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NON-DESTRUCTIVE EVALUATION TECHNIQUES FOR EVALUATION OF NUCLEAR CONCRETE STRUCTURES WITH LIMITED ACESSIBILITY

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ABSTRACT

To support the aging management of concrete containment, nuclear safety-related structures including the structures for radioactive waste storage, enhanced evaluation capabilities are required. It is preferable to use Non-Destructive Evaluation (NDE) methods whenever possible as these do not cause damage to structures and thus do not require repairs. NDE would also be beneficial for Quality Assurance (QA) purposes (e.g., verifying sound, well consolidated, void free concrete) during construction and to support investigations.

While there is a variety of NDE methods available to evaluate integrity of concrete structures, their application is limited, particularly when the access is limited to only one side of the structure and when no access to concrete exists (e.g., steel lined containment structures, steel lined nuclear waste storage containers).

A multi-year project was initiated to identify the methods that can be easily applied in the field to inspect these types of structure and to identify the cracks, voids, delaminations, consolidation issues (e.g. honeycombing), concrete strength degradation and corrosion of steel.

INTRODUCTION

In the nuclear industry in Canada, in-service examination requirements for containment and safety-related structures including structures for the storage of irradiated fuel are described in CSA N287.7 (CSA, 2017) and CSA N291(CSA 2019) respectively. In-service examination methods include visual inspection, non-destructive tests, invasive techniques and instrumented monitoring. In order to select the exact method and extent of examination, such factors as accessibility, effectiveness, accuracy of the test methods as well as importance of the structure and expected deformation and degradation should be considered. Typically, visual inspection is performed whenever possible. Based on the results of visual inspection, other methods (e.g. NDE, invasive, etc.) may be applied. However, if the structure is not available for visual inspection, other methods should be considered. Also, some types of degradation may not manifest itself on the surface of the structure for a long period of time, thus consideration to using other methods of examination (e.g. NDE) should be given. NDE may also be required as part of a Condition Assessment (refer to requirements of CSA N287.8 (CSA, 2015) and CNSC REGDOC 2.6.3(CNSC, 2014)).

Several NDE techniques applicable for detection of degradation in concrete where access is available from only one side of the structure have been identified based on review of Research and

Development (R&D) results and Operating Experience (OPEX) review. Some of these NDE techniques are being successfully used in the field to evaluate integrity of concrete structures in nuclear installations.

However, with regards to testing of concrete behind the steel liner, it appears that while it is possible to detect voids and delaminations on the interface of steel liner and concrete, it is rather challenging to detect defects inside the concrete behind steel liner.

NDE FOR CONCRETE STRUCTURES

NDE methods are typically applied for the purposes of inspecting, testing, or evaluating materials, components or structures for discontinuities or variations in properties without causing damage. In case of the concrete structures, the objective of NDE is typically to provide information about the condition of the structure without removing any material.

The purpose of NDE for concrete structures typically includes determining the characteristics of the concrete structure as constructed (such as concrete thickness, concrete cover thickness, location of reinforcement and embedments). Furthermore, NDE methods may be used to infer or directly indicate concrete properties such as compressive strength and modulus of elasticity. NDE may also be used to evaluate condition of concrete and detect the presence of degradation (e.g. cracks, delaminations, voids, etc.)

There are four main reasons to apply NDE methods to concrete structures (ACI, 2013):

1. Quality control of new construction;
2. Troubleshooting problems with new and old construction;
3. Condition evaluation of older concrete for rehabilitation purposes;
4. Quality assurance of concrete repairs.

To be available for use in the field, NDE method should be reliable, simple, portable and sensitive to small flaws. Reliability of the NDE method can be affected by a variety of factors including:

1. Geometry and accessibility of component;
2. Flaw size, location and orientation;
3. Correct selection and application of NDE method;
4. Material properties;
5. Environmental factors; and
6. Human factors.

NDE of concrete has inherent difficulties due to heterogeneity of concrete which makes it difficult to distinguish between defects and naturally occurring inclusions and due to the lack of universal failure criteria for concrete structures as it may be difficult to establish universal acceptance criteria.

In concrete several degradation mechanisms may occur simultaneously and it is not easy to determine which one of them is primarily responsible for the damage. Hence, it is necessary to have an understanding of the basic underlying causes of damage in concrete and their manifestation. Different causes of defects may require different NDE methods. In addition, the geometry and composition of the structure would also have an influence on the selection of the NDE method. For example, some methods may not be suitable for concrete with high-density aggregate material. Different crack types are expected as a result of different degradation mechanisms; for example pattern cracks are expected as a result of Alkali Aggregate Reaction (AAR) or ettringite formation while cracks parallel to the reinforcing bars are expected as a result of reinforcement corrosion. Contaminated or water-filled cracks may cause difficulties for NDE, depending on the method being used.

