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**ENCLOSURE 2**

**MPR-4288, Revision 0, "Seabrook Station: Impact of Alkali-Silica Reaction on Structural Design Evaluations," July 2016.**

**(Non-Proprietary)**

--Non-Proprietary Version--

MPR

MPR-4288
Revision 0
(Seabrook FP# 101020)
July 2016

# *Seabrook Station: Impact of Alkali-Silica Reaction on Structural Design Evaluations*

**QUALITY ASSURANCE DOCUMENT**
This document has been prepared, reviewed, and approved in accordance with the Quality Assurance requirements of 10CFR50 Appendix B and/or ASME NQA-1, as specified in the MPR Nuclear Quality Assurance Program.

Prepared for

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P. O. Box 300; Lafayette Rd. Seabrook, NH 03874

--Non-Proprietary Version--

MPR

# Seabrook Station: Impact of Alkali-Silica Reaction on Structural Design Evaluations

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Revision 0
(Seabrook FP# 101020)

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# RECORD OF REVISIONS

| Revision | Affected Pages | Description |
|---|---|---|
| 0 | All | Initial Issue |

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# 1 Introduction

## 1.1 Purpose

This report describes the effect of alkali-silica reaction (ASR) on the structural design basis of affected concrete structures at Seabrook Station and provides guidance for performing evaluations for structural adequacy. The impact of ASR on structural limit states (flexure, shear, and compression capacities and that of the attachments to concrete structures) as well as several additional design considerations (strain in reinforcing bars, fracture of reinforcing steel, seismic response, concrete material properties, and building deformation related issues) are discussed. The content of this report is based on the results of MPR-sponsored large-scale test programs performed for NextEra as well as information available in the published literature, as it relates to the topics listed above.

This report has been prepared as a companion to MPR-4273, *Seabrook Station – Implications of Large-Scale Test Program Results on Reinforced Concrete Affected by Alkali-Silica Reaction.* The large-scale test programs discussed in MPR-4273 provided representative test data that support assessing the effect of ASR on specific portions of the structural design basis. Key conclusions from MPR-4273 are used in the overall evaluation herein.

## 1.2 Background

### *1.2.1 Alkali-Silica Reaction (ASR)*

ASR occurs in concrete when reactive silica in the aggregate reacts with hydroxyl ions ($OH^-$) and alkali ions ($Na^+$, $K^+$) in the pore solution. The reaction produces an alkali-silicate gel that expands as it absorbs moisture, exerting tensile stress on the surrounding concrete and resulting in cracking. Typical cracking caused by ASR is described as "pattern" or "map" cracking and is usually accompanied by dark staining adjacent to the cracks. Figure 1-1 provides an illustration of this process.

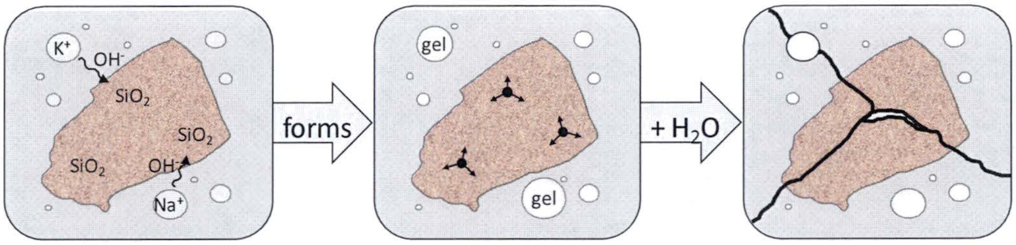


**Figure 1-1.** ASR Expansion Mechanism

The cracking degrades the mechanical properties of unconfined concrete, necessitating an assessment of the adequacy of the affected structures and supports anchored to the structures.

### *1.2.2 ASR at Seabrook Station*

NextEra has identified ASR in multiple safety-related, reinforced concrete structures at Seabrook Station (Reference 7). After an extent of condition determination that identified affected structures at the site, MPR performed an interim structural assessment (Reference 21) of selected ASR-affected structures to evaluate their adequacy given the presence of ASR. Based on the low level of observed cracking and the apparent slow rate of change, MPR concluded that the evaluated structures were suitable for continued service for at least an interim period (i.e., at least several years). The interim structural assessment supports continued operability of plant structures affected by ASR.

The interim structural assessment (Reference 21) utilized a conservative treatment of data from existing literature, supplemented by limited testing of anchor bolts, to produce conclusions suitable for a short-term structural assessment. In support of long-term evaluations, MPR conducted large-scale test programs at Ferguson Structural Engineering Laboratory (FSEL) using specimens that were designed and fabricated to represent reinforced concrete at Seabrook Station to the maximum extent practical. The methodology for the long-term evaluation will rely on a combination of published literature data and results from the large-scale test programs to determine the potential effects of ASR on adequacy of structures at Seabrook Station.

# 2 Summary

The presence of ASR in reinforced concrete structures at Seabrook Station impacts the structural design basis of the affected structures and requires evaluation. This section summarizes the impact of ASR on applicable structural limit states and other design considerations necessary for evaluation of Seabrook Station structures.

The effects of ASR expansion on the structural behavior of reinforced concrete structures can be explained with basic structural mechanics. These effects can be evaluated using the provisions of the structural design codes applicable to Seabrook Station (ACI 318-71 and ASME B&PV, Section III, Division 2, 1975 edition). Guidance on performing the evaluations is summarized in Sections 2.1 and 2.2.

## 2.1 Structural Limit States

The applicable design codes provide methodologies to calculate structural capacities for the various limit states and loading conditions applicable to Seabrook Station. MPR evaluated each relevant limit state using published literature and the results of the MPR/FSEL large-scale test programs that used specimens designed and fabricated to represent reinforced concrete at Seabrook Station. The following guidance applies for structural evaluations of ASR-affected concrete structures at Seabrook Station:

- Flexure/Reinforcement Anchorage - Based on the MPR/FSEL large-scale test program results, structural evaluations should consider that there has been no adverse impact on flexural capacity and reinforcement anchorage (development length) performance, provided that through-thickness expansion is at or below [redacted]% and expansion behavior is comparable to the test specimens,

- Shear – Based on the MPR/FSEL large-scale test program results, structural evaluations should consider that there has been no adverse impact on shear capacity, provided that through-thickness expansion is at or below [redacted]% and expansion behavior is comparable to the test specimens.

- Compression – ASR expansion in reinforced concrete results in compressive load in directions where expansion is restrained by reinforcing steel. The ASR-induced compressive load is additive to compressive stresses due to other loads and should be included in design calculations performed in accordance with the original design code (including determination of an appropriate load factor). Our evaluation concludes that ASR expansion does not reduce the compressive strength of confined concrete, in its structural context. However, inclusion of the chemical prestressing effect due to ASR will have an impact on total loading of compression elements. This effect can be calculated in accordance with the appropriate design code, by treating ASR as a chemical prestressing mechanism that results in a self-equilibrating state of stress in reinforced concrete.

- Anchors and Embedments – Based on the MPR/FSEL large-scale test program results, structural evaluations should consider that there is no adverse effect to post-installed or cast in place anchor/embedment capacity, provided that in-plane expansions remain at or below [redacted]%. Through-thickness expansion is not relevant for anchor/embedment capacity.

## 2.2 Other Design Considerations

In addition to the impact on structural limit states, MPR reviewed other design considerations that are potentially affected by ASR. Key conclusions from these evaluations are as follows:

- Reinforcement Strain
  - Safety-Related Structures (other than Containment) – Reinforcement strain beyond yield is permitted for ultimate strength calculations by ACI 318-71, the design code for Seabrook Station. Furthermore, reinforcement yielding is a design feature required by ACI 318-71 for flexural elements in ultimate capacity calculations to prevent a brittle failure mechanism. Therefore, evaluation of reinforcing steel in ASR-affected structures at Seabrook Station should be performed in accordance with the provisions of the original design code, taking into account chemical prestressing and any deformation effects. This approach ensures that reinforced concrete elements meet the ductility requirements that are implicit in flexural design criteria stipulated in ACI 318-71.
  - Containment – Seabrook Station has identified local regions in the Containment structure where ASR development could result in the local yielding of the reinforcement steel. The effect of this ASR development (taking into account chemical prestress and deformation effects) on the Containment structure should be evaluated using provisions in the ASME Code for reinforcement yielding due to secondary stresses as well as those for local yielding. Evaluation using the original design code ensures that both the ductility and concrete serviceability requirements implicit in the original design basis of the Containment are maintained.

