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MPR-4153, Revision 2, “Seabrook Station – Approach for Determining Through-Thickness Expansion from Alkali-Silica Reaction,” July 2016 (Seabrook FP# 100918)

(Non-proprietary)

MPR

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Revision 2
(Seabrook FP # 100918)
July 2016

-- Proprietary to NextEra Energy Seabrook and MPR Associates --

Seabrook Station - Approach for Determining Through-Thickness Expansion from Alkali-Silica Reaction

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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MPR

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RECORD OF REVISIONS

Revision	Affected Pages	Description
0	All	Initial Issue
1	Body of Report, Appendix A	Included corrected data for expansion of FSEL test specimens in the through-thickness direction. Also made minor editorial changes throughout the body of the report.
2	Body of Report, Appendix A, Appendix D	Updated to include final test program results. Included expansion data for all FSEL test specimens in the through-thickness direction and data for the first campaign of extensometer locations at Seabrook Station. Expanded discussion of uncertainty. Also made minor editorial changes throughout the body of the report.

Executive Summary

This report recommends a methodology for determining the extent of through-thickness expansion of reinforced concrete structural members at Seabrook Station. Quantifying through-thickness expansion will enable NextEra to apply the results of the structural testing programs to Seabrook Station based on the condition of existing plant structures and ensure that action is taken before expansion at Seabrook Station exceeds the bounds of the testing programs.

Data from the structural testing programs show that expansion in the in-plane direction plateaus at low expansion levels, while expansion in the through-thickness direction continues to increase as alkali-silica reaction (ASR) proceeds. Accordingly, the test programs provide results that correlate structural performance to expansion in the through-thickness direction.

NextEra is installing instruments (i.e., extensometers) in concrete structures at Seabrook Station to measure expansion in the through-thickness direction that occurs after time of installation through the end of plant life. To calculate total expansion, NextEra will need to determine expansion from original construction until the time the extensometer is installed (pre-instrument expansion).

MPR recommends the following approach for determining total ASR-induced through-thickness expansion at each instrumented location at Seabrook Station. The recommended method determines the pre-instrument expansion based on the observed reduction in modulus of elasticity.

1. Determine the current elastic modulus of the concrete by material property testing of cores removed from the structure. Elastic modulus testing requires companion compressive strength testing. As a result, MPR recommends obtaining a minimum of four test specimens at each proposed monitoring location. Two test specimens are for compressive strength testing and two test specimens are for subsequent elastic modulus testing.

2. Establish the original elastic modulus of the concrete by either (1) using the ACI 318-71 correlation to calculate elastic modulus from 28-day compressive strength records or (2) obtaining cores from representative ASR-free locations and testing for elastic modulus.

3. Calculate the reduction in elastic modulus by taking the ratio of the test result from the ASR-affected area to the original elastic modulus.

4. Quantify through-thickness expansion from original construction to the time the extensometer is installed using the correlation developed in this report. The correlation relates reduction in elastic modulus with measured expansion from beam specimens used during the large-scale ASR structural testing programs and provides a conservative estimate of pre-instrument expansion levels at Seabrook Station.

5. Calculate total expansion levels by adding the extensometer measurements to the expansion at the time of instrument installation.

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Introduction

1.1 PURPOSE

This report recommends a methodology for determining the extent of through-thickness expansion of reinforced concrete structural members that are affected by alkali-silica reaction (ASR) at Seabrook Station. Quantifying through-thickness expansion of existing plant structures is necessary to relate the extent of ASR in a given structure to the results of the structural testing programs at Ferguson Structural Engineering Laboratory (FSEL).

The methodology recommended in this report is part of determining if expansion levels at Seabrook Station are within the limits of the test programs.

1.2 BACKGROUND

1.2.1 Overview of Alkali-Silica Reaction

ASR occurs in concrete when reactive silica in the aggregate combines with alkali ions (Na^+, K^+) in the pore solution. The reaction produces a 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.

