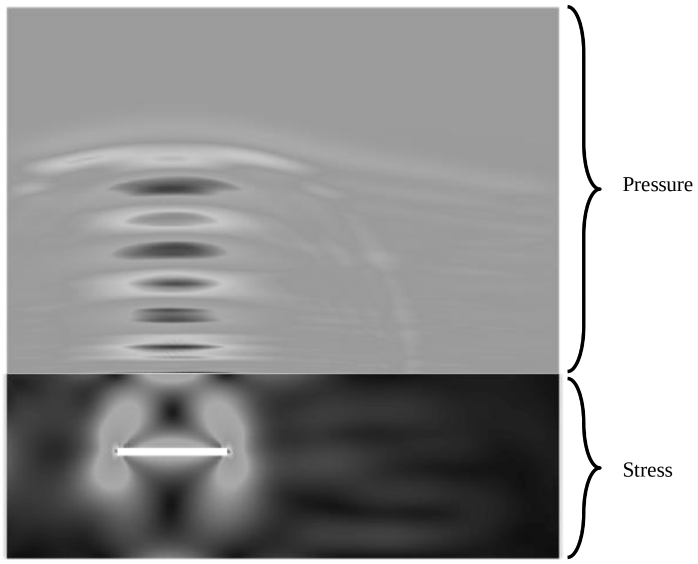


Figure 3. Snapshot of stress and pressure field at time, t = 0.4 ms after impact.

3. Result and analysis
Figure 3 shows the pressure field in the air and stress in solid at time, t = 0.4 ms after impact force is applied on the concrete slab. Three types of wave are observed which are leaky Rayleigh waves, direct acoustic waves and airborne (due to flexural mode in concrete) waves. Leaky Rayleigh waves radiates in a conical shape wavefront. Direct acoustic waves radiating with a velocity of 343 m/s creates perfect spherical wavefront. A series of airborne periodic plane waves above the impact location are

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also observed in Figure 3. These waves indicate local resonant mode were built around impact location. Hollow zone is observed in concrete slab on both delamination edge, on the top of delamination surface and at the air-concrete boundary is caused by a flexural mode vibration of the entire delaminated region. The resulting pressure and air fields show good agreement with the result form previous study [7]; thus, validity of the model was verified.

Table 3 summarized peak frequencies obtained at different impact-to-sensor distance, x and sensor height from concrete surface, y for conventional impact echo (IE) and air-coupled impact echo (ACIE) tests performed at concrete slab model without delamination. Based on Eq. 1, expected frequency peak for sound concrete with 100 mm thickness and 0.96 shape factor is 19.68 kHz. A consistence peaks are observed throughout entire testing locations for ACIE test at 19.53 kHz. A slight difference occurs starting at 80 mm and above is cause by frequency scale where sensitivity of the scale is 0.12 kHz. Consistency of IE test result is observed until impact-to-sensor distance reaching 70 mm, where 36.74 and 59.94 kHz peaks are collected after 60 mm. The ratios of these peaks with expected resonance frequency are 1.88 and 3.07, corresponding to second and third resonance modes. Therefore, three resonance modes are successfully captured by this numerical simulation. Normalized amplitude of these peaks are plotted in Figure 4. Variation of peak frequency captured is based on search algorithm explained in section 2.3. By analyzing plots in Figure 4 manually, the expected frequency is always exists and significant, however maximum frequency captured by the algorithm is a global maximum without considering any expected value. Therefore, IE and ACIE are actually able to detect concrete thickness (100 mm) at any sensor distance up to 100 mm from impact point. This is also true for microphone with height from concrete surface up to 30 mm. The result implied that all previous studies summarized in Table 1 are acceptable. The differences in preferred configurations are due to factors affecting during tests conducted. In this study, the FEM model is in ideal condition that is not affected by any external factors.

Table 3. Variation of peak frequency (kHz) obtained at different impact-to-sensor distance and sensor height for concrete slab model without delamination. (Expected frequency = 19.68 kHz)

Test	**Height,**	**Distance from impact source, *x* (mm)**									
	***y* (mm)**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**
IE	-	19.53	19.53	19.53	19.53	19.53	19.53	59.81	59.94	36.74	36.74
	10	19.53	19.53	19.53	19.53	19.53	19.53	19.53	19.41	19.41	19.41
ACIE	20	19.53	19.53	19.53	19.53	19.53	19.53	19.53	19.41	19.41	19.41
	30	19.53	19.53	19.53	19.53	19.53	19.53	19.53	19.41	19.41	19.41

Table 4. Variation of peak frequency (kHz) obtained with different impact-to-sensor distance and sensor height for concrete slab with delamination. (Expected frequency = 49.20 kHz)

Test	**Distance,**	**Distance from impact source, *x* (mm)**									
	***y* (mm)**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**
IE	-	48.58	48.71	9.89	10.01	48.58	48.71	50.29	50.29	51.03	50.05
	10	9.89	9.89	9.89	10.01	10.01	48.58	48.71	50.29	50.78	9.89
ACIE	20	9.89	9.89	9.89	10.01	10.01	9.89	1.46	9.89	10.01	10.01
	30	9.89	9.89	9.89	9.89	10.01	1.46	1.59	9.89	9.89	9.89