- Reinforcement Fracture – The reinforcement steel at Seabrook Station is not susceptible to brittle fracture due to ASR-induced expansion, which has been observed in Japanese structures. Seabrook Station was designed and constructed in accordance with codes that do not permit rebar bending to the extent (i.e., small diameter) that would be required for susceptibility to rebar fracture. Additionally, quality control requirements in effect during original construction at Seabrook Station were sufficient to ensure that design and construction practices were consistent with code requirements.

- Seismic Analysis – The MPR/FSEL large-scale test program results indicated that ASR development affected the flexural stiffness of the specimens, but MPR concludes that the effect on structures at Seabrook Station is not significant and is bounded by the current seismic analysis. In general, flexural stiffness increased with severity of ASR. An increase in flexural stiffness can be viewed as an improvement to the seismic response, in the context of Seabrook Station's design basis, although it is not enough to be significant. At low loading prior to flexural cracking, specimens exhibited a slight decrease in flexural stiffness that corresponds to a [redacted]% change in seismic response, as explained in Section 6.3. This difference is small compared to other uncertainties in the seismic analysis and is covered by peak broadening of the seismic spectrum in the UFSAR.

- Design Concrete Material Properties – Published literature identified that ASR reduces unconfined material properties of concrete (compressive strength, elastic modulus, tensile strength), which is consistent with the results obtained in the MPR/FSEL large-scale test programs. However, the test program results also showed that the reduction in concrete material properties does not have an adverse effect on structural performance of ASR-affected structures when through-thickness expansion is less than [redacted]%. These results confirm that structural performance of reinforced concrete structures cannot be reasonably re-evaluated for ASR simply by adjusting the ASR-affected properties of unconfined concrete and neglecting the self-equilibrating state of stress due to ASR-induced prestress. Based on this observation, structural evaluations of ASR-affected structures at Seabrook Station should conservatively use the material properties specified in the original design specifications.

- Effect of Building Deformations – Operating experience at Seabrook Station has shown that ASR expansion can result in building deformations, the structural effects of which must be taken into account in a comprehensive structural evaluation. That is, supplementary loads can be generated when ASR-induced expansions in a structural element are restrained by (1) interference with another structure, or a component thereof, or (2) connection to a non ASR-affected region (e.g., expansion of an ASR affected wall restrained at the foundation mat connection or adjacent ASR-affected and non ASR-affected wall segments). The calculation of supplementary loads due to restraint of expansion can be significant and must be addressed on a on a case-by-case basis, by taking boundary conditions into account. The approach for performing this assessment is outside the scope of this report and is being addressed by NextEra in a separate effort.

# 3 Key Elements of Structural Design Basis

This section summarizes key elements of the structural design basis for reinforced concrete structures at Seabrook Station. The discussion focuses on elements of the design basis that are potentially impacted by ASR. The complete design basis information is provided in the Seabrook Station Updated Final Safety Analysis Report (UFSAR; Reference 1) and Seabrook Structural Design Criteria (Reference 9).

## 3.1 Codes of Record

### *3.1.1 Safety-Related Structures except Containment*

Safety-related structures other than Containment were designed and constructed to comply with the 1971 edition of ACI 318, *Building Code Requirements for Reinforced Concrete* (Reference 3) per the Seabrook Station UFSAR Section 3.8.4.

The applicable loads are determined in accordance with ACI 318-71. These loads include normal loads (startup, operation and shutdown), environmental loads (severe and extreme), abnormal loads, and site-specific loads. The applicable load combinations define the required strength at various locations from normal and unusual load conditions. The load combinations are listed in UFSAR Table 3.8-16 and determined in accordance with ACI 318-71. While ACI 318-71 contains provisions for Working Strength Design (WSD) and Ultimate Strength Design (USD), the Seabrook design methodology for safety-related structures other than Containment is USD.

### *3.1.2 Containment*

The Containment structure was designed and constructed to the 1975 edition of the ASME Boiler & Pressure Vessel Code Section III, Division 2, Subsection CC (Reference 2), as described in the Seabrook Station UFSAR Section 3.8.1.

The applicable loads are determined per Reference 2, Article CC-3000. These loads include test pressure loads, normal loads (startup, operation and shutdown), environmental loads (severe and extreme), and abnormal loads[1]. The applicable load combinations define the required strength of Containment at various locations. The load combinations are listed in UFSAR Table 3.8-1 and determined per Reference 2, Article CC-3000 and reflect a combination of WSD and USD methodologies. Using WSD, stresses are computed based on the assumption of an elastic strain profile. In USD, a non-linear strain profile can be used, which models the behavior of concrete much more accurately at its limit state.

[1] Several site-related (site-specific) loads were considered, but none had a significant effect on containment design.

The Containment structure must behave elastically to these external loads and satisfy the structural acceptance criteria listed in UFSAR Table 3.8-2 and described in UFSAR Section 3.8.1.5 which complies with Reference 2, Article CC-3000.

A secondary stress is defined as a normal or shear stress developed by the constraint of adjacent material or by self-constraint of the structure. Secondary stresses are self-limiting; additional strain reduces the internal forces required to maintain local equilibrium, thus reducing the stress; primary stresses are not self-limiting. For the Containment structure, the applicable code limits may be exceeded for peak, localized or secondary stresses. Local yielding, minor distortions, and concrete cracking are permitted for these self-limiting conditions, Article CC-3136.4 of the ASME Code (Reference 2). However, it is important to note that the treatment of expansion-type stresses can vary in Reference 2, depending on the specific situation. Therefore, the appropriate classification of ASR-induced stresses should be made in accordance with the original design code when performing design evaluations of ASR-affected structures.

## 3.2 Key Elements of Design

### *3.2.1 Reinforcement*

The steel reinforcing bars used in safety-related structures at Seabrook Station conform to ASTM Specification A615-75 (Reference 12) per Reference 11. Typical reinforcement is Grade 60 and ranges in size from #8 to #11 (for structures other than Containment; References 13 and 14) or #14 and #18 (Containment structure; Reference 31). Reinforcing bars were typically placed in two-directional mats with one mat near each concrete face of a structural member. The spacing between individual bars typically ranges from 6 to 12 inches. Clear concrete cover for rebar is typically 2 inches for internal faces and 3 inches for external faces. Transverse reinforcement (i.e., reinforcement provided through the wall thickness) is only provided in some areas (e.g., Containment and Containment Enclosure Building (CEB)).

### *3.2.2 Seismic Design*

The seismic design of safety-related structures is described in UFSAR Section 3.7(B). All safety-related structures are supported on competent bedrock or concrete fill over bedrock which fixes the structure bases against translation and rotation. The design basis seismic analyses for reinforced concrete structures are elastic models with suitable linearized material properties.

The seismic response is a function of the natural frequency and damping characteristics of the structure and the seismic demands acting upon the structure. The seismic demand on safety-related structures is the ground motion response spectra provided in UFSAR Section 2.5.

### *3.2.3 Concrete Material Properties*

The selection of material properties for design of concrete structures at Seabrook Station is based on the standard concrete mix specification (including Containment and other safety-related structures) from original plant construction (Reference 10). ACI 318-71 recognizes the concrete mix specification as the primary location to specify the design concrete compressive strength.

Other material properties for concrete design (e.g., elastic modulus) are calculated based on the specified concrete compressive strength.

### *3.2.4 Anchorage to Concrete*

A variety of designs and configurations for anchorage to concrete are used in safety-related applications at Seabrook Station. These designs can be divided into two broad categories: cast-in-place anchorages and post-installed anchors.

**Cast-In-Place Anchorages**
Cast-in-place anchorages (including anchors and embedments) are suspended in the supporting structure's formwork and concrete is then cast around it. Load is transferred through bearing from the anchorage directly to the concrete. Cast-in place anchorages in use at Seabrook Station include embedded plates (with Nelson studs), embedded Unistrut type channels (with embedment studs), Richmond Studs, and anchor bolts.

The design of safety related concrete structures at Seabrook Station is governed by ACI 318-71, which requires that cast-in-place anchorages must be capable of developing adequate strength without damage to the concrete and that their adequacy be demonstrated with testing. This means cast-in-place anchors (e.g., Nelson studs or embedded Unistrut-type channels) are designed with embedment depths such that the limiting failure mode is ductile failure of the anchor steel.

**Post-Installed Anchors**
Post-installed anchors are installed by drilling a hole in the existing concrete and inserting an anchor bolt. The anchor transfers load to the concrete through friction and/or bearing at the anchor/hole interface. Post-installed anchors in use at Seabrook Station include both expansion anchors (e.g., Hilti Kwik Bolts) and undercut anchors (e.g., Drillco Maxi-Bolts).

