UNITED STATES OF AMERICA
NUCLEAR REGULATORY COMMISSION

ATOMIC SAFETY AND LICENSING BOARD

In the Matter of NEXTERA ENERGY SEABROOK, LLC (Seabrook Station, Unit 1)	Docket No. 50-443-LA-2 ASLBP No. 17-953-02-LA-BD01

Hearing Exhibit

Exhibit Number: INT023

Exhibit Title: Simpson Gumpertz & Heger Document No. 170444-L-003 Rev. 1, Response to RAI-D8-Attachment 1 Example Calculation of Rebar Stress For a Section Subjected to Combined Effect of External Axial Moment and Internal ASR (Enclosure 4 to Letter SBK-L-18074)

Enclosure 4 to SBK-L-18074

Simpson Gumpertz & Heger Document No. 170444-L-003 Rev. 1, "Response to RAI-D8-Attachment 1 Example Calculation of Rebar Stress For a Section Subjected to Combined Effect of External Axial Moment and Internal ASR."

		PROJECT NO:	170444
		DATE:	Dec 2017
CLIENT:	NextEra Energy Seabrook	BY:	MR.M.Gargari
SUBJECT:	Example Calculation of Rebar Stress	VERIFIER:	A. T. Sarawit

RESPONSE TO RAI-D8-ATTACHMENT 1

EXAMPLE CALCULATION OF REBAR STRESS FOR A SECTION SUBJECTED TO COMBINED EFFECT OF EXTERNAL AXIAL AND MOMENT AND INTERNAL ASR

1. REVISION HISTORY

Revision 0: Initial document.

2. OBJECTIVE OF CALCULATION

The objective of this calculation is to provide an example calculation of rebar stress used in parametric studies 1 and 2 in response to RAI-D8.

3. RESULTS AND CONCLUSIONS

Table 1 summarizes the tensile stress in rebars corresponding to constant axial force and moment with an increasing ASR expansion. The results are also plotted in Figure 1b. This data is used to draw diagrams similar to what presented in Figure 3b of parametric study 1.

4. DESIGN DATA / CRITERIA

Diagrams presented in the response to RAI-D8 are extracted for two extreme sections one with minimum reinforcement ratio and the other with maximum reinforcement ratio. There is no other criteria.

5. ASSUMPTIONS

5.1 Justified assumptions

The concrete material is represented by compression only elastoplastic material with compressive strain cutoff of 0.003. This simple constitutive model satisfactorily captures the response of concrete in compression because stresses are not near reaching the compressive strength. Attachment 2 Appendix H provides a comparison study between the stresses in rebars of the critical component of two structures (with high and low compressive stress in concrete) computed using two different constitutive models for concrete, namely:

- Accurate model that uses Kent and Park concrete response in compression
- Simple model/idealized model which is an elastoplastic model with compressive stress cutoff at compressive strain of 0.003

The concrete strength in tension is conservatively neglected.

5.2 Unverified assumptions

There are no unverified assumptions.

6. METHODOLOGY

As an example calculation, Case I for a section with high reinforcement ratio is considered. The section is 2ft thick with 3000psi concrete that is reinforced with #11@6in. on both faces. The point corresponding to case I is highlighted on P-M interaction diagram provided in Figure 1. The amount of axial force and moment for Case I are -128.5kip/ft and 174.2kip-ft/ft, respectively.

To calculate the diagram in parametric study 1, the axial force and moment are kept constant while the internal ASR load is increased. Such a diagram is presented in Figure 3 of the response to RAI-D8. For the second parametric study, specific ASR expansion is selected and the amount of moment is increased. The calculation presented here provides an example for both parametric studies. In fact, the loading sequence does not matter.

The stress in rebars is calculated considering the following steps:

1) The geometry including thickness, rebar size, spacing, etc. are provided.
2) The compatibility and equilibrium equations are satisfied for concrete and steel when the concrete undergoes expansion due to internal ASR. Consequently, the initial stresses in concrete and steel are calculated.
3) Appropriate material model are assigned for concrete and steel. Specifically, elastic material for steel and an elastoplastic material for concrete are used.
4) Section is discretized into 20 layers, and appropriate functions are developed to facilitate the calculation of strain and stress at middle of each layer. Steel layers are also used at the center of rebars at each faces.
5) By knowing the value of axial force "P" (P = -128.5kip/ft), the curvature value "φ" is iterated to minimize the difference between the target moment (M = 174.2kip-ft/ft) and the moment from sectional analysis based on inputted axial force and trial curvature.
6) Using the developed functions, the strain and consequently stress are calculated for each steel fiber and at the farthest edge of the concrete compressive fiber.

7. REFERENCES

There are no references

8. COMPUTATION

8.1. Strain in Steel and Concrete due to Internal ASR expansion

Input Data

ASR expansion

Measured crack index $\varepsilon_{CI} := 0.8 \frac{mm}{m}$

Threshold factor $F_{thr} := 1$

Material properties

Compressive strength of concrete $f_c := -3ksi$

Young's modulus of concrete $E_c := 3120ksi$

Yield strength of steel $f_y := 60ksi$

Young's modulus of steel $E_s := 29000ksi$

Geometry

Width of fibers $b := 12in$

Total thickness or height $h := 24in$

Area of concrete $A_c := b \cdot h = 288 \cdot in^2$

Area of tensile reinforcement (#8@12 in.) $A_s := 2 \cdot 1.56in^2$

Number of reinforcement in row, e.g. equal to 2 for tensile and compressive $Steel_{Num} := 2$

Depth to reinforcement $d := 20.3in$

Finding the strain in steel and concrete by satisfying compatibility and equilibrium

Initial Guess

Initial mechanical strain in concrete $\varepsilon_{o.conc} := 0$

Initial strain in steel $\varepsilon_{o.steel} := 0$

Given

Compatibility equation $F_{thr} \cdot \varepsilon_{CI} = \varepsilon_{o.steel} - \varepsilon_{o.conc}$

Equilibrium equation $\left(E_c \cdot A_c\right) \cdot \varepsilon_{o.conc} + \left(E_s \cdot A_s \cdot Steel_{Num}\right) \cdot \varepsilon_{o.steel} = 0$

