Transactions, **SMiRT-22**
San Francisco, California, USA - August 18-23, 2013
Division V – Modeling, Testing and Response
Analysis of Structures, Systems and Components

COMPREHENSIVE ASSESSMENT AND IMPACT OF ALKALI-SILICA REACTION ON THE SEISMIC RESPONSE OF A NUCLEAR STRUCTURE

Said Bolourchi [1], Jesse L. Beaver [2], Theodore Vassallo [3]

[1] Senior Principal, Simpson Gumpertz & Heger Inc., Waltham, MA
[2] Senior Project Manager, Simpson Gumpertz & Heger Inc., Waltham, MA
[3] Principal Engineer, NextEra Energy Seabrook Station, Seabrook, NH

ABSTRACT

Many nuclear plant structures, including those at Seabrook Nuclear Power Station, were built more than 25 years ago with concrete mixes that were either not reviewed for Alkali-Silica Reaction (ASR) or were reviewed using tests that do not identify slow-reacting aggregates. Some nuclear structures were constructed with concrete mixes that included reactive aggregates. These concrete structures are at risk for ASR, with higher likelihood when submerged or exposed to frequent wetting or high relative humidity. ASR-impacted concrete will experience cracking that affects the concrete elastic modulus and impacts the distribution of static and dynamic forces.

This paper presents a comprehensive method that was used to assess the impact of ASR-induced degradation on the structural response and design of a containment enclosure structure that is partially buried and below the water table. The process included materials evaluation, site inspection, distressed condition measurement, determination of distressed concrete properties and their use in conducting a simplified seismic analysis, and detailed three-dimensional finite element analysis for evaluating structural safety. The evaluation classified degradation by localized areas to analyze the structure condition. Overall dynamic responses of the structure were not significantly altered, though the concrete modulus of elasticity had reduced to as much as 57% of design values. Detailed static analysis showed that loads are redistributed moderately from localized areas showing ASR related distress to areas showing little or no impact of ASR. Calculations show the original design of the structure had sufficient margin of safety to meet the requirements with redistribution of loads.

INTRODUCTION

Reinforced concrete buildings and other structures for nuclear facilities, such as at Seabrook nuclear power station, are analyzed for seismic loadings using concrete stiffness, and designed based on concrete strength parameters. The analysis and design includes the implicit assumption that the concrete mechanical properties will vary little throughout the service life, or in the case of strength, may be assumed to increase somewhat under ideal conditions during service. Consequently, reduction in concrete strength or stiffness could present concerns for the structure design adequacy.

Concrete quality is monitored during construction by testing for compression strength at 28 days to show compliance with the design assumptions. However, beyond construction quality testing, strength is typically no longer assessed by physical testing. This approach can be problematic when the concrete service conditions include exposure to environmental or other phenomena that reduce the concrete mechanical properties during the aging process. When these phenomena are present for critical structures, the reduced mechanical properties should be used to evaluate any changes to the structure design basis. For nuclear structures, the seismic design basis includes both the static and dynamic responses of the building or structures.

There are many serviceability and environmental phenomena that impact concrete properties during aging such as creep, delamination, cracking, freezing/thawing, and alkali-aggregate reactions (AAR) including ASR. The effects of environmental degradation on concrete durability have been studied for bridges, dams, and other structures; however, the impact on nuclear structures has not received similar attention or investigation, even though their safety critical function clearly warrants thorough review of all possible degradation factors.

ASR is one of the most common causes of concrete deterioration in older concrete structures, and occurs when certain types of silica-containing reactive aggregates react with the hydroxyl and alkali ions in the concrete to form an expansive silica gel. After formation, the gel absorbs water, causing it to swell and cause propagation of cracks within the aggregates and the surrounding cement paste. The gel then migrates along the existing cracks, where it absorbs additional water causing additional swelling and cracking, resulting in interconnection of the cracks ACI (2008). ASR will continue as long as the concrete contains a sufficient supply of alkalis, reactive material, and a relative humidity above approximately 80%, ACI (2008). Since its discovery of ASR by Thomas Stanton, ACI (2008), it has been reported to affect various structures around the world. Recently, ASR has been reported in concrete structures at Seabrook Station nuclear plant, in accordance with the plant's Corrective Action Program. ASR has also been detected in the Containment structure concrete at the Tihange-2 nuclear plant, FANC (2013).