Seabrook Station is committed to the requirements of NRC IE Bulletin 79-02 (Reference 15) for post-installed anchor design. In accordance with this commitment, a safety factor of 4 on mean failure load is used for the design of post-installed anchors for pipe supports. This safety factor is applied to all safety-related post-installed anchors at Seabrook Station. Review of relevant design documentation (Reference 21) indicates that design practices at Seabrook Station are consistent with these requirements.

Post-installed anchor allowable loads are based on the following:

- Expansion Anchors: The allowable loads for all expansion anchors (e.g., Hilti Kwik Bolts) specified for use at Seabrook Station are based on qualification testing performed by Hilti or a third party (Abbot Hanks) (References 16, 17, & 19)[2]. The tensile load capacities

[2] For Hilti Kwik Bolt 2 anchors, the design loads provided in Reference 17 are consistent with those specified in the Hilti Kwik Bolt 2 Technical Guide (Reference 18), with a Safety Factor of 4 applied.

were determined by unconfined tensile testing in unreinforced test specimens[3]. Allowable loads are based on the tested mean failure load with an applied safety factor of four.

- Undercut Anchors: The Station Pipe Support Design Guidelines (Reference 20) indicate that undercut anchors (e.g., Drillco Maxi-Bolts) must be embedded to sufficient depth such that tensile failure of the anchor steel is the limiting failure mode. Review of anchor dimensions and the material specification (Reference 21) shows that the design allowable loads are based on tensile failure of the anchor bolt shank with a safety factor of 4 applied. While the basis for specified minimum embedment depths is not provided, scoping calculations indicate that the minimum embedment depths provide 40% margin between shank tensile failure and theoretical concrete breakout failure, based on the 45° shear cone method, a commonly used approach during the original construction period of Seabrook Station.

[3] Based on a review of qualification test reports (References 16, 17, & 19), which did not note the presence of reinforcing steel.

# 4 Overview of MPR Evaluations

Determining the effect of ASR development on the structural design basis of safety-related structures at Seabrook Station is based on a detailed review of data provided in publicly available literature supplemented with data from a series of large-scale test programs that MPR conducted at FSEL.

MPR-4273, *Seabrook Station – Implications of Large-Scale Test Program Results on Reinforced Concrete Affected by Alkali-Silica Reaction* (Reference 8) contains a more detailed discussion of the test programs and the literature review that supported development of the test approach.

## 4.1 Summary of Literature Review

MPR conducted a comprehensive review of published research on the structural implications of ASR and industry guidance for evaluating ASR-affected structures. A focused review of published research on the structural implications of ASR (Reference 5) identified dozens of technical references on testing of ASR-affected concrete. The most relevant references were used to support the interim structural assessment for Seabrook Station by providing a conservatively bounding capacity reduction factor for structural limit states (e.g., shear and reinforcing bar anchorage) accounting for the presence of ASR to evaluate the continued operability of ASR-affected plant structures.

While most research on ASR has focused on the science and kinetics of ASR, there is a substantial body of knowledge that exists in the literature on structural testing of ASR-affected concrete specimens. However, the application of the conclusions from the literature to structures at Seabrook Station can be challenged by lack of representativeness. As a result, for selected structural limit states, NextEra commissioned MPR to perform large-scale structural testing using specimens that were designed and fabricated to be representative of structures at Seabrook Station. Consequently, results from the large-scale test programs provide information that can be used in lieu of less representative data from published literature for the limit states that were within the scope of the test programs.

## 4.2 Importance of Confinement

The presence of confinement is a central factor for the effect of ASR on structural performance. Reinforcing steel, loads on the concrete structure (e.g., self-weight), and the configuration of the structure (i.e., restraint offered by the structural layout) may provide confinement that restrains in-situ expansions due to ASR and limits the resulting cracking in concrete. Confinement limits ASR expansion of the in-situ structure, which reduces the extent of deleterious cracking and the resultant decrease in structural performance[4]. Accordingly, evaluation of the effect of ASR at Seabrook Station must consider the confinement conditions that exist at the plant (i.e., mostly two-dimensional reinforcement mats for safety-related structures).

When reinforcement is present to restrain the tensile force exerted by ASR expansion, an equivalent compressive force develops in the concrete that is comparable to prestressing. If loads applied on the structure result in tensile stresses (direct, diagonal, or otherwise), the compressive stresses in the concrete must be completely overcome before additional tensile load is reacted by the reinforcement. Cracking in confined concrete would not occur until the tensile stress imposed by external loads exceeds the compressive stress in the concrete from the prestressing effect plus the tensile strength of concrete which can be conservatively taken as zero. The prestressing effect does not reduce the ultimate tensile capacity of the reinforcement. In some cases, literature indicates that the prestressing effect of ASR creates a stiffer structural component with a higher ultimate strength than an unaffected member –the mechanics of which can be explained by using the first principles of prestressed concrete behavior and design. Test data show that this prestressing effect applies even when ASR expansion has yielded the reinforcing bars (Reference 5). Once again, this behavior is consistent with the behavior of presetressed elements behavior under external loads.

## 4.3 MPR Structural Test Programs

MPR directed three structural test programs at FSEL to support NextEra's efforts to resolve the ASR issue identified at Seabrook Station. In each test program, ASR developed in the fabricated test specimens and was routinely monitored so that load testing could be performed at particular levels of ASR distress. The magnitude of ASR-distress was isolated as the primary test variable and structural response for the wide range of ASR distress was studied. This approach enabled systematic development of trends for structural performance with the progression of ASR. The resulting data sets were a significant improvement upon the collection of published literature sources, because test data across the range of ASR levels were obtained using a common methodology and identical test specimens.

A brief overview of each structural test programs is provided below.

- Anchor Test Program – This test program evaluated the impact of ASR on performance of expansion anchors and undercut anchors installed in concrete. Test specimens included seven large-scale blocks that were designed and fabricated to represent the reinforced concrete structures at Seabrook Station and two sections of reinforced concrete bridge girders that were available at FSEL. The test program consisted of a total of [redacted] anchor tests.

- Shear Test Program – This test program evaluated the impact of ASR on shear capacity of reinforced concrete specimens. Three-point load tests were performed on large-scale beams that were designed and fabricated to represent the reinforced concrete structural

[4] The restraint offered by some parts of a structure on other parts of it, needs to be explicitly taken into account, as discussed in other sections of this report.

components at Seabrook Station. FSEL fabricated [redacted] shear test specimens and conducted a total of [redacted] tests (two tests performed on most specimens).

- Reinforcement Anchorage Test Program – This program evaluated the impact of ASR on reinforcement anchorage of rebar lap splices embedded in concrete and also provided insights on flexural strength and stiffness. Four-point bending tests were performed on large-scale beams that were designed and fabricated to represent the reinforced concrete structures at Seabrook Station. FSEL fabricated [redacted] reinforcement anchorage test specimens and conducted a total of [redacted] tests (one test per specimen).

The test specimens fabricated for the MPR/FSEL test program were designed to be representative of the structural characteristics of safety-related structures of Seabrook Station. The specimen dimensions and reinforcement configurations were similar to a reference location at Seabrook Station, with minor modifications made to ensure the specimen's failure mode was consistent with test objectives. Additionally, cement, coarse and fine aggregates were chosen to ensure that the specimen was representative of the mechanical behavior of the concrete mix used at Seabrook Station. Refer to MPR-4273 (Reference 8), Sections 2 and 3 for a more detailed discussion of the test program and test specimen design.

## 4.4 Scope of Evaluations

The comprehensive literature review identified a number of areas where the structural design basis could be affected by development of ASR. This report divides the potentially impacted areas into two groups: structural limit states and design considerations. This report evaluates the potential impact of ASR for each of these areas and provides guidelines for structural evaluations of ASR-affected structures at Seabrook Station.

**Table 4-1.** Scope of Evaluations

| Structural Limit States (Section 5) | Design Considerations (Section 6) |
|---|---|
| • Flexure & reinforcement anchorage/ reinforcing steel development<br>• Shear strength<br>• Compression<br>• Anchor bolts and structural attachments to concrete | • Reinforcement steel strain<br>• Reinforcing bar fracture<br>• Seismic response<br>• Applicability of design basis material properties<br>• Effect of structural deformations |

Axial tension is not included in the scope of evaluations. The impact of ASR on gross axial tension in concrete is not considered significant as tensile strength of concrete is commonly neglected in reinforced concrete designs compliant with, for example, ACI 318. The methodology of the Seabrook Station design codes for reinforced concrete structures (ASME B&PV, Section III, Division 2, 1975 Edition and ACI 318-71) requires that the contribution of the gross concrete section in tension is neglected in axial (and flexural) limit states.

