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Integrity Assessment of Thick Concrete Slabs Using NDT Impact-Echo

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ABSTRACT: Efficient, cost-effective, and reliable techniques for the inspection of thick high strength concrete structures, used for offshore structures and containment structures for nuclear power plants are in demand. Traditionally, structural components have been inspected by visual means or destructive methods such as coring, drilling, or load tests. However, these methods can not be applied for such structures as they cause adverse effects on an originally sound structure.
Nondestructive testing (NDT) of concrete structures has a key role in detecting a variety of defects in concrete structures including cracks, voids, determining the depth of surface-opening cracks, and delaminations in the concrete plates. Early detection of damage can save lives and costly repairs. The information obtained from the inspection is generally used to plan and design maintenance activities, increase the safety, verify hypotheses, and reduce uncertainty.
Impact-echo is a method for NDT of concrete and masonry structures that is based on the use of impact-generated stress (sound) waves that propagate through concrete and masonry and are reflected by internal flaws and external surfaces to reflect the integrity of the structure or to determine the location of flaws.
In this study, a thick high strength concrete plate used for offshore applications was nondestructively evaluated in the laboratory using the impact-echo technique. Impact-echo tests were performed concurrently with dynamic load test. Impact-echo tests were performed before and after the loading sequence for each plate. The main objective is to study the efficiency of the impact-echo technique to detect the extent and location of cracks and local damage, and to develop practice guidelines to identify the best locations to apply the impact-echo method to the structures for further inspections. That enables continuous inspection of the structure as well as the capability to detect locally damaged and overstressed spots.
This method can be used for early detection of structural damage of offshore structures. Through the use of this method, operators of such structures will be able to maintain safe and economic operation of their facilities. Maintenance costs as well as shutdown cost will be reduced. In addition danger to human life and the environment will be reduced.

1 BACKGROUND

1.1 *Impact-Echo Method*

The impact-echo method is a NDT method used for testing concrete or masonry structures using impact-generated stress waves that propagate through a structure and are reflected at any property change (internal flaws or interfaces). An impact-echo test was performed by introducing a stress pulse by impact source (such as a ball hammer strike) at the surface of a structure and monitoring the resulting stress waves with a transducer attached to the same surface. Stress waves reflect between the surface and existing voids or delaminations to create a resonant condition that can be observed in a frequency analysis of the acquired waveforms. One advantage of the method is that access to only one surface of a structures needed, making this technique suitable for rapid assessment of bridges and offshore structures.

The stress waves were generated by means of a dynamic point impact applied to the surface using a steel ball bearing or impact hammer. A displacement transducer or accelerometer was used for monitoring surface movements caused by the arrival of the reflected waves back to the surface. The fast Fourier transform (FFT) was used to transfer the time domain data to the frequency domain for analysis. The dominant peaks in the frequency spectrum represent the frequencies of reflected P-waves from the bottom of the specimen, side boundaries, or any discontinuity present in the specimen. By measuring the P-wave velocity C_p and knowing the frequency f of the reflected waves from an interface, the depth D to the interface can be calculated using the following equation:

$$D = \frac{\beta C_p}{2f} \quad (1)$$

where, f = slab frequency; and D = slab thickness; for concrete plates, the shape factor β is equal to 0.96 and accounts for the thickness mode of vibration (Sansalone and Streett 1997).

Typical indication of cracks is the shift of the expected thickness frequency to a lower frequency. This shift is due to a reduction in the stiffness of the structure near the crack that reduces the P-wave velocity C_p and is related to the dynamic elastic modulus E as follows:

$$C_p = \sqrt{\frac{E(1-\nu)}{(1+\nu)(1-2\nu)\rho}} \quad (2)$$

where ν is the Poisson's ratio, and ρ is the density.