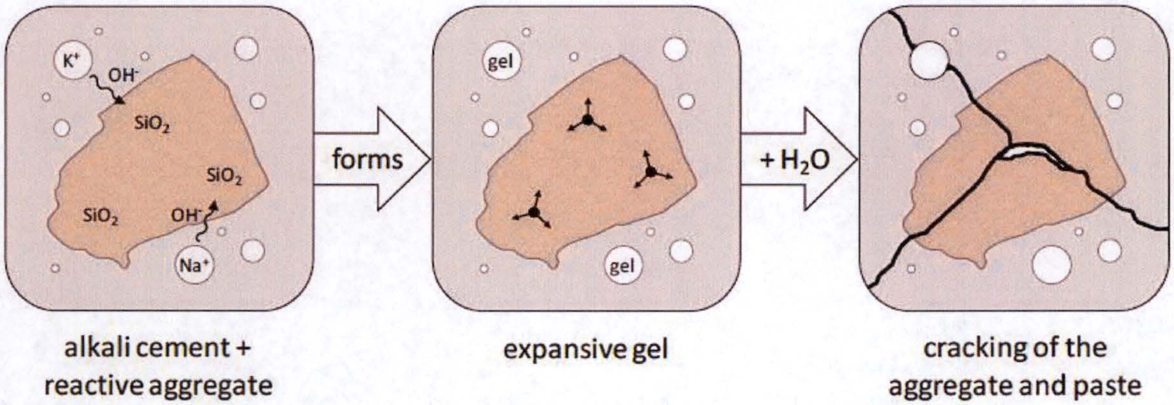

Figure 1-1. ASR Expansion Mechanism

Several publications indicate that the cracking may degrade the material properties of the concrete (References 1, 2, and 3). The concrete properties most rapidly and severely affected are the elastic modulus and tensile strength. Compressive strength is also affected, but less rapidly and less severely.

While development of ASR causes a reduction in material properties, there is not necessarily a corresponding decrease in structural performance. As discussed in previous MPR reports on ASR at Seabrook Station and the approach for the FSEL test program (References 4 and 5), cores removed from a reinforced ASR-affected structure are no longer confined by the reinforcement and do not represent the structural context of the in-situ condition. Therefore, material properties obtained from cores have limited applicability for evaluating the capacity of a structure.

1.2.2 ASR at Seabrook Station

NextEra has identified ASR in multiple safety-related, reinforced concrete structures at Seabrook Station (Reference 6). MPR performed a structural assessment (Reference 4) 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 these structures are suitable for continued service for at least an interim period (i.e., at least several years).

The interim structural assessment considered the various limit states for reinforced concrete and applied capacity reduction factors based on test data in publicly available literature. Based on the lack of representative literature data, MPR executed large-scale test programs to evaluate shear capacity, reinforcement anchorage, and anchor bolt capacity of ASR-affected reinforced concrete.

Follow-up evaluations will assess the long-term adequacy of the concrete structures at Seabrook Station. The evaluations will consider the results of the large-scale test programs performed at FSEL using test specimens that were specifically designed and fabricated to represent reinforced concrete at Seabrook Station.

1.2.3 Test Programs at FSEL

MPR sponsored four test programs at FSEL to support NextEra's efforts to resolve the ASR issue identified at Seabrook Station. The test programs were designed to ensure the test results are applicable to the range of structures at Seabrook Station. Three of the test programs focused on the structural performance data necessary to complete a definitive assessment of ASR-affected structures. The fourth test program evaluated instruments for monitoring expansion of Seabrook Station. A brief overview of each test program is provided below.

- Anchor Test Program: This program evaluated the impact of ASR on performance of anchors installed in the concrete. Tests were performed at multiple levels of ASR degradation.
- Shear Test Program: This program evaluated the impact of ASR on shear performance of reinforced concrete beams. Tests were performed at multiple levels of ASR degradation.

- Reinforcement Anchorage Test Program: This program evaluated the impact of ASR on reinforcement anchorage using beams that had reinforcement lap splices. Tests were performed at multiple levels of ASR degradation.

- Instrumentation Test Program: This program evaluated instruments for measurement of through-thickness expansion. Insights gained from this program were used to select which instrument to use at Seabrook Station and to refine installation procedures.

As part of the test programs, FSEL monitored development of ASR. For the Shear, Reinforcement Anchorage, and Instrumentation Test Programs, FSEL measured expansion of the test specimens and determined the effect on material properties of concrete, which are related to ASR development. Using this information, this report recommends a methodology for determining the extent of ASR-induced expansion at Seabrook Station. (Similar data were not obtained as part of the Anchor Test Program, so this report does not utilize expansion data from the Anchor Test Program.) Quantifying the extent of ASR development will enable comparison of the test data to the condition of existing structures at Seabrook Station.

Testing was conducted under FSEL's project-specific quality system manual with quality assurance oversight from MPR. MPR commercially dedicated the testing services performed by FSEL. Commercial grade dedication of services from the test programs relevant for this report is documented in Reference 22 and Reference 26 and presented in Reference 5 unless noted in Appendix A.

2

Expansion Behavior in Test Specimens

This section discusses expansion behavior observed in the test specimens and the implications for monitoring ASR development in structures at Seabrook Station. An overview of test specimen design is included to provide context for understanding the observed expansion behavior.