# 5 Structural Limit States

This section evaluates the potential impacts of the ASR aging mechanism on structural limit states that are applicable for ASR-affected reinforced concrete structures at Seabrook Station. The applicable limit states include flexure (including reinforcement anchorage), shear, and compression.

## 5.1 FLEXURE

Evaluation of the effect of ASR on the flexure limit state considered both flexural capacity and reinforcement anchorage development.

### *5.1.1 MPR/FSEL Large-Scale Test Program Results*

The MPR/FSEL large-scale test program evaluated the effect of ASR on reinforcement anchorage development (Reference 8). These tests can also be used to investigate the effect on flexural capacity and flexural stiffness. Reinforcement anchorage and flexural capacity are evaluated in this section; flexural stiffness is evaluated in Section 6.3.

Results from the large-scale test program demonstrated that ASR-affected specimens with through-thickness expansion of up to [redacted]% were able to fully develop the minimum reinforcement lap splice specified by ACI 318-71 and exhibited no reduction in the flexural capacity. The test specimens had two-dimensional reinforcement mats without transverse reinforcement similar to structures at Seabrook Station (similar reinforcement size, spacing and material).

Through-thickness expansion of [redacted]% was the highest ASR level exhibited by the test specimens. The lack of an adverse effect on reinforcement anchorage and flexural capacity may extend to higher expansion levels. For in-plane expansion, all test program specimens leveled-off at [redacted]% to [redacted]%. Expansions occurred predominately in the through-thickness direction, making through-thickness expansion the best indicator of ASR development. Additionally, flexural stiffness tracked with through-thickness expansion level, indicating that through-thickness expansion is an appropriate parameter for monitoring ASR progression.

### *5.1.2 Comparison to Literature*

#### Flexural Performance

The results of the most applicable publically available test data regarding the effect of ASR on flexural performance are based on large-scale specimens (20 inch by 20 inch), as reported in References 5 and 28.

- For specimens without transverse reinforcement, the test results of ASR-affected test specimens showed a range that was predominately better than control test specimens. Specifically, the flexural capacity of the ASR-affected test specimens ranged from a 43% increase to 7% decrease relative to the control specimens.

- For specimens with transverse reinforcement, the test results showed the ASR-affected specimens performed better than the control specimens by approximately 5% (Reference 5). The increase in flexural capacity is due to ASR-induced prestressing.

Overall, testing performed on relatively large-scale specimens shows no significant loss of strength or stiffness in ASR affected specimens (Reference 5).

Considering the effects of chemical prestressing due to ASR, and putting that into context with axial load-bending moment interaction diagrams available in prestressed concrete design textbooks, the improvement in flexural capacity due to ASR can be explained. That is, axial load levels that are less than the balanced flexural load tend to increase the flexural capacity of the concrete elements. In a broad sense, the chemical pressing effect imposes axial loads on concrete sections resulting in an increase in flexural capacity. However, no credit will be taken for an increase in flexural capacity.

**Reinforcement Anchorage**

The most applicable publically available test data for reinforcement anchorage are based on a bar pullout test in ASR-affected concrete (Reference 5). The bar pullout test method is the least desirable method of reinforcing bar anchorage testing as boundary conditions present in a typical pullout test do not represent actual boundary conditions present in a typical structural component (Reference 27). While such tests were common in the early days of structural testing, and informed reinforcing bar development design, the engineering community moved away from this type of testing on the basis of a wide range of representativeness issues associated with them. With that context, the results still provide an insight into the significant performance benefit provided by transverse reinforcement in ASR-affected structures, regardless of the testing methodology and problems associated with that methodology.

For specimens without transverse reinforcement, the test results showed a 40% loss in capacity. The large observed loss is a result of the test method generating stress fields that are different and significantly more severe than those found in actual structural elements subjected to flexure. In brief, such a drop in capacity is attributed to free expansion experienced in the relatively small concrete blocks tested. The same study produced test results for specimens with transverse reinforcement that were indicative of a 10% strength loss.

### *5.1.3 Evaluation*

**Flexural Capacity**

Results from large-scale tests are available regarding the impact of ASR on flexural performance with and without transverse reinforcement. Published results from large-scale testing of more representative specimens with transverse reinforcement (Reference 5) indicate no loss in flexural capacity due to the presence of ASR. The MPR/FSEL test programs of specimens without transverse reinforcement also indicate no loss of flexural capacity. Accordingly, flexural performance will not be adversely affected by ASR at the expansion levels exhibited in the large-scale test programs.

**Reinforcement Anchorage**

The MPR/FSEL test program used a more representative test method (e.g., flexural test of a large-scale beam containing a rebar splice, as compared to a rebar pullout test of a small specimen), which provides several advantages:

- the test method is viewed as being among the best methods that produces *"more realistic measures of bond strength in actual structures"* according to the technical report produced by ACI Technical Committee 408 (Reference 27) and reapproved by the committee in 2012.
- specimens were more representative of structures at Seabrook Station with respect to mechanical properties of concrete, reinforcing bar size, and clear cover.
- the test results were highly repeatable.

As a result, structural evaluations for Seabrook Station can use the MPR/FSEL test programs conclusions (i.e., no loss of reinforcement anchorage or flexural capacity for through-thickness expansion up to [redacted]%) in lieu of the results from the published literature. ASR-affected structures with transverse reinforcement are expected to maintain their performance at higher levels of ASR expansion than those without transverse reinforcement, so the large-scale test results are conservative with respect to structures with transverse reinforcement.

For structural evaluations at Seabrook Station, the additional compressive stress due to the effect of ASR chemical prestressing on the overall stress state in flexural elements must be checked in the appropriate structural calculations. While flexural elements at Seabrook Station were designed to be tension controlled (Reference 21), ASR-affected elements should be evaluated to verify that tension-controlled design criteria are still satisfied with the additional ASR-induced compressive stress.

### *5.1.4 Conclusion*

The calculated flexural strength per the Seabrook Station design codes (ACI 318-71 or ASME B&PV Section III, Division 2, 1975 Edition) is appropriate because testing showed no decrease in flexural capacity. Note that these tests were performed in a context where all flexural capacity calculations were performed according to ACI 318-71. A limitation of [redacted]% through-thickness expansion is applied consistent with the level of ASR expansion exhibited by specimens in the MPR/FSEL large-scale test programs. Structural behavior at levels greater than [redacted]% expansion may be acceptable. A limit on in-plane expansion is not necessary, as expansion is predominately in the through-thickness direction.

## 5.2 SHEAR

Evaluation of the effect of ASR on the shear limit state focused on one-way shear (beam shear), but also included two-way (punching) shear.

### 5.2.1 MPR/FSEL Large-Scale Test Program

The MPR/FSEL large-scale test program evaluated the effect of ASR on shear capacity. Results demonstrated that ASR-affected specimens with through-thickness expansion of up to [redacted]% did not exhibit a loss of shear capacity (Reference 8).

Through-thickness expansion of [redacted]% was the highest ASR level exhibited by the shear test specimens. The lack of an adverse effect on shear capacity may extend to higher expansion levels. The calculated shear strength per the Seabrook Station design codes (ACI 318-71 and ASME B&PV Section III, Division 2) is appropriate to use for evaluation of ASR-affected structures for expansion levels up to this limit.

Expansion behavior of the shear test specimens was consistent with the reinforcement anchorage test specimens (Reference 8). Because in-plane expansion of all test specimens level-off at [redacted]% to [redacted]%, through-thickness expansion was used to characterize ASR development. The test results showed that shear capacity increased with increasing through-thickness expansion. However, no credit will be taken the increase in shear strength due to ASR.

### 5.2.2 Comparison to Literature

Published literature on structural testing of ASR-affected reinforced concrete includes a range of results that generally reflects the degree of reinforcement. Previous studies note that triaxially reinforced concrete will only be slightly affected, even by fairly severe ASR expansions (Reference 7). The results from large-scale specimens (i.e., specimens with a cross-section of 42″ × 21″) with transverse reinforcement showed a 16% gain in shear strength due to the presence of ASR (Reference 5). These test specimens were tested at in-plane expansion levels varying from 0.7% to 1.2% measured in the direction of shear reinforcement.

Test data available in published literature show that ASR-affected test specimens without shear reinforcement displayed shear capacities ranging from a slight increase to a loss of 25% (Reference 29). Test specimens for results at the low end of this range had a relatively small cross section (5″ × 3″). It should be noted that the study that generated the results suggesting a 25% reduction specifically noted that the small test specimens likely exaggerated the deleterious effect of ASR, because the depth of ASR cracks is relatively greater in smaller specimens.

