STP-NU-069

ANALYSIS OF SELECTED NONDESTRUCTIVE EXAMINATION (NDE) METHODOLOGIES FOR THE ASSESSMENT OF CRACKING IN CONCRETE CONTAINMENTS

ASME STANDARDS TECHNOLOGY, LLC

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ANALYSIS OF SELECTED NONDESTRUCTIVE EXAMINATION (NDE) METHODOLOGIES FOR THE ASSESSMENT OF CRACKING IN CONCRETE CONTAINMENTS

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FOREWORD

This report provides exploratory research into the reliability of available NDE technology to detect delaminations and cracking. It also provides the foundation for further interactions with the industry and ASME code to develop appropriate in-service inspection methodologies to perform detailed assessments of the integrity of aging concrete containment structures. This project is part of a larger initiative at EPRI to research aging of concrete and reliability of inspection techniques for nuclear structures.

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1 INTRODUCTION

As the current nuclear fleet enters into long term operation (LTO), challenges are occurring due to the degradation of concrete structures. ASME Section XI, Subsection IWL currently provides in-service inspection requirements to assess the structural condition of concrete containments, through visual examination of the accessible surfaces. However, no specific guidance is provided for assessment of the internal condition of concrete.

To ensure long term safe operation and sustainability of the nuclear fleet, research is needed to determine if nondestructive examination (NDE) tools can provide the level of reliability required to assess existing and emerging degradation issues in concrete containments.

EPRI, through its concrete inspection and aging initiative is performing and directing some of the needed research in this area. It seemed natural that this effort is leveraged with this ASME research grant and, in that way, benefit ASME and EPRI by exploiting synergies in this area.

1.1 Objective

This project supports an action item within ASME Section XI Working Group Containment to evaluate examination requirements for determining concrete internal condition.

The objective of this project is to test nondestructive examination techniques and tools to perform detailed assessments on the structural integrity of concrete containment structures. Specifically, three parameters are tested: the depth of flaw detection, the operator dependence and the ease of deployment of each technique. The primary defects of interest include delaminations and cracking. Note that due to the limited scope of this project only three techniques were evaluated. Further work can focus on additional techniques.

2 NDE TECHNIQUES

Three NDE techniques were evaluated: impact-echo, impulse response and shear wave tomography.

2.1 Impact-echo

Impact echo is described in ASTM standard C1383, ACI 228, and ICRI Guideline No. 210.4. The technique consists of introducing stress waves into concrete and measuring the response of the concrete using an adjacent receiving displacement transducer. Initiation of the stress waves is accomplished through impact with a small steel ball. The impactor ball size usually ranges between approximately 0.5 and 3 cm (~0.2 to 1.2 in). The impact generates wave-motion of particles within the concrete. The adjacent transducer consists of piezoelectric material. The piezoelectric material requires coupling to the concrete which is usually accomplished with lead. The contact transducer measures the displacement response of the concrete to stress waves generated by the impact.

The types of stress waves that are generated are compression waves (also called longitudinal-, L-, and P-waves), shear waves (also called secondary- and S-waves), and surface waves (also called Rayleigh waves). The stress waves reflect at boundaries of material with varying acoustic impedance – a physical property based on acoustic velocity and density of a material. The reflected stress waves reverberate between the impact surface boundary and internal boundaries. The measured and recorded data is the back-and-forth reflecting of the stress waves. Analysis includes using a Fast Fourier Transform algorithm to develop an amplitude spectrum in a frequency domain. This mathematical manipulation is utilized to extract depth resonance produced by the compression wave. The resonance is best identified when it is indicated as a single, dominant peak which is used to indicate the depth of an anomaly (acoustic-impedance boundary).

This technique has been used to indicate internal voids, honeycombing, cracks, member thickness, bond quality, areas of incomplete grouting in tendon ducts, and delamination.

This technique has been used for testing of delamination in concrete structures such as pavements and bridges. It has the advantage of allowing the evaluation of a concrete member from one side, which is very useful in the case of containments. Alternatively, the technique is based on a point-by-point measurement technique that results in a rather slow process when large structures are involved.

2.2 Shear Wave Tomography

Currently, there are no standards that provide a uniform approach for the specific use of shear wave tomography.

Shear waves propagate at approximately 62% of the speed of compression waves for concrete with Poisson's ratio equal to 0.2. However, the shear wave energy that gets created by an impact is approximately five times greater than the compression wave energy that is generated. Depending on attenuation, the greater energy allows for greater penetration into concrete and allows deeper investigation compared to other more surface-based techniques.

Ultrasonic shear wave tomography is a stress-wave technique whereby shear waves are specifically generated, utilized, and introduced into a concrete structural member. The structural member will absorb, refract, and/or reflect the wave energy. Consistent with impact echo, shear waves are reflected at boundaries where there is a difference in acoustic impedances of the materials on each side of the boundary. The introduction and reception of these stress waves are accomplished through the use of dual-mode, dry-contact transducers operating at relatively low frequency (e.g., 50± kHz). The transducers perform a "pitch-catch" action in which they introduce ("pitch") the shear wave into the concrete material and, subsequently, measure ("catch") the reaction to the shear waves.

The device utilized at EPRI is configured with transducers configured in a 4 x 10 array. One line of transducers actuates a shear wave and adjacent transducers behave as receivers, and then another line of transducers will actuate a shear wave signal, and so forth. This device is sometimes called a "phased-array" system because of the sequencing of transducer actuation. Using algorithms, color images are generated that identify deviations from sound concrete areas. Shear waves propagate and pass through solid concrete but will reflect, in part or wholly, at deviations from sound concrete. These deviations, as previously noted, occur at boundaries of different acoustic impedances. This information can be utilized to generate a three-dimensional image where color is used to indicate areas of high reflectivity.

As such, the technique is useful for thickness measurements, void characterization in regularly reinforced concrete structures, void characterization of grout-filled ducts, delamination, cracking, honeycombing, and bonding of repairs and overlays. An advantage of the shear wave tomography device is that it provides an image over a larger area (10 x 30 cm) (~4 x 12 in) compared to other NDE techniques. However, it is still a rather small area when large structures are involved. Additionally, this technique does not provide near-surface (~5 to 7.5 cm) (2 to 3 in) results.