Impact methods began to be used for integrity testing of deep foundations, such as piles to determine the length of piles (Sansalone and Carino 1986; Malhotra and Carino 1991). In the early 1980s research engineers at the U.S. National Bureau of Standards explored the use of short duration mechanical impacts, produced by small steel spheres, as a source of stress waves for testing concrete structural elements, such as slabs (Sansalone and Carino 1986; Sansalone 1997). Tests were performed to evaluate the feasibility of using the impact-echo method to determine setting time and to monitor strength development of concrete (Pessiki and Carino 1980; Pessiki and Johnson 1996; Pessiki and Rowe 1997; Nazarian et al. 1997). Several studies showed that the impact-echo method successfully located the voids in grouted post-tensioning tendon ducts cast in a 1-m thick concrete wall specimen (Carino and Sansalone 1992).

In the current paper, experimental investigation that included the testing of a reinforced concrete slab in the structural lab at Memorial University was conducted. Full-scale, two-way slab specimen was cast, instrumented, and tested in the current research program. This study presents the results of a NDT testing program performed to assess the damage in concrete bridge decks subjected to full-scale dynamic loading using the impact-echo method. The impact-echo method was selected for this study because it is a simple, well-established procedure that can provide a baseline with which other newly emerging techniques can be compared. The objective of this testing program was to nondestructively assess the distribution of damage throughout deteriorated concrete bridge slabs and to evaluate the initiation and generation of damage, such as cracking, within the concrete slab subjected to various loading conditions.

2. METHODOLOGY

2.1 *Slab Specimens*

In this research, impact-echo technique was used to non-destructively assess the change in condition of reinforced concrete slab specimen subjected to cyclic load. Impact-echo tests were first performed to assess the initial condition throughout the slab by analyzing the variation in apparent P-wave velocity. Then, impact-echo tests were performed concurrently with a cyclic load test at two loading levels. The change in the apparent P-wave velocity was monitored by examining the frequency shift of the first mode present in each response spectrum. As loading progressed, new peaks were observed in the response spectra, indicating the presence of damage and propagating cracks. The depth to the cracks was calculated using the frequencies of the new peaks and was compared with visual observations.

The main objective of the experimental program is to study the efficiency of the Impact-Echo technique to detect the extent and location of cracks and local damage for a concrete slab. The tested slab has a side dimension of 1900 mm in both directions. Two-way thick reinforced concrete slab was tested in this research program. The test specimen was simply supported along all four edges with the corners free to lift. The tested slab represents the region of negative bending moment around an interior column in a flat plate system and the simply supported edges simulate the lines of contra-flexure (Fig. 1). After the cyclic load application, this slab had visible external cracks on the bottom as noted in Fig. 2.

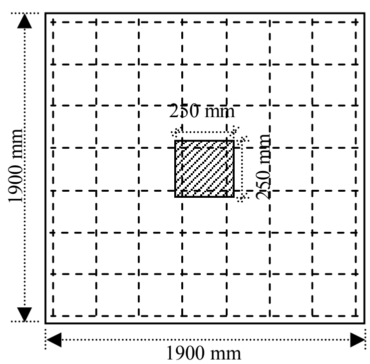

Figure 1 Reinforced Concrete Slab Details

Figure. 2 Crack Pattern of the Reinforced Concrete Slab

3. EXPERIMENTAL INVESTIGATION

The experimental investigation includes the testing of two reinforced concrete slabs in the structural lab at Memorial University. Full-scale, two-way slab specimens were cast, instrumented, and tested in the current research program. The tested slabs were square with a side dimension of 1900 mm in both directions and were simply supported along all four edges with the corners free to lift. The test slab represents the region of negative bending moment around an interior column in a flat slab system and the simply supported edges simulate the lines of contra-flexure. A central load was applied on the slab through a 250×250 mm column stub. The dimensions and reinforcement details of a typical test slab are shown in Fig. 1.

The specimens were made with high-strength concrete of 70 MPa. The slabs were cured under moisture saturation of plastic sheeting to cover the surface for more than 3 weeks until the preparation of instrumentation and during the fourth week of curing, the specimens were prepared for testing of panels at an age of 28 days. The specimens were tested in a specially designed frame in the vertical position, as shown in Fig. 3.

