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INSPECTION AND MONITORING OF ASR-AFFECTED STRUCTURES AT SEABROOK STATION, NH

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ABSTRACT

Recently, alkali-silica reaction (ASR), one of the common causes of concrete deterioration, was discovered at the NextEra Energy Seabrook Station nuclear power plant (Seabrook Station), 25 years after plant construction. Seabrook Station initiated an action plan and retained Simpson Gumpertz & Heger Inc. (SGH) to investigate and evaluate the implications of the ASR distress on the physical properties of the concrete material and the structural performance of the existing structures.

This paper presents a comprehensive ASR field investigation and assessment approach for the Seabrook Containment Enclosure Building (CEB) wall, which included unique site access for visual and digital imaging as well as crack mapping measurements on the concrete surfaces. The results from the field investigation are combined with laboratory evaluation to estimate the material properties of the ASR-affected concrete to classify the CEB walls into zones of different ASR severity with associated reduced material properties. The results were used for structural analysis and modeling. This paper also describes a long-term monitoring program currently being used to monitor additional ASR-affected structures for continued expansion within Seabrook Station, primarily through cracking index (CI) and expansion measurements.

The customized inspection and analysis program used at Seabrook Station is based on the conceptual approaches used in available guidelines and publications for highway structures, modified for the larger concrete thickness, reinforcement ratio, gravity loads, and design exposures of nuclear plants.

INTRODUCTION

In the summers of 2010 and 2011, Simpson Gumpertz & Heger Inc. (SGH) conducted petrographic examinations and physical testing on concrete core samples extracted from five structures within the Seabrook Station as part of a condition survey. The examinations and testing indicated varying degrees of alkali-silica reaction (ASR) distress within the concrete that was likely contributing to visually observed surface cracking. The ASR distress was also correlated to a reduction in the concrete modulus of elasticity as determined in laboratory testing.

Subsequently, NextEra Energy Seabrook, LLC (NextEra) retained SGH to investigate the cracking of the containment enclosure building (CEB) wall (one of the five structures from which core samples were extracted and tested) and to evaluate the implications of the ASR distress.

What is Alkali-Silica Reaction (ASR)?

ASR was first recognized in 1940 publications by Thomas Stanton. Since its discovery, ASR has been reported to affect various structures around the world. Although New England concrete aggregates were thought to have been of generally high quality and ASR-free, reports of ASR in New England are becoming more frequent as concretes with slowly reactive New England aggregates age and newer concretes use less reliable aggregate sources.

Alkali-silica reaction (ASR) is one of the most-common causes of concrete deterioration and occurs when certain types of silica-containing reactive aggregates (typically strained quartz, chert, and greywacke) react with the hydroxyl and alkali ions in the concrete to form a silica gel. The gel absorbs significant quantities of water causing it to swell and crack the aggregates and surrounding cement paste. The gel can then migrate into the cracks where it can absorb additional water and continue swelling and causing additional cracking and interconnection of the cracks. ASR will continue as long as the concrete contains a sufficient supply of alkalis and has a relative humidity above approximately 85%. Moisture fluctuation can exacerbate the signs of distress.

Effect of ASR Distress on the Physical Properties of Concrete

ASR-affected concrete deterioration is primarily characterized by internal expansion leading to an interconnected network of cracks. This deterioration affects physical properties of concrete including compressive and tensile strength and the modulus of elasticity. ISE (1992) published physical properties measured on unrestrained concrete specimens for various amount of free expansion as summarized in Figure 1 below.

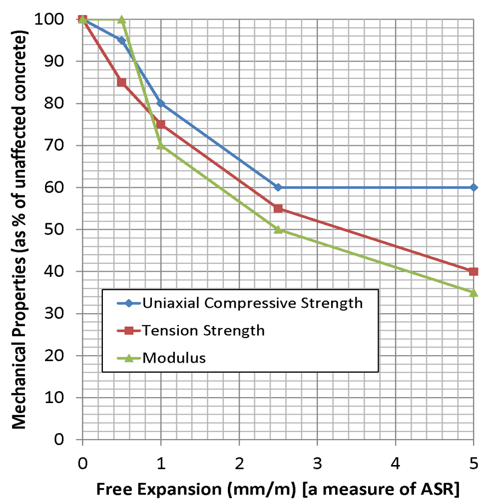


Figure 1. Residual mechanical properties vs. free expansion, from ISE (1992), Table 4.