2.3 Impulse Response

Impulse Response is described in ASTM Standard C1740, ACI 228, and ICRI Guideline No. 210.4.

Similar to impact echo, impulse response measures the surface response of concrete resulting from a localized mechanical impact. For concrete application, the impact utilizes a rubber-tipped mallet. For structural concrete application the mallet usually weighs 1.1 kg (2.4 lbs) and has a tip diameter of approximately 5 cm (2 in). The compressive stress of the impact is related to the elasticity of the mallet tip. The mallet contains a built-in load cell which measures the force of the impact onto the concrete. The increased impact energy, relative to other NDE tests such as impact echo, creates a low-strain bending mode of the concrete member or deformation of the concrete surface.

Measurement of the surface mobility is achieved by an adjacent geophone (velocity transducer). Both the impact and response functions are processed using Fast Fourier Transform and the resulting quotient of the two is referred to as the mobility of the concrete. The mobility of an element is averaged across the frequency band between 100 and 800 Hz, and is defined as the average mobility of the element. The slope of the best-fit line of the mobility between 100 and 800 Hz is the mobility slope. The dynamic stiffness is defined as the inverse slope of the mobility of the object between 0 and 40 Hz. The average mobility, slope mobility, and dynamic stiffness are calculated and plotted. These values are indicative of concrete quality and flexibility. More specifically, increased average mobility is indicative of under-consolidation, voids, and/or delamination. A contour plot of the average mobility indicates areas of potentially degraded concrete.

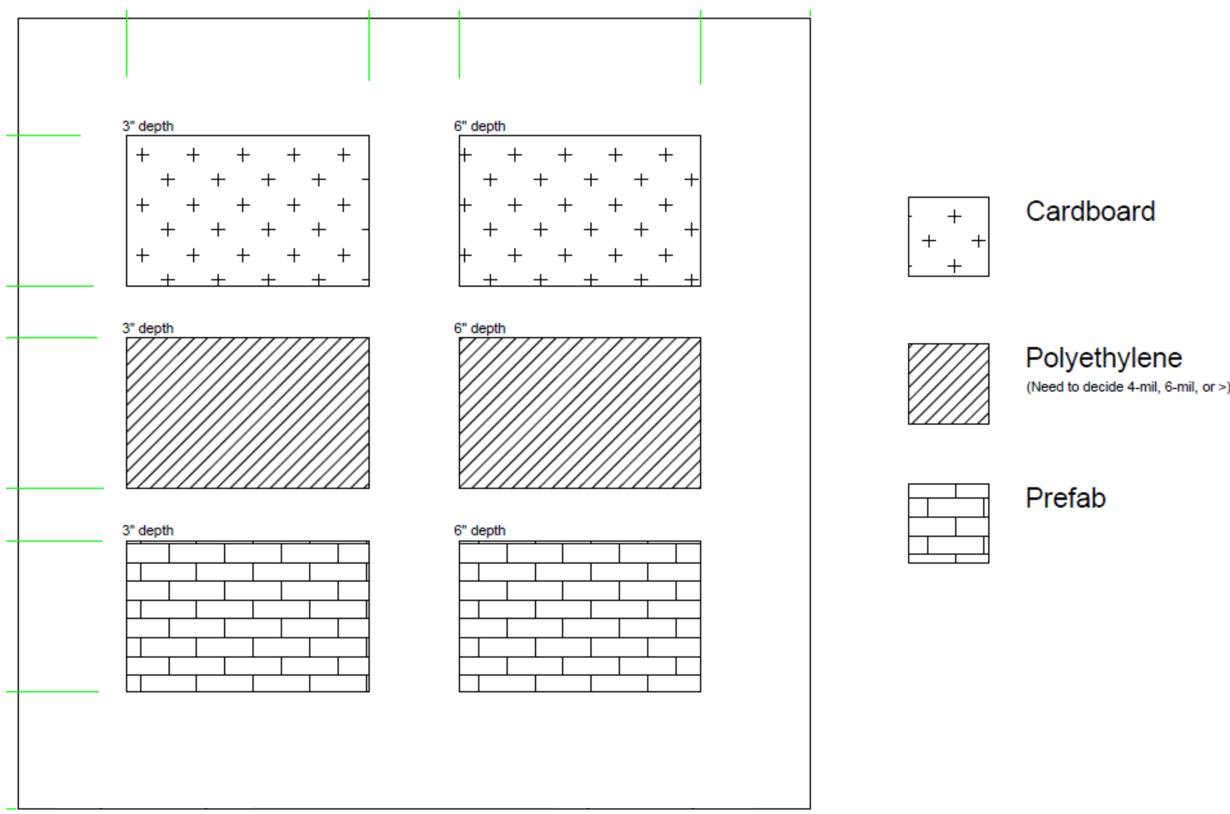
An advantage of this technique is the relative speed at which results can be interpreted compared to some other NDE techniques. Secondly, the transducer is not as influenced by high frequency vibration which allows clearer and more consistent results for analysis. One notable limitation is that element configuration and/or bracing will affect the stiffness of the member and thereby the results of a test location. Consequently, interpretation of boundary conditions is important.

3 MOCKUPS WITH EMBEDDED FLAWS

The main goal of the EPRI's NDE in concrete project is to assess the reliability and ease of deployment of NDE inspection techniques in concrete structures. For that purpose, research performed on mockups with embedded flaws is needed. Mockups with flaws simulating delaminations were prepared. The flaws were designed and fabricated using a variety of methods in order to evaluate the suitability of different fabrication techniques.

The American Concrete Institute defines delamination as a planar separation in material that is roughly parallel to the surface of the material. A literature review consisting of research performed on mockups reveals that most delamination flaws are often simulated using polyurethane sheets or cardboard. EPRI designed and constructed concrete mockups with these materials. Two large mockups with the approximate dimensions of 2 m x 2 m x 0.25 m (6.5 ft x 6.5 ft x 0.8 ft) were constructed (see Figure 3-1).

Figure 3-1: Mockup Design with Embedded Defects



In addition to placing flaws in these mockups using the materials referenced above, prefabricated concrete panels were sandwiched together and placed within the fresh concrete (See Figure 3-2). The surfaces of the prefabricated panels were purposefully rough in order to be consistent with the undulations and asperities found in "real" delamination conditions.