Empirical equations have been developed to estimate the concrete strength as a function of time, ACI (1997). In order to obtain the aged concrete properties, the empirical equations may be used to estimate the impact of aging and environmental factors. However, these equations cannot accurately describe site-specific materials and conditions. The preferable method for assessing degraded and aged properties of concrete is to extract and test concrete cores from the structure. To evaluate the impact of ASR at Seabrook nuclear power station, the aged concrete properties are evaluated based on performing a series of visual inspections, monitoring the surface cracking of ASR impacted regions, and correlating the visual rating of aged concrete to the properties of cores from other structures constructed using the same materials and subjected to the same environmental conditions. The aged concrete properties are used to prepare models that are used for two-dimensional (2D) dynamic and three-dimensional (3D) static finite element analyses to evaluate the impact of ASR on the seismic performance of the containment enclosure building (CEB) at the Seabrook nuclear power station.

The complete process used to assess, evaluate, and manage ASR impacts to concrete structures of the nuclear facility includes:

- Obtain limited concrete cores from the safety critical containment enclosure building (CEB) and test for mechanical properties of the concrete.
- Conduct visual inspection of the entire surface of the CEB below grade, and classify sections using the system of visual ratings.
- Obtain concrete cores from other structures exhibiting ASR related distress for additional testing of concrete mechanical properties.
- Relate the visual signs of distress on the other structures to the mechanical concrete properties, using the same system of visual ratings used for the CEB.
- Assign concrete material properties to zones of the CEB, using the correlation of the visual ratings and the mechanical properties of the concrete.
- Create 3D finite element models (FEMs) of the CEB with design properties and with ASR impacted properties.
- Create equivalent stick models with elements' stiffnesses and eccentricities based on 3D FEM.
- Calculate the dynamic responses of CEB using the stick models and apply the accelerations as seismic loading to the 3D FEM along with non-seismic loadings.

- Evaluate the structural design of the CEB using loads that are redistributed due to the ASR-impacted zones.
- Create a system to monitor the concrete for further degradation from ASR and conduct regular inspections.

STRUCTURAL DESCRIPTION

The Containment Enclosure Building (CEB) is located at Seabrook Station in Seabrook, New Hampshire. The CEB surrounds the perimeter and roof of the Containment Building (CB), creating the Containment Enclosure and Ventilation Area (CEVA) between the structures. The CEVA is an approximately 4 ft-3 in. wide space that represents an enclosed environment that can be monitored and controlled. Construction of Seabrook Station was completed in 1983.

CEB is a cylindrical reinforced concrete wall, 228 ft tall, with an inside diameter of 158 ft and closed at the top with a 1 ft-3 in. thick hemispherical concrete dome (Figure 1). The wall thickness varies from 3 ft-0 in. at the base to 2 ft-3 in. from EL -11 ft to EL 40 ft, and 1 ft-3 in. above EL 40 ft. The wall is supported on a 10 ft thick concrete base slab. The top of the base slab is at EL -30 ft, 50 ft below finished grade, which is at approximately EL 20 ft. The bedrock surface is at EL 0. The lower portion of the CEB structure is below the exterior grade and was constructed in an excavation into granite bedrock. The structure was not cast directly against the granite, but was instead formed on both surfaces. A butyl rubber waterproofing membrane system was installed on the exterior of the CEB concrete walls at the time of construction and the exterior portions of the below-grade structure were backfilled with nonstructural concrete fill. The structure consists of conventionally reinforced concrete with very close spacing and layout of reinforcing bars (two to three layers of #9 to #14 at 6 to 12 in.), which is significantly more reinforced as compared to typical building or bridge structures.

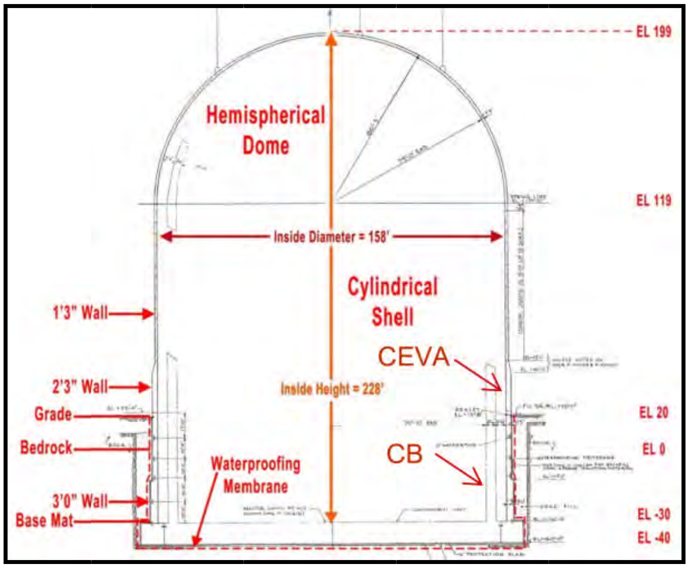


Figure 1. Seabrook Station Containment Enclosure Building - Cross-Section

The CEB has several large openings (penetrations) through the lower elevations of the cylindrical wall. Access into the CEVA is available into three annuli between the penetrations. Figure 2 shows an exploded view of the CEB with the three annulus locations along with the significant penetrations, such as the mechanical penetration that is called out.