Guidelines on Assessment and Management of ASR-affected Structures

Unlike other concrete deterioration processes such as cyclic freeze-thaw deterioration or corrosion of reinforcing bars, ASR cannot be easily treated or mitigated because the three conditions, alkali (from cement), reactive silica (from aggregates), and moisture (from rain or groundwater), are typically present in the concrete and difficult to eliminate after construction. However, Typical ASR-induced concrete deterioration is a gradual process that changes the properties of concrete over time. A concrete structure undergoing ASR can often still serve its intended purpose and design functions; therefore, many owners initiate programs to assess and manage ASR-affected structures.

Protocols for managing the ASR are not well developed, but available options range from long-term structural-health monitoring and evaluation to structural retrofits or structure replacement. Two primary guidelines follow:

- FHWA-HIF-09-004 (2010) – This report provides a basis for the correlation of visible distress and deterioration in concrete structures to ASR, prescribes CI and cracking criteria to identify the extent of the ASR distress, and describes the reductions of mechanical properties of concrete affected by ASR. The report is based on studies of highway structures.

- ISE (1992) – This document provides standardized classifications and tables to assist the user in rating the effects of ASR distress and in developing a management plan. This document provides some of the basis for FHWA-HIF-09-004 (2010).

According to both documents, the CI can be used to estimate the expansion to date in the ASR-affected concrete. As described in these References, the CI is obtained by measuring and summing the crack widths along a set of lines drawn on the surfaces of a concrete member. Both documents also describe an expansion monitoring method that works in concert with the CI to allow for periodic in situ monitoring of expansion, providing a comparative and quantitative rating of any future ASR-induced expansion or deterioration.

Both documents were developed to provide for diagnosis and prognosis for ASR distress in transportation structures and typical building or parking structures. Because critical nuclear structures typically contain concrete members with larger thickness, dense reinforcement ratio, large compressive loadings, and various exposure conditions (radiation, soil, etc.) which may change the relative scale of the physical signs of ASR distress, the investigation at Seabrook Station recognized that the numerical values described in the documents may not be applicable to critical nuclear structures.

Identification of Potentially Reactive Aggregate in Construction of Seabrook Station

Since the discovery of the ASR in the 1940s, various test methods to identify potentially reactive aggregate have been developed. At the time of construction of Seabrook Station, 1977 through 1983, multiple tests were routinely performed to identify potentially reactive aggregate. These tests include: ASTM C289 – Potential Alkali-Silica Reactivity of Aggregates (Chemical Method); ASTM C227 – Potential Alkali Reactivity of Cement-Aggregate Combinations (Mortar-Bar Method); ASTM C342 – Potential Volume Change of Cement-Aggregate Combination (withdrawn 2001); and ASTM C295 – Petrographic examination of Aggregate for Concrete. The complexity inherent in diagnosing ASR for slow and rapid reacting aggregates diminished the reliability of early testing, and the industry has since learned that both ASTM C227 and C289 are not accurate predictors of expansion for slow reactive aggregates and are considered useful only if used in combination with other more reliable tests [ACI 221, Farney et al. 1997]. Unfortunately, slowly reactive coarse aggregates were used in the concrete of Seabrook Station. Since that time, other more reliable tests such as ASTM C1260 – Potential Alkali Reactivity of Aggregates (Mortar-Bar Method), ASTM C1293 – Determination of Length Change of Concrete Due to Alkali-Silica Reaction, and ASTM C1567 – Determining the Potential Alkali-Silica Reactivity of Combinations of Cementitious Materials and Aggregate (Accelerated Mortar-Bar Method) – have been developed and put into use.