### 5.2.3 Evaluation

As discussed above, the MPR/FSEL large-scale test specimens without transverse reinforcement showed no loss in shear capacity due to ASR expansion. This behavior is similar to triaxially reinforced concrete. Because the MPR/FSEL test program specimens were much more representative of Seabrook Station than published literature (e.g., [redacted]″ × [redacted]″ specimen cross-section, as compared to 5″ × 3″) and the MPR/FSEL test results were highly repeatable, structural evaluations for Seabrook Station should consider that there is no impact to shear capacity.

### *5.2.4 Other Limit States Considered*

**Two-Way (Punching) Shear**

Results from the one-way shear evaluation described above are applicable to punching shear (two-way shear). Punching shear involves a truncated pyramid ( as opposed to a diagonal shear plane seen in a beam test) and this difference in geometry does not affect the overall conclusion of the MPR/FSEL testing that there is no adverse impact for through-thickness expansion up to [redacted]%.

The literature review performed in Reference 5 identified a study of punching shear in reinforced concrete plates. Specimens with a thickness of 8 cm (~3 in) and ASR-induced expansions up to 0.7% were studied. This study concluded that ASR had little effect, provided that delamination had not occurred. The study (Reference 6) states that the beneficial effects of ASR-induced prestress appear to counteract the detrimental effects of ASR on material properties such that there is not a general reduction in punching shear performance. As discussed in the previous section, the use of small scale testing to represent shear performance of large elements is conservative, as it exacerbates the detrimental effects of ASR. Because the test specimens from Reference 6 were significantly thinner (~3 in) than structural members at Seabrook Station (2 to 4 ft), the results of that study conservatively bound the behavior of structural walls at Seabrook Station.

Considering the results reported in Reference 6 and the performance of the shear specimens tested at FSEL, punching shear strength of structural walls and slabs at Seabrook Station is not affected by ASR.

## 5.3 Compression

ASR expansion resisted by steel reinforcement results in a compressive stress in the concrete. In the case of structural elements in which the concrete is loaded in tension (e.g., shear or flexure), the ASR-induced expansion acts as a chemical prestress, in which the reinforcement tensile load due to the expansion is opposed by concrete compression to produce a state of internal force balance. The load associated with overcoming the pre-compression due to ASR is likely greater than that which would cause cracking of concrete in a case where ASR-induced prestress does not exist. However, the compressive stress caused by ASR is additive to the applied compressive stress in all elements, and must be included in design calculations.

### *5.3.1 Mechanics of ASR-Induced Concrete Compression*

In the absence of external loads, the tensile force developed in reinforcing bars due to ASR-induced expansions must be equal to the compressive resultant forced developed in concrete. If the in-plane expansions are known, or can be conservatively estimated, the tensile force in the reinforcing bars can be calculated from first principles. Once the tensile force is known, the area of concrete that serves to counteract that force (i.e. the cross-sectional area) can be used to calculate the compressive stress in concrete. The application of design basis loads should be considered in conjunction with the self-equilibrating stresses generated by ASR. That is, the impact of ASR on structural performance can be modeled on the basis of first principles.

The concept of accounting for internal prestress due to reinforcement strain is typical in prestressed concrete design (Reference 30, Section 19.2).

### 5.3.2 Literature Review

Initial review of the potential implications of ASR on structures at Seabrook Station (Reference 5) identified one test program in the literature with results relevant to the evaluation of axial compression (Reference 23). This test program used medium-scale specimens (9 inch square cross-section), and showed an 18% loss of performance at 0.7% longitudinal (in-plane) expansion.

### 5.3.3 Evaluation

Understanding the implications of the compression testing discussed in Reference 23 requires determining if the reason for decreased compression capacity observed in the testing was the addition of ASR-induced compressive stress prior to loading or a change in the unconfined compressive strength of the concrete.

The limiting test result in Reference 23 showed an 18% reduction in compressive capacity. Based on the test specimen parameters provided in Reference 23 and using the approach discussed in Section 5.3.1, a scoping calculation determined that the ASR-induced compressive stress in the limiting test specimen would reduce the axial compressive capacity by approximately 9%. The difference in axial compressive capacity between the first-principles scoping calculation (9% reduction) and the test result (18% reduction) from Reference 23 is negligible when examined in the context of the normal strength variation tolerated within reinforced concrete construction, especially with reduced-scale specimens. For reference, the acceptable variation between two concrete cylinder compression tests is 8-10% per ASTM C39 (Reference 24). Accordingly, MPR concludes that the decrease in compression capacity from the testing documented in Reference 23 was due to the addition of ASR-induced compressive stress rather than a change in compressive strength of confined concrete.

Results of the MPR/FSEL large-scale flexural testing support this conclusion. Specifically, this testing demonstrated that the theoretical flexural capacity determined using ACI Code calculations was realized. A decrease in compression capacity due to a change in unconfined concrete compressive strength would likely have resulted in compression zone failure of the flexural specimen prior to yielding of flexural reinforcement and reaching full flexural capacity.

### 5.3.4 Conclusion

Increased compressive stress due to ASR expansion is additive to compressive stresses due to other loads. The additional compression load due to ASR expansion must be included in the evaluation of ASR-affected structures at Seabrook Station. The magnitude of the additional compressive stress can be calculated using basic structural mechanics based on the measured in-plane expansion. This effect should also be considered in the evaluation of flexural elements, as the additional compression will affect the development of tensile reinforcement strain. Additionally, our evaluation concludes that structural evaluation of ASR-affected structures should be performed using the nominal (specified) compressive strength, consistent with current practices.

### 5.3.5 Bearing Performance

Our literature review and evaluation did not identify any plausible means through which ASR could directly impact bearing capacity, which is a function of the in-situ (e.g., confined) compressive strength. That said, increased loading on a bearing surface due to constrained ASR expansion, (e.g., loading due to contact between structures) should be considered in structural calculations using the approach for calculating ASR-induced compressive stress discussed above.

## 5.4 Structural Attachments

Literature providing test data on anchor capacity of ASR-affected concrete was not publicly available. Therefore, MPR and FSEL performed a large-scale test program to determine the tensile capacity of shallow embedment anchors in ASR-affected concrete, the conclusions of which are provided below. Refer to Reference 8 for a more detailed discussion of the test program.

### 5.4.1 MPR/FSEL Large-Scale Test Program

The large-scale testing program included unconfined tension tests[5] of post-installed wedge-style anchors (Hilti Kwik Bolt 3) and undercut anchors (Drillco Maxi Bolts). The undercut anchors also represent cast-in-place embedments. The testing program did not include anchor shear tests, because tension tests would be more sensitive to ASR expansion than shear tests. The test results show no loss of tensile performance up to [redacted]% in-plane expansion.

The test program also concluded that anchor performance is not sensitive to through-thickness expansion or time of anchor installation relative to the ASR expansion. Through-thickness expansion has the potential to create microcracks perpendicular to the axis of an anchor. An anchor loaded in tension would compress the through-thickness expansion and close any potential microcracks within the area of influence of that anchor. Without a "short-circuit" of the breakout cone, through-thickness expansion does not affect anchor performance. Degradation of performance exists at higher levels of in-plane expansion because increased cracking due to ASR interferes with shear cone development during anchor loading.

### 5.4.2 Evaluation

The structural capacity of anchors and other concrete attachments identified in Seabrook's responses to IE Bulletin 79-02 (Reference 15) are not adversely affected by ASR for in-plane expansion of up to [redacted]%.

As discussed in Section 3.3, Seabrook Station has a series of Hilti expansion anchor designs in service. Our review of the available design information (e.g., anchor configuration and design

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[5] The MPR/FSEL full-scale testing program did not include direct shear tests on anchors installed in test samples. Tension tests are more sensitive to ASR expansion than shear tests. Therefore, direct shear tests on test samples were not necessary.

capacities) concluded that the test results using Hilti Kwik Bolt 3 anchors are applicable to the other Kwik Bolt designs in service at Seabrook Station.

Based on this, we conclude that the current design basis capacities anchors and other concrete attachments are acceptable for use in design calculations when in-plane expansion is less than [redacted]%.

# 6
# Design Considerations

This section evaluates the potential impacts of the ASR aging mechanism on design considerations that are applicable for ASR-affected reinforced concrete structures at Seabrook Station. Specifically, this section addresses reinforcement steel strain, reinforcement fracture, seismic response, applicability of design basis material properties, and the effect of structural deformation.

## 6.1 Reinforcement Steel Strain

ASR expansion results in tensile strain of the embedded steel reinforcement, while placing the concrete in compression. This section discusses provisions from the applicable design codes that pertain to reinforcing steel strain due to ASR expansion.