$ans := Find\left(\varepsilon_{o.conc}, \varepsilon_{o.steel}\right)$

Initial strain in concrete and steel

$\varepsilon_{o.conc} := ans_1 = -1.341 \times 10^{-4}$

$\varepsilon_{o.steel} := ans_2 = 6.659 \times 10^{-4}$

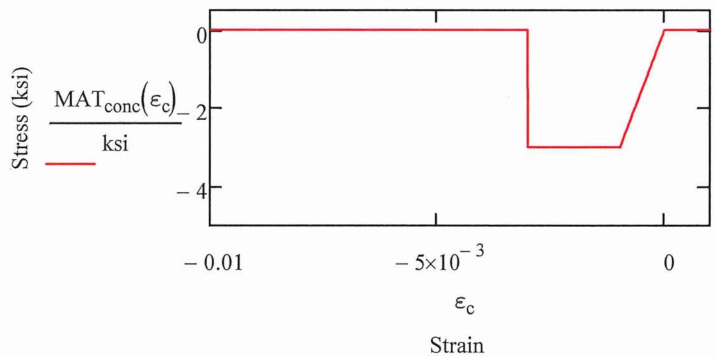
8.2. Sectional Analysis

Input Data

Concrete Material Model

Constitutive model for concrete

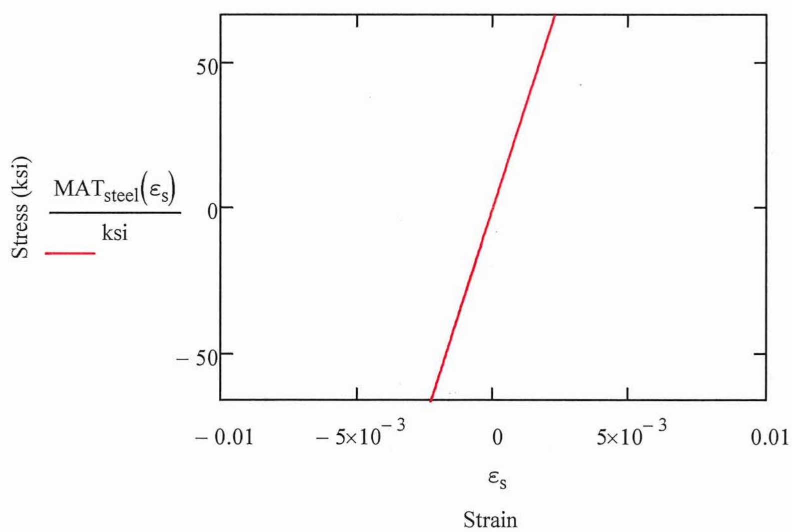
$$MAT_{conc}(\varepsilon) := \begin{vmatrix} 0 \text{ if } \varepsilon > 0 \\ f_c \text{ if } -0.003 \le \varepsilon < \dfrac{f_c}{E_c} \\ 0 \text{ if } \varepsilon < -0.003 \\ \left(E_c \cdot \varepsilon\right) \text{ otherwise} \end{vmatrix}$$



Steel Material Model

Constitutive model for steel

$MAT_{steel}(\varepsilon) := E_s \cdot \varepsilon$



Concrete Fibers

Number of fibers $Conc_{Num} := 20$

Height of fibers $Conc_H := \dfrac{h}{Conc_{Num}} = 1.2 \cdot in$

Concrete fiber coordinates

$$Conc_y := \left| \begin{array}{l} \text{for } i \in 1..Conc_{Num} \\ \quad ans_i \leftarrow -\dfrac{h}{2} + \dfrac{Conc_H}{2} + (i-1) \cdot Conc_H \\ ans \end{array} \right.$$

Concrete fiber strain

$$Conc_\varepsilon(\varepsilon_{o.conc}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{for } i \in 1..Conc_{Num} \\ \quad ans_i \leftarrow \varepsilon_{o.conc} + \varepsilon - \varphi \cdot Conc_{y_i} \\ ans \end{array} \right.$$

Concrete fiber stress

$$Conc_\sigma(\varepsilon_{o.conc}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{for } i \in 1..Conc_{Num} \\ \quad ans_i \leftarrow MAT_{conc}\left(Conc_\varepsilon(\varepsilon_{o.conc}, \varepsilon, \varphi)_i\right) \\ ans \end{array} \right.$$

Concrete fiber force

$$Conc_F(\varepsilon_{o.conc}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{for } i \in 1..Conc_{Num} \\ \quad ans_i \leftarrow Conc_\sigma(\varepsilon_{o.conc}, \varepsilon, \varphi)_i \cdot (b \cdot Conc_H) \\ ans \end{array} \right.$$

Reinforcement/Steel fibers

Depth to reinforcement fiber

$$Steel_{y_1} := -\left(d - \frac{h}{2}\right) = -8.3 \cdot in$$

$$Steel_{y_2} := d - \frac{h}{2} = 8.3 \cdot in$$

Area of reinforcement fiber

$$Steel_{As_1} := A_s = 3.12 \cdot in^2$$

$$Steel_{As_2} := A_s = 3.12 \cdot in^2$$

Steel fiber strain

$$Steel_\varepsilon(\varepsilon_{o.steel}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{for } i \in 1..Steel_{Num} \\ \quad ans_i \leftarrow \varepsilon_{o.steel} + \varepsilon - \varphi \cdot Steel_{y_i} \\ ans \end{array} \right.$$

Steel fiber stress

$$Steel_\sigma(\varepsilon_{o.steel}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{for } i \in 1..Steel_{Num} \\ \quad ans_i \leftarrow MAT_{steel}\left(Steel_\varepsilon(\varepsilon_{o.steel}, \varepsilon, \varphi)_i\right) \\ ans \end{array} \right.$$

Steel fiber force

$$Steel_F(\varepsilon_{o.steel}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{for } i \in 1..Steel_{Num} \\ \quad ans_i \leftarrow Steel_\sigma(\varepsilon_{o.steel}, \varepsilon, \varphi)_i \cdot Steel_{As_i} \\ ans \end{array} \right.$$