Figure 3 Test Set-up

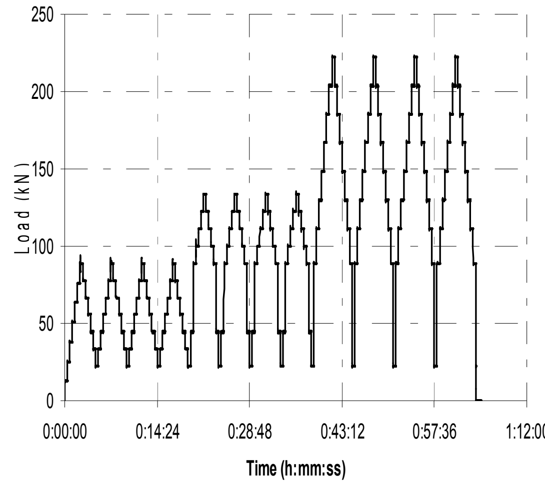

Figure 4 Load-Time History for the Applied Cyclic Load

4. Load Testing

The reinforced concrete slab was dynamically tested under cyclic loading (a fatigue test) using a closed-loop (MTS) testing machine with a maximum capacity of 670 kN. The loading rate was 445 N/sec, which resulted in a peak failure load of 222 kN and a peak deflection of 4.2 mm. The slab was subjected to three levels of cycles. The slab was initially loaded between 10 and 90 kN at a loading rate of 2 Hz. The load was then increased to oscillate between 10 and 130 kN at the same loading rate. Finally, the load was increased to oscillate between 10 and 222 kN at a rate of 1 Hz until failure, see Fig. 4.

The concrete slab was tested in a vertical position in order to detect and mark the cracks as it develops. The load was applied to the slab centrally through the stub column. Rubber packing pieces was provided immediately under the slab surface to insure uniform contact along the supports. The test was carried out using a closed-loop (MTS) testing machine with a maximum capacity of 670 kN. The load was applied by means of a hydraulic actuator. During testing, the slab was carefully inspected and cracks were marked at each load set. Deflection at the slab center was measured with an LVDT gauge. The loading process involved applying cyclic load test till the failure.

5. NON-DESTRUCTIVE TESTING (NDT) EQUIPMENT

Impact-echo test system used in the current study consists of three basic components:

- A mechanical impactor capable of producing short-duration impacts, the duration of which can be varied,
- A high-fidelity receiver to measure the surface response, and
- A data acquisition-signal analysis system, that captures the output of the transducer, stores the waveforms of surface motion, and performs signal processing and analysis.

The NDT system used in this study consisted of two Piezo-electric sensors, steel impact transducers, two-channel portable digitizer and Windows compatible software capable of graphing, calculations and presenting for report creation, as shown Fig. 5.

A grid spaced at 10 mm was designed for the reinforced concrete slab, as shown in Fig. 6. The grid was spaced at 0.10 m in both directions to avoid coinciding with the design steel arrangement and achieve a clear response of the slab's thickness. A complete set of impact-echo tests was implemented on all grid points on the slab (as numbered in Fig. 6) to evaluate the response of the slab before and after the load test.

Figure 5 Portable Impact-Echo System Field Kit

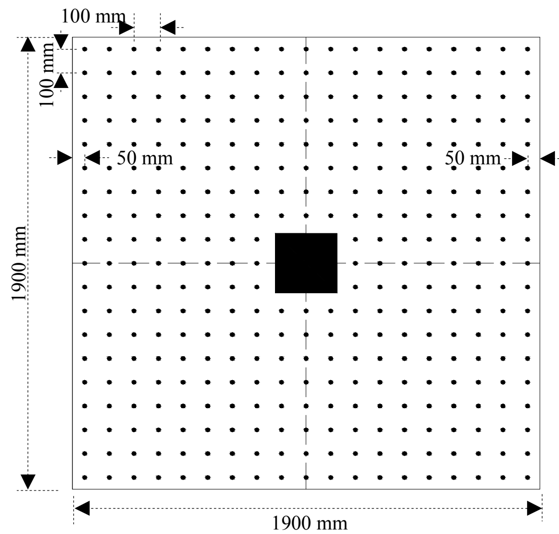

Figure 6 Grid Point Numbering System

During the loading sequence, some points experienced a severe level of damage caused by extensive shallow cracks. The frequency associated with the reflections from these cracks was detected. When this condition occurred, it was defined as local failure because the impact-echo method could capture the change in the slab response through measuring the change in velocities and frequencies of the generated sound wave reflect by the occurred cracks.