### *6.1.1 Reinforcement Strain in ACI 318-71*

ACI 318-71 recommends that flexural elements be designed such that they are tension-controlled, which ensures sufficient ductility prior to failure. A tension-controlled element is designed such that the reinforcing steel on the tension side will yield prior to compressive failure of the concrete on the compression side of the element, with sufficient margin. Tension-controlled sections are advantageous because they provide visual evidence of structural distress (e.g., large deflections and substantial flexural cracking) prior to failure.

The design of flexural elements limits the amount of tensile reinforcement to less than 75% of the amount necessary to produce balanced conditions under flexure (ACI 318-71, 10.3.2). A balanced condition in a flexural cross section is defined as a section where the tensile reinforcement reaches yield (for example at a strain of 0.00207 for, ASTM A615, Gr. 60 reinforcing bars) just as the concrete on the compression side reaches its assumed failure strain of 0.003 (ACI 318-71, 10.3.3). Design of a flexural element with 75% of the balanced-section reinforcement results in tension reinforcement steel with 0.376% tensile strain (for Gr. 60 reinforcement) at nominal capacity, which is a value well beyond the yield point (0.207%), and as such accommodation for ductility is made in flexural designs. The 75% limit is further reduced to permit additional load redistribution of negative moments resulting in yielding in continuous flexural members (ACI 318-71, 8.6).

The discussion above demonstrates that reinforcement strain beyond yield is permitted by the design code for Seabrook Station (ACI 318-71), for the purposes of flexural capacity calculation. Furthermore, reinforcement strains that correspond to levels of straining that are well above yielding is a USD design feature, to ensure ductile performance, and is required by ACI 318-71 for flexural elements.

### *6.1.2 Reinforcement Strain in ASME B&PV Code, Section 3, Division 2*

**Code Design Approach**

The Containment structure at Seabrook Station was designed in accordance with the ASME B&PV Code, Section 3, Division 2, 1975 Edition (Reference 2). The design intent of this code is to ensure that the overall Containment structure behaves elastically under design and service external loading. To accomplish this, the code limits the average tensile stress of reinforcement to the following:

- Service Loads (Normal): 50% of yield stress (WSD)
- Factored Loads (Severe/Abnormal): 90% of yield stress (USD)

These code limits on the design stress of reinforcement are applied on an average stress basis and are not applicable to peak or localized stresses. Specifically, local yielding, minor distortions, and concrete cracking are permitted in self-limiting conditions (i.e., secondary stresses such as expansion due to ASR), per Reference 2, Article CC-3136.4. The allowance of reinforcement yielding is limited such that increased concrete cracking does not cause deterioration of the Containment (Reference 2, CC-3110(d)(2)).

While it should be noted that the treatment of expansion stresses under the B&PV code varies depending on the configuration and loading it is clear that the code permits reinforcement yielding due to secondary stresses (e.g., thermal stresses or bending at gross discontinuities) as well as local yielding due to primary loads, provided the structure remains in structural equilibrium and general yielding does not occur. Additionally, the code provides specific guidance for the evaluation of regions with local yielding (Reference 2, CC-3511.1 (c)).

**Effect of ASR on Reinforcement Design**

ASR expansion of reinforced concrete produces a displacement-limited chemical prestress. Additional stresses may be imposed due to the restraint of ASR-affected elements by unaffected elements. As described above, the ASME B&PV Code provides guidance for evaluating primary and secondary stresses from ASR-induced expansion, including reinforcement yielding due to local effects. As such, the evaluation of the effect of ASR expansion on the Containment structure should be performed in accordance with the original design code.

## 6.2 REINFORCEMENT FRACTURE

Operating experience from ASR-affected structures in Japan, particularly within the Japanese transportation industry, has raised the possibility of ASR expansion contributing to the fracture of reinforcing steel. Examples of such failures have been documented in a number of structures in Japan, such as bridge piers and protective walls (Reference 25). This section discusses relevant research determining the cause of these failures and evaluates the susceptibility of ASR-affected structures at Seabrook Station to similar failures.

### *6.2.1 Literature Review*

The Japanese Society of Civil Engineers created a task force to investigate the causes and structural implications of the reinforcement fractures discussed in Reference 25. This effort produced a significant amount of information available in the public literature. In 2011, researchers at FSEL performed a study of steel reinforcement brittle fracture[6]. This study included a detailed literature review and a series of tests to better understand the factors contributing to steel reinforcement embrittlement and crack initiation (Reference 26). The FSEL review of Japanese field studies and laboratory testing available in the public literature identified the following:

- Reinforcing steel brittle fractures were observed in bent reinforcement only (e.g. stirrups or hooks).
- The fractures largely occurred in rebar bent to diameters smaller than would be permitted by current American design codes or ACI 318-71.
- The failures were all brittle in nature, indicating a change in mechanical properties in the normally ductile low carbon steel reinforcement.
- Laboratory testing concluded that the fractures initiated at the sites of compression cracks in the intrados (inside surface at the bend) of the bent steel.

As part of their study, FSEL performed a series of reinforcement bend tests to investigate the correlation between bend diameter and deformation pattern on the initiation of compression cracks on the bend intrados. Applicable results of the FSEL testing are included in the following discussion.

### 6.2.2 Crack Initiation Mechanics

The mechanics of the crack initiation and material embrittlement resulting in reinforcement fracture are described in Reference 26. Bending a steel reinforcement bar results in elongation of the bar along the bend extrados (outside) and compression at the intrados (inside). Additionally, contact with the bending pin flattens the bar deformations (ridges on the bar surface to aid concrete bonding), resulting in large stress concentrations. Compression stresses at the intrados increase as the rebar is bent to a smaller diameter, potentially resulting in compression cracks at the stress concentration locations.

Subsequent to bending the bar, the application of a tensile force has two effects. First, tensile force produces local tensile straining at the crack locations potentially resulting in crack propagation. Second, the tensile load causes a change in the mechanical properties of the low carbon steel bar, referred to as strain aging. This has the effect of increasing the tensile strength (strain hardening) and decreasing the ductility (strain embrittlement) such that brittle failure can occur.

### 6.2.3 Susceptibility of Reinforcement to Fracture at Seabrook Station

As discussed above, the potential for reinforcing steel brittle fracture requires the steel bar to be bent to a very tight diameter. The FSEL study (Reference 26) noted that observed failures were

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[6] This effort was not part of the MPR/FSEL test programs performed for NextEra.

in reinforcing bars bent to diameters smaller than permitted by current US design codes, which are equivalent to those provided in ACI 318-71 and ASME B&PV Code Section III, Division 2, 1975 Edition. Note that the bend tests performed in the FSEL study included bend diameters consistent with the Seabrook design codes. Additionally, bend tests performed by FSEL using deformed reinforcement bent in accordance with ACI requirements did not show evidence of compression cracking at the intrados (only one specimen tested showed evidence of small compression crack formation).

The issue of brittle reinforcement fracture is largely limited to older structures in Japan. MPR is not aware of any operating experience in the United States indicating that the brittle fracture of steel reinforcement designed in accordance with ACI 318 had occurred. Finally, it is important to note that steel reinforcement brittle fracture is a function of excessively small bend diameters and is not directly related to the development of ASR. The addition of any expansive or tensile force on the crack site could result in brittle fracture of cracked and strain embrittled bars.

Based on the discussion above, the reinforcement steel at Seabrook Station is not susceptible to brittle fracture. Seabrook Station was designed and constructed in accordance with codes that do not permit rebar bending to the extent that would be required for susceptibility to rebar fracture. Additionally, quality control requirements in effect during original construction of Seabrook Station would have prevented the poor construction practices that resulted in the observed rebar fractures in Japan.

## 6.3 Seismic Response

This section discusses the potential effects of ASR-induced cracking on the structural rigidity (i.e., stiffness) of the seismic Category I reinforced concrete structures at Seabrook Station. Cracked concrete sections have reduced stiffness properties in comparison to un-cracked concrete sections. In general, a change in the stiffness of the structural member would modify:

- the deflections of structures for a given static load (e.g., dead loads), and
- the dynamic response of the structure when subjected to vibratory loads (e.g., rotating equipment loads and seismic loads).

The change to deflections from static loads is addressed as part of the plant's normal structural monitoring program and corrective action process. Likewise, changes to the dynamic response for non-seismic vibratory loads (e.g., modal separation for rotating equipment) also would be addressed as part of the plant's normal monitoring programs. The consequences of changes to the dynamic response of structures for seismic loads are of particular interest because this could affect the seismic design and qualification of all safety-related structures, systems, and components (SSCs). A change in the dynamic response of the overall structure would change the seismic loads, seismic deflections, and also the in-structure amplified response spectra at the mounting location SSCs located in the structures.