Work conducted in Seabrook Station by SGH

Since November 2011, SGH has conducted the following work at Seabrook Station:

- Immediate ASR assessment of the CEB: Development and implementation of ASR field investigation and associated evaluation of ASR on Seabrook Station CEB wall.
- Long-term ASR monitoring: Development and implementation of a program to monitor ASR-affected structures for continued degradation.

IMMEDIATE ASR ASSESSMENT OF THE CEB

The Seabrook Station CEB is a partially buried structure that surrounds the Containment Building (CB), creating the Containment Enclosure and Ventilation Area (CEVA) in the annulus between the structures. The CEVA space is approximately 4 ft-3 in. wide and provides for an enclosed environment that can be monitored and controlled. When ASR distress was identified on the concrete core samples from the CEB wall, Seabrook authorized SGH to conduct an immediate ASR field investigation and assessment of the buried regions of the wall, where the observed cracking was located.

The CEB is an approximately 229 ft tall, 164 ft diameter cylindrical structure topped with an integral dome-shaped roof. The wall and roof thickness of the CEB varies by elevation, with the thickest section (3 ft) occurring at the base. The CEB structure consists of conventionally reinforced concrete with more-densely spaced reinforcement (a reinforcing ratio of approximately 2.5%) near the lower portion (below grade) of the wall.

The lowermost 50 ft portion of the structure is below the exterior grade and was constructed in an excavation within the native granite. The structure was not cast directly against the granite but was instead formed on both surfaces, with the formwork later removed and the exterior portions of the below-grade structure backfilled with concrete fill. A waterproofing system was installed on the exterior of the CEB at the time of construction.

Field Investigation – Inspection Plan

SGH visited Seabrook Station from 3 November through 29 December 2011 to conduct a field investigation of the lowermost 50 ft of the interior surface of the CEB wall and of other structures where core samples were previously retrieved and tested. The field investigation included the following tasks:

- *Overall Visual Assessment*. The objective of the visual survey was to provide data on the overall nature and extent of any distresses and deterioration affecting the concrete structure and to identify areas of different performance levels for further characterization. The visual survey included areas readily accessible from the ground, platforms, or scaffolding.
- *Digital Image Survey*. To survey the 50 ft high portion of the CEB wall, where installation of scaffolding was impractical, SGH designed a digital image system to capture features of interest (distresses and deterioration) on the concrete surface and to produce an overall image of the entire area over the full 50 ft height and the full circumference. This system included an extendable mast set on a mobile stand, a high-resolution digital SLR camera with an ultra-wide-angle lens, and compact fluorescent lights mounted on the top of the mast stand to image the interior face of the CEB wall. A system of linear lasers was used to project vertical lines on the CEB wall to allow the individual photos to be accurately "stitched" together during later post-processing to produce the overall image of the interior face of the CEB wall. Figure 2 shows the camera mast stand and linear lasers in use.

Figure 2. Digital Image System with Camera Mast Stand and Linear Lasers

- *Detailed Visual Survey and Cracking Index (CI) Measurements on the CEB Wall*. A total of fifteen representative areas on the CEB wall were selected for detailed visual survey, including the area where cores had been retrieved and tested previously. At each location, the concrete condition was documented, CI measurements were conducted using an optical magnifying comparator at each reference line of six interconnected 10 in. by 10 in. square reference grids on the concrete surface, and gage points were installed at the corners of the reference grids to allow baseline expansion monitoring measurements to be made to allow for future expansion monitoring.
- *Detailed Visual Survey and Cracking Index (CI) Measurements on Four Additional Structures*. Detailed visual survey and CI measurements were conducted at four additional structures that were previously cored because of cracking suggestive of ASR in order to provide a correlation between physical tests of the samples and the surveys. Expansion-monitoring baseline measurements were also taken to provide a basis for future monitoring.