Table 4 summarized peak frequencies obtained at different impact-to-sensor distance, x and sensor height from concrete surface, y for conventional impact echo (IE) and air-coupled impact echo (ACIE) tests performed at concrete slab model with delamination. Based on Equation 1, expected frequency

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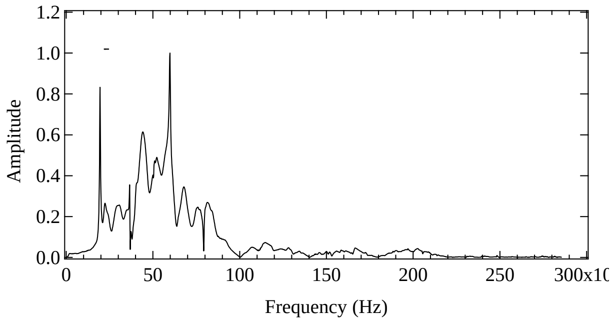
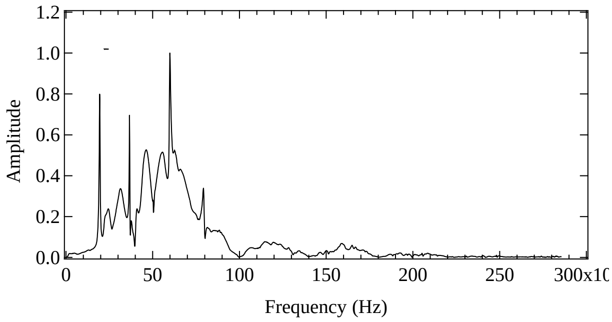
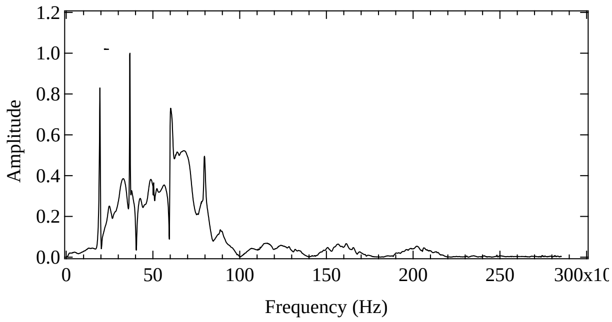
peak for concrete with 40 mm delamination depth and 0.96 shape factor is 49.20 kHz. Result for IE test is considerably consistence by ignoring scale sensitivity effect, except for distance 30 and 40 mm. Based on Figure 5, frequency spectrum at distance 30 and 40 mm showing a clear peak at expected resonance frequency. As previously discussed, the algorithm is picking up global maximum. Therefore, IE test is again able to detect concrete delamination depth (40 mm) at any sensor distance up to 100 mm from impact point. However for ACIE measurement, only sensors at height of 10 mm are capturing the right resonance frequency at distance between 60 to 90 mm. The presence of hollow stress contour around delamination may contribute to this issue. As can be seen in Figure 6 (b) to (d), frequency domain plot is dominated by low frequency energy corresponding to flexural mode peak response. Therefore, it can be concluded that ACIE magnifying flexural modes more compared to thickness-types mode. Similar finding are also found in previous study by [1].



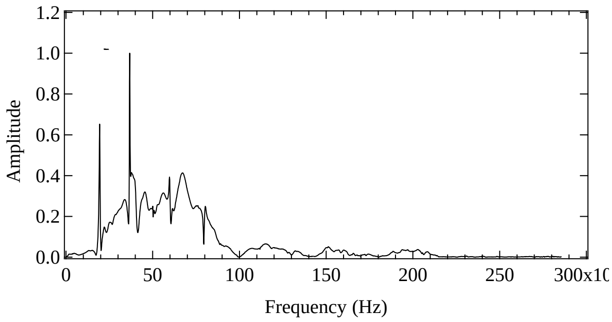
(a) x = 70 mm



(b) x = 80 mm

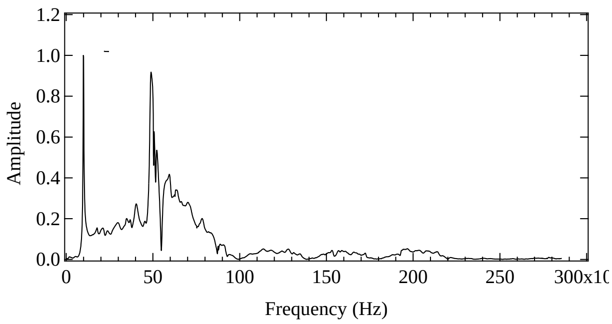


(c) x = 90 mm

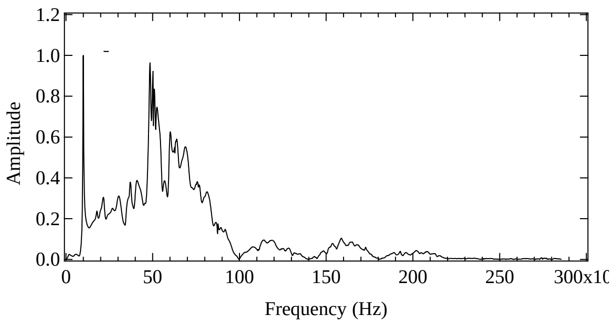


(d) x = 100 mm

Figure 4. Frequency spectrum of acceleration for concrete model without delamination. Sensor-to-impact distance ranging from 70 mm to 100 mm.