6. DAMAGE ASSESSMENT OF DYNAMICALLY STATICALLY LOADED SLAB

6.1 *Initial Condition (Unloaded Stage)*

Figure 7(a) presented the impact-echo results obtained for all grid points on the slab before the cyclic load applictaion. In general, the wave velocity ranged from 4302 to 4612 m/s before the application of the cyclic load. These values were within the acceptable velocity range for normal concrete quality. The variation in velocity of the concrete throughout the slab reflected the variation of the concrete batch quality.

Approximate symmetry was observed in the impact-echo results. The average wave velocity on the slab was found to be approximately 4450 m/s. This value of the wave velocity approximately covered the slab from ($x = y = 0.40$ m) to ($x = y = 1.60$ m).

6.2 *Condition after Cyclic Loading (Load Level = 90 kN)*

The impact-echo results obtained for all grid points after the cyclic load test was performed (P = 90 kN) and were shown in Fig. 7(b). The reduction in propagation velocity due crack propagation (degradation of the axial stiffness) due to the application of the cyclic load was shown in Fig. 8. The results indicated that the slab experienced crack propagation concentrated in the middle third of the slab between transverse lines at ($x = y = 0.60$ m) and ($x = y = 1.40$ m). This damage was signified by a 1.0 to 4.5% reduction in the velocity in that zone. The level of damage was the highest (4.5% reduction) near the center of the slab, where the loading column stub caused a high stress concentration. The level of damage decreased to (1.0% reduction) near Lines 1 and 2, see Fig. 8. In contrast, the concrete sections in the outer zones of the slab (0 to 0.60 m) and (1.40 to 1.90 m) in both *x* and *y* directions did not indicate any damage.

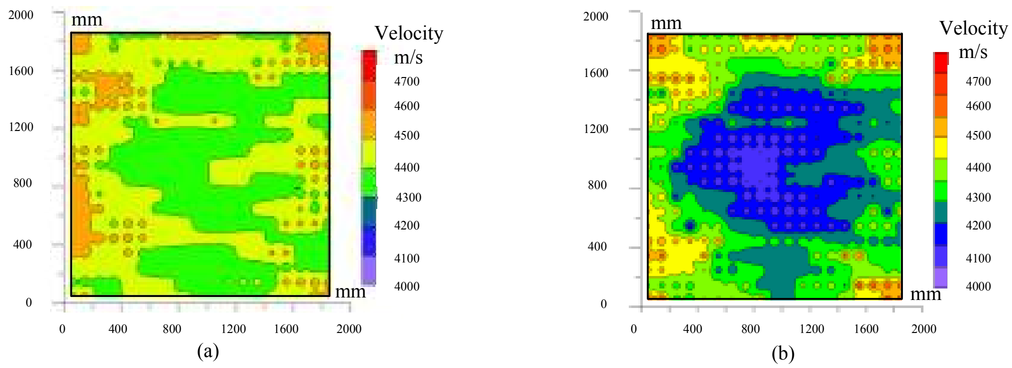

Fig. 7-Velocity Profile of Dynamically Loaded Slab: (a) Before Loading; (b) After Loading