Figure 3-2: Embedded Flaw Consisting of Two Prefabricated Panels Sandwiched Together and Placed within the Concrete

Another technique was implemented for six smaller mockups which were dimensioned 0.60 m x 0.75 m x 0.25 m (2 ft x 2.5 ft x 0.8 ft). These mockups contained reinforcing steel that were placed at varying spacing and depths. By inducing corrosion in the reinforcing steel, tensile stresses were generated within the concrete which fractured the specimen. The spacing and size of the reinforcing steel will affect the direction and size of the fracture; so, delamination may be created using a natural occurring phenomenon such as corrosion. Delamination was successfully created with this technique. However, scaling this up to larger mockups (needed for our tests) was not successful and therefore only the technique of embedding flaws was used for these tests.

4 SHEAR WAVE TOMOGRAPHY

The data obtained through shear wave tomography is usually displayed in C, B or D scans. The system output is user-friendly and easy to manipulate to obtain signals. Shear wave tomography can be used to detect defects at different depths.

4.1 Depth of Defects

Detection of delamination at approximate 0.30 m (~12 in) depth. Shear wave tomography tests were performed at Crystal River with the objective of evaluating the capability of this equipment to detect a deep delamination. A shear wave tomographer with a 4 x 10 array of transducers was used. Figure 4-1 shows the B, C and D scans from a delaminated area. Note that a single layer of rebar was present between the surface and the delamination in this image, which largely facilitated the identification of the flaw. The area chosen for this demonstration was later shown to have a crack width of about 2.5 cm (~1 in). For more information on this particular case see [1].

Detection of voids located at 0.30 m (~12 in) below the surface. In this case, a smaller shear wave tomographer consisting of a 4 x 6 transducer array was used with the objective of determining the depth of voids previously embedded in the mockup shown in the top left corner of Figure 4-2. C-scans at different depths are also shown with the voids marked by a circle at depths of 20 cm and 31 cm. Note that despite the fact that several layers of reinforcement were present between the surface and the voids, the voids can be clearly seen at 0.20 m and 0.30 m (~8 in and ~12 in) deep.

Figure 4-1: Results from the Shear Wave Tomography Tests Performed at Crystal River, showing the Delaminated Area