There is an inherent level of uncertainty when using a single NDE testing method, particularly when quantification is required. Thus it is advisable applying more than one method to confirm the findings and performing calibration using analysis results of limited number of cores extracted from the structure. An engineer knowledgeable in design and performance requirements of the structure and concrete degradation mechanisms in consultation with NDE specialists should decide on appropriate NDE methods to be used to detect signs of expected degradation or to confirm construction quality.

Several NDE techniques are applicable for detection of degradation in concrete structures where the access is limited to only one side of the structure. Some of these methods (e.g. Impulse Response, Impact Echo, GPR, Half Cell potential) are being successfully used in the field to evaluate integrity of concrete structures in nuclear installations. While some NDE techniques are ready for deployment on the field, caution must be exercised when applying these techniques in the field as it is very important to select the right technique for anticipated degradation. Typically, a use of a combination of methods improves reliability.

NDE FOR NUCLEAR STEEL-CONCRETE STRUCTURES

Steel-concrete composite structures are used in nuclear as well as non-nuclear industry. Composite structures have a variety of applications in a non-nuclear industry, e.g. in bridge construction as steel-concrete slabs and rigid connections between piers and beams. Examples of steel-concrete composite structures in nuclear industry include concrete containment lined with a steel liner and certain design of nuclear waste storage structures.

A number of cases have been reported in the nuclear industry, where the presence of foreign material in concrete adjacent to the steel liner has caused corrosion. Such materials including pieces of wood, gloves, etc. were left in concrete at the time of construction. These materials typically have low pH value which causes initiation of pitting corrosion as illustrated in Figure 1. Example of corrosion occurrence evidenced by peeling of the paint on the surface of the containment steel liner is illustrated in Figure 2.

A few experiments were conducted over the recent years to test applicability of the NDE to detect defects in concrete behind steel plates as discussed in (Haack, Wu, 2011, Clayton, 2013, Wiggenhauser, 2013, Yanagihara, 2015, CSNI, 2015 and Fülöp, 2016). It appears that it is possible to detect voids (delaminations) on the interface of steel liner and concrete. However, it is very challenging to detect voids and other defects inside the concrete, particularly when the voids are present on the interface of the liner and concrete. A few techniques such as impulse response, impact echo and surface wave method) were identified as promising to detect flaws in concrete behind steel plate and were selected for further study.

EXPERIMENTS

Two large scale specimens (Wall 1 and Wall 2) with nominal dimensions of 6 ft x 6 ft x 1 ft thick and 10 ft x 7 ft x 1.67 ft thick respectively have been constructed at the Olson Engineering Laboratory in Wheat Ridge, Colorado using 6000 psi concrete mix.

Wall 1 was built with grade 60 steel reinforcement (#4 bars) and a ½" steel plate on the front face with 4" embedded studs on 1 ft centres. Wall 2 was built with grade 60 steel reinforcement (#4 bars) and a ½" steel plate on the front face with 6" embedded studs on 1 ft centres.

It was expected that the degree of debonding (loss of contact between the steel plate and concrete) will affect the ability of the NDE instruments to detect the defects in concrete. Therefore, prior to constructing two large scale wall specimens, different materials have been tested to be used for simulation of various degree of debonding between concrete and steel as shown in Figure 3 and Figure 4. Simulation of other defects has also been tested, e.g. honeycombing was created by covering coarse aggregate in cement as illustrated in Figure 4.

Wall 1 was constructed horizontally as a slab with the steel plate at the bottom of the specimen as shown in Figure 5. While in horizontal position, the tests were performed on the top face of the specimen (concrete side) using Ultrasonic Pulse Velocity (UPV) method to initially confirm the placement of the defects. After that, the specimen was lifted and placed on its side so that the tests could be conducted on the steel plate face. Wall 2 was constructed vertically as illustrated in Figure 6.

Various degree of contact between the concrete and the steel plate has been imitated using different debonding agents. The following defects have been placed at various depths inside the concrete specimens:

- internal concrete delaminations / delamination due to corrosion of rebar;
- void/honeycomb at varying depths from the wall face;
- cracks parallel to wall face at varying depths;
- cracks perpendicular to wall face;
- angled cracks;
- water accumulation in cracks;
- area of low-strength concrete.