Field Investigation – Overall Condition of CEB Wall

The interior concrete surface of the CEB wall exhibits signs of distress and deterioration, including cracking, efflorescence, water staining, and leakage. The visual assessment and digital image survey provide the overall information regarding the condition of the CEB wall:

- There are no visual indications of uneven or differential concrete swelling, or of distress such as relative movement, distortion, or excessive deflection.
- There is no concrete spalling or delamination indicative of reinforcement corrosion.
- The concrete surface exhibits pattern-cracking, random cracking, vertical cracking, and localized diagonal cracking.
- Within the lowermost 10 to 12 ft of the CEB wall, various severities of cracking, efflorescence, and moisture staining are present. The portions of the wall more than 10 ft above the foundation appear to be in generally good condition, with little cracking.
- The cracks are typically very narrow and difficult to see without close-up examination and additional lighting. The majority of the cracks observed during the detailed visual survey were very narrow (0.003 in. or less); frequently, the cracks under the efflorescence deposits were very narrow (0.002 in.) or not visible to the naked eye after cleaning.

Laboratory Testing – Scope of Work and Summary of Finding

To provide a correlation between the visual survey information and measured properties, SGH conducted laboratory testing on multiple core samples that were retrieved from the walls of the CEB and the four additional structures (Bravo Electrical Tunnel, Diesel Generator Building, EFW Pump House, and RHR Vault) where the visual surveys and CI were conducted due to suspected ASR distress on the concrete surfaces of these structures. The laboratory testing included petrographic examinations and associated petrographic ASR visual rating on twelve samples, damage rating index (DRI) testing on twelve samples, compression testing on twenty samples, and modulus of elasticity testing on twenty samples.

The petrographic ASR visual rating system developed by SGH provides a numerical 0 (little to no ASR) to 6 (very severe ASR) scale based on a modified “best practice” procedure initially developed at the Building Research Establishment [BRE] in the UK. The DRI method was developed by Dr. Grattan-Bellew in the 1990s and is used to quantify the degree of ASR-related damage by counting the number of typical petrographic features of ASR on polished concrete sections.

The specific details for each test (petrographic examination and petrographic ASR rating, DRI, and compressive and modulus testing), findings and test results will be discussed and presented in a separate article. The findings from the laboratory testing used in ASR evaluation of the CEB wall are summarized below:

- The severity of ongoing ASR varies, with petrographic ASR ratings ranging from 0 to 4.
- ASR distress was more severe near the exposed face than at the center of the wall thickness in two of the three cores.
- Compressive strengths range from 5,500 psi to 8,590 psi. All tested cores achieved strength levels higher than the nominal design strength of 4,000 psi for the CEB structure and 3,000 psi for the other structures.
- Moduli of elasticity range from 1.93 x 10^6 psi to 4.4 x 10^6 psi, with all cores exhibiting a reduction in modulus of elasticity as compared to expected values calculated using the equations provided in ACI 318. The ratio of measured-to-expected modulus ranged from 0.43 to 0.94. The degree of reduction of modulus is in general agreement with the severities of ASR distress and associated petrographic ASR rating.

Evaluation Procedure and Results – Overall Evaluation Approach

The FHWA-HIF-09-004 (2010) and ISE (1992) documents do not provide a codified method to analyze the effects of ASR on a structure. Rather, they provide a stepwise means of obtaining information and relating the results of different tests to reach a recommendation for further action. The evaluation of the CEB followed this general framework, using the overall visual survey to obtain an overview of the CEB condition, using the camera-based visual survey to gather a large amount of high-resolution data from the entire inside face of the CEB to group portions of the CEB walls into categories, and then using the information from the detailed survey areas, CI measurements, and other information sources to interpret and "calibrate" the camera-based visual survey categories. The evaluation approach is illustrated as a flowchart in Figure 3 and described in the following sections.