2.1 OVERVIEW OF TEST SPECIMENS

2.1.1 Reinforcement Pattern

The test program specimens were large, reinforced concrete beams. Most test specimens were [redacted] feet [redacted] inches long, [redacted] inches wide, and [redacted] inches thick (References 7.1 and 7.2). The test specimens were designed to represent the configuration of reinforced concrete structural members at Seabrook Station. In particular, the test area of each test specimen included two-dimensional reinforcement mats on two opposite faces, which is the same reinforcement detailing used for most reinforced concrete buildings at Seabrook Station (e.g., walls that have reinforcement mats on the interior and exterior faces). Figure 2-1 provides a schematic of the reinforcement pattern in an example shear test specimen (Reference 7.3). The reinforcement anchorage and instrumentation test specimens had some design differences (e.g., [redacted]), but all test specimens contained two-dimensional reinforcement mats consistent with the example in Figure 2-1 (References 7.4 and 7.5).

[redacted]

Figure 2-1. Example Reinforcement Pattern in Shear Test Specimen (Reference 7.3)

2.1.2 Expansion Measurements

The methods for monitoring expansion in shear and reinforcement anchorage test specimens included crack indexing, mechanical measurements of reference points embedded in the concrete during fabrication (embedded pins), and measurement of the expansion profile across the test specimen height using a custom frame (z-frame).

[redacted] embedded pins were used to characterize in-plane expansion. As ASR occurred, the concrete between a given set of pins expanded, and the distance between the pins increased. Measurements were taken at both the backside and the inside faces[1] of each test specimen, [redacted] in the perpendicular direction and [redacted] in the longitudinal direction, as shown in Figure 2-2. For each direction, the [redacted] expansion values on each face were averaged to obtain the percent expansion in that direction for that face.

[redacted]

Figure 2-2. In-Plane Expansion Measurement Using Embedded Pins (Reference 5)

A custom frame (i.e., z-frames) designed and fabricated by FSEL was used to assess expansion in the through-thickness direction. The z-frame (Figure 2-3) contacted the test specimens at [redacted] on formed concrete surfaces and was aligned to both ends of the [redacted] pins embedded for through-thickness measurements. The arrangement allowed for a total of [redacted] measurements to be taken using a calibrated depth micrometer, [redacted] from each side at corresponding locations across the inside and backside faces. Measurements from the z-frame allowed the thickness of expanded test specimens to be calculated at [redacted] locations such that the profile of the expanded test specimen could be determined. The average of thickness readings from all [redacted] locations was used.

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[1] The top and bottom of the test specimens are referred to as the "backside" face and "inside" face, respectively, and correspond to the exterior and interior surfaces of a wall at Seabrook Station.

[redacted]

Figure 2-3. Through-thickness Expansion Measurements Using the z-frame (Reference 5)

Prior to adopting the z-frame, through-thickness expansion was monitored using embedded pins, shown in Figure 2-4. [redacted] measurement of the through-thickness expansion was taken per face using the [redacted] embedded pins. For test specimens that were tested before the z-frame methodology was adopted, the through-thickness expansions measured using embedded pins were adjusted using the relationship described in Reference 5.[2] The difference between the z-frame methodology and the embedded pins methodology is that the gage length of the z-frame is the full [redacted]-inch thickness of the specimen, whereas the gage length of the embedded pins is only [redacted] inches. The relationship in Reference 5 accounts for the sensitivity of the percent expansion to gage length when expansion is concentrated in a single, large longitudinal crack.

For the instrumentation specimen, through-thickness expansion was monitored using a depth gage inserted into small bore holes that go completely through the specimen.

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[2] All through-thickness expansion values associated with shear and reinforcement anchorage test specimens presented in the this report are either expansion values obtained directly from the z-frame or were estimated from embedded pin measurements and Equation 5-1 in Reference 5.

2.2 EXPANSION IN REINFORCED CONCRETE

2.2.1 Test Specimens

Expansion of the test specimens was significantly more pronounced in the through-thickness direction (i.e., perpendicular to the reinforcement mats) than the in-plane direction (i.e., on the faces of the specimens parallel to the reinforcement mats). Expansion in the in-plane direction plateaued at low levels, while expansion in the through-thickness direction continued to increase. This behavior can be seen in Figure 2-4, which is a plot of expansion for Specimen [redacted] based on monitoring the distance between the embedded rods.[3] Expansion behavior in this test specimen is representative of other test specimens.

[redacted]

Figure 2-4. Expansion Trends in Example Test Specimen

The difference between in-plane expansion and through-thickness expansion is due to the reinforcement detailing and the resulting difference in confinement between the in-plane and through-thickness directions. The reinforcement mats confined expansion in the in-plane direction. Through-thickness expansion, on the other hand, was not confined because there was

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[3] Figure 2-4 is for illustrative purposes only. Periodic monitoring of expansion is considered for information only, whereas the measurements at the time of testing are formal test measurements.

no reinforcement in that direction. Therefore, expansion occurred preferentially in the through-thickness direction.