Initial Stress State

Initial stress in concrete

$$\text{Concrete}_{\sigma} := \text{Conc}_{\sigma}\left(\varepsilon_{o.conc}, 0, 0\right)$$

$$\text{Concrete}_{\sigma_1} = -0.418 \cdot \text{ksi}$$

Initial stress in steel

$$\text{Rebar}_{\sigma} := \text{Steel}_{\sigma}\left(\varepsilon_{o.steel}, 0, 0\right)$$

$$\text{Rebar}_{\sigma_1} = 19.311 \cdot \text{ksi}$$

Axial Equilibrium

$$\text{Force}\left(\varepsilon_{o.conc}, \varepsilon_{o.steel}, \varepsilon, \varphi\right) := \left| \begin{array}{l} \text{ans1} \leftarrow 0 \\ \text{for } i \in 1 .. \text{Conc}_{Num} \\ \quad \text{ans1} \leftarrow \text{ans1} + \text{Conc}_F\left(\varepsilon_{o.conc}, \varepsilon, \varphi\right)_i \\ \text{ans2} \leftarrow 0 \\ \text{for } i \in 1 .. \text{Steel}_{Num} \\ \quad \text{ans2} \leftarrow \text{ans2} + \text{Steel}_F\left(\varepsilon_{o.steel}, \varepsilon, \varphi\right)_i \\ \text{ans} \leftarrow \text{ans1} + \text{ans2} \end{array} \right.$$

Moment Equilibrium

$$\text{Moment}\left(\varepsilon_{o.conc}, \varepsilon_{o.steel}, \varepsilon, \varphi\right) := \left| \begin{array}{l} \text{ans1} \leftarrow 0 \\ \text{for } i \in 1 .. \text{Conc}_{Num} \\ \quad \text{ans1} \leftarrow \text{ans1} + -1 \cdot \text{Conc}_F\left(\varepsilon_{o.conc}, \varepsilon, \varphi\right)_i \cdot \text{Conc}_{y_i} \\ \text{ans2} \leftarrow 0 \\ \text{for } i \in 1 .. \text{Steel}_{Num} \\ \quad \text{ans2} \leftarrow \text{ans2} + -1 \cdot \text{Steel}_F\left(\varepsilon_{o.steel}, \varepsilon, \varphi\right)_i \cdot \text{Steel}_{y_i} \\ \text{ans} \leftarrow \text{ans1} + \text{ans2} \end{array} \right.$$

Solution

Known parameters

Axial force $P := -128.52 \text{kip}$

Iteration

Curvature $\phi := 0.000046 \cdot \frac{1}{\text{in}}$ Requires iteration

Solve for strain at centroid

Axial strain at centroid (initial guess) $x_o := 0.0$

Axial force equilibrium

$$f(x) := \text{Force}(\varepsilon_{o.conc}, \varepsilon_{o.steel}, x, \phi) - P$$

$$\varepsilon_{cent} := \text{root}(f(x_o), x_o) = -7.471 \times 10^{-5}$$

Sectional forces

$$\text{Force}(\varepsilon_{o.conc}, \varepsilon_{o.steel}, \varepsilon_{cent}, \phi) = -128.52 \cdot \text{kip}$$

$$\text{Moment}(\varepsilon_{o.conc}, \varepsilon_{o.steel}, \varepsilon_{cent}, \phi) = \blacksquare \cdot \text{kip} \cdot \text{ft}$$

Stress and strain in concrete and steel

Steel fiber stress and strain

$$\text{Rebar}_{\varepsilon} := \text{Steel}_{\varepsilon}(\varepsilon_{o.steel}, \varepsilon_{cent}, \phi) = \begin{pmatrix} 9.73 \times 10^{-4} \\ 2.094 \times 10^{-4} \end{pmatrix}$$

$$\text{Rebar}_{\sigma} := \text{Steel}_{\sigma}(\varepsilon_{o.steel}, \varepsilon_{cent}, \phi) = \begin{pmatrix} 28.217 \\ 6.072 \end{pmatrix} \cdot \text{ksi}$$

$$\text{Steel}_{F}(\varepsilon_{o.steel}, \varepsilon_{cent}, \phi) = \begin{pmatrix} 88.036 \\ 18.946 \end{pmatrix} \cdot \text{kip}$$

$$\text{Concrete}_{y} := \text{Conc}_{y}$$

Concrete fiber stress and strain

$$\text{Concrete}_{\varepsilon} := \text{Conc}_{\varepsilon}(\varepsilon_{o.conc}, \varepsilon_{cent}, \phi)$$

$$\text{Concrete}_{\sigma} := \text{Conc}_{\sigma}(\varepsilon_{o.conc}, \varepsilon_{cent}, \phi)$$

Maximum compressive strain in concrete

$$\varepsilon_{max.comp} := \frac{\text{Concrete}_{\varepsilon_{ConcNum}} - \text{Concrete}_{\varepsilon_{ConcNum-1}}}{\text{Conc}_{y_{ConcNum}} - \text{Conc}_{y_{ConcNum-1}}} \cdot \left(\frac{h}{2} - \text{Conc}_{y_{ConcNum-1}}\right) \dots + \text{Concrete}_{\varepsilon_{ConcNum-1}} = -7.608 \times 10^{-4}$$

Maximum compressive stress in concrete

$$\sigma_{max.comp} := \text{MAT}_{conc}(\varepsilon_{max.comp}) = -2.374 \cdot \text{ksi}$$

9. TABLES

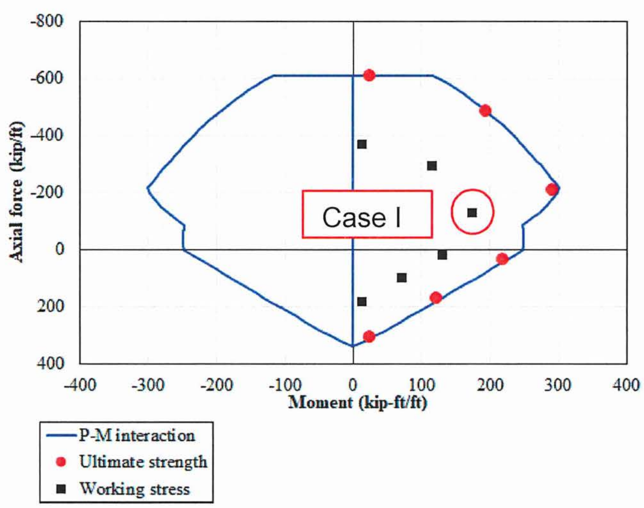
Table 1: Stress in rebars of 2ft thick section with high reinforcement ratio for P=-128.52kip/ft and M=174.24kip-ft/ft

			Total stress in steel (ksi)		Maximum compressive stress in concrete (ksi)
CI (mm/m)	initial stress in concrete (ksi)	Curvature, φ (1/in)*	Rebar 1	Rebar 1	
0	0	0.00007	19.737	-13.961	-2.31
0.4	9.655	0.000056	22.869	-4.089	-2.334
0.8	19.311	0.000046	28.217	6.072	-2.374
1.2	28.966	0.00004	35.511	16.255	-2.457
1.6	38.622	0.000038	44.377	26.084	-2.624
2	48.277	0.0000375	53.851	35.799	-2.821