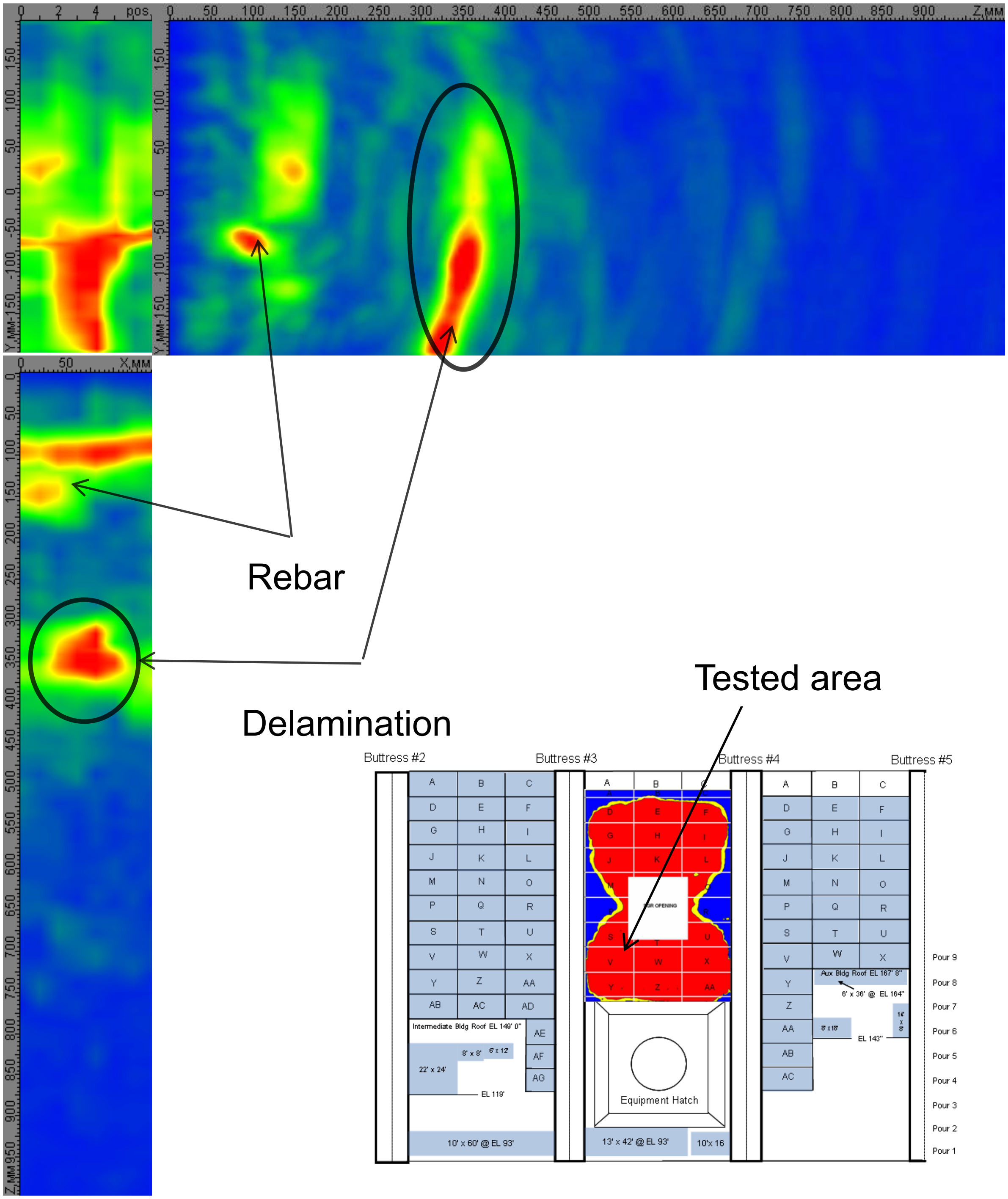
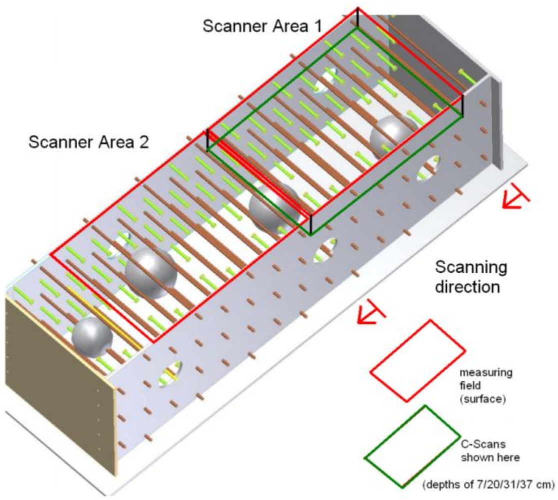
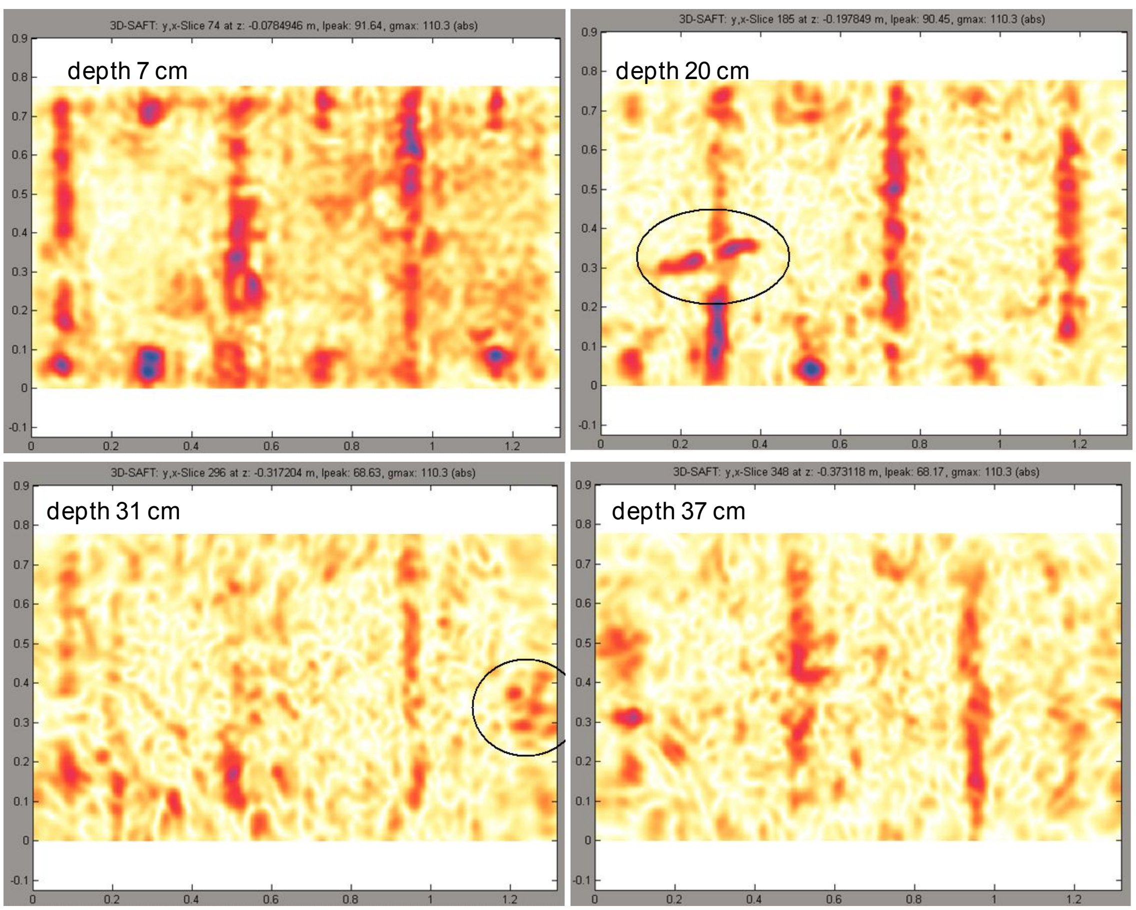