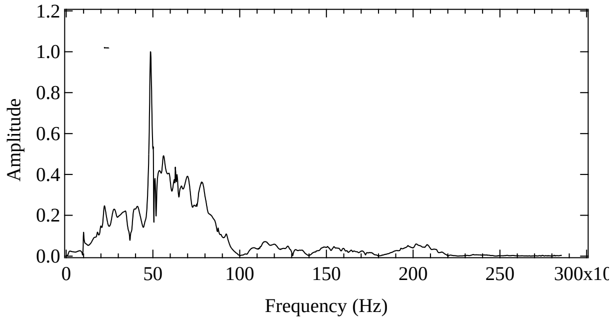


(a) x = 30 mm

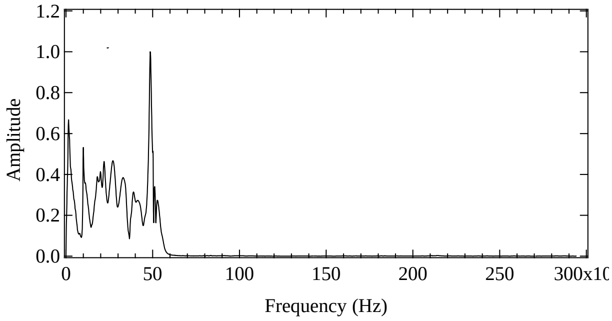


(b) x = 40 mm

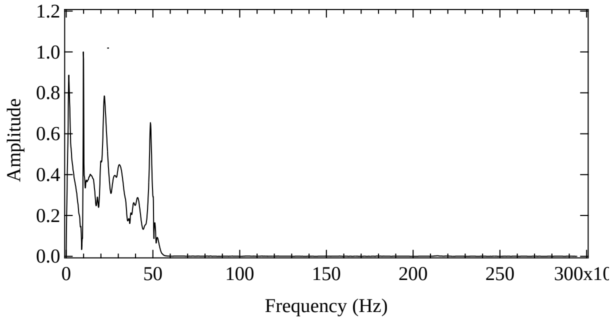
Figure 5. Frequency spectrum of acceleration for concrete model with delamination. Sensor-to-impact distance is at 30 mm and 40 mm.



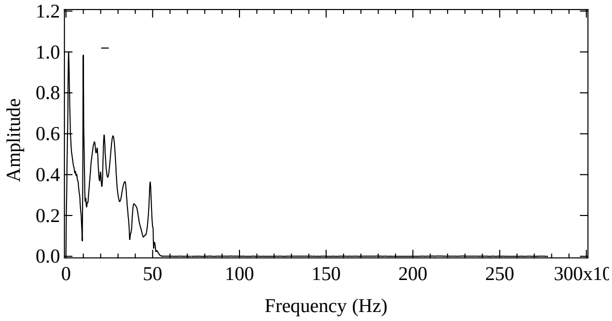
(a) Acceleration



(b) Pressure at *y* = 10 mm



(c) Pressure at *y* = 20 mm



(d) Pressure at *y* = 30 mm

Figure 6. Frequency spectrum of acceleration and pressure for concrete model with delamination. Sensor-to-impact distance, *x* at 60 mm and sensor height form concrete surface is ranging from 10 mm up to 30 mm.

4. Summary and Conclusions

Numerical simulations performed to investigate the effectiveness of IE test with contactless sensor compared to contact sensor in term of sensor-to-source distance. Effects of contactless sensor lift-off from concrete surface were also investigated. Two concrete models were built, one without delamination and one with delamination. 40 sensors points with 10 mm distance apart distributed at 100 mm by 30 mm area above the concrete surface were considered in each simulation. Time signal data were transformed into frequency spectra by fast Fourier transform. The validity of FEM model was verified against previous study. An algorithm dedicated for peak frequency search was developed. The algorithm sped up data reduction process. However, in some cases it fails to extract actual peak frequency and therefore, manual consideration were involved. For intact concrete, both IE and ACIE tests were able to detect concrete thickness at any sensor location within the specified location range in this study. Effectiveness of both sensor types was considerably equivalent. However, for defected concrete with 40 mm depth delamination, only 10 mm sensor height was effective in detecting delamination depth starting from 60 mm away from the impact point.

Acknowledgments

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