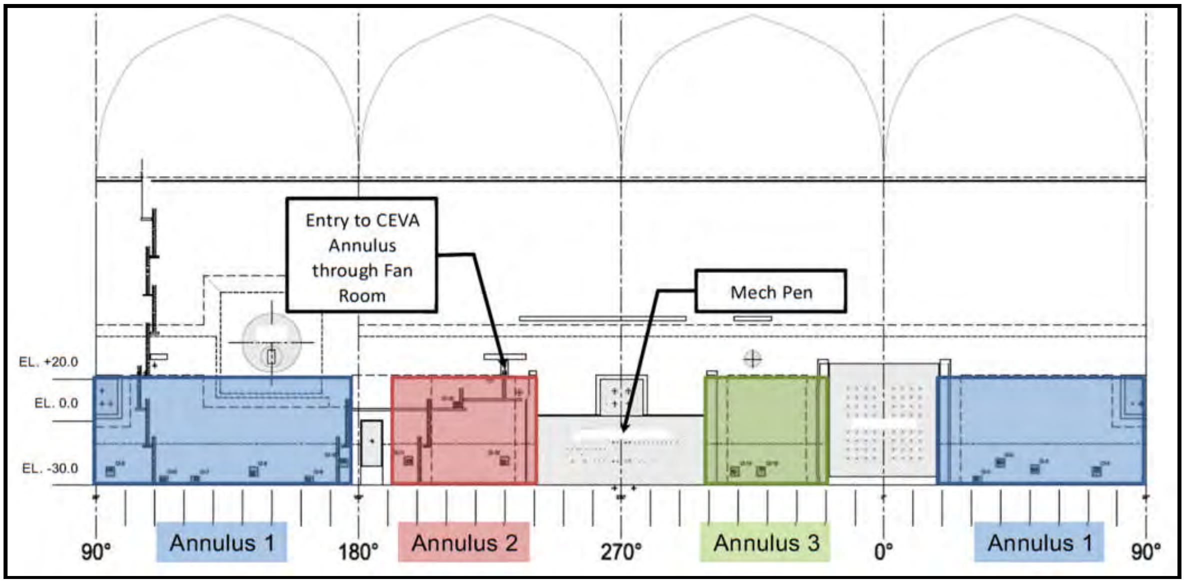


Figure 2. Seabrook Station Containment Enclosure Building - Exploded View

CONCRETE PROPERTIES

Alkali-silica reaction (ASR) is one of the two recognized types of alkali-aggregate reaction and is a common cause of concrete deterioration. ASR occurs when silica-containing reactive aggregates react with the hydroxyl and alkali ions in concrete to form silica gel. The gel absorbs water, causing it to swell and crack aggregates and cement paste, allowing openings for additional expansion. Since the discovery of the ASR in the 1940s, varies test methods to identify potentially reactive aggregate have been developed. At the time of construction of Seabrook Station in 1983, multiple test methods were routinely performed to identify potentially reactive aggregate sources; however, the concrete industry has since learned that some of these test methods were not accurate or reliable for identifying slow-reacting aggregates like those used to construct Seabrook Station.

After identification of orthogonal surface cracking patterns in the concrete that are indicative of ASR, preliminary materials testing was conducted to evaluate the condition of the concrete structures at Seabrook Station. This preliminary testing included limited petrographic examination of concrete cores. The preliminary testing indicated that the concrete contained reactive coarse aggregate and that the level of ASR distress varied by location. These findings led to more extensive investigations.

FHWA (2010) provides a systematic procedure for identification of the presence of ASR, quantification of the level of distress, and strategies for its management in conventional highway structures. The FHWA procedures include Level 1 routine visual inspection, Level 2 preliminary investigation, and Level 3 detailed investigation. ASR distress is then quantified based on damage levels seen in many transportation structures; however, these damage levels are not applicable to typical nuclear structures.

Differences between transportation structures and nuclear structures, including concrete thicknesses, reinforcement ratios, exposure conditions, typical compression loadings, and the availability for destructive sampling, prevented direct application of the FHWA procedures and led to their modification for application to nuclear structures. FHWA cracking index (CI) measurements were not directly applicable for CEB due to the unusually high near-face reinforcement ratios. Therefore, a new rating system was established based on the visual survey and laboratory test results that we conducted for Seabrook Station. The rating system accounted for the different levels of concrete cracking and mechanical property deterioration rates in concrete below the water level. Procedures were established to (1) visually assess the CEB condition and classify the level of distress into zones with ASR distress ratings and (2) conduct physical testing and petrographic examination on concrete from other structures than those under inspection for correlation of mechanical properties with visual distress ratings.