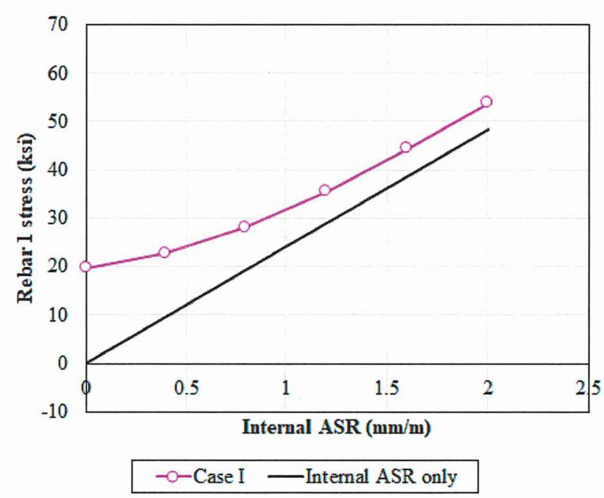
***The curvature needs to be found iteratively to satisfy the moment equilibrium**

Example in Section 8

10. FIGURES



(b) Location of Case I in P-M interaction



(b) Stress in the critical rebar of Case I

Figure 1: Results for Case I

RESPONSE TO RAI-D8-ATTACHMENT 2

EVALUATION OF MAXIMUM STRESS IN REBARS OF SEABROOK STRUCTURES

1. REVISION HISTORY

Revision 0: Initial document.

Revision 1: Revised pages 9, 10, 11 and 12 from Revision 0 to 1. The revision was made to remove footnotes 'a' and 'b' which identified CEB results to be preliminary, and WPC/PH and EMH results to be pending final review. Revised pages 1 to update Revision history section. Revised page 13 to update revision of references 7 and 8.

2. OBJECTIVE OF CALCULATION AND SCOPE

The objective of this calculation is to evaluate the stress in rebars of the structures at NextEra Energy (NEE) Seabrook Station in Seabrook, New Hampshire for in-situ load combinations considering unfactored normal operating loads when adding the loads due to ASR. All demands are from the ASR susceptibility evaluation of each structure.

The scope of this calculation includes the following structures:

- Control Room Makeup Air Intake structure (CRMAI)
- Residual Heat Removal Equipment Vault structure (RHR)
- Containment Enclosure Building (CEB)
- Enclosure for Condensate Storage Tank (CSTE)
- Main steam and feed water west pipe chase and Personnel Hatch (WPC/PH)
- Containment Equipment Hatch Missile Shield structure (CEHMS)
- Containment Enclosure Ventilation Area (CEVA)
- Safety-Related Electrical Duct Banks and Manholes (EMH) W01, W02, W09, and W13 through W16

3. RESULTS AND CONCLUSIONS

Stress evaluation results are listed below:

- The structure is evaluated for the load combinations listed in Section 4. The load combination listed below controls the calculation of maximum stress in rebars.
  - $D + L + E + T_o + E_o + H_e + F_{THR}.S_a$ (LC2)
- The stress in rebars of all structural components remain below yield strength. The following components give the highest stress in rebars:
  - Rebars along the horizontal strip of east exterior wall of the RHR structure at approximate elevation of -30 ft are stressed to 56.5 ksi subjected to LC2. The high stress is expected to occur in localized area, and therefore, the moment can distributed to mid span in susceptibility evaluation of the structure [3]. In addition, the stresses are expected to less because of the conservatism including a limited model of PAB as connected to RHR as explained in Section 6.3.
  - The maximum axial stress of 55.6 ksi is expected in rebars of the wall above east corner of Electrical Penetration at EL +45 ft subjected to LC2 in CEB.
  - Rebars along the horizontal strip at east wall of CRMAI structure are expected to experience tensile stress as high as 43.3ksi. The CI/CCI value over the walls of the structure is zero, and the induced demands are mainly due to relative expansion of the base mat with respect to walls.
  - Rebars in the east-west direction at the base slab of CEVA are expected to be stressed to 44 ksi if the CI value increases 200% beyond the current state. As explained in Section 6.6, the actual value is expected to be less because of the conservatism in computing unfactored demands due to original loads.

4. DESIGN DATA / CRITERIA

In response to RAI-D8 request, the maximum stress in the rebars of Seabrook structures is calculated and compared with yielding strength of rebars (f_y = 60ksi). In this evaluation, the following in-situ load combinations (also called service load and unfactored normal operating load) are considered:

- $D + L + E + T_o + S_a$ (In-situ condition, LC1)
- $D + L + E + T_o + E_o + H_e + F_{THR}.S_a$ (In-situ condition plus seismic load, LC2)

where D is dead load, L is live load, E is lateral earth pressure, T_o is operating temperature, E_o is the operating basis earthquake (OBE), H_e is dynamic earth pressure due to OBE, and S_a is ASR load. Operating temperature T_o is only applicable to the WPC/PH. For the second in-situ load combination, ASR loads are further amplified by a threshold factor (F_{THR}) to account for the future ASR expansion.

5. METHODOLOGY

To calculate the stress in rebars of structural components subjected to in-situ load combinations, sectional analysis based on fiber section method is used. In this method, the cross section is discretized into fibers (or layers), and an appropriate material model is assigned to each fiber. Figure 1 demonstrates a typical fiber section discretization. The total moment and axial force are calculated by integrating force over all fibers.

The concrete material is represented by compression only elastoplastic material with compressive strain cutoff of 0.003. This simple constitutive model satisfactorily captures the response of concrete in compression because stresses are not near reaching the compressive strength. Appendix H provides a comparison study between the stresses in rebars of the critical component of two structures (with high and low compressive stress in concrete) computed using two different constitutive models for concrete, namely:

- Accurate model that uses Kent and Park concrete response in compression
- Simple model/idealized model which is an elastoplastic model with compressive stress cutoff at compressive strain of 0.003

Both models are schematically depicted in Figure 2a. The concrete strength in tension is conservatively neglected. Reinforcing steel bars are modeled using elastic perfectly plastic material in compression and tension. Figure 2b demonstrates the steel material model used for the section analysis. The initial slope (Young modules) are 29,000 ksi for steel and $57{,}000\sqrt{f'_c}$ for concrete.