The subsections below summarize results from the MPR/FSEL tests and provide justification that the structural dynamic response does not change for the ASR affected members at Seabrook Station.

In general, the response of a structure to a seismic event is affected by the stiffness of structural members in flexure and shear, and their stiffness in response to axial loads. Flexural stiffness is the most sensitive to cracking and would be most affected by ASR-induced cracking. Modern design codes such ACI 318-11 allow the flexural stiffness of cracked beams and walls to be represented as a fraction of the nominal flexural rigidity in a linear analysis. By comparison, this version of ACI 318 does not specify any reduction factor for axial rigidity or any reduction factor for shear rigidity if the shear loads are less than the shear capacity. Therefore, the effects of ASR on the seismic performance of Category I structures were evaluated based on the effects of ASR on flexural stiffness.

### 6.3.1 ASR Test Results on Stiffness

The MPR/FSEL large-scale testing (Reference 8) produced the following key observations regarding stiffness in ASR-affected reinforced concrete members.

- The initial flexural stiffness of ASR-affected test specimens (i.e., prior to flexural cracking) was less than the control specimen. The reduction is attributed to the presence of numerous ASR-induced cracks in the test specimen prior to the application of load during the structural test. There was no discernible relationship between the severity of ASR versus the flexural stiffness prior to flexural cracking. On average, the initial flexural stiffness of ASR-affected test specimens was about [redacted]% less than what would be the calculated flexural stiffness (Reference 8).

- The service level flexural stiffness (i.e., from 0% to 60% of yield moment) of ASR-affected test specimens was greater than the control specimen. The increased stiffness is attributable to the ASR-induced prestressing in the test specimens. The flexural stiffness of ASR-affected test specimens was [redacted]% to [redacted]% larger than the control specimen, with stiffness generally increasing with through-thickness expansion.

### 6.3.2 Plant Seismic Design Basis

The Seabrook Station UFSAR (Reference 1), Section 3.7(B) describes the seismic design of safety-related structures. All safety-related structures, with the exception of some electrical manholes and ductbanks, are supported on competent bedrock or concrete fill over bedrock, which fixes the structure bases against translation and rotation. The design basis seismic analyses for reinforced concrete structures are elastic models with suitable linearized material properties. Two methods of seismic analysis are used: (1) response-spectrum and (2) time-history. Seismic response-spectrum analyses are used to obtain the structural displacements and seismic loads. Time-history analyses are used to obtain the in-structure response spectrum used for design and qualification of other SSCs.

In either analysis method, mathematical models for the overall reinforced concrete structures are constructed with lumped masses connected by simplified linear elastic springs, commonly referred to as a "stick model." The stick model is used to obtain the seismic response of the overall structure. As necessary, separate analyses are performed with individual models to obtain the amplified seismic response spectrum or seismic loads at specific locations such as floor slabs or walls.

The seismic response is a function of the natural frequency of the structure, structural damping, and the seismic demands acting upon the structure. The seismic demand on safety-related structures is the ground motion response spectra provided in UFSAR Section 2.5. Figure 6-1 illustrates the horizontal and vertical design basis ground response spectra for Seabrook Station using data from UFSAR Figures 2.5-43 and 2.5-44. The design basis ground response spectra are also known as the safe shutdown earthquake (SSE) spectra. The operating basis earthquake (OBE) is defined as one half of the SSE.

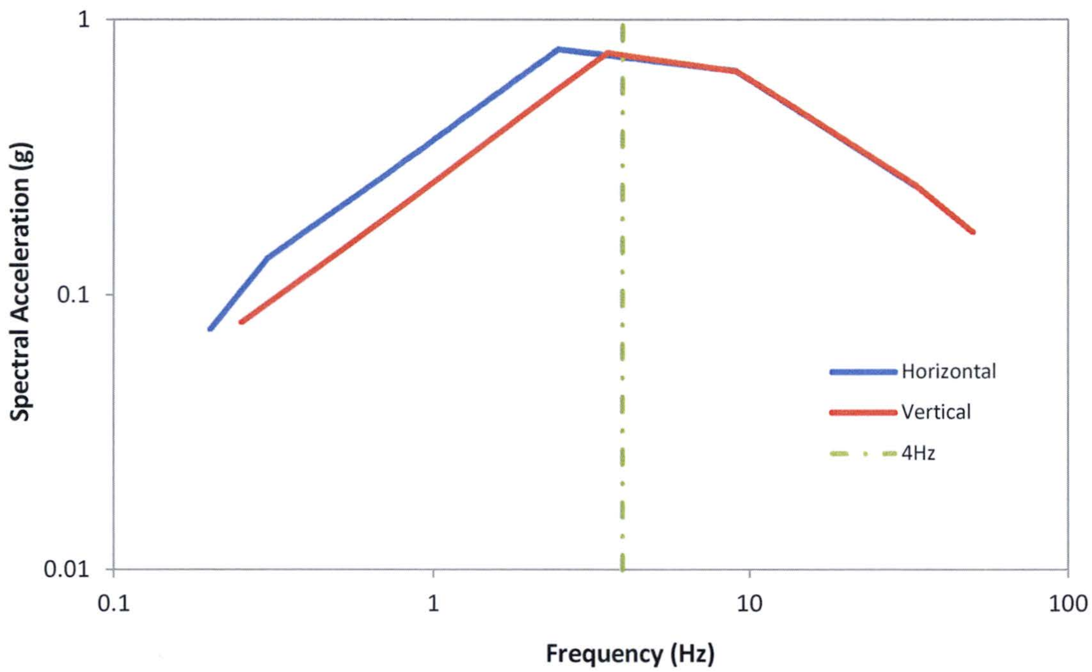


**Figure 6-1.** Design Basis Seismic Ground Response Spectrum, 5% Damping (Reference 1)

### *6.3.3 ASR Effect on Structural Damping*

In general, seismic analyses include damping to account for energy dissipation during structural vibration. The seismic response of a structure is inversely proportional to the magnitude of damping. Cracked concrete has larger effective damping ratio than un-cracked concrete, reducing the seismic response with respect to concrete unaffected by ASR. Therefore, it is conservative to neglect the additional damping due to ASR-induced cracking.

### *6.3.4 ASR Effect on Natural Frequency*

The tables in UFSAR Section 3.7(B) summarize the natural frequencies of the Category I structures at Seabrook Station. Based on review of the tables, the smallest natural frequency of any Category I structure at Seabrook Station is about 4 Hz. The natural frequency of the structure is proportional to the square root of the structural stiffness ($k$) divided by the mass ($m$). ASR does not change the mass of the structure. Accordingly, the natural frequency of the structure would change proportionally to the square root of the change in the stiffness. In general, there are three types of member stiffnesses considered in a structural seismic analysis.

- Flexural Stiffness – governs deflections of slabs, columns, beams, and beam-like members subject to bending loads. The flexural stiffness is directly proportional to the product of a member's modulus of elasticity (*E*) and area moment of inertia (*I*) of the cross section that resists the bending load.

- Shear Stiffness – governs deflections of members loaded in-plane, in cases where shear stress related distortions contribute significantly to overall deflected shape of a member. The shear stiffness is directly proportional to a member's shear modulus of elasticity (*G*) and the cross-section area (*A*) parallel to the direction of loading.

- Axial Stiffness – governs deflections of members subject to longitudinal loads. The axial stiffness is directly proportional to a member's modulus of elasticity (*E*) and cross-section area (*A*) perpendicular to the direction of loading.

Of all the three stiffness types listed above, the flexural stiffness is the most significantly affected by cracks overall. Modern design codes allow the flexural stiffness of cracked beams and walls to be represented as a fraction of the nominal flexural rigidity (*EI*) in a linear analysis. Such reductions are not common practice for axial or shear rigidity. For example, the importance of flexural stiffness with respect to cracks is illustrated in ASCE 43-05 (Reference 22). Table 3-1 of ASCE 43-05 provides reduction factors for flexural rigidity that range from 0.50 to 0.70 to account for crack effects. Similarly, modern versions of ACI 318 (e.g., the 2011 Edition) allow the flexural stiffness of cracked beams and walls due to service loads to be taken as 0.35 times the nominal elastic stiffness (*EI*). By comparison, ACI 318-11 and ASCE 43-05 do not specify any reduction factor for axial rigidity or any reduction factor for shear rigidity if the shear loads are less than the shear capacity. Furthermore, the linear material properties for shear modulus (*G*) and cross sectional areas (A) can be written in terms of the elastic modulus (*E*) and moment of inertia (*I*), respectively.