Visual inspection of ASR impacted concrete surfaces

Visual inspection included overall visual assessment of the CEB, digital image survey of the full internal surface of the CEB wall located below grade (over a 50 ft height), and detailed visual survey with cracking index (CI) measurements on the portion of the CEB wall located below grade, as well as on four additional concrete structures at Seabrook Station. The inspection process is described in a companion paper also submitted to SMiRT-22, Jiang et al (2013). The surveyed surface of the CEB was categorized into five zones of visual distress ratings as shown in Figure 3. Zones 1 through 4 reflected ASR distress, while Zone 5 included distress primarily unrelated to ASR. Representative photographs of concrete representing Zones 1 through 4 are shown in Figure 4.

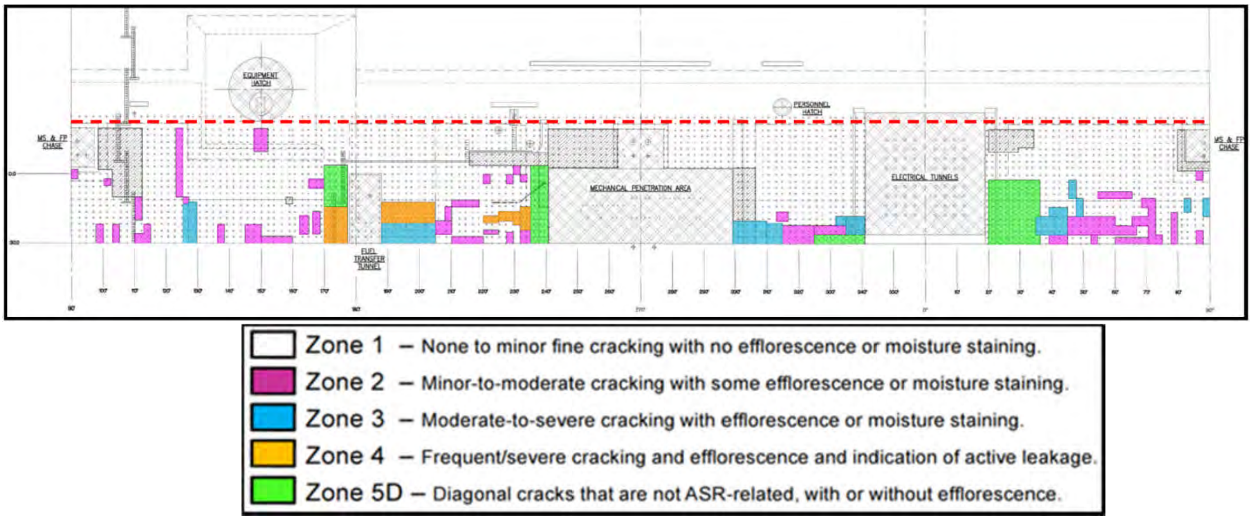


Figure 3. Visual Rating Map – CEB Wall Full Circumference

☐ Zone 1

🟪 Zone 2

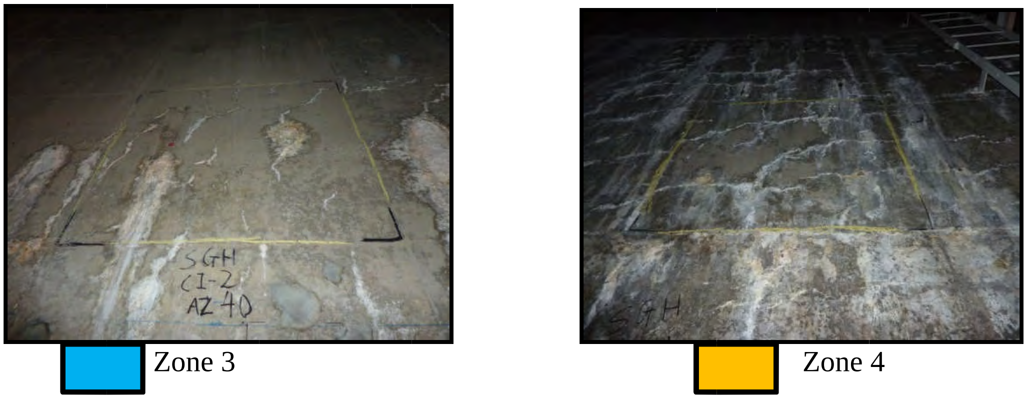


Figure 4. Photographs of ASR Visual Rating Zones

Testing and examination of concrete

The second inspection step included mechanical testing and petrographic examination of the concrete. Due to the safety-critical function of the CEB, limited concrete cores were collected. However, cores were also collected from four other locations at Seabrook Station. All core locations were visually rated, using the same rating scale used for the CEB. Petrographic examination was conducted to (1) evaluate presence and level of aggregate (ASR) reactivity and (2) to compare the aggregate type and degree of ASR related distress in other structures at Seabrook Station with that observed in the CEB.