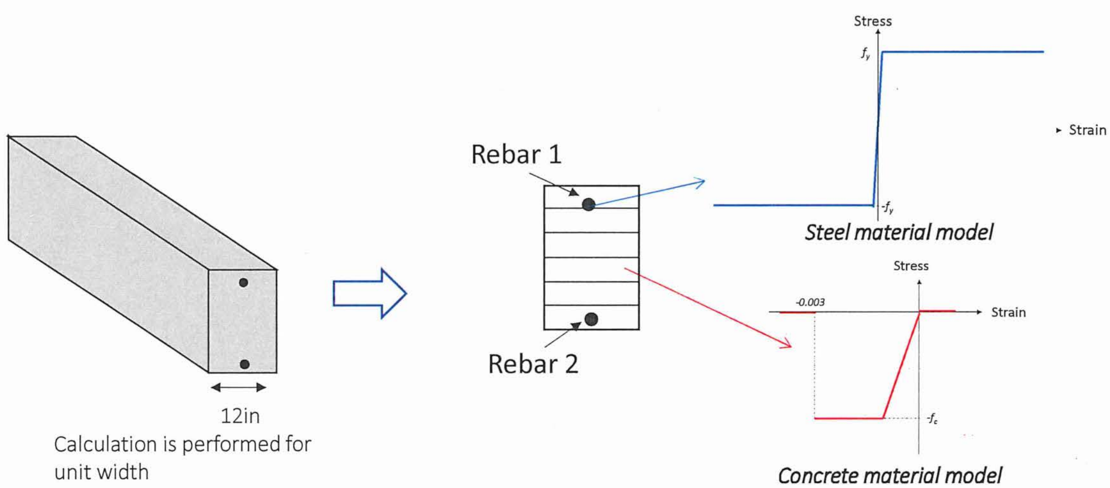
In this evaluation the ASR load effect causes:

- The axial force and bending moment that are induced by ASR expansion of other components (adjacent structural component)

- The internal stress in rebars due to ASR expansion of the component itself

The latter induces tensile stress in rebars and compressive stress in concrete that is called initial stress state. The effect of internal ASR expansion is considered by adding autogenous strain to the concrete and steel material. The input strain magnitude is set to be the ASR strain value measured over the specific component, and the output strains (initial strain in concrete and steel after application of ASR strain) are calculated by satisfying equilibrium and compatibility equations. If a member does not show any sign of internal ASR or the internal ASR expansion of the member was conservatively set equal to zero during ASR susceptibility evaluation of the structure, the initial stress in concrete and rebar are set to zero.

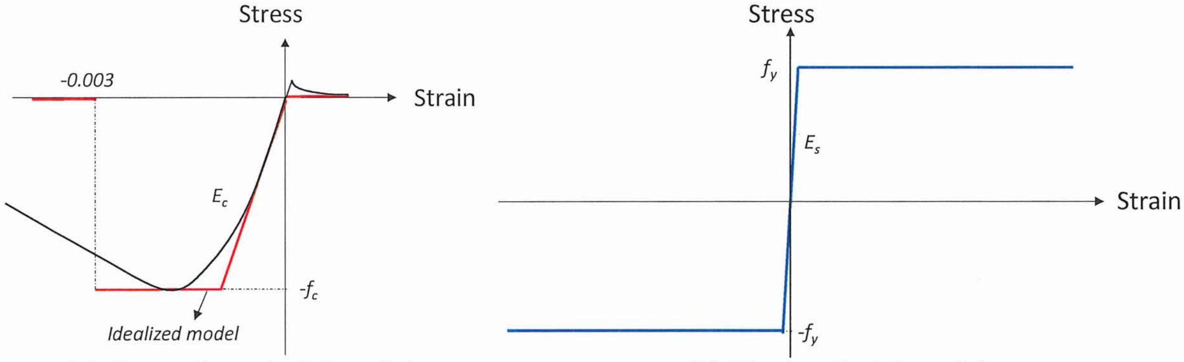
The critical sections that governed the calculation of threshold factor of each structure are selected for the evaluation, and demands due to combined effects of internal ASR expansion and induced ASR expansion of other components are computed with methods used in susceptibility evaluation of the structures. Appendix J provides Run ID logs. These demands are added to the demands subjected to original design loads, and the stress in rebars are calculated.



Actual concrete member

Fiber section discretization and material models

Figure 1 – Schematic representation of fiber section method



(a) Concrete material model (b) Steel material model

Figure 2 – Concrete and steel material model

6. ANALYSIS AND EVALUATION COMPUTATIONS

This section summarizes the maximum stress that are computed in rebars and concrete of several Seabrook structures at critical sections.

6.1 Control Room Makeup Air Intake structure

The stress in rebars of the critical components of CRMAI structure that governed the calculation of threshold factor is calculated and presented in Appendix A. Calculation of the threshold factor for the CRMAI structure is primarily governed by axial-flexure interaction along the horizontal strip of the east wall that occurs at the middle of the wall [1]. A threshold factor of 1.4 was determined from evaluation of the CRMAI structure, which indicates that ASR-related demands are amplified by 40% beyond the factored values.

Tables 1 and 2 summarize the stress in rebars of east wall and base mat of CRMAI structure. As can be seen from the table, the maximum axial stress is 43.3 ksi expected to form in a horizontal rebar of the walls close to the interior of the structure. The maximum stress in base mat that has highest ASR expansion within the structure is 39.1 ksi. Both stresses are below the yield strength of rebars.

6.2 Containment Enclosure Building

The stress in rebars at the critical section of the CEB structures is calculated and presented in Appendix B. The calculated threshold factor was 1.3 [2]. Tables 1 and 2 summarize the stress in rebars at two critical locations. The maximum axial stress of 55.6 ksi is expected in rebars of the wall above east corner of Electrical Penetration.

6.3 Residual Heat Removal Equipment Vault

The stress in rebars of the critical components of RHR structure that governed the calculation of threshold factor is calculated and presented in Appendix C. Calculation of the threshold factor for the RHR structure is primarily governed by axial-flexure interaction along the horizontal strip along the south side of the east exterior wall [3]. A threshold factor of 1.2 was determined from evaluation of the RHR structure, which indicates that ASR-related demands are amplified by 20% beyond the factored values.