2.2.2 Literature Review

The observed preferential expansion in the through-thickness direction is consistent with literature on ASR-induced expansion (References 2 and 9). Literature suggests that when reinforcement is present to restrain the tensile force exerted by ASR-induced expansion, an equivalent compressive force develops in the concrete, which creates a prestressing effect. If tensile loads are applied to the structure, the compressive stresses in the concrete from prestressing must be overcome before there is a net tensile stress. Cracking in confined concrete would not occur until a net tensile stress is applied.

2.3 IMPLICATIONS FOR MONITORING ASR AT SEABROOK

Based on the expansion behavior observed in the test specimens, expansion in the through-thickness direction is the best indicator of ASR development in the test specimens and at Seabrook Station. In-plane expansion is a readily available parameter that can be used to assist with diagnosis of ASR-affected reinforced concrete. However, the test data suggest that through-thickness measurement is a more sensitive parameter for characterizing ASR-induced expansion at Seabrook Station in the long term. Accordingly, the results of the Shear and Reinforcement Anchorage Test Programs were correlated to expansion in the through-thickness direction.

NextEra is in the process of installing instruments (i.e., extensometers) in concrete structures at Seabrook Station to monitor expansion in the through-thickness direction. The current plan includes installing instruments in ASR-affected areas and in some areas unaffected by ASR. The instruments in areas unaffected by ASR will provide a reference measurement to gauge effects, such as thermal expansion, that could influence the ASR-induced expansion measurements.

The instruments measure through-thickness expansion that occurs after the instrument is installed. To determine the cumulative expansion since original construction, this expansion measurement must be added to the expansion up to the time the instrument is installed. The subsequent sections of this report provide a methodology for determining the pre-instrument expansion.

3

Determining Pre-Instrument Expansion from Elastic Modulus

This section describes the technical basis and methodology for using the reduction in elastic modulus to quantify the total ASR-induced expansion in the through-thickness direction prior to instrument installation (pre-instrument expansion). The methodology depends on determining the elastic modulus at the time of instrument installation from cores and establishing the original elastic modulus to provide a point of reference. The original elastic modulus may be determined by testing reference cores from concrete without symptoms of ASR or by using original construction data with an ACI correlation that relates compressive strength to elastic modulus.

Specific topics discussed in this section include:

- Evaluation of changes in material properties that indicate ASR-induced expansion,
- Development of the correlation between expansion and elastic modulus based on test data from the large-scale ASR testing programs, and
- Determination of the original elastic modulus at Seabrook Station, which is used as the point of reference for determining reduction in elastic modulus.

The discussion in this section relies on test results obtained from the large-scale ASR testing programs at FSEL (Reference 5).

The correlation between normalized elastic modulus and through-thickness expansion presented in this section determines best-estimate pre-instrument expansion values for concrete structures at Seabrook Station. As discussed in Section 4, a normalized modulus reduction factor of [redacted] is applied so that the final calculated through-thickness expansion is conservative.

3.1 MATERIAL PROPERTIES OF TEST SPECIMENS

As part of the large-scale structural testing programs, FSEL obtained material property data on the test specimens at different levels of ASR-induced expansion. The difference between the 28-day material property result and the material property result at the time of testing may be used to quantify development of ASR.

3.1.1 Material Property Testing during FSEL Structural Testing Programs

During fabrication of the test specimens, FSEL prepared cylinders (approximately 8 inches in height and 4 inches in diameter) using the same batch of concrete as the test specimens (FSEL Procedure 1-5, Reference 5). A subset of these cylinders were tested 28 days after fabrication to provide initial values for the material properties of the specimen, including compressive strength, elastic modulus, and splitting tensile strength (Reference 12). At the time of load testing a shear or reinforcement anchorage specimen, FSEL obtained cores from the specimen and performed testing for material properties. For the instrumentation specimen, FSEL obtained cores and performed material property testing at selected expansion levels.

The 28-day cylinders were fabricated in accordance with ASTM C31-10 and C192-07 (FSEL Procedure 1-5, Reference 5). Cores for material property testing were obtained in accordance with ASTM C42-12. Compressive strength testing was conducted in accordance with ASTM C39-12 (FSEL Procedure 5-3, Reference 5); elastic modulus testing was performed in accordance with ASTM C469-10 (FSEL Procedure 5-4, Reference 5), and splitting tensile testing was carried out in accordance with ASTM 370-12 (FSEL Procedure 5-5, Reference 5).

Data from all ASR-affected test specimens were included in MPR's evaluation. Data from control test specimens were not included.