The petrographic examination showed that the coarse aggregates used for Seabrook Station concrete were reactive and that some of the aggregates used in other concrete structures were similar to those used in the CEB concrete, and had the same potential, but variable degrees of ASR. The fine aggregate was determined to be non-reactive. The examination also evaluated the level of ASR distress at the exposed surface, as compared to the level of ASR distress within the wall thickness. This evaluation demonstrated that the damage, as quantified using a damage rating index (DRI), is greatest at the exposed surface. The petrographic examinations confirmed the presence of ASR and justified use of a surface visual distress rating as a valid indicator of ASR distress levels in nuclear structures. Figure 5 shows a photograph of a Seabrook Station concrete aggregate with ASR related distress features and a DRI plot of ASR features for a set of three core samples removed from the CEB. The DRI plot shows greater ASR damage at the exposed (outer) surfaces within the CEVA.

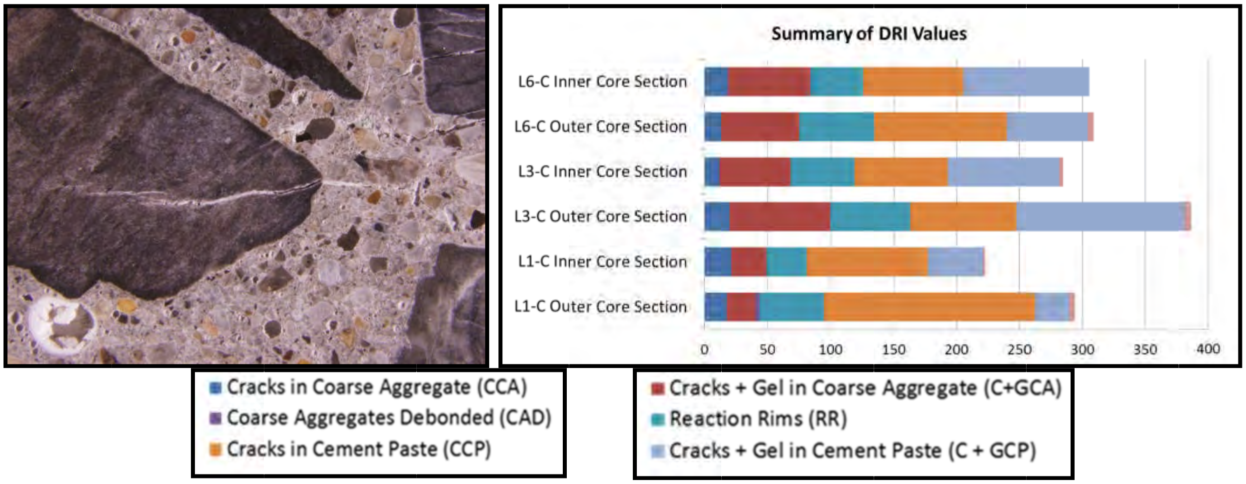


Figure 5. Illustration of Cracks and Gel in a Coarse Aggregate Sample and DRI Summary based on petrographic examination of concrete Cores from Seabrook Station

ASR damage has been shown to reduce the concrete tensile strength, concrete compressive strength, and concrete stiffness, and negatively impact the quality of bond between reinforcement bars and the surrounding paste structure. ISE (1992) published physical properties measured on unrestrained concrete specimens for various amounts of free expansion that showed a reduction in mechanical properties with increasing ASR damage. Laboratory testing on Seabrook Station cores included compressive strength and modulus of elasticity testing. Figure 6 provides the tested strength and stiffness versus the visually rated concrete surface condition that illustrates good correlation between the visual rating and the mechanical properties. These findings justify the use of visual rating to estimate reduced mechanical properties for the CEB concrete.