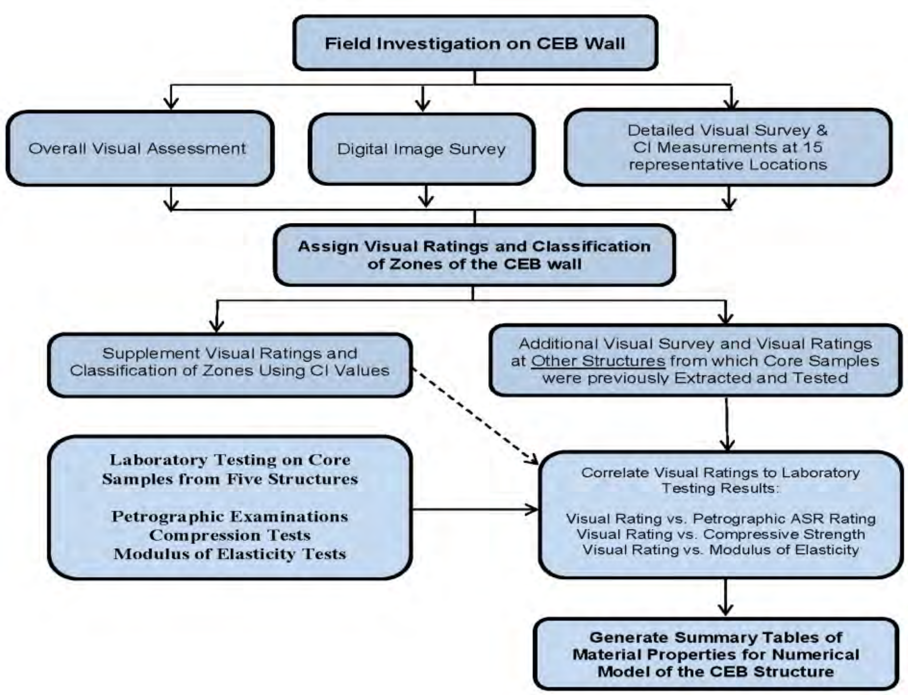


Figure 3. ASR Overall Evaluation Approach Flow Chart

Evaluation Procedure and Results – Visual Ratings and Classification of Zone to the CEB Wall

Based on overall condition of the CEB wall, SGH developed a five-tiered visual rating scale to classify the degree of visible distress in the surveyed areas. The scale includes elements of the classification system for "Low," "Medium," and "High" severity cracking, expansion, discoloration, and exudation as described in FHWA (2010). In the scale, Ratings 1 through 4 describe increasing levels of distress characteristic of ASR (cracking, efflorescence, and evidence of moisture/active leakage). Rating 5D is specified for areas with a diagonal cracking pattern that is likely unrelated to ASR. For illustration, examples of Visual Rating 1 and 4 are shown in Figure 4. SGH developed a map of the entire CEB wall that is categorized by visual ratings/zone, as shown in Figure 5.

Figure 4. Examples of visual rating of ASR distress on CEB Wall (Left: 1; Right: 4)

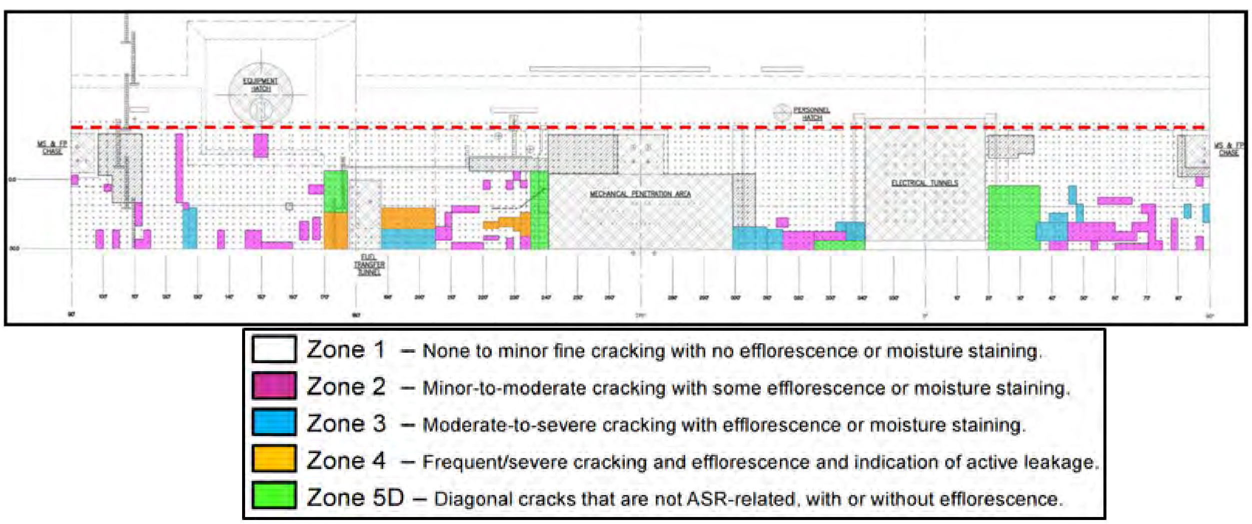
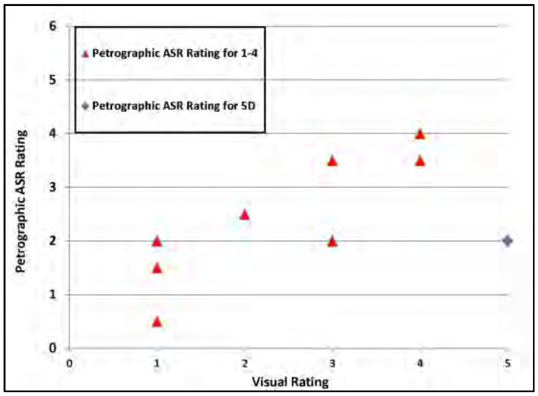