3.1.2 Compressive Strength and Elastic Modulus

Figure 3-1 is a plot showing the normalized values for compressive strength and elastic modulus as a function of expansion (Reference 13). A normalized material property is the ratio of the property at the time FSEL obtained the expansion measurement divided by the material property obtained from testing a cylinder 28 days after fabrication.

[redacted]

Figure 3-1. Compressive Strength and Elastic Modulus as a Function of Through-Thickness Expansion from Test Data (Reference 13)

Key observations from Figure 3-1 include the following:

- Normalized elastic modulus follows a trend where elastic modulus decreases sharply at expansion levels less than about [redacted]%. The trend indicates a more gradual decrease at higher expansion levels.

- Normalized compressive strength shows a general decreasing trend with increasing expansion levels; however, compared to elastic modulus, there is lower sensitivity with expansion (i.e., the slope is shallower) and there is more data scatter.

Literature data indicate that trends for the normalized material properties discussed above are consistent with the material property results from the test programs (References 1 and 2). In particular, the literature concludes that reduction in elastic modulus is more sensitive to ASR development than compressive strength.

3.1.3 Splitting Tensile Strength

Figure 3-2 shows the splitting tensile strength values as a function of through-thickness expansion. Normalized splitting tensile strength results (which require a 28-day value) are not available because the test program did not start obtaining these results until May 2014, after FSEL had fabricated many of the test specimens. In addition, FSEL Procedure 5-6 (Reference 5) allows for omission of splitting tensile tests on cores due to the difficulty in extracting testable cores from members with significant cracking due to ASR. Using this provision, splitting tensile strength was not performed on cores from [redacted] Similarly, only two cores from [redacted] and one core from [redacted] were tested (Reference 5).

[redacted]

Figure 3-2. Splitting Tensile Strength as a Function of Through-Thickness Expansion from Test Data (Reference 13)

As shown above, splitting tensile data from higher expansion levels have approximately the same splitting tensile strength values as data from low expansion levels. Even if normalized data were available, sensitivity with expansion would still be low (i.e., shallow slope). Accordingly, MPR concludes that a correlation to expansion using normalized tensile strength is unlikely to be more sensitive than a correlation using normalized elastic modulus.

3.2 DEVELOPMENT OF CORRELATION BETWEEN MODULUS AND EXPANSION

3.2.1 Data from Test Program

Figure 3-3 includes a plot of the test data for reduction in modulus of elasticity and the corresponding through-thickness expansion measurements (Reference 13; Appendix A). The plot uses a normalized modulus value that is the ratio of the elastic modulus at the time the expansion measurement was obtained (E_t) divided by the 28-day elastic modulus (E_o).

[redacted]

Figure 3-3. Elastic Modulus as a Function of Through-Thickness Expansion from Test Data (Reference 13)

Results of calculations using the data from Figure 3-3 include the following:

- The correlation shown in Figure 3-3 has the following equation determined by [redacted] least-squares regression (Reference 13; Appendix A):

  [redacted] [Equation 1]

- The correlation fits well with the data and therefore supports use of [redacted] formulation. The coefficient of determination (R^2) is [redacted] (Reference 13; Appendix A). MPR performed scoping evaluations of several different forms of the equation for the correlation and determined that a [redacted] formulation [redacted] provided the best fit.

3.2.2 Data from Literature

As part of the Reference 13 calculation, MPR compared the relationship developed from the FSEL test data against data available in literature (References 14, 15, and 16) in Figure 3-4. The literature data reflect small specimens that were cast and cured as unconfined concrete.

[redacted]

Figure 3-4. Comparison of Derived Relationship with Literature Data (Reference 13)

Overall, the trend from the literature data compares favorably with the correlation generated from the FSEL data. Accordingly, the comparison to literature data corroborates application of the experimentally-determined correlation at Seabrook Station.

3.2.3 Applicability of Correlation to Seabrook Station

The correlation developed from the FSEL data relating expansion to reduction in elastic modulus is applicable to reinforced concrete structures at Seabrook Station. The test data used to generate the correlation were obtained from test specimens that were designed to be as representative as practical of the concrete at Seabrook Station, including the reinforcement detailing. Additionally, comparison against literature data shows that the correlation follows a trend that is consistent with other published studies which cover a range of concrete mixtures.

3.3 ESTABLISHING ORIGINAL ELASTIC MODULUS AT SEABROOK

The correlation shown in Figure 3-3 and provided in Equation 1 uses the 28-day elastic modulus as an input for determining expansion. However, consistent with typical construction practices, material property testing of concrete used at Seabrook Station verified only the 28-day compressive strength; the elastic modulus was not measured. This section describes two approaches for establishing the 28-day elastic modulus for concrete at Seabrook Station.