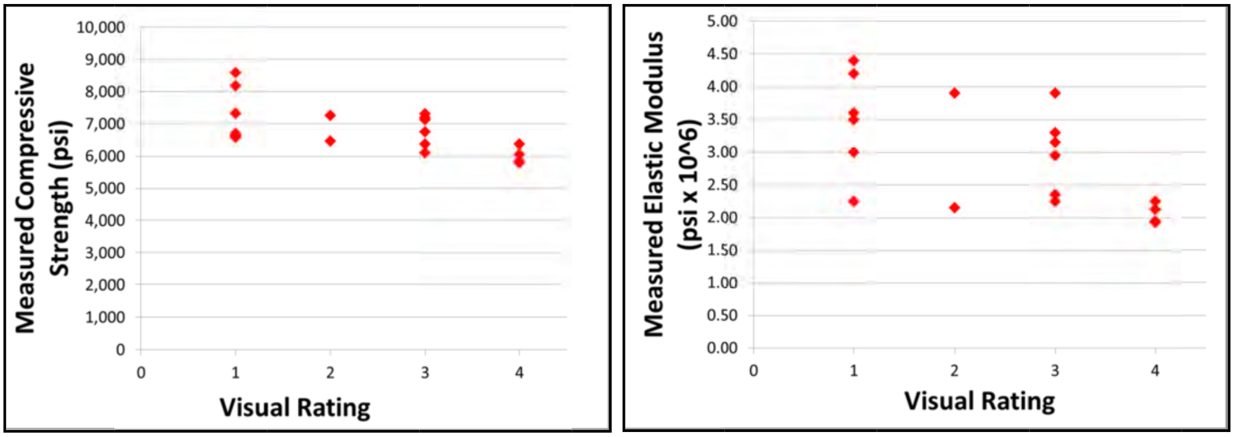
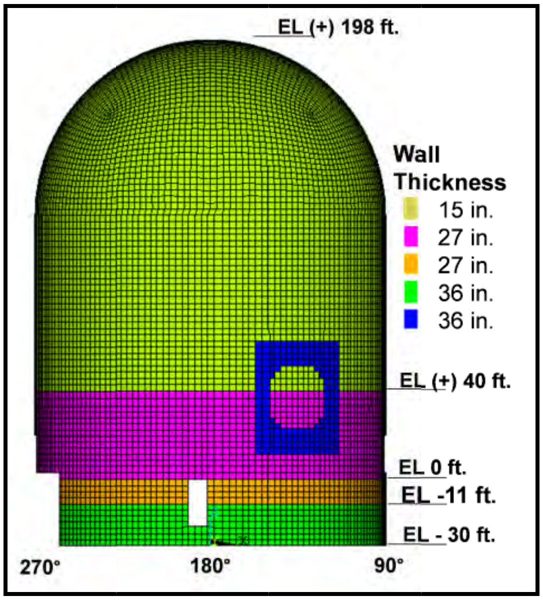


Figure 6. Correlations between SGH Visual Rating and Laboratory Test Results

STRUCTURAL MODELS

A detailed three-dimensional finite element model (3D FEM) of the CEB was prepared using the ANSYS program. The wall and dome were modeled by element SHELL181, which has in-plane extension, out-of-plane bending stiffness, and allows section offsets. Shell elements had average size of 3 ft and an overall thickness matching the design concrete wall in the CEB. All penetrations were included in the model, as shown in Figure 7. Two 3D models are used including a undistressed condition where the design properties are used for elements representing concrete areas, and a distressed condition which includes areas with different severity of ASR impacts that were mapped into the 3D FEM. The reduction in elastic modulus, E, with increasing levels of ASR distress, based on visual ratings, for the distressed condition model, are shown in Figure 7.

Stick models were used for calculating overall seismic behavior of CEB. Detailed 3D models were used to calculate the properties and offsets for beam elements representing different elevations of the overall structural model. Two sets of stick models were prepared: one based on undistressed 3D FEM and other based on the distressed 3D FEM. The offsets, as well as the beam model properties, for the distressed stick model were different, as compared to the corresponding properties for the undistressed model.



Visual Rating	Modulus of Elasticity (% of undistressed concrete)
1	97 %
2	84 %
3	83 %
4	57 %

Figure 7. 3D Finite Element Model and Ratio of ASR Distress Relative to Undistressed Specimens

STRUCTURAL ANALYSES AND RESULTS

The stick models were used to calculate the overall dynamic behaviors of the CEB, and acceleration profiles for undistressed and distressed structures. Figure 8 shows typical overall orthogonal acceleration profiles due to a north-south input motion. This Figure shows responses for the original design calculations, and calculated responses for undistressed and distressed stick models. The acceleration profiles for both undistressed and distressed conditions closely follow the original design profiles. This comparison demonstrates that the models developed in this project closely backfit the original design, and ASR impacted mechanical properties of the concrete do not significantly impact the overall dynamic behavior of the CEB.

The 3D FEMs were subjected to both non-seismic and seismic loadings. The dynamic seismic loadings were simulated by static inertia loadings based on the seismic acceleration profiles. Total responses were calculated based on design load combinations that were used in the original Final Safety Analysis Report (FSAR) for the Seabrook plant. The element forces and moments were used to re-evaluate the undistressed structure and to evaluate the distressed structure. The structural capacities were calculated based on ACI 318-71, ACI (1971), procedure both on element level as well as by use of section cut procedures. Ratios of the structural responses for the distressed and undistressed conditions were used to evaluate the impact of ASR on structural responses.