Figure 4-2: C-scans Slices at Depths of 7, 20, 31, and 37 cm



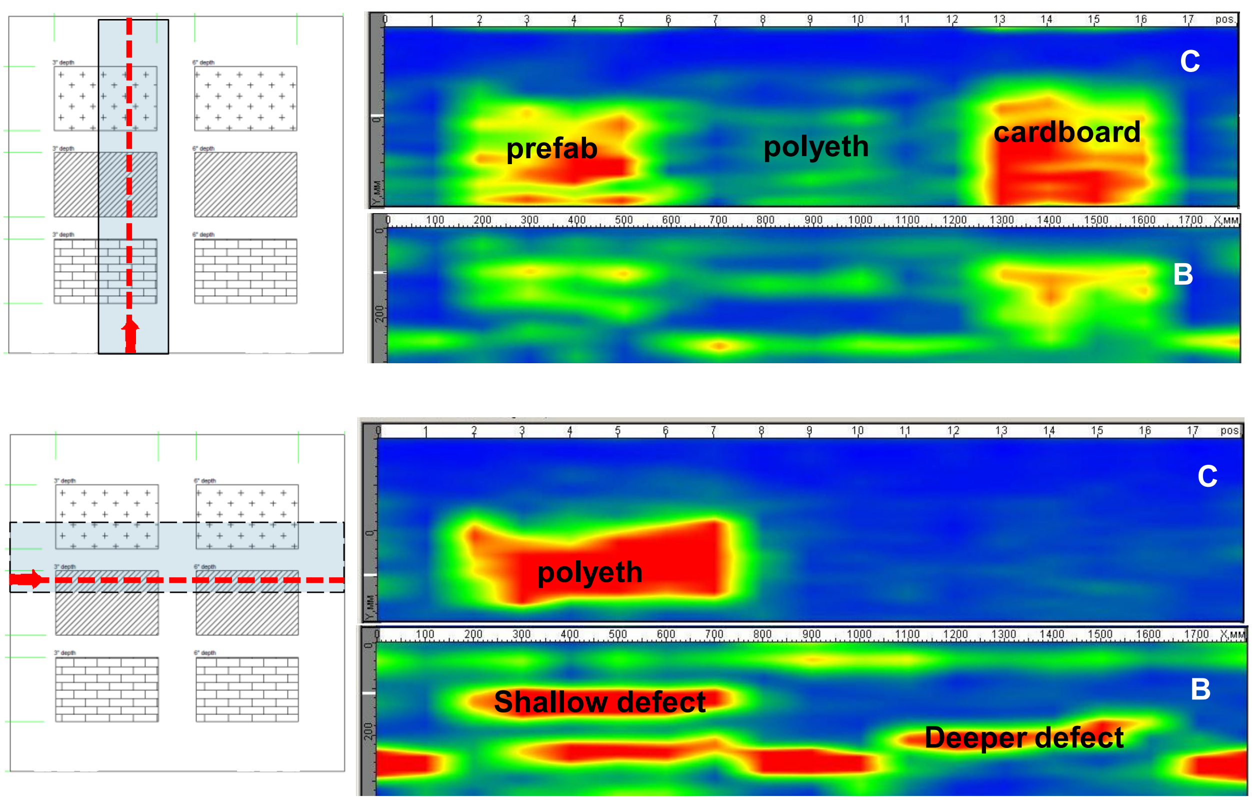


Both voids could be located (marked with circles)

Detection of flaws located at 7.6 cm (~3 in) and 15.2 cm (~6 in) below the surface. Figure 4-3 shows the B and C scans from the mockups referenced in Figure 3-1 showing delaminations located at 7.6 cm (~3 in) and 15.2 cm (~6 in) depth. Main observations follow:

- The depth of the back wall (25 cm / ~10 in) can be easily identified.
- There is a blind zone near the surface of about 5-7 cm (2-3 in), where defects cannot be seen by the ultrasonic shear waves.
- The defect positioned at 7.6 cm (3 in) depth is seen at 10-12 cm (~5-6 in) depth. The defect positioned at 15.2 cm (~6 in) depth is seen approximately at 20 cm (~8 in) depth. The depth at which features are observed with this device needs to be corrected to reflect the actual measurement (not done here). This method appears very robust to give an idea of the location of the defect, but precise depth determination does not seem accurate.
- Note that the reinforcing bars located near the back wall cannot be identified and get merged with the images of the back wall.

Figure 4-3: C-scans at Depths of 10 cm



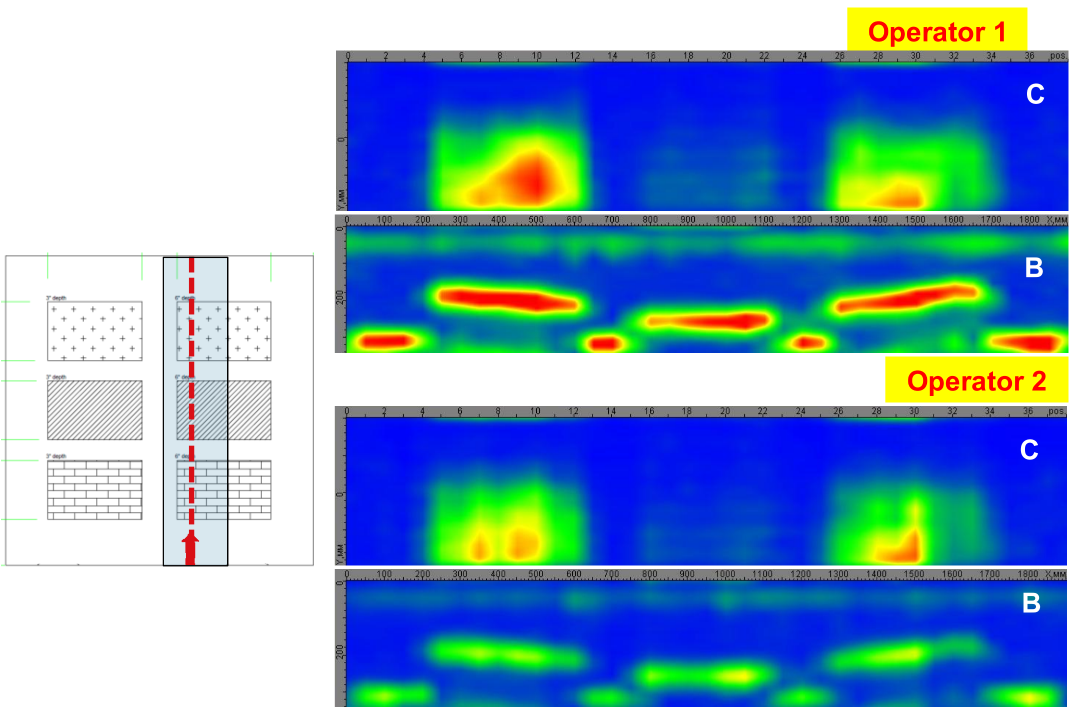
B scans taken over red dotted line

4.2 Operator Dependence

In order to test the operator dependence, two sets of tests were performed by two different operators. Main observations follow:

- There is little to no operator dependence. These tests were performed by two different operators. The results are very consistent when comparing both data sets. Figure 4-4 shows an example from data at a location where one of the defects has a slight tilt.
- The data acquisition and data processing of this device is quite straight forward for simple geometries and in case of delaminations. However, in cases of complex geometry, or if tendons or other materials (such as steel liners) are present, the signal processing is more involved and may require the use of software that is not provided by the commercially available device. In that case, the A-scans can be extracted and the data is processed through another system.
- Furthermore, phase evaluation of the signals may result in more refined images that allow differentiating empty voids with voids filled with water. In that case, the raw data needs to be extracted and analyzed through additional software.

Figure 4-4: Comparison of Results from Two Operators



Note: the technique does not seem to be operator dependent

4.3 Ease of Deployment – Automation

The speed of testing is slow when compared to the other tests performed here (impact echo and impulse response). In general, in order to obtain a good definition the tests are performed by overlapping shots.