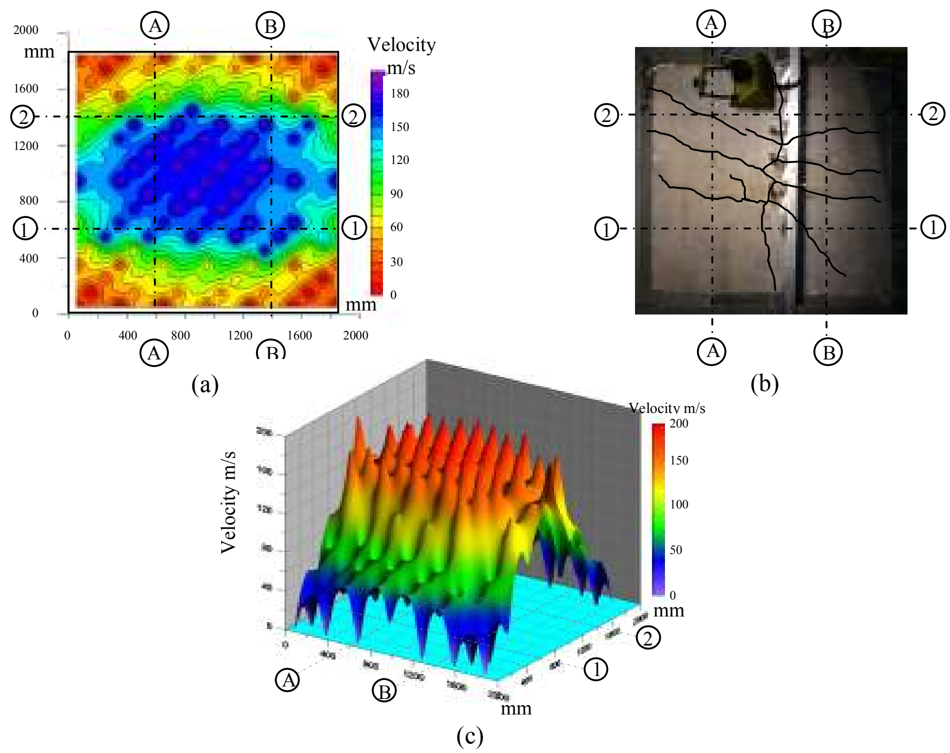

Fig. 8 Velocity Reduction Profile of Dynamically Loaded Slab ((Load Level = 90 kN)

These results showed a favorable agreement with the experimental results for the crack propagation where the cracks were marked manually at each stage of loading throughout the experiment. Most of the marked cracks propagated along the middle third zone of the slab in both *x* and *y* directions, as illustrated in Fig. 8(b). Fig. 8(c) presented the variation of the measured velocity using the impact Echo technique. The middle third zone showed the highest decrease in the wave velocity. This variation in the velocity decreased towards the edge of the reinforced concrete slab, see Fig. 8(c).

6.3 *Condition after Cyclic Loading (Load Level = 222 kN)*

As the cyclic load was applied, more cracks were developed and a continuous decrease for the slab stiffness was observed. The results indicated that the slab experienced new cracks propagation at that level of loading (P = 222 kN) parallel with the increase of the depth of the old cracks. The impact-echo results obtained for all grid points after the cyclic load test was performed. The reduction in propagation velocity due to the application of the cyclic load was shown in Fig. 9 (a, c). This damage was associated by a 1.6 to 7.0 % reduction in the velocity in through the different zones of the reinforced concrete slabs. The level of damage was the highest (7.0% reduction) near the center of the slab, where the loading column stub caused a high stress concentration in that zone. The level of damage decreased to (1.6% reduction) over the outer zones of the slab, see Fig. 9(a, c).