MPR notes that there are differences between the original elastic modulus data used to generate Equation 1 and data that will be used to determine pre-instrument expansion at Seabrook Station. These differences are assessed in Section 4.2.

3.3.1 Approach 1: Code Equation Based on Compressive Strength

ACI 318-71 (Reference 17) provides the following equation for the elastic modulus of concrete (E_c) calculated based on compressive strength (f_c') and the density of concrete in lb/ft^3 (w_c):

$$E_c = 33 \times w_c^{1.5} \times \sqrt{(f_c')} \qquad \text{[Equation 2]}$$

The equation presented in ACI 318-71 is based on fitting a curve to publicly available information on compressive strength and elastic modulus of various concrete specimens. The data used cover a range of concrete mixtures from lightweight concrete to normal weight concrete.

Confirmation of Code Equation for FSEL-Generated Data

Using data from the test program for 28-day compressive strength and elastic modulus for a concrete mix design that represented Seabrook Station, MPR confirmed that the ACI equation is applicable (Reference 18; Appendix B). ACI 318-71 states that the actual elastic modulus is expected to be within ±20% of the calculated value. As shown in Figure 3-4, [redacted] of [redacted] data points ([redacted]%) obtained from the test program met this criterion.

[redacted]

Figure 3-5. Comparison of Test Data to ACI Equation (Reference 18)

MPR concludes that the ACI 318-71 equation is applicable for concrete at Seabrook Station for the following reasons:

- The FSEL data are consistent with the equation from ACI 318-71 and the stated variance of ±20%.
- The concrete test specimens fabricated by FSEL were designed to be representative of the concrete used at Seabrook Station and therefore better represent the concrete at Seabrook than the range of mixtures used to generate the code equation.

Original Compressive Strength
Using original construction records for compressive strength tests and the ACI 318-71 correlation, NextEra could establish the 28-day elastic modulus.

NextEra has retrieved records for concrete fabrication from original construction for selected buildings. For convenience, MPR Calculation 0326-0062-CLC-02 (Reference 19; Appendix C) summarizes the currently-available 28-day compressive strength test results and the buildings associated with those results. NextEra may need to retrieve additional original construction records to implement this approach. [4]

In addition, NextEra has statistical analysis of over 5,000 compressive strength specimens representing 12 mix classes used during original construction (Reference 20). These data could be applied if NextEra can identify the mix class used for a particular concrete surface.

3.3.2 Approach 2: Reference Cores

An alternative approach for determining the original elastic modulus is to obtain and test reference cores for elastic modulus from concrete at Seabrook Station that is not affected by ASR. The elastic modulus determined using the reference cores would then be applied as equivalent to the 28-day elastic modulus ($E_{o,\text{ ref. core}}$).

NextEra is installing through-thickness expansion monitoring instrumentation in "control" locations where ASR has not affected the concrete. NextEra would test the cores obtained during installation to obtain elastic modulus results.

To implement this approach, NextEra would need to justify that the reference cores were representative of original construction concrete for the location in question. Petrographic examination of the cores (potentially after elastic modulus testing) would conclusively determine that the reference core is not affected by ASR. The original construction data discussed in Appendix C indicate that there are differences in material properties among the buildings at Seabrook Station. NextEra should evaluate selection of a representative reference core on a case-by-case basis.

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[4] Seabrook Station has installed eighteen extensometers and has provided MPR with applicable original construction records and material property information (i.e., elastic modulus data from cores taken at the locations of interest). MPR calculated the expansion to-date using the data provided by Seabrook and the correlation described in Section 4. The values are recorded in Reference 27.

3.3.3 Selection of an Approach for Determining Original Elastic Modulus

The approach (Approach 1 or Approach 2) should be selected based on specific considerations of the area being evaluated. If both approaches are feasible, both approaches may be used to validate the results using two independent means.

4

Recommended Approach

4.1 OVERVIEW OF APPROACH

MPR recommends the following approach for determining ASR-induced through-thickness expansion for instrumented locations at Seabrook Station.

1. Determine the current elastic modulus of the concrete by testing of cores removed from the structure. Elastic modulus testing requires companion compressive strength testing, so MPR recommends obtaining a minimum of four specimens. Two test specimens are for compressive strength testing and two test specimens are for subsequent elastic modulus testing.

2. Establish the original elastic modulus of the concrete by one of the following methods:

   - Using the ACI 318-71 correlation to calculate elastic modulus from 28-day compressive strength test results.

   - Obtaining cores from ASR-free locations and testing for elastic modulus.

3. Calculate the reduction in elastic modulus by finding the ratio of the test result from the ASR-affected area to the original elastic modulus.

