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Nondestructive Evaluation of Infrastructure Systems

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ABSTRACT: Nondestructive tests (NDT) have been used to evaluate and assess conditions of infrastructure systems including bridges, buildings, tunnels, water tanks and refineries. The implementation of the nondestructive testing techniques in the evaluation process of structures provides comprehensive and scientific assessment of existing conditions. It also provides the information needed to design and select the optimum rehabilitation system. Impulse Response (IR), Impact-Echo (IE) systems and Ultrasonic Pulse Velocity (UPV) which are based on stress wave principal, are used to evaluate the integrity of the structure. These techniques are also used to locate voids within structures. Impulse Radar is used to locate defects in concrete members and provide steel reinforcement profiles needed for further analysis. The above mentioned technologies were used in the Gulf region to evaluate defects occurred in structures during construction and structures subjected to fire damage. The findings of these tests were used in assessing the integrity of the structures and selecting the most efficient repair and rehabilitation methods to restore the integrity of the structures. Summary of evaluation results recommendations of using such technologies for evaluating concrete infrastructure systems will be presented in the paper.

1 INTRODUCTION

Non-destructive testing (NDT) is known to civil engineers for many years especially in the area of steel structures. However, the use of NDT for concrete structural systems is more complicated than that of steel. This is mainly due to the non-homogeneity of concrete compared to other materials such as steel. However, there are methods that have been developed and standardized for concrete testing. Development of NDT for concrete took two directions; methods used for in-place strength testing and methods for locating defects in existing structures (Malhotra & Carino 2004).

1.1 In-Place Strength Test Methods

- Rebound hammer (Schmidt hammer): one of the oldest NDT techniques. The strength is predicted based on concrete surface hardness. The method provides a relative concrete strength and should not be used to predict the concrete strength. Care must be taken to ensure that a representative area is tested, and that the results are not based upon one single test point.

- Probe penetration (Windsor Probe): this method is also based on surface hardness. The strength is predicted based on its resistance to steel probes driven into concrete by an actually controlled powder charge. The use of this test is limited due to the partial damage to the surface of concrete and due to its accuracy.

- Ultrasonic Pulse Velocity (UPV): this is the most effective technique. It can be used to predict strength of hardened concrete and also can be utilized for locating defects in concrete structures. The method is based on measuring how long it takes an ultrasonic wave to pass through concrete and calculate the wave velocity based on the structure dimensions.

- Pullout Tests: this test measures the ultimate load required to pull out from concrete a specifically shaped steel insert whose enlarged end has been cast in concrete. The strength is estimated based on the pull out force. Correlation charts should be prepared for each concrete mix to be used in the field. The surface concrete has to be repaired after the test.

- Maturity Concept: strength of concrete at any age is a function of its thermal history. Strength can be evaluated based on the concept of maturity that is expressed as a function of time and the curing temperature. Tools needed for this test are thermocouples that can be pre-placed in the concrete and temperature-monitoring device or maturity meters.

1.2 Defect-Detecting Test Methods

This type of tests is used to evaluate the presence of defects in concrete structures. These tests are important inspection tools needed to evaluate the damaged structures and determine the extent of their physical deterioration.

- Sounding methods: these are probably, the oldest NDT techniques used on concrete structures. The test is simple; detection is performed by striking the concrete surface and listening to the response. The characteristic of the sound indicates the condition of the structure. Iron rods, hammers and chains are commonly used as sounding tools.

- Ground Penetrating Radar (GPR): contrary to the sounding methods, GPR is the most sophisticated NDT system used in concrete. The development of low-power high frequency pulsed radar system was the base for its application in concrete (Lim et al 1999). The principle of GPR operation is based on reflection of electromagnetic waves from varying dielectric constant boundaries in the material being probed. The impulse radar equipment is self-contained, compact, and portable. The system consists of the main radar unit, antenna and transducer cable. All data is stored in the main radar unit, by means of a computer hard drive. The radar is a very efficient tool in locating metallic and non-metallic objects in concrete, provide concrete cover profile and thickness of concrete members (Nagi, 2005).

- Cover meter: is a very common tool used for locating steel and measuring depth of cover. It is based on monitoring the interaction of the reinforcing bars and a low frequency, electromagnetic field. The cover meters are usually limited to 75 to 100 mm cover depths.