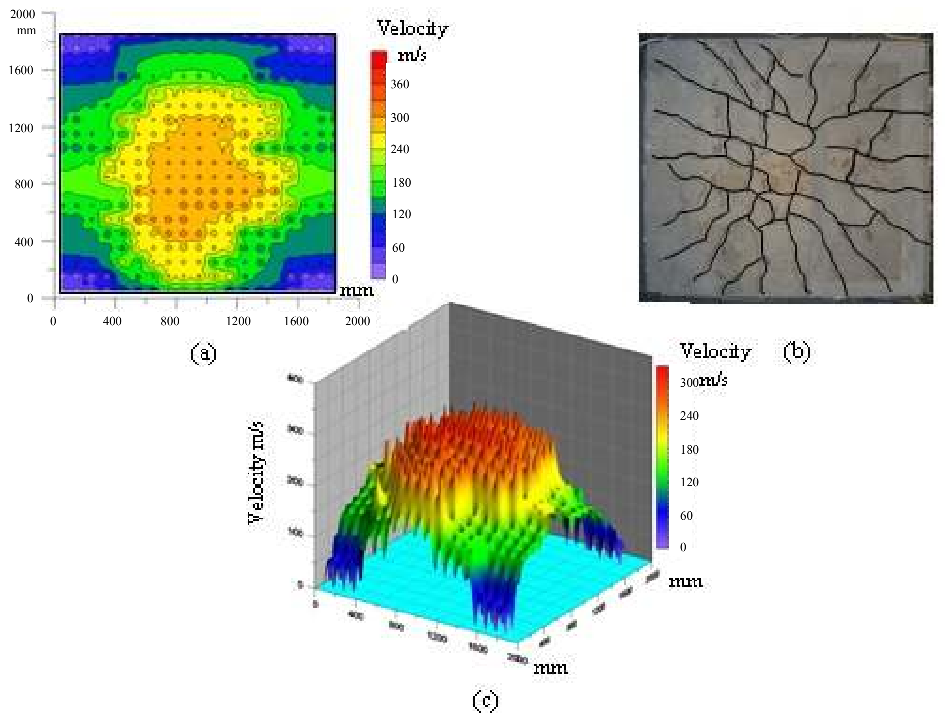

Fig. 8 Velocity Reduction Profile of Dynamically Loaded Slab ((Load Level = 222 kN)

High concentration of the cracks with higher depth was observed through middle third zone of the slab as illustrated in Fig. 9 (b). These experimental observation showed a favorable agreement with measured reduction in the wave velocity using the Impact Echo technique, see Fig 9 (a, c).

The impact-echo testing is a reasonable method for the nondestructive assessment of the structural integrity. The method has been successful for the reinforced concrete slabs based on the characteristics of the wave propagation in the structure.

7. SUMMARY AND CONCLUSIONS

This study presented the results of impact-echo tests performed on two way thick concrete slab. Tests were first performed to nondestructively assess the initial condition and the distribution of frequencies and velocities of the sound wave throughout the slabs. Tests were then performed concurrently with dynamic load tests to evaluate the initiation and generation of damage within the slab. Cracking from the cyclic loading was detected at most of the tested locations and was supported by visual inspection. The locations of the detected cracks of the two way slabs were predicted with an acceptable accuracy. The impact-echo technique can be used to track the change in the apparent P-wave velocity along the web of the girder and relate it to the crack propagation throughout the experimental test. These results can be used by bridge and offshore inspectors to asses the concrete condition to help identifying problems before significant damage accumulates. Based on the results of this study, the following conclusions can be drawn:

1. Non-destructive testing has a key role to play as an input parameter to bridge and offshore structures maintenance and reliability systems. Tomographic surveys used in conjunction with Impact echo technique provide a valuable aid to the interpretation of the cracking response of the concrete structures.
2. The relative quality of concrete throughout a structure that has suffered extensive damage and crack propagation during service life can be assessed by analyzing the variations in P-wave velocity. In this study, decrease in P-wave velocity on the order of 1.0 % to 4.5 %, were associated with the crack propagation in the concrete slab at cyclic load of 90 kN.
3. The wave velocity decreased by a range of 1.6 % to 7.0 % at cyclic load level of 222 kN, indicating higher crack propagation at that loading level.
4. It was shown that as the depth of the crack increases, the amplitude of vibration of the wave velocity also increases as expected. This is true because of the stiffness reducing is inversely proportional to the depth of a crack.
5. NDT Impact echo method can be used for early damage detection so that a structure can be rehabilitated before further damage accumulates and leads to service failure of the structure.

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