This device has been previously mounted in a robot used to inspect horizontal surfaces like bridges or parking decks [2]. Hence, automation is possible, but this device and the mode of testing ares rather slow for scanning large areas.

This device is more suitable for getting in depth information of a rather small area, than to scan large areas such as a containment structure.

5 IMPACT ECHO

The data obtained through impact echo is usually displayed in a frequency domain with main frequency peaks representing depth of delaminations or back wall. The system output is not very user friendly.

Multiple reflections can be a source of error when using this technique. In this particular case, the edges of the mockup generate reflections that make it very difficult to characterize the regions close to the edges. Boundary effects and multiple reflections need to be accounted for when using this technique.

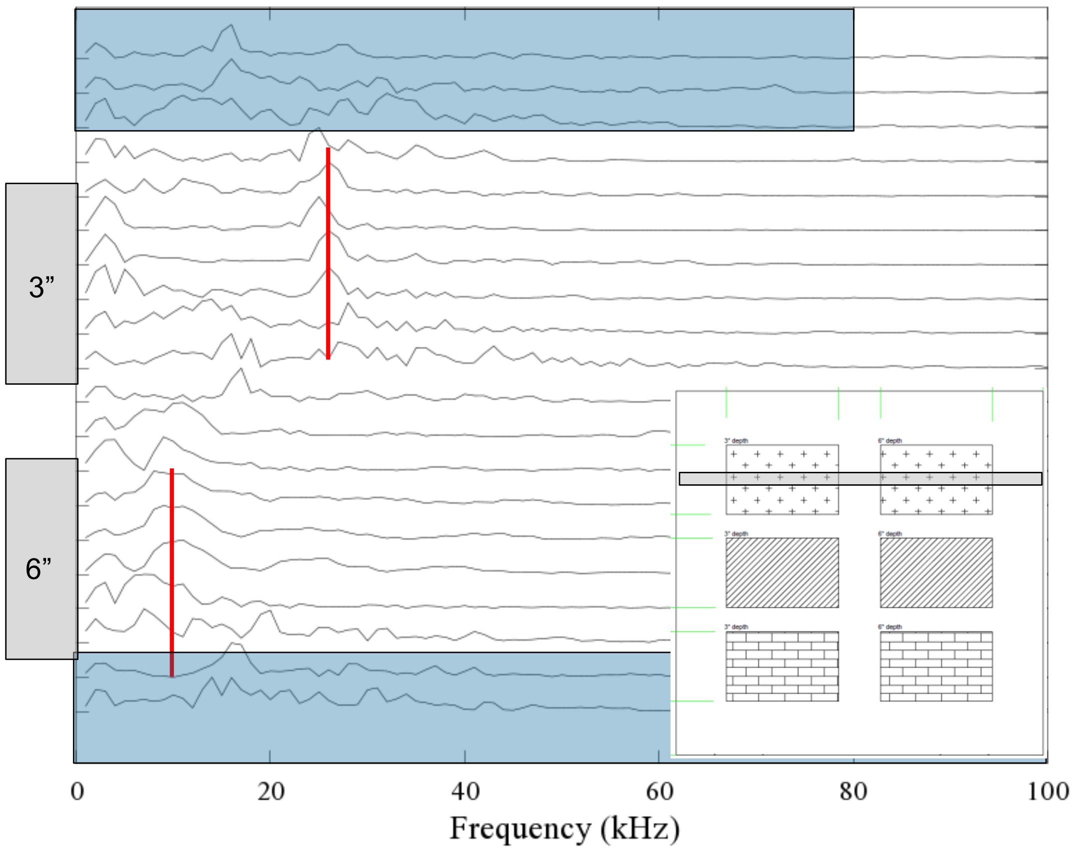
5.1 Depth of Defects

This study shows detection capabilities of delaminations at 7.5 cm (3 in) and 15 cm (6 in) depth. Figure 5-1 shows the frequency signals from a section of the mockup covering both depths of defects. Main observations follow:

- Areas shaded in grey represent the part of the signals that are influenced by the boundary effects. Hence, the analysis is performed in the non-shaded areas.
- The depth of the back wall cannot be determined here since it falls under the grey shaded area (boundary effects).
- As previously explained, the frequency if the main peaks determines the depth of the delamination or the back wall. In this case, the frequencies of concern are: 26 kHz for the shallow flaw (7.5 cm) and 13 kHz for the deeper flaw (15 cm).
- Impact echo plots can be presented in different forms. Here, the signals in the frequency domain are shown in the form of a cascade graph, with one signal per point tested.

This study shows delaminations up to a depth of ~15 cm (6 in). In general, the majority of studies on impact echo are focused on transportation infrastructure and the depths of delamination are shallow (usually less than 15 cm). However, this technique can be used for deeper defects as long as the problem with multiple reflections is overcome. Wiggenhauser [3] shows tests on concrete structures with a back wall of 83 cm (~33 in), and reports that the depth of the back wall could be reliably identified.

Figure 5-1: Impact Echo Signals Shown Here in Frequency Domain



Note: shaded areas denote boundary affected area; red lines denote characteristic frequencies for each depth; the lower right corner shows the area of the mockup tested

5.2 Operator Dependence

Impact echo is the technique among the ones tested here that is more operator dependent and requires higher level of training. Signal interpretation is not straight forward and repeatability and consistency are not guaranteed. Furthermore, multiple reflections due to boundary effects, honeycombs, non-planar defects, etc., complicate the signal interpretation. *Operator training is crucial and absolutely required* for data collection and analysis with this technique.

A large amount of research is being performed on the interpretation of these tests, which has the potential to overcome some of the limitations with signal interpretation [3].

- In nuclear plants ultrasonic techniques are commonly used to perform examinations in primary and secondary systems. The need of having trained and certified inspectors to perform inspections in safety related components has been recognized for some time in the nuclear industry. Training requirements, certification programs and qualification of procedures and personnel are required by the ASME code for ultrasonic in-service inspection of safety related piping and components in nuclear power plants.

- There are no certifications or training available to perform NDE tests on concrete structures today. Hence, when a plant is required to perform one of these tests it relies on vendor expertise with little verifiable qualifications.