Based on the above, the effects of ASR on the seismic performance of Category I structures are therefore evaluated based on the effects of ASR on flexural stiffness alone.

### 6.3.5 ASR Effects on Flexural Stiffness

For heavily loaded reinforced concrete members in flexure, the Seabrook design analyses would consider some reduction factor to account for flexural cracking. Results from the tests of ASR-affected specimens demonstrated that the flexural rigidity increases with the severity of ASR. The increased rigidity could be viewed as an improvement for the seismic response. As shown in Figure 6-1, the seismic demands decrease for frequencies larger than about 3 Hz. The smallest natural frequency is about 4 Hz. Accordingly, there is no adverse effect on the seismic displacements and seismic loads for heavily loaded concrete members loaded in flexure.

For lightly loaded flexural members, design analyses may be based on uncracked section properties using the nominal flexural rigidity (*EI*). Results from the tests of ASR-affected specimens indicate some decrease in the flexural rigidity should be expected prior to the onset of flexural cracking. There was no correlation in the decrease in flexural rigidity with the severity of ASR, but the measured flexural stiffness in ASR-affected specimens was about [redacted]% smaller than the calculated flexural stiffness. As described in the previous section, relative changes to the stiffness change the natural frequencies by a square root relationship. Accordingly, a [redacted]% reduction in the nominal flexural rigidity could reduce the calculated natural frequencies by about [redacted]%.

Reducing the natural frequency of Category I structures does not significantly affect the seismic response (loads or deflections) itself. Figure 6-1 shows the seismic demands in the high frequency range (>10 Hz) have an approximately linear relationship when plotted on a log-log scale. This means that a [redacted]% reduction in the natural frequency could only increase the seismic response by [redacted]% for high frequency modes. The seismic demands have even less sensitivity in the 4 Hz to 9 Hz range, which is the range of the dominant structural modes.

Furthermore, the [redacted]% frequency shift due to ASR effects is well within the normal variation in concrete properties overall. ACI 318-95 states that the modulus of elasticity can typically vary as much as ±20% about the specified values. Such large uncertainties in material properties are factored into the Seabrook seismic design. UFSAR Section 3.7(B).2.9 indicates that the peaks of the calculated in-structure response spectra are broadened by at least ±10% to account for uncertainties in material properties and modeling techniques. Figure 6-2 illustrates the effect of peak broadening. The dashed lines illustrate the calculated response with discrete peaks at the structural natural frequencies ($f_n$). The solid dark line illustrates the broadened spectra that are ±10% of the structural natural frequency ($f_n$).

Based on the above, MPR concludes ASR does not significantly affect the flexural stiffness and there is no adverse effect on the seismic analyses.

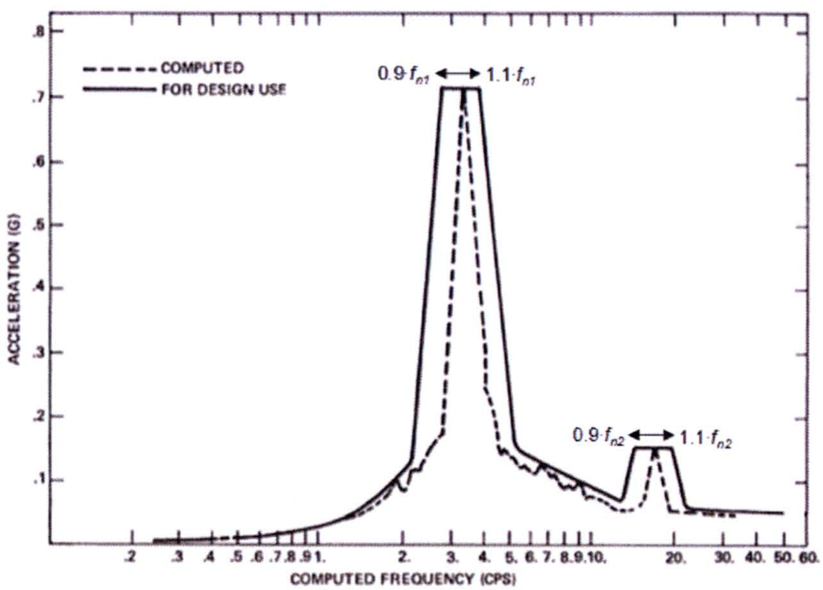


**Figure 6-2.** Illustration of Peak-Broadened Spectrum about Structural Frequencies ($f_n$)

## 6.4 APPLICABILITY OF DESIGN BASIS MATERIAL PROPERTIES

### *6.4.1 Literature Review*

The observed expansion on the surface of unconfined concrete can be correlated to degraded properties such as uniaxial compression, modulus of elasticity, and tensile strength. Reference 4 provides lower-bound degraded properties based on measured free expansion in unconfined concrete. The lower bound properties tabulated in Reference 4 show that compressive strength is a weak function of the observed expansion, while tensile strength and elastic modulus are much stronger functions of the extent of ASR degradation. However, ASR affects confined (i.e., reinforced) concrete structures differently than unconfined structures. The effect of confinement must be taken into account when evaluating reinforced concrete structures affected by ASR.

### *6.4.2 MPR/FSEL Large-Scale Test Programs*

The MPR/FSEL large-scale test programs (Reference 8) included extensive cylinder and core testing corresponding to the various beam test specimens. Testing and evaluation of material properties of extracted cores show significant reduction in elastic modulus and moderate reductions in compressive and splitting tensile strength, which is similar to Reference 4. As part of load testing, FSEL determined the theoretical capacity based on design equations from ACI 318-71 and the 28-day cylinder test results, which did not exhibit deleterious expansion due to ASR. The load test results of ASR-affected specimens exceeded the theoretical capacities calculated using nominal material properties, indicating that the use of material properties obtained from extracted cores to calculate the structural capacity of an ASR-affected element is not appropriate.

### *6.4.3 Conclusion*

Given the interplay between ASR-induced cracking and structural restraint, it is imperative that evaluation of the structural impacts due to ASR focus on structural testing rather than simply material property testing of concrete cores removed from the structure and neglecting the effects of confinement in structural evaluation . The ASR-induced prestressing effect is only present when the expansion is confined. If the concrete is removed from its native stress field (i.e. its structural context), the prestressing effect is lost. A core sample from an ASR-affected, reinforced concrete structure will not be confined by the stresses imparted by the reinforcement and surrounding concrete after it is removed from the structure. Therefore, such a core is not directly representative of the concrete within its structural context. Measured mechanical properties from a core taken from a confined ASR-affected structure have limited applicability to in-situ performance; such results only represent the performance of an unconfined or unreinforced concrete. The use of these properties by themselves without recognizing and explicitly modeling the effects of confinement would result in an analysis which does not represent actual structural behavior and could have adverse consequences (i.e., inaccurate determination of structure dynamic response).

Evaluations of ASR-affected structures at Seabrook Station could conservatively use the material properties specified in the original design specifications. As shown in MPR/FSEL large-scale test programs, the experimental evidence suggests that effects of confinement more than compensate the mechanical property degradation of unconfined concrete. The reduction in concrete material properties does not have an adverse effect on structural performance of ASR-affected structures at Seabrook Station when through-thickness expansion is less than [redacted]%.

## 6.5 EFFECT OF STRUCTURAL DEFORMATION

Unrestrained expansion of ASR-affected concrete in a structure does not produce any structural loads. In the case of ASR expansion in reinforced concrete, expansion restrained by reinforcing steel results in a balanced set of internal forces which do not impact the overall structural equilibrium of the structure (i.e., the state of balance between externally applied forces and moments and reaction forces and moments). In addition to these strain-limited internal loads, supplementary loads can be generated when ASR-induced expansions in a structural element are restrained by:

- interference with another structure, or a component thereof, or
- connection to a non ASR-affected region (e.g., expansion of an ASR affected wall restrained at the foundation mat connection, or adjacent ASR-affected and non ASR-affected wall segments).

These supplementary loads are most significant when ASR-induced expansion occurs over a large area, the effects of which have been observed at Seabrook Station in the form of building deformation. The loads created by the restraint of expansion in ASR-affected concrete by adjacent structural elements must be considered in design evaluations of ASR-affected structures. The effect of ASR-induced building deformation on structural loading is a function not only of the amount of ASR expansion but on the structure geometry and restraint conditions. These loads may be significant and must be evaluated on a case-by-case basis. NextEra has initiated a program at Seabrook Station for the monitoring and evaluation of ASR-affected structures which includes assessing the effect of structural deformation on the ability of the structure to meet its design requirements. The details of this effort are outside the scope of this report.

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