Experimental program included performing the tests on the steel side using Slab Impulse Response (SIR); Impact Echo Scanning (IES); and Spectral Analysis of Surface Waves (SASW) methods with the equipment produced by Olson Instrument Inc. (Figure 7 - Figure 10).

Prior to testing from the steel plate face, UPV testing was again performed between the concrete and steel faces of the specimen to confirm the location of defects. The UPV test results agreed well with the planned placement and expected behaviour of the flaws as shown in Figure 11. As expected, the UPV method is sensitive to cracks and voids that are generally in-plane with the front face of the specimen and is not very sensitive to flaws located perpendicular to the test surface.

The IES was performed on the steel plate face of Wall 1 specimen along vertical grid spaced at 0.5 ft and the measurements were recorded at 1" interval along each vertical line. The results shown in Figure 12 illustrate that majority of the constructed flaws have been detected by IES. Colour coding shows the thickness based on the dominant frequency peak in the IE spectrum. Ringing vibrations caused by the flaws shift the resonant frequency peak to lower values thus increasing the calculated thickness. One of the flaws (a void) has been created such that it could be tested with air or water inside. However, while the void was detectable by IES, it was impossible to detect if it is an air filled or water filled. It should be noted that this flaw was also located in the area of partial debonding between the steel plate and the concrete reducing the sensitivity of the instrumentation for characterizing deeper defects.

The SIR testing was performed on 0.5 ft by 0.5 ft grid mainly to map out the areas of debonding between the steel plate and the concrete. The results illustrated in Figure 13 confirm that SIR method is sensitive to debonding. The colour scale displays average mobility; the areas with high mobility identified by warmer colours indicate debonding. SIR method could also indicate the defects that are near the surface (e.g. location of lower strength concrete and some cracks); however it could not identify deeper defects.

The SASW testing was performed on the steel plate face of Wall 1 on 0.5 ft by 0.5 ft grid and the with reduced results are illustrated in Figure 14. The colour coding represents surface wave velocity in ft/s. The SAWS method is sensitive to the flaws and discontinuities in concrete as well as the areas properties (e.g. lower strength). SAWS method is expected to be most sensitive to cracks and voids oriented in the direction perpendicular to the test surface. SASW testing results correlated well with the constructed defects, however, it has shown to be the most sensitive method to the loss of contact between concrete and steel. Two cracks that were located perpendicular to the steel plate have not been identified because all of the SASW tests have been performed parallel to these cracks rather than across the cracks.

The testing of Wall 2 produced results similar to those discussed above and is not further discussed in this paper.

SUMMARY AND CONCLUSIONS

Based on the results of the tests, the following conclusions can be made:

- SIR and IE methods can be effectively applied to the steel plate side of steel lined concrete structures to evaluate the contact between the concrete and the steel plate.
- SASW and IE methods applied to the steel side of steel lined concrete structures are useful in detecting cracks and other defects in concrete if at least partial contact exists between the concrete and the steel plate.
- It is recommended to perform SASW in two directions.
- Scanning techniques allow for much faster data collection than point by point measurements.
- Experienced operator is required for interpretation of test results.

The study continuous and as part of its next phase the same equipment was used to perform "blind tests" of concrete and steel composite mock up specimens constructed by EPRI. Collected data is being evaluated.

ACKNOWLEDGEMENT

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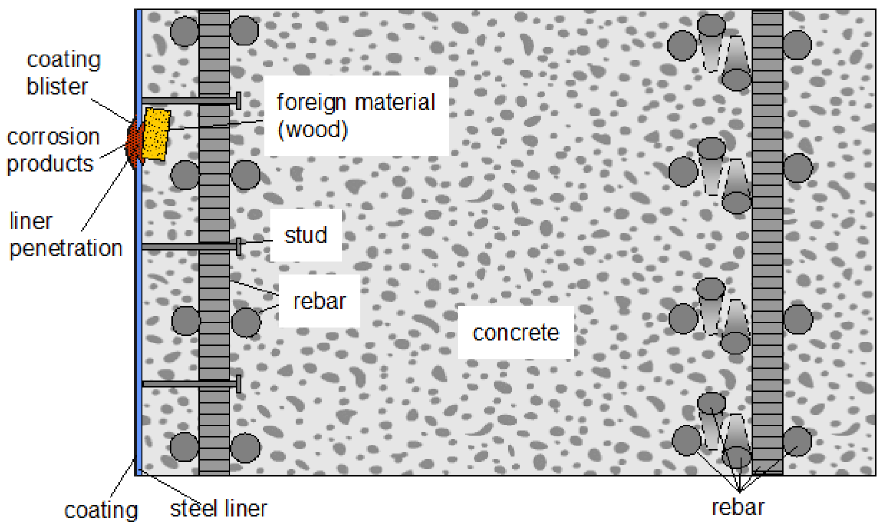

Figure 1 Schematic of a Reinforced Containment Cross-Section with Embedded Foreign Object (Dunn, et.al.)