- Infrared Thermography Technique: the principle of this method is based on the idea that temperature of concrete surface over a delaminated area will be different from the surrounding areas. Thermographic scanners are used for temperature scanning. The application of this technique is mainly limited to delamination survey.

- Stress Wave Methods: stress wave is the disturbance generated when a stress is applied suddenly to a solid. The basic principle of these methods is to generate stress waves on the surface of concrete structures, the waves propagate through the concrete and reflect at any interface (e.g., defects, voids, reinforcement). The reflected waves are then recorded and analysed. Waves can be generated electronically (ultrasonic method) or mechanically (impact-echo and impulse response).

- Ultrasonic Pulse Velocity (UPV): As mentioned above, the method is based on measuring how long it takes an ultrasonic wave to pass through concrete and calculating the wave velocity based on the structure dimensions. Changes in wave travelling time and velocity indicate the presence of defects in the structure. UPV can be used to measure surface crack depth (ACI 228 1998).

- Impact-Echo (I-E) test: This test uses induced stress waves to detect flaws within concrete structures. However, the frequency range used in I-E testing is considerably higher than that of the Impulse Response test given that much shorter wavelengths are required to detect smaller anomalies. Surface displacements caused by reflecting stress waves can be viewed versus time as a displacement waveform. The amplitude spectrum of this waveform is computed by FFT, which is also applicable for the Impulse Response. This spectrum has a periodic nature, which is a function of the depth to the reflective boundary (either the back of the element, or some anomaly such as a crack in the element under test). The depth of a concrete/air interface (internal void or external boundary) is determined by:

$$d = v_c \ / \ 2f \qquad (1)$$

where d is the interface depth, v_c is the primary stress wave velocity and f is the frequency due to reflection of the P wave from the interface.
If the material beyond the reflective interface is acoustically stiffer than concrete (e.g. concrete/steel interface), then the following equation applies:

$$d = v_c \ / \ 4f \qquad (2)$$

The difference in the acoustic impedance of the two materials at an interface is important because it determines whether the presence of an interface will be detected by an I-E test. For example, a concrete/grout interface gives no reflection of the stress wave because the acoustic impedance of concrete and grout are nearly identical. In contrast, at a concrete/air interface, nearly all the energy is reflected given that the acoustic impedance of air is much less than concrete (Sansalone 1997 & Abraham et al 2000).

- Impulse response: the Impulse Response (IR) method consists of positioning a geophone at a known location on the surface to be tested and uses a hand-held hammer equipped with a load cell to strike the surface of the concrete. The hammer blow excites the surface on which the geophone is positioned causing an internal oscillation of the geophone as well as the test structure. Although several structural parameters can be calculated using this method, the *Average Mobility* is the most relevant parameter. *Average Mobility*, which is a measure of the flexibility of the test area and therefore the stiffness of the structure, is used to create a relative comparison between sound and distressed areas of the structure. Internal delaminations and other flaws can be accurately detected using this technique (Davis 1974 & Davis 2003). Typical impulse response output is shown in Figure 1.