4. Quantify through-thickness expansion from original construction to the time the extensometer is installed using the correlation developed in this report. The correlation relates reduction in elastic modulus with measured expansion from beam specimens used during the large-scale ASR structural testing program. A normalized modulus reduction factor of [redacted], discussed in Section 4.2, is used to address uncertainty.

5. Calculate the total expansion by adding the extensometer measurement to the expansion at the time of instrument installation.

4.2 UNCERTAINTY CONSIDERATIONS

This section discusses the sources of uncertainty and summarizes the impact it has on the recommended approach. The uncertainties associated with taking cores and with the overall methodology are addressed separately.

4.2.1 Taking Cores

Dimensions

The approximate dimensions of the cores obtained from the large-scale test specimens and the cores obtained from Seabrook Station will be nominally identical (4-inch diameter and 8-inch length). Material tests of specimens with dimensions that are nominally identical will not require corrections for reduced size specimens. Consequently, uncertainty associated with size variation will be negligible for the majority of the cores obtained from Seabrook Station.

MPR acknowledges that, in some cases NextEra may not be able to obtain cores of the planned length due to the fact that the core boring process can result in fracture of the core specimen, which reduces the usable length for material property testing. ASTM guidance regarding reduced length cores will be followed in these situations.

Orientation

The orientation of cores obtained from the large-scale test specimens and cores obtained from Seabrook Station will also be the same (i.e., perpendicular to the embedded reinforcement mats). Therefore, there is no uncertainty related to orientation of the core relative to the dominant direction of expansion.

Location

For the large-scale test program, the cores were obtained from locations that were in the central portion of the test specimens, through the openings in the reinforcement mats. These locations were not subject to edge effects and laboratory procedures required strict controls on specimen treatment (e.g., exposure in the environmental conditioning facility). Therefore, exposure conditions were consistent across the entire specimen and variability in ASR development within a test specimen was low.

At Seabrook Station, ASR-related expansion is not typically consistent across a single concrete member. As a result, the locations for extensometer placement (and therefore coring) will be in the areas that have the greatest symptoms of ASR-related expansion. This approach will conservatively characterize the elastic modulus of the concrete member in question.
Because this approach is inherently conservative, quantitative treatment of uncertainty for core location is not necessary.

4.2.2 Methodology

Adjusted Correlation

A normalized modulus reduction factor of [redacted] can be applied to Equation 1 to add conservatism to the calculated through-thickness values. This added conservatism helps to address the uncertainty associated with the original modulus (calculated from the original compressive strength using the ACI 318-71 correlation) and the measurement variability in current modulus.

The reduction factor should be applied using Equation 3.

[redacted] [Equation 3]

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Equation 1 (purple line), Equation 3 (green line), and the averages of the FSEL data (blue diamonds) are plotted in Figure 4-1. As shown in the graph, Equation 3 bounds or closely approximates all but one of the FSEL data points.

[redacted]

Figure 4-1. Adjusted Correlation

Equation 3 will yield conservative results on a consistent basis. For example, consider a location in which the ratio of the current elastic modulus to the original elastic modulus (i.e., the normalized elastic modulus) is [redacted]. Use of Equation 1 will result in a through-thickness expansion value of [redacted] while use of Equation 3 will result in a through-thickness expansion value of [redacted]. In this case, application of Equation 3 will provide a conservatism of [redacted] (i.e., [redacted] delta expansion / [redacted] nominal expansion), increasing the calculated expansion by [redacted] expansion.

Variability in Current Elastic Modulus

The current elastic modulus at Seabrook Station will be determined using cores from the plant. This process is identical to the approach used to determine the elastic modulus from the test data used to develop the correlation. In addition, elastic modulus testing has been and will continue to be performed per ASTM C469-10. The inherent conservatism provided by use of Equation 3 is sufficient to account for any uncertainty associated with the testing method.

Determining Original Elastic Modulus

For the data used to prepare Equation 1, the original elastic modulus is the average elastic modulus test result from cylinders tested 28 days after test specimen fabrication. There are differences between the data used to obtain Equation 1 and the data that will be used to determine pre-instrument expansion at Seabrook Station.

- For Approach 1 at Seabrook Station, the original elastic modulus will be calculated using the 28-day compressive strength test results and the correlation in ACI 318-71.
- For Approach 2 at Seabrook Station, the original elastic modulus will be calculated using the average elastic modulus test result of "reference" cores obtained at the time of extensometer installation. The reference cores will be obtained from a nearby area from the same concrete placement that does not exhibit signs of ASR.

As shown in Figure 3-5, the ACI 318-71 correlation calculates the original elastic modulus within ±20% of the actual original elastic modulus. In instances in which the correlation over-predicts the original elastic modulus, use of the correlation adds conservatism to the approach. In instances in which the correlation under-predicts the original elastic modulus, application of the normalized modulus reduction factor of [redacted] adds sufficient conservatism to account for the delta.