The American Concrete Institute (ACI) is developing a training certification for NDE devices, which is a good starting point to address this challenge. However, certification should not be confined only to training, but also should require a set amount of hours of field testing, conducing to a similar program as the one for Level II and Level III inspectors.

5.3 Ease of Deployment – Automation

Impact echo devices have the potential for deployment in automated testing of large structures. Vertical concrete structures, such as containments, could be inspected with this method as it is being explored by EPRI through its concrete strategic program initiative [4][5]. Note that impact echo devices have previously been mounted on small robots for inspection of bridge decks and parking decks, generally on horizontal surfaces [2].

Testing and data collection can be performed rather fast covering large areas in short time. A relatively new development on impact echo testing is the incorporation of non-contact receivers to capture the signals, normally called “air-coupled impact echo” [6]. Air-coupled impact echo is not yet a commercially available technique, but it is an R&D stage with several tests performed by University groups. The advantages of this technique are that it can result in faster inspections and more data collection which could lead to a higher spatial resolution. EPRI has analyzed the potential of using this technique with an automated device and for the particular type of noise that we were concerned (vacuum from the robot), it was concluded that the maximum depth of penetration was ~15 cm (6 in).

6 IMPULSE RESPONSE

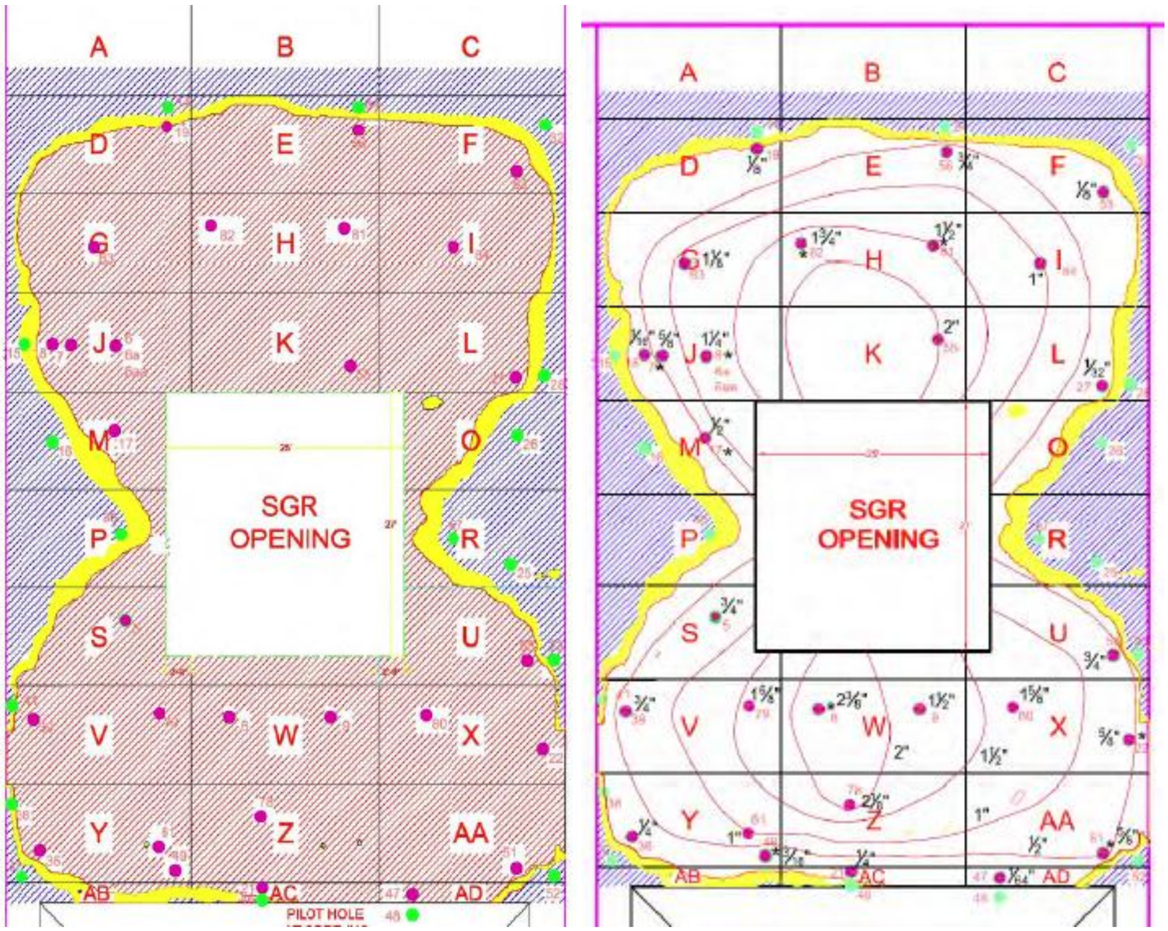
Different data can be obtained with impulse response: average mobility, slope mobility and dynamic stiffness. However, the data most used is the average mobility. Impulse response is an excellent technique to be used in structures that behave like plates with a minimum ratio of length / depth (L/D) of 6. The mockups built at EPRI are not suited for this technique so the analysis is performed based on previous studies at large containments.

6.1 Depth of Defects

Impulse Response has been extensively used in large concrete structures when delaminations and laminar cracking were being investigated. EPRI has been involved in two cases where this technique was tested at nuclear structures as an independent reviewer of the inspection of these containments. Main observations follow:

- 0.25 m to 0.30 m (10 to 12 in) deep cracks ranging between 0.05 cm to 7 cm (0.02 to 2.75 in) width. This technique has been used at Crystal River to assess the extent of condition of the concrete containment [1][7]. Figure 6-1 shows a graph of the bay with the impulse response results (red: delaminated; blue: intact) and a picture of the locations where cores were take (red dots: delaminated core; yellow dot: clean core). Note that although the delamination was deep, the cracks were rather wide making it easier to detect the flexural mobility of the delaminated area. The extensive tests performed at Crystal River have shown the adequacy of this technique for that type of delamination.
- 0.10 m to 0.38 m (4 to 15 in) deep cracks with widths of less than 0.03 cm (0.013 in). The cracks encountered at Davis-Besse shield building were thinner and shallower than in Crystal River. This technique was the preferred NDE method for determining the extent of condition after cracks were identified [8]. Again, the technique performed very well and allowed for a 100% testing of the shield wall as shown in tests in Figure 6-2.
- Shallower cracks can also be identified with impulse response as shown in numerous publications, as summarized in [9].
- When a wall is too thick, or the crack too deep, the delaminated structure does not behave like a plate and the reliability of this technique may be compromised.