Figure 9 shows a typical impact of ASR on structural response for the ratio of the bending moments about the horizontal axis. The bending moment increases locally due to a reduction in the concrete mechanical properties where ASR impact is more significant. In general, non-seismic and seismic loads are partially redistributed to the undistressed concrete zones, based on the relative stiffness of undistressed concrete zones compared to distressed concrete zones. Therefore areas with no damage or minor damage will be more highly loaded than predicted in the original design; however, our calculations demonstrated that the original design had sufficient margin to resist the additional local demands due to load redistribution from distressed to undistressed areas of the structure.

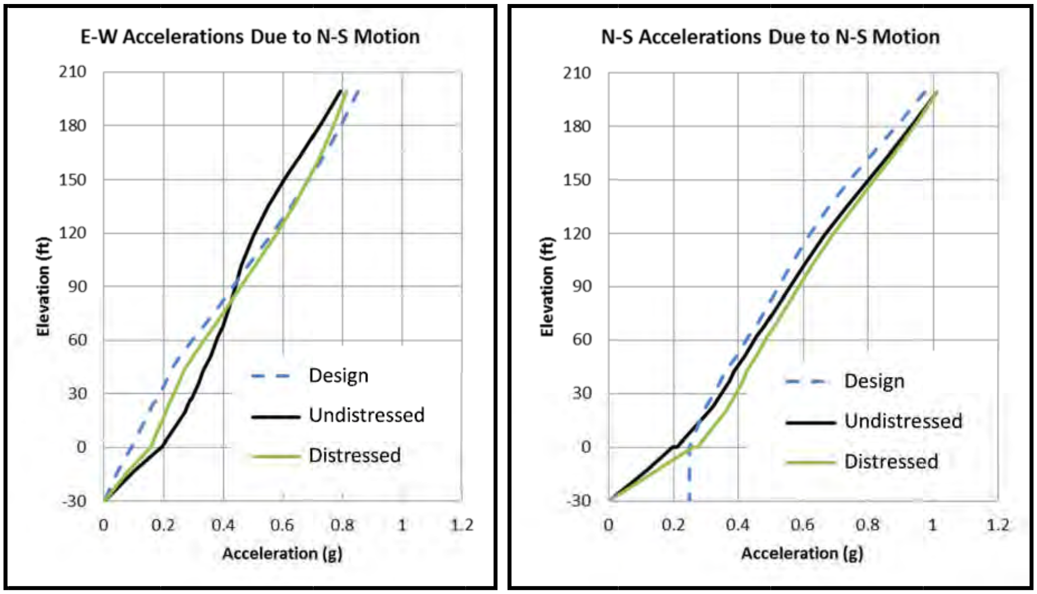


Figure 8. Variation of Maximum Acceleration with Elevation of the CEB

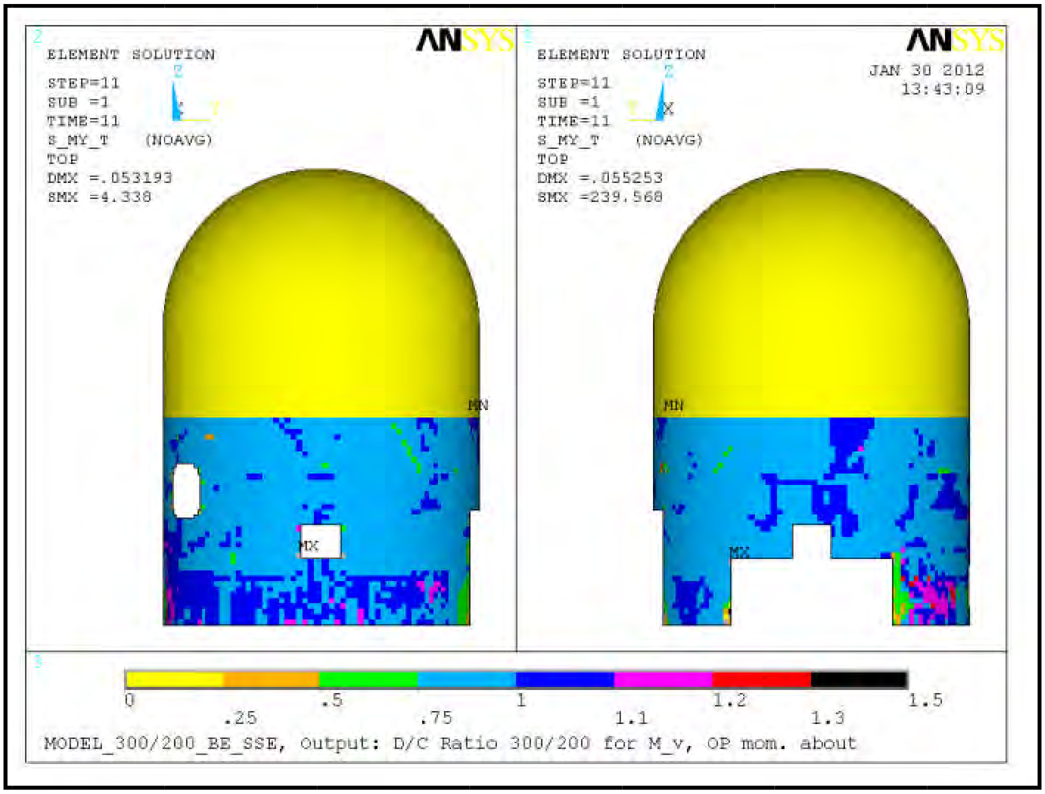


Figure 9. Reduction in Flexural Stress as Ratio of ASR distressed to undistressed Models

CONCLUSIONS

This project describes the method used to conduct a comprehensive assessment of the Seabrook nuclear power station containment enclosure building. The assessment demonstrates that the ASR impacted concrete structure meets the original design requirements. Structural monitoring is ongoing to evaluate any changes in structure condition. Following are specific conclusions from this project:

The concrete CEB wall has varying identifiable degrees of ASR-related distress; however, there is no visual sign of expansion-related distress that indicates impairment of the near-term structural integrity of the CEB. We divided the near- and below-grade interior surface of the CEB wall into zones based on signs of ASR-related concrete distress, such as cracking, efflorescence, and moisture staining. CI values and typical crack widths at CEB wall surfaces are less than the minimum values specified in Report HIF-09-004, FHWA (2010), as indicative of concrete likely undergoing ASR. Therefore a modified version of CI procedures was developed for CEB walls which have significantly more reinforcement than structures considered in the FHWA report.

Visual ratings for distress are correlated to material properties. Supplemental petrographic analysis on core samples from wall structures other than the CEB wall reveal that the ASR distress is more severe near the exposed face of the concrete (facing towards the interior of the hallway from which it was removed) than at its center, which justifies the use of a visual rating system approach. Petrographic analysis indicates that the petrology and mineralogy of rock samples are very similar for samples retrieved from the CEB wall and other structures at Seabrook Station that are exhibiting ASR distress.