Tables 1 and 2 list the stress in horizontal rebars of east exterior wall, and the stress in vertical rebars in west and east interior walls of RHR structure. As can be seen from the table, the maximum tensile stress of 59.5 ksi is expected in the vertical rebars of the east interior wall due to LC2. However, the RHR walls are designed to span horizontally between intersecting walls; and therefore, the vertical rebars are not part of the main load path for the RHR. Figure C1 shows the contour plots of vertical strains in the interior walls due to LC1. The contour plots show that the overall vertical strains are reasonable compared to the yielding strain of rebars. Localized strain concentration is observed close to the door openings at approximate El. (-) 30 ft. and El. (-) 45 ft.

The next highest tensile stress is 56.5 ksi calculated for the horizontal rebars of exterior east wall. The specific section also governed the determination of threshold factor for the RHR structure. As explained in the susceptibility evaluation of RHR [3], moment can distribute to mid span and along the width of the wall, therefore, localized strain concentration is not of concern. The majority of the stresses that develop at this location are due to the RHR connection to PAB. The PAB foundation locally stiffens the connection between the RHR and the PAB which attracts the moment demand about the vertical axis in the east exterior wall of the RHR. In addition, the PAB base slab is subject to uplift pressure from backfill expansion which in turns induces forces in the RHR external walls near the connection. The stresses in the RHR evaluation and as reported here are conservative due to only including a limited model of PAB as connected to RHR which introduces extra overturning moment as well as the expected vertical shear force at this connection.

6.4 Condensate Storage Tank Enclosure

The stress in rebars of the critical components of CSTE structure that governed the calculation of threshold factor is calculated and presented in Appendix D. Selection of threshold factor for the CSTE structure is primarily governed by hoop tension at the top of the tank enclosure wall and vertical moment at the base of the tank enclosure wall [4]. A threshold factor of 1.6 was determined from evaluation of the CSTE structure, which indicates that ASR-related demands are amplified by 60% beyond the factored values.

Tables 1 and 2 summarize the stress in rebars of the tank enclosure wall of the CSTE structure. As can be seen from the table, the maximum axial stress of 26.7 ksi is expected to form in vertical rebars at the bottom of the tank enclosure wall.

6.5 Containment Equipment Hatch Missile Shield

The stress in rebars of the critical components of CEHMS structure that governed the calculation of threshold factor is calculated and presented in Appendix E. Selection of threshold factor for the CEHMS structure is primarily governed by out-of-plane moment at the base of east wing wall [5]. A threshold factor of 1.5 was determined from evaluation of the CEHMS structure, which indicates that ASR-related demands are amplified by 50% beyond the factored values.

Tables 1 and 2 summarize the stress in rebars of east wing wall of CEHMS structure. The maximum axial stress is 41.6 ksi expected to form in vertical rebars of the east wing wall at top of the column.

6.6 Containment Enclosure Ventilation Area

The stress in rebars of the critical components of CEVA structure that governed the calculation of threshold factor is calculated and presented in Appendix F. Selection of threshold factor for the CEVA is primarily governed by out-of-plane moment at the base slab located in Area 3 (Areas are defined in Ref. 6). A threshold factor of 3.0 was determined from evaluation of the

CEVA structure, which indicates that ASR-related demands are amplified by 200% beyond the factored values.

Tables 1 and 2 summarize the stress in rebars at the base slab. The maximum computed axial stress in rebars of the base mat is 44 ksi. However, as explained in Appendix F, the original design calculation did not provide demands due to unfactored load cases/combinations; hence, a conservative value was selected for the evaluation of rebar stress presented in Appendix F.

6.7 West Pipe Chase and Personnel Hatch

The stress in rebars at the critical flexural section of the WPC/PH structures is calculated and presented in Appendix I. The threshold factor of 1.8 was calculated based on out-of-plane shear of the WPC west wall [7]. Tables 1 and 2 summarize the stress in rebars at the base of the WPC north wall, the critical tensile stress location. A maximum tensile stress of 44.4 ksi develops in horizontal rebars of the WPC north wall.

6.8 Electrical Manholes

The stress in rebars at the critical flexural section of the EMH W13 and W15 is calculated and presented in Appendix G. The calculated threshold factor was 3.7 [8]. Tables 1 and 2 summarize the stress in rebars in EMH W13 and W15. A maximum tensile stress of 27.0 ksi develops in the horizontal rebars of EMH W13 and W15.

PROJECT NO: 170444
DATE: Feb 2018
CLIENT: NextEra Energy Seabrook
BY: MR. M. Gargari
SUBJECT: Evaluation of maximum stress in rebars of Seabrook structures
VERIFIER: A.T. Sarawit

Table 1 – Stress in rebars of structural components subjected to LC1

	Component	Item		Internal ASR (mm/m)	Location	Total stress in steel (ksi)		Maximum compressive stress in concrete (ksi)	Maximum compressive mechanical strain in concrete
						Rebar 1	Rebar 2		
CRMAI	East Wall	M = 5.2	(kip-ft/ft)	0	East wall, horizontal strip, at the middle of the wall	36.2	26.8	0	>0
		P = 49.8	(kip/ft)						
	Base mat	M = 20.8	(kip-ft/ft)	0.99	North-south strip, at intersection with south walls	27.8	26.4	-0.28	-8.96e-5
		P = -28.4	(kip/ft)						
CEB	Wall	M = 459.5	(kip-ft/ft)	0.60	Between Mechanical & Electrical Penetration at Elev. -30ft.	27.1	5.60	-2.21	-6.61e-4
		P = -141.2	(kip/ft)						
	Wall	M = -39.6	(kip-ft/ft)	0.10	Wall between Mechanical & Electrical Penetration, below personal hatch	24.6	2.73	-0.71	-1.88e-4
		P = 14.1	(kip/ft)						
RHR	East exterior wall	M = -98.5	(kip-ft/ft)	0.75	East exterior wall, horizontal strip, at the approximate El. (-) 30 ft	46.9	11.4	-1.9	-6.09e-4
		P = -35.0	(kip/ft)						
	East interior wall	M = 28.6	(kip-ft/ft)	0.0	East interior wall, vertical strip, at the approximate El. (-) 45 ft	41.6	5.5	0.0	>0
		P = 37.2	(kip/ft)						
	West interior wall	M = 11.0	(kip-ft/ft)	0.0	West interior wall, vertical strip, at the approximate El. (-) 30 ft	26.5	12.5	0.0	>0
		P = 30.8	(kip/ft)						