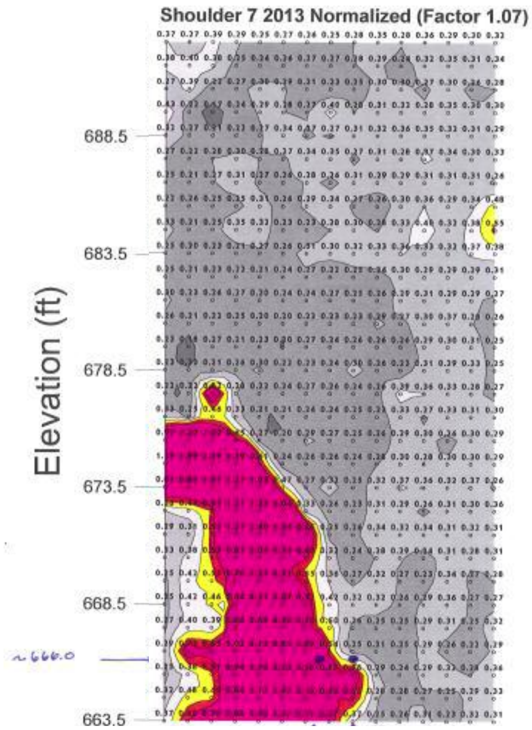
Figure 6-1: Impulse Response Tests in Crystal River Containment Wall



Note: Shaded blue shows non-delaminated area; yellow shows transition zone; shaded red (left) or white (right) shows delaminated area

Left hand side shows the accuracy of the impulse response readings, with red dots representing cores taken showing delamination and green dots representing intact cores. Right hand side shows the widths of the cracks within the hour glass delaminated shape [7]

Figure 6-2: Impulse Response Tests in Davis Besse Shield Building



Note: Grey shows non-delaminated area; yellow shows transition zones; purple shows delaminated areas [8]

6.2 Operator Dependence

Impulse response is a reliable technique. However, operator training is required, albeit it is less necessary than with impact echo.

6.3 Ease of Deployment – Automation

Testing and data collection are performed rather fast compared with other techniques like ultrasound imaging or impact echo. Hence, large areas can be covered in a relatively short time. Impulse response would be an excellent method for application in an automated device. However, the main concern is the size and weight of the impactor, which will be challenging to automate, though not impossible.

7 DEPLOYMENT: AUTOMATION OF NDE INSPECTIONS OF CONCRETE STRUCTURES

The infrastructure in the energy industry includes several types of large, curved vertical structures such as cooling towers, nuclear containments and hydroelectric dams. Inspections of these structures are often performed manually by means of scaffolds. Automating such inspections will reduce time and costs, make them more efficient, increase inspection frequency and reduce safety risks.

The first step in automating large civil infrastructure inspections was to search on other industries, in the US as well as internationally, for devices that could be adapted to this need. For this purpose, EPRI has evaluated different types of technologies and their technology readiness levels, which concluded with the selection of a device that could be perfectly adapted to industry needs. The ideal device should be rugged enough to withstand field use outdoors, have a battery or independent power supply, be able to carry a device for nondestructive tests in concrete, and be able to move over a rough concrete surface.

The device selected, developed by International Climbing Machines, can crawl up curved, vertical concrete structures carrying a payload of approximately 20 kilograms. It can also navigate gaps, seams and obstacles on the surface such as conduit. However, the device identified does not include a positioning system or an NDE device.

A mapping and positioning system is crucial for this application. Again, a search was performed to identify the best available system. Several options were considered, such as a Simultaneous Mapping and Location System (SLAM) and a total station device. Both were mounted in the crawler and their performance was evaluated. Likewise, an NDE device, in this case an air-coupled impact echo, was mounted on the crawler.

A demonstration of the device climbing the face of a hydroelectric dam can be seen in Figure 7-1 and on www.youtube.com/EPRIvideos/. Currently, work is focused on a better integration of the three systems, sensors, crawler and mapping/location system. The vision is to have a system that is flexible enough to accommodate different devices according to the needs for inspection of each concrete structure [5].

Figure 7-1: Concrete Crawler Inspecting a Concrete Dam with an Air-Coupled Impact Echo Sensor and Local Positioning System

8 SUMMARY

The objective of this project was to test nondestructive examination techniques and tools to perform detailed assessments on the structural integrity of concrete containment structures. The primary defects of interest include delaminations and cracking that are of interest to ASME Section XI.

Three techniques were tested: shear wave tomography, impact echo and impulse response. The main parameters studied were the depth of detection, the operator dependence, and ease of deployment. Main conclusions follow:

(1) *Shear wave tomography* appears as a very reliable technique that allows for a detailed imaging of deep defects in concrete. This technique can detect the presence of a delamination and its depth. However, depth determination needs to be calibrated. The method of data collection is rather slow, although the quality of the data is good. This technique seems more suitable for in depth analysis of a structure rather than scanning of large areas.

(2) *Impact echo* is a technique that has the potential to be used for a rapid and automated scanning of large concrete structures. This technique can detect whether the structure is delaminated <u>and</u> the depth of delamination. However, results can be misleading because of multiple reflections when borders, edges, tendons, or other geometry related features are encountered. For that reason, impact echo requires a highly trained operator. ASME should consider collaborating with ACI on the training and certification required for inspecting a concrete containment.

(3) *Impulse response* is a reliable technique that has shown its usefulness in two cases of inspection of large concrete containments in the US. This technique (unlike impact echo) is not suitable to detect the depth of delamination, but can only detect whether the structure is delaminated or not. It can only give an idea of the relative depth of the delamination. Testing with this technique can be accomplished at a faster rate than the other two techniques tested here. Additionally, data processing is rather simple.

This project assessed the ease of deployment of each technique and the potential for automation. In that context EPRI has been working on integrating a device (robot) that could facilitate the inspection of a concrete containment by carrying an inspection device such as the ones analyzed here.

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