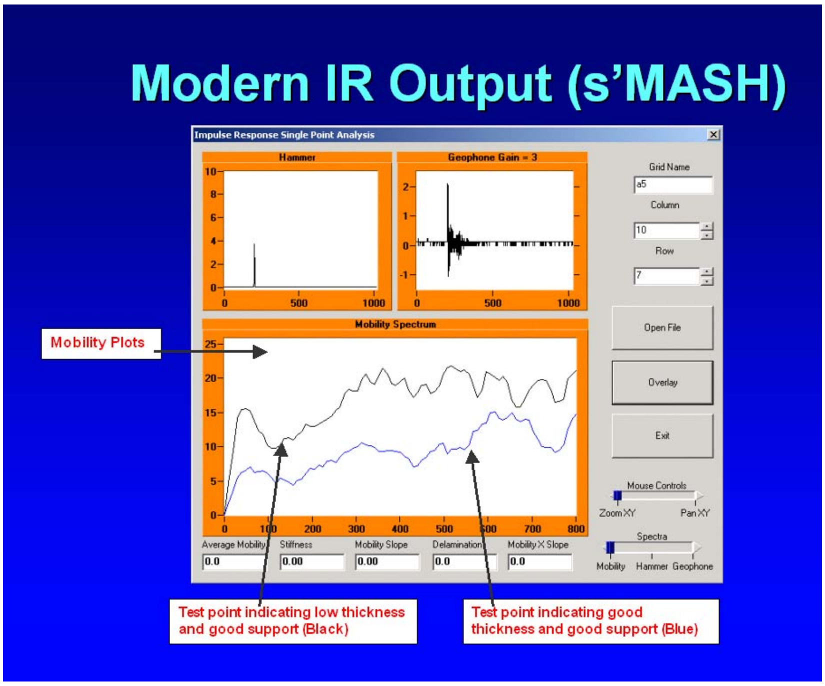

Figure 1. Typical response output of Impulse Response test.

2 NDT IN THE MIDDLE EAST

In many cases of structural evaluation, NDT is the only tool available to engineers to assess the conditions of structures. The use of NDT in structural assessment in the Middle East can be divided into two categories, existing structures and new construction. For existing structures, NDT is used for assessing structures conditions, regular inspections (e.g., bridges inspection), assessment of fire and other natural damaged structures and estimating the remaining service life structures.

In new construction, both NDT groups are used. In-place tests are utilized to assess the strength of concrete to define the form-time removal and defect detecting methods are used to evaluate damages occuring during construction.

In the last few years in the Gulf region, due to construction booming and market pressure to complete structures on time have lead to an increase in the use of various NDT methods. Poor consolidation, shallow covers, cold joints and other construction defects have occurred more than usual and increased demand by local authorities and consultants to investigate such cases.

3.0 TYPICAL CASE STUDIES

3.1 Poor Consolidation in Concrete Industrial Structure

An evaluation of foundation columns was performed due to the presence of surface honeycombing, which was noted on the surface of the columns after the forms were removed

(Figure 2,3). The columns were part of the foundation system for a large mechanical engine. Nondestructive testing was performed to evaluate the presence of internal honeycombing. Impact Echo, Impulse Response and Ultrasonic Pulse Velocity were utilized to evaluate the condition of the concrete comprising the aforementioned columns.

Figure 2. Surface damage at the bottom of the column.

Figure 3. Exposed reinforcement due to poor consolidation of concrete.

The columns were relatively large and heavily reinforced in order to be able to carry the required loads. Initial visual inspection of the surface of the columns noted minor pockets of unconsolidated concrete or entrapped air on the surface of the column in addition to sections where the concrete was unconsolidated. Limited surface chipping had been performed in an effort to "repair" the columns.

Initially, the testing program was setup to evaluate the structure with the three testing methods mentioned above. The trial testing evaluated the effectiveness of each test method in locating the internal honeycombing within the column. The results of the initial testing program noted that both the Ultrasonic Pulse Velocity and the Impulse Response test methods were acceptable methods for identifying anomalies within the column. The dense mat of reinforcing steel present in the column section affected the received signal when the columns were tested with the Impact Echo test method. The large diameter bars and the large mass of reinforcing resulted in multiple reflections, making signal analysis very time consuming. As a result, the investigation relied solely on the Ultrasonic Pulse Velocity and Impulse Response testing methods.

Visual inspection of the columns noted isolated pockets of unconsolidated concrete at the surface of the columns. The nondestructive testing program noted that both the Impulse Response and Ultrasonic Pulse Velocity test methods were successful in evaluating the internal condition of the concrete in the column. Typical test result of impulse response test (average mobility) is shown in Figure 4.