Table 1 – (Continue)

	Component	Item		Internal ASR (mm/m)	Location	Total stress in steel (ksi)		Maximum compressive stress in concrete (ksi)	Maximum compressive mechanical strain in concrete
						Rebar 1	Rebar 2		
CSTE	Tank Enclosure Wall	M = 41.0	(kip-ft/ft)	0.43	Bottom of tank enclosure wall, vertical direction	15.8	8.6	-0.68	-1.89e-4
		P = -12.9	(kip/ft)						
CEHMS	East wing walls	M = 159.6	(kip-ft/ft)	0.72	East wing wall, at intersection with column	23.4	15.0	-0.78	-2.50e-4
		P = -8.3	(kip/ft)						
CEVA	Base slab	M = 83.7	(kip-ft/ft)	0.31	Base slab rebar along east-west direction	32.8	5.1	-0.89	-2.8e-4
		P = 1.7	(kip/ft)						
WPC/PH	North wall	M = 3.8	(kip-ft/ft)	0.24	North wall below pipe break beam	7.8	6.6	-0.07	-0.22e-4
		P = 19.1	(kip/ft)						
EMH	W13/W15	M = 7.4	(kip-ft/ft)	0.25	W13/W15 walls	11.2	5.6	-0.28	-9.61e-6
		P = -3.2	(kip/ft)						

Table 2 – Stress in rebars of structural components subjected to LC2

	Component	Item		F_{THR}	Internal ASR (mm/m)	Location	Total stress in steel (ksi)		Maximum compressive stress in concrete (ksi)	Maximum compressive mechanical strain in concrete
							Rebar 1	Rebar 2		
CRMAI	East Wall	M = 7.7	(kip-ft/ft)	1.4	0**	East wall, horizontal strip, at the middle of the wall	43.3	29.6	0	>0
		P = 57.6	(kip/ft)							
	Base mat	M = 26.5	(kip-ft/ft)		0.99	North-south strip, at intersection with south walls	39.1	37.3	-0.33	-1.06e-4
		P = -32.3	(kip/ft)							
CEB	Wall	M = 614.7	(kip-ft/ft)	1.3	0.60	Between Mechanical & Electrical Penetration at Elev. -30ft.	42.5	1.97	-2.68	-8.51e-4
		P = 10.5	(kip/ft)							
	Wall	M =22.8	(kip-ft/ft)	1.3	0.10	East side of Electrical Penetration at Elev. 45ft.	55.6	12.9	-1.33	-3.67e-4
		P = 52.8	(kip/ft)							
RHR	East exterior wall	M = -119.5	(kip-ft/ft)	1.2	0.75	East exterior wall, horizontal strip, at the approximate El. (-) 30 ft	56.5	13.8	-2.1	-6.73e-4
		P = -40.8	(kip/ft)							
	East interior wall	M = 33.0	(kip-ft/ft)		0.0**	East interior wall, vertical strip, at the approximate El. (-) 45 ft	59.5*	17.7	0.0	>0
		P = 60.9	(kip/ft)							
	West interior wall	M = 13.4	(kip-ft/ft)		0.0**	West interior wall, vertical strip, at the approximate El. (-) 30 ft	36.6*	19.6	0.0	>0
		P = 44.4	(kip/ft)							

Table 2 – (Continued)

	Component	Item		F_{THR}	Internal ASR (mm/m)	Location	Total stress in steel (ksi)		Maximum compressive stress in concrete (ksi)	Maximum compressive mechanical strain in concrete
							Rebar 1	Rebar 2		
CSTE	Tank Enclosure Wall	M = 65.7	(kip-ft/ft)	1.6	0.43	Bottom of tank enclosure wall, vertical direction	26.7	13.9	-1.11	-3.08e-4
		P = -12.9	(kip/ft)							
CEHMS	East wing walls	M = 311.6	(kip-ft/ft)	1.5	0.72	East wing wall, at intersection with column	41.6	20.8	-1.52	-4.87e-4
		P = -0.7	(kip/ft)							
CEVA	Base slab	M = 83.7	(kip-ft/ft)	3.0	0.31	Base slab rebar along east-west direction	44.0	20.6	-1.08	-3.46e-4
		P = 1.7	(kip/ft)							
WPC/PH	North wall	M = 78.8	(kip-ft/ft)	1.8	0.24	North wall below pipe break beam	44.4	8.0	-1.36	-4.37e-4
		P = 34.4	(kip/ft)							
EMH	W13/W15	M = 0	(kip-ft/ft)	3.7	0.25	W13/W15 walls	27.0	24.5	-0.30	-9.69e-5
		P = 23.6	(kip/ft)							

* Vertical strips (strips that engage vertical rebars) are not part of primary load path for RHR, and therefore, are not designed following ACI 318 strength design method. These members do not need to be considered for the evaluation of stress in rebars.
** Members with zero internal ASR expansion that satisfy the ACI 318 requirements for strength design method do not yield subjected to unfactored normal operating load condition.

7. REFERENCES

[1] Simpson Gumpertz & Heger Inc., *Evaluation of Control Room Makeup Air Intake Structure*, 160268-CA-08 Rev. 0, Waltham, MA, May 2017.

[2] Simpson Gumpertz & Heger, Inc., *Evaluation and Design Confirmation of As-designed CEB 150252-CA-02* Rev 1, Waltham, MA, Dec. 2017.

[3] Simpson Gumpertz & Heger Inc., *Evaluation of Residual Heat Removal Equipment Vault*, 160268-CA-06 Rev. 0, Waltham, MA, Dec 2016.

[4] Simpson Gumpertz & Heger Inc., *Evaluation of Condensate Storage Tank Enclosure Structure*, 160268-CA-03 Rev. 0, Waltham, MA, Dec. 2016.

[5] Simpson Gumpertz & Heger Inc., *Evaluation of Containment Equipment Hatch Missile Shield Structure*, 160268-CA-02 Rev. 0, Waltham, MA, Oct. 2016.

[6] Simpson Gumpertz & Heger Inc., *Evaluation of Containment Enclosure Ventilation Area*, 160268-CA-05 Rev. 0, Waltham, MA, Mar. 2017.

[7] Simpson Gumpertz & Heger, Inc., *Evaluation of Main Steam and Feedwater West Pipe Chase & Personnel Hatch Structures 170443-CA-04* Rev. 0, Waltham, MA, Jan. 2018.