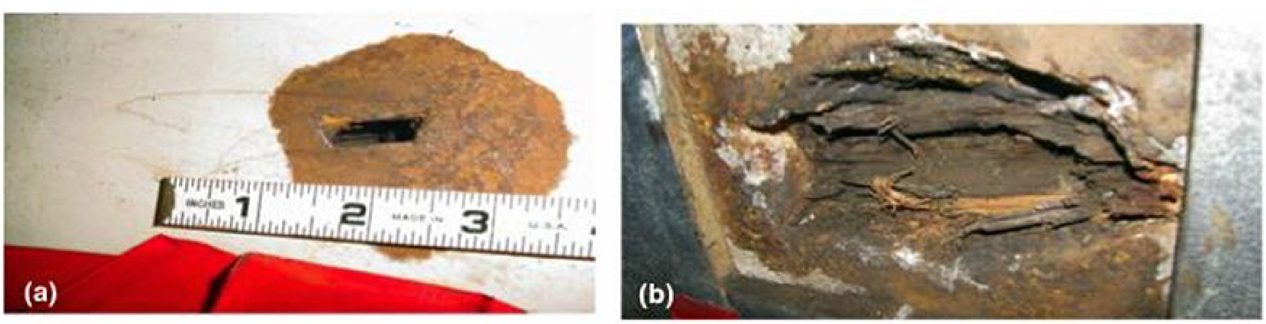

Figure 2 Example of Corrosion Occurrence Originating from the Concrete Side of the Liner (First Energy, 2009)

Figure 3 Materials to Simulate Various Degree of Debonding of Steel Plate from Concrete