It is important to note that Approach 2 uses cores, so the variability associated with the ACI 318-71 correlation is not applicable.

5

Implementation of Recommended Approach

5.1 EXPANSION TO-DATE AT SEABROOK STATION

Seabrook Station is installing extensometers to monitor through-thickness expansion. Eighteen extensometers have been installed to date. Cores were taken at each extensometer location and elastic modulus testing was performed to support determination of the through-thickness expansion to-date (i.e., the pre-instrument expansion values). The original elastic modulus values were determined using Approach 1. The through-thickness expansion values were calculated using Equation 3, which includes the normalized modulus reduction factor of [redacted].

Determination of the through-thickness expansion values is documented in MPR Calculation 0326-0062-CLC-04 (Reference 27, Appendix D). The results of the calculation are provided in Table 5-1 for reference. NextEra will add these values to the extensometer readings going forward in order to determine the current through-thickness expansion at each extensometer location.

Table 5-1. Through-Thickness Expansion To-Date (Reference 27)

Location ID	Through-Thickness Expansion
E1	[redacted]
E2	[redacted]
E3	[redacted]
E4	[redacted]
E5	[redacted]
E6	[redacted]
E7	[redacted]
E8	[redacted]
E9	[redacted]
E10	[redacted]
E11	[redacted]
E12	[redacted]
E13	[redacted]

Table 5-1. Through-Thickness Expansion To-Date (Reference 27)

Location ID	Through-Thickness Expansion
E14	[redacted]
E15	[redacted]
E16	[redacted]
E18	[redacted]
E19	[redacted]

Note:
E17 was not a part of the first set of extensometer locations.

5.2 CONSERVATISM IN THROUGH-THICKNESS EXPANSION FROM THE NORMALIZED MODULUS REDUCTION FACTOR

Table 5-2 compares the resultant through-thickness values for the initial eighteen extensometer locations using Equation 1 (i.e., nominal) and Equation 3 (i.e., adjusted) to assess the level of conservatism provided by using a normalized modulus reduction factor of [redacted].

Table 5-2. Comparison of Through-Thicknesses for Equations 1 and 3

Location ID	Nominal Through-Thickness Expansion (Equation 1)	Adjusted Through-Thickness Expansion (Equation 3)
E1	[redacted]	[redacted]
E2	[redacted]	[redacted]
E3	[redacted]	[redacted]
E4	[redacted]	[redacted]
E5	[redacted]	[redacted]
E6	[redacted]	[redacted]
E7	[redacted]	[redacted]
E8	[redacted]	[redacted]
E9	[redacted]	[redacted]
E10	[redacted]	[redacted]

Table 5-2. Comparison of Through-Thicknesses for Equations 1 and 3

Location ID	Nominal Through-Thickness Expansion (Equation 1)	Adjusted Through-Thickness Expansion (Equation 3)
E11	[redacted]	[redacted]
E12	[redacted]	[redacted]
E13	[redacted]	[redacted]
E14	[redacted]	[redacted]
E15	[redacted]	[redacted]
E16	[redacted]	[redacted]
E18	[redacted]	[redacted]
E19	[redacted]	[redacted]

Key observations include the following:

- For the highest through-thickness expansion value of [redacted] (location E9), use of Equation 3 increased the expansion value to [redacted] (i.e., +[redacted] expansion). The impact of the normalized modulus reduction factor (in absolute terms) increases with ASR progression (i.e., at higher levels of expansion).
- In relative terms, application of Equation 3 to the highest through-thickness expansion value (location E9) produced a conservatism of [redacted] (i.e., [redacted] expansion / [redacted] expansion).

Furthermore, the relative conservatism associated with Equation 3 is higher at lower ASR progression levels. As an example, for location E1, where nominal expansion is [redacted] the relative conservatism of using Equation 3 is [redacted] (i.e., [redacted] expansion/[redacted] expansion).

6
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7. Test Program Drawings

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   7.2. FSEL Drawing DWG_0326-0063_[redacted]-G, [redacted]-*Inch Anchorage Specimen Geometry*, Revision 3.

   7.3. FSEL Drawing DWG_0326-0063_[redacted]-R1, [redacted]-*Inch Shear Specimen Reinforcement*, Revision 1.

   7.4. FSEL Drawing DWG_0326-0063_[redacted]-R1, [redacted]-*Inch Anchorage Specimen Reinforcement*, Revision 3.

   7.5. FSEL Drawing DWG_0326-0063_[redacted]-R2, [redacted]-*Inch Instrumentation Specimen Reinforcement - Assembly*, Revision 0.

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