[8] Simpson Gumpertz & Heger, Inc., *Evaluation of Seismic Category I Electrical Manholes – Stage 1 160268-CA-12* Rev. 0, Waltham, MA, Jan. 2018.

SIMPSON GUMPERTZ & HEGER
Engineering of Structures and Building Enclosures

CLIENT:	NextEra Energy Seabrook	PROJECT NO:	170444
SUBJECT:	Evaluation of maximum stress in rebars of Seabrook structures	DATE:	Dec 2017
		BY:	MR.M.Gargari
		VERIFIER:	A. T. Sarawit

APPENDIX A
TENSILE STRESS IN REBARS OF CONTROL ROOM MAKEUP AIR INTAKE STRUCTURE

A1. REVISION HISTORY

Revision 0: Initial document.

A2. OBJECTIVE OF CALCULATION

The objective of this calculation is to compute the maximum tensile stress that can form in the rebars of Control Room Makeup Air Intake (CRMAI) structure.

A3. RESULTS AND CONCLUSIONS

Table A1 summarizes the tensile stress in rebars of the CRMAI structure calculated at critical locations. The maximum tensile stress is 43.3 ksi computed for the horizontal rebar of east wall close to the interior of the structure and subjected to the second In Situ load combination.

Besides, although the stress due to internal ASR expansion is high for the base mat, the stress due to loading is small. Therefore, base mat does not govern the calculation of the maximum stress in rebars.

A4. DESIGN DATA / CRITERIA

See Section 4 of the calculation main body (Calc. 160268-CA-08 Rev. 0).

A5. ASSUMPTIONS

A5.1 Justified assumptions

There are no justified assumptions.

A5.2 Unverified assumptions

There are no unverified assumptions.

A6. METHODOLOGY

The critical demand that controlled the selection of threshold factor of the CRMAI structure was axial-flexure interaction along the horizontal strip of the east wall and close to the middle which is considered for evaluation. Additionally, the north-south strip of the base mat is also considered to check a location with high internal ASR expansion. Finite element analyses are conducted to calculate the axial force and bending moment at critical sections of the structure. The FE model and analysis method are similar to what explained in susceptibility evaluation of CRMAI structure [A1]. The axial force and bending moments are calculated using section cuts method. The computed demands are:

- LC1 for the walls: M = 5.2 kip-ft/ft, P = 49.8 kip/ft
- LC1 for the base mat: M = 20.8 kip-ft/ft, P = -28.4 kip/ft
- LC2 for the walls: M = 7.7 kip-ft/ft, P = 57.6 kip/ft
- LC2 for the base mat: M = 26.5 kip-ft/ft, P = -32.3 kip/ft

To calculate the stress in rebars subjected to a combination of axial force and bending moment, sectional analysis based on fiber section method, as explained in calculation main body, is used. The calculation is conducted per 1 foot width of the walls/slabs, and each section is discretized into 20 fibers. An example calculation that evaluates the stress in rebars of the east wall is presented in Section A8. The CI value for the base mat was 0.99 mm/m which included in the analysis to find the initial stress state due to internal ASR alone. Value of zero internal ASR is used for the walls as it leads to conservative demands.

A7. REFERENCES

[A1] Simpson Gumpertz & Heger Inc., *Evaluation of Control Room Makeup Air Intake structure,* 160268-CA-08 Rev. 0, Waltham, MA, May 2017.

[A2] United Engineers & Constructors Inc., Seabrook Station Structural Design Drawings.

[A3] United Engineers & Constructors Inc., *Design of Makeup Air Intake Structure*, *MT-28-Calc Rev.* 2, Feb. 1984.

A8. COMPUTATION

A8.1. Strain in Steel and Concrete due to Internal ASR expansion

Input Data

ASR expansion

Measured crack index	$\varepsilon_{CI} := 0 \dfrac{mm}{m}$	
Threshold factor	$F_{thr} := 1.4$	

Material properties

Compressive strength of concrete	$f_c := -3ksi$	Ref. [A1]
Young's modulus of concrete	$E_c := 3120ksi$	
Yield strength of steel	$f_y := 60ksi$	
Young's modulus of steel	$E_s := 29000ksi$	

Geometry

Width of fibers	$b := 12in$	Ref. [A2]
Total thickness or height	$h := 24in$	
Area of concrete	$A_c := b \cdot h = 288 \cdot in^2$	
Area of tensile reinforcement (#8@12 in.)	$A_s := 0.79in^2$	
Number of reinforcement in row, e.g. equal to 2 for tensile and compressive	$Steel_{Num} := 2$	
Depth to reinforcement	$d := 20.5in$	

Finding the strain in steel and concrete by satisfying compatibility and equilibrium

	Initial Guess
Initial mechanical strain in concrete	$\varepsilon_{o.conc} := 0$
Initial strain in steel	$\varepsilon_{o.steel} := 0$
	Given
Compatibility equation	$F_{thr} \cdot \varepsilon_{CI} = \varepsilon_{o.steel} - \varepsilon_{o.conc}$
Equilibrium equation	$(E_c \cdot A_c) \cdot \varepsilon_{o.conc} + (E_s \cdot A_s \cdot Steel_{Num}) \cdot \varepsilon_{o.steel} = 0$
	$ans := Find(\varepsilon_{o.conc}, \varepsilon_{o.steel})$

Initial strain in concrete and steel

$\varepsilon_{o.conc} := ans_1 = 0$

$\varepsilon_{o.steel} := ans_2 = 0$

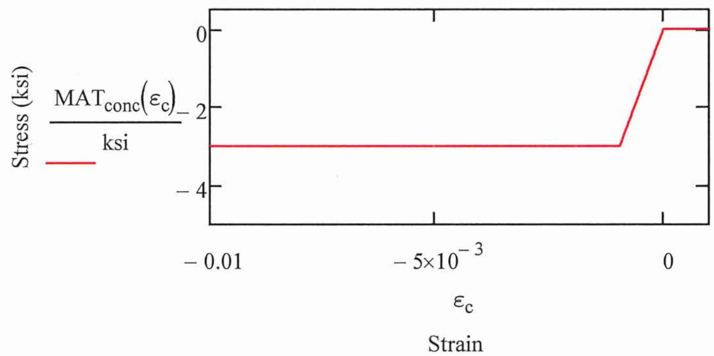
A8.2. Sectional Analysis

Input Data

Concrete Material Model

Constitutive model for concrete