Figure 4 Testing of 16 Different Bond Breakers and Simulation of Honeycomb

Figure 5 Wall 1 Construction

Figure 6 Wall 2 Construction

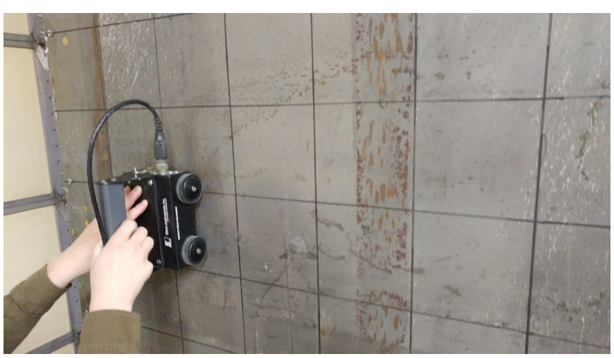

Figure 7 IES Testing

Figure 8 SASW Testing

Figure 9 SIR Testing

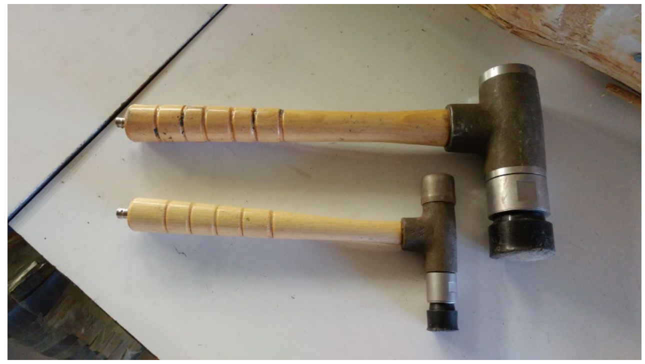

Figure 10 Hammers used for SIR Testing

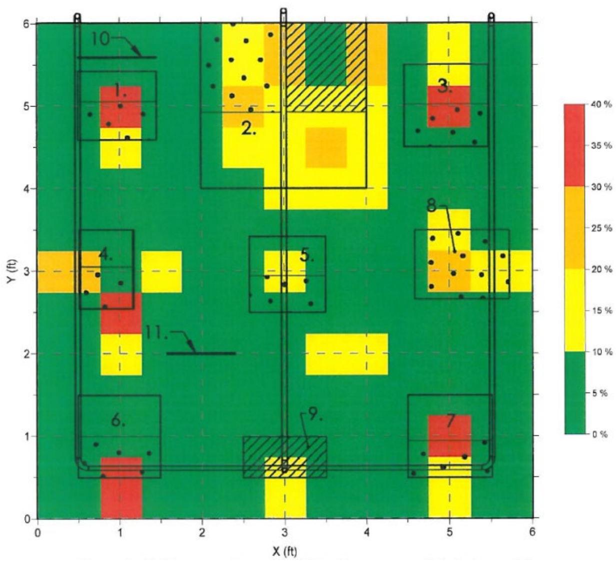

Figure 11 UPV Test Results on Wall 1 with Constructed Defects Overlain

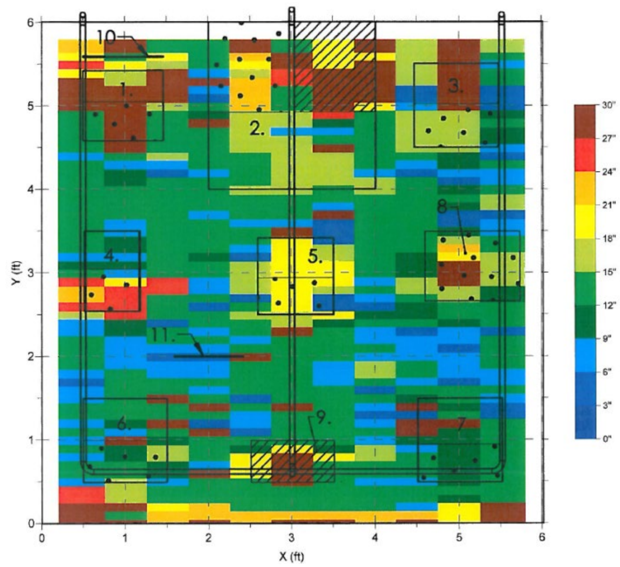

Figure 12 IES Test Results on Wall 1 with Constructed Defects Overlain

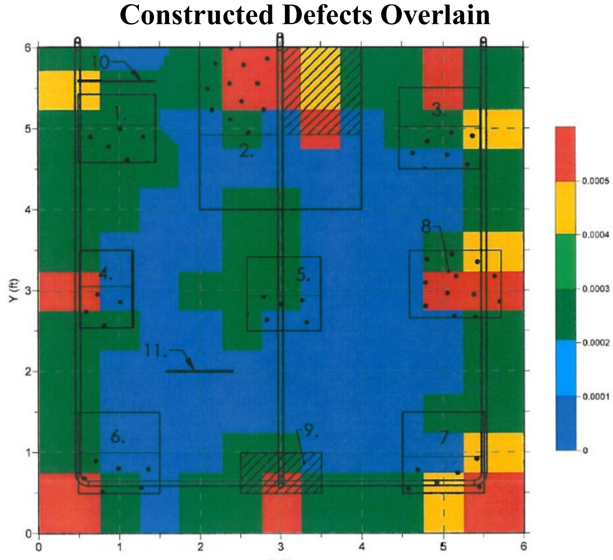

Figure 13 SIR Test Results on Wall 1 with Constructed Defects Overlain

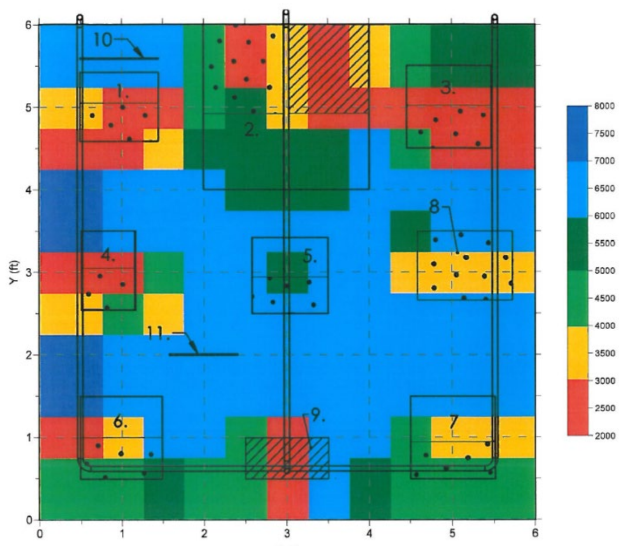

Figure 14 SASW Test Results on Wall 1 with Constructed Defects Overlain