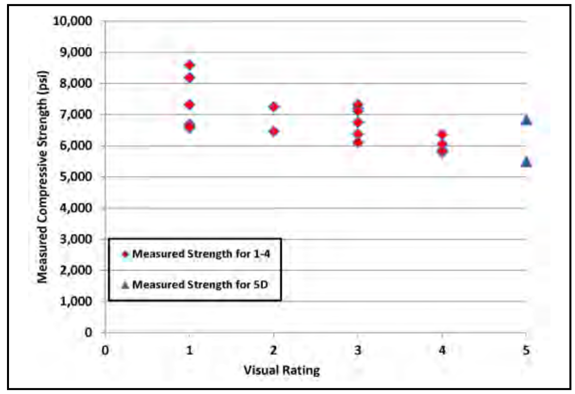
Figure 5. Visual Rating Map – CEB Wall Full Circumference

a. Correlations between Visual Rating and Laboratory Testing Results

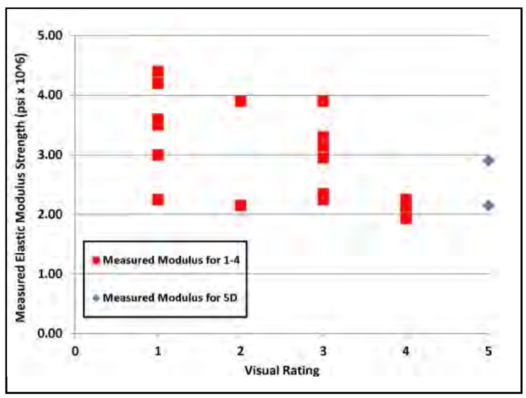
The detailed visual surveys conducted at the locations where cores were taken allowed a comparison of the visual ratings to the petrographic ASR ratings, modulus of elasticity, and compressive strength of the core samples. The comparisons in Figure 6 show good correlation between our visual rating (defined in Figure 5) and each of the concrete tests. The measured compressive strength and modulus of elasticity decrease with increasing severity of observed ASR-related distress on the CEB wall, which is in agreement with the ISE (1992). The scatter in these data can be attributed to the limited availability of core samples from all structures and, in particular, from the CEB Wall.



(a) Visual Rating vs. Petrographic ASR Rating



(b) Visual Rating vs. Compressive Strength



(c) Visual Rating vs. Compressive Strength

Figure 6. Correlations between SGH Visual Rating and Laboratory Testing Results

SGH correlated visual ratings in the CEB with visual ratings at locations where cores were tested from the CEB and four other structures to estimate ASR-affected materials properties in the CEB. This method was further justified by the use of petrographic examinations that indicated similar concrete mixture proportions and similar aggregate geologies and reactivity for the core samples collected from all five structures. This approach has several limitations.

- Test data comprises a small total sample size with limited results from the CEB wall and consequently cannot be used to provide high statistical confidence.
- Correlation between the tested concrete and the concrete throughout the CEB is established purely on the qualitative visual rating of the severity of ASR distress.
- CI and crack width values measured at the CEB wall were very different from those at other Seabrook structures (likely due to the higher quantity of reinforcing steel in the CEB wall) and could not be used to supplement the visual rating.

LONG-TERM MONITORING OF ASR-AFFECTED STRUCTURES AT SEABROOK STATION

Following the initial onsite field investigation, NextEra retained SGH to conduct long-term monitoring of ASR-affected structures at Seabrook Station using periodic CI measurements and expansion monitoring measurements to provide for relatively high-accuracy comparative and quantitative rating of any future ASR induced expansion/deterioration. NextEra selected a total of twenty-six ASR Monitoring Locations from various structures. These locations exhibited some of the highest ASR distress at Seabrook Station, based on CI values from a set of 131 locations measured by others, and included both exterior (exposed) and interior surfaces of various structures within Seabrook Station. These measurements have been ongoing since 2011.

Figure 7 illustrates an example of the crack widths at an ASR Monitoring Location. Figure 8 shows the measurement of the distance between gage points using the mechanical stain gage.

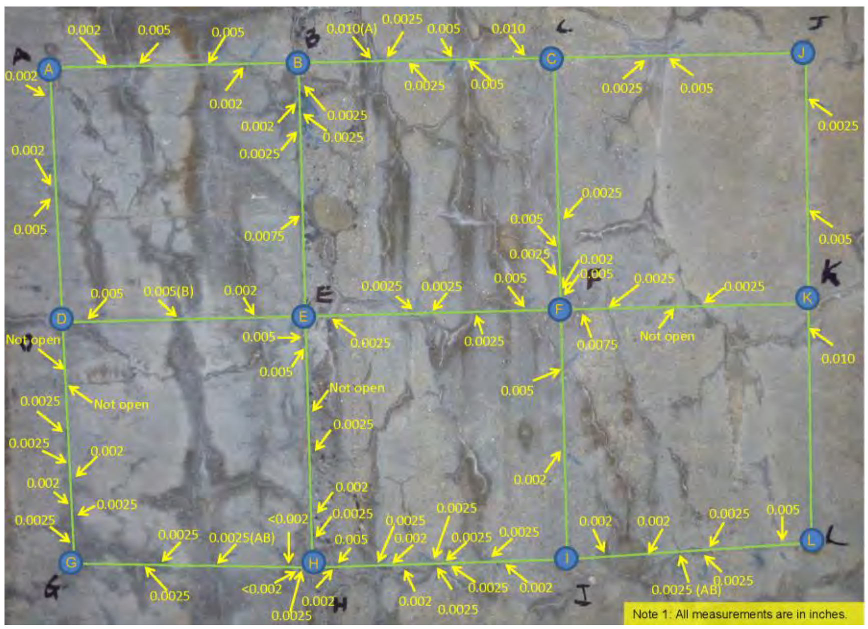


Figure 7. Crack widths and the crack location at an ASR Monitoring Location

Figure 8. Measurements with Mechanical Strain Gage

Frequency of Measurements and Preliminary Results

At present, the CI and expansion measurements are scheduled to be conducted twice each year. After 3 years, the frequency of measurements will be re-evaluated.

Preliminary results from the twenty-six ASR Monitoring Locations, both CI values and length-changes, indicate no to very slow progression of ASR-related expansion or cracking after six months to 1 year of monitoring. The long-term ASR expansion cannot be quantified at present due to the short monitoring period.

CONCLUSIONS

- A comprehensive ASR investigation and assessment approach on concrete nuclear structures was successfully established. The change in concrete mechanical properties due to ASR distress was quantified and can be used for structural analysis and modeling.
- This approach builds upon available guidelines for managing ASR-affected structures and customizes them to account for the different types of structures in the nuclear industry.
- Preliminary results from the short-term ASR monitoring program in structures at Seabrook Station show no change in crack widths or crack width variations that are within the tolerance of our measurement methods.
- Long-term monitoring will be used to evaluate the structures for ongoing ASR.

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