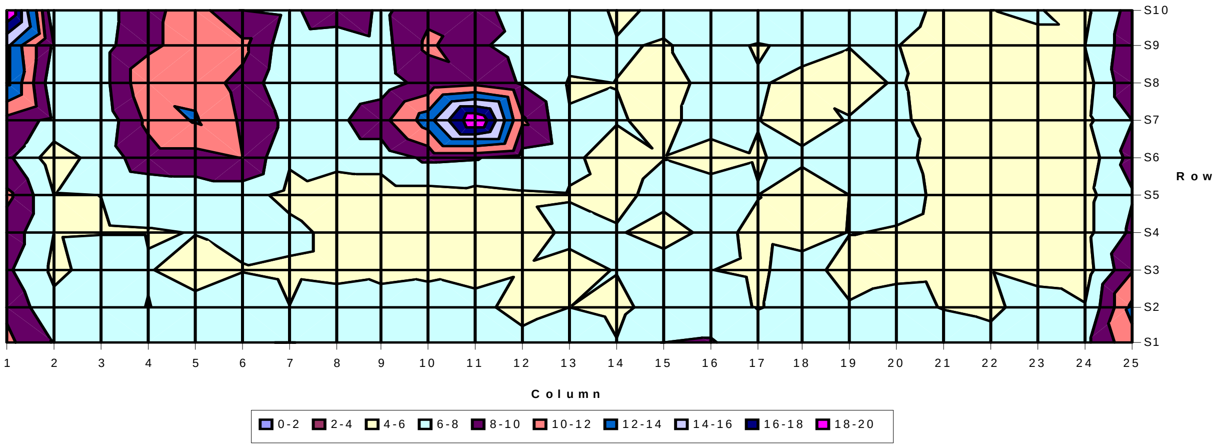

Figure 4 Typical average mobility test results showing isolated zones of higher mobility.

The nondestructive testing noted that besides the anomalies noted on the surface of the column, several isolated locations also noted anomalies within the body of the column. Majority of the anomalies noted were relatively small in nature. Coring of the columns at these locations confirmed the presence of honeycombing within the body of the column. The results were presented to the engineer of record to determine whether these anomalies had an effect on the structural integrity of the column.

3.2 Fire-Damaged Reinforced Concrete Building

An investigation was conducted on a building under construction where a fire broke out at basement level (B2). The fire caused a significant damage to the reinforced concrete structure.

The local buildings authority was concerned about the impact of the fire damage on the safety of the structure and requested an independent assessment of condition of the structure after the fire-damage.

Condition assessment included visual inspection, delamination survey, concrete and reinforcement testing and ultrasonic pulse velocity test.

3.2.1 Visual Inspection

All accessible / visible areas were inspected. Extent of the damage in each element was recorded on survey forms along with selected photographs.

The survey included a visual inspection of concrete for signs of distress due to the fire. Type and extent of distress exhibited by fire-damaged concrete was used to establish the temperature profile at various depths of concrete during the fire and also to assign a damage classification to the various elements with the aim of establishing a remediation strategy (Concrete Society Technical Report No. 33 1990).

Visual inspection included noting the colour change in concrete, if any, following the fire. The elements were also inspected for crazing, presence of cracks, extent of spalling, cross-sectional loss in concrete, condition or reinforcement and deflection (Figures 5 and 6).

Figure 5. Buff colour observed on a concrete column.

Figure 6. Extensive crazing on a column surface.

3.2.2 Delamination Survey

The delamination survey was carried out on almost all accessible areas of columns. Delamination survey was also conducted on walls, slabs and beams. Delamination survey was conducted by hammer sounding the concrete surface. A dull "hollow" response indicates that the concrete below the surface is not sound due to either concrete delamination or voids. A "ringing" noise indicates that the concrete is sound (Nagi et al 2003).

The reason for conducted an extensive delamination survey is to identify areas that appear to be undamaged on the surface but might be delaminated due to reinforcement expansion at high temperatures below the concrete surface.

Survey results were then transferred onto a database. The database was set up such that, if the survey results for a particular element satisfied at least one criterion for a particular damage class, then, it is classified as the highest damage class rating.

3.2.3 Compressive Strength and Petrographic Analysis

Fire damage causes a layered effect on concrete. Compressive strength loss at various depths with increase in temperature clearly indicates that the loss of compressive strength decreases with increased depth from the external surface. Therefore, the extracted concrete cores when tested for compressive strength will not produce an accurate idea about the loss of compressive strength in fire damaged concrete and the strength of the unaffected concrete below the fire damaged external surface.

A petrographic analysis was conducted on concrete core samples extracted from various parts of the fire damaged structure and adjacent areas. Petrographic examination is one of the key tests that are used to determine the alterations in the concrete due to exposure to high temperatures. Petrographic analysis is also useful to determine if concrete adjacent to the worst damaged area is affected by the fire. During inspection, these areas appeared to be unaffected on the external concrete surface; however, they might have undergone some damages due to the exposure to elevated temperature.