Natural frequencies and maximum accelerations of backfit, (undistressed) and ASR-distressed models were calculated. Maximum acceleration profiles of backfit models closely match the corresponding values reported in the original design. The overall responses of the CEB including maximum acceleration and in-structural response spectra, were not significantly impacted by ASR, since the ASR distressed areas are localized.

The ASR distress in concrete did not significantly impact the overall forces/moments in the wall; however, the less-distressed areas attract more force since they become relatively stiffer the localized area impacted by ASR. Structural capacities for both undistressed and ASR distressed cases have been calculated in accordance with the requirements of ACI 318-71 based on original design parameters. Even with redistributed forces, 99% of the finite elements describing the CEB structure have demand/capacity ratios less than 0.50 for all load combinations, and the remainder of the elements had sufficient reserve capacity to resist the added demands load redistribution due to ASR impact.

REFERENCES

ACI 209R-92 (1997) “Prediction of Creep, Shrinkage, and Temperature Effects in Concrete Structures”, American Concrete Institute, Farmington Hills, Michigan.

ACI 221.1R-98 (2008) “Report on Alkali-Aggregate Reactivity”, *Reported by ACI Committee 221*, American Concrete Institute, Farmington Hills, Michigan.

ACI 318-71 (1971) “Building Code Requirements for Reinforced Concrete”, American Concrete Institute, Farmington Hills, Michigan.

FANC (2013), “Tihange 2 Reactor Building Concrete Issues”, Federal Agency for Nuclear Control, Presentation.

Fournier, B., Bérubé, M.A., Folliard, K.J., and Thomas, M. (2010) “Report on the Diagnosis, Prognosis, and Mitigation of Alkali-Silica Reaction (ASR) in Transportation Structures”, *Report No. FHWA-HIF-09-004*, Federal Highway Administration, Office of Pavement Technology, Washington, DC.

ISE (1992), *Structural Effects of Alkali-Silica Reaction*, Institution of Structural Engineers, London, England.

Jiang, L., Beaver, J., Sherman, M., and Vassallo, T. (2013) “Inspection and Monitoring of ASR-Affected Structures at Seabrook Station, NH”, SMiRT-22 Conference, San Francisco, CA.

NextEra Energy, “Design of Structures, Components, Equipment and Systems, Rev. 11”, Seabrook Station FSAR.