3.2.4 Ultrasonic Pulse Velocity Test

Ultrasonic pulse velocity tests were conducted to verify the quality of concrete and also to predict compressive strength at various locations of concrete elements.

Concrete cores extracted for compressive strength testing were tested for ultrasonic pulse velocity before crushing. A graph was plotted between the ultrasonic pulse velocity test values and the compressive strength test result. A best-fit curve was derived based on the values plotted (Figure 7).

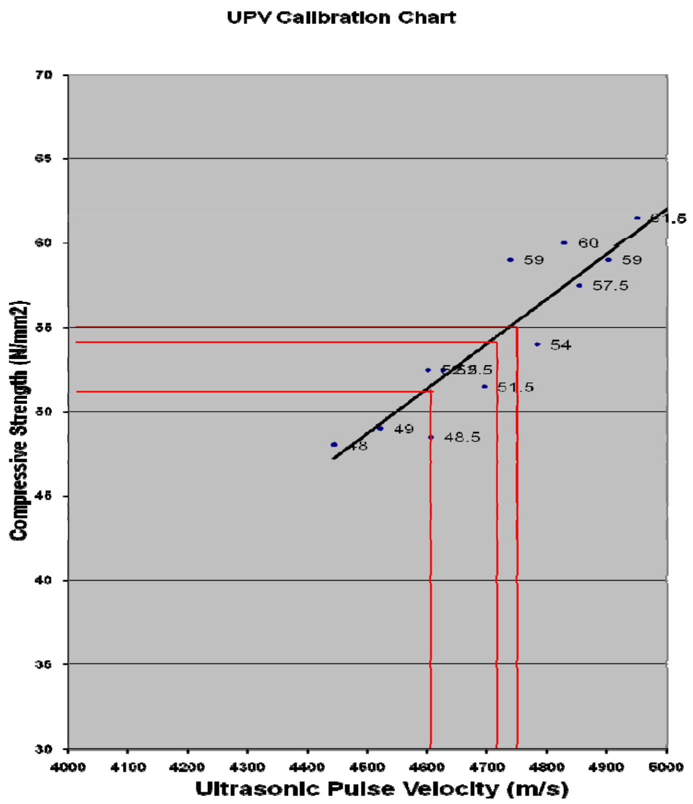

Figure 7. Typical UPV vs. compressive strength calibration chart.

Ultrasonic pulse velocity tests were conducted at different locations in the basement concrete structure on columns and beams. These values were then compared against the curve to derive the compressive strength value.

The ultrasonic pulse velocity readings are also used as indicators for the quality of concrete within the element tested.

Generally, concrete with ultrasonic pulse velocity readings over 4000 m/s, is considered to be a good quality concrete. Variations in the ultrasonic pulse velocity readings also indicate the variation in concrete quality in the same element.

In the case of the fire-damaged basement, the ultrasonic pulse velocity of concrete cores extracted from the worst fire damaged locations was measured. A review of the readings indicates that all the readings are over 4000 m/s. This indicates that the concrete quality in the elements tested is good.

3.2.5 Recommended Repair Procedures

Following the above mentioned assessment, each member of the structures was classified following Concrete Society Report 33 guidance and based on extent of damage in the concrete member. Recommended repairs, by the engineer of record, included simple patching, concrete encasement and breaking out and replacing damaged section.

4 SUMMARY

Nondestructive testing techniques are very useful tools for assessing and evaluating all types of concrete structures. NDT is used for in-situ strength prediction and defect detection in damaged structures.

More applications of NDT methods in the Middle East are used in new construction. They are also used in assessing existing structures, mainly corrosion damaged concrete infrastructure.

Several advanced nondestructive test methods were implemented and used in the last 15 to 20 years for concrete structures evaluation. These tests provide more comprehensive, scientific, and quantitative assessment of structural conditions. They also provide the information needed to design and select the optimum rehabilitation system.

Impulse Response test used to assess the poor consolidated concrete columns gives computer-generated data and drawings which will be easily utilized for repair, planning and design.

The Ultrasonic pulse velocity technique used to assess the fire-damaged building provides useful information about hidden damage within the structural members and also used to predict the compressive strength at any point in the structure based on the limited number of cores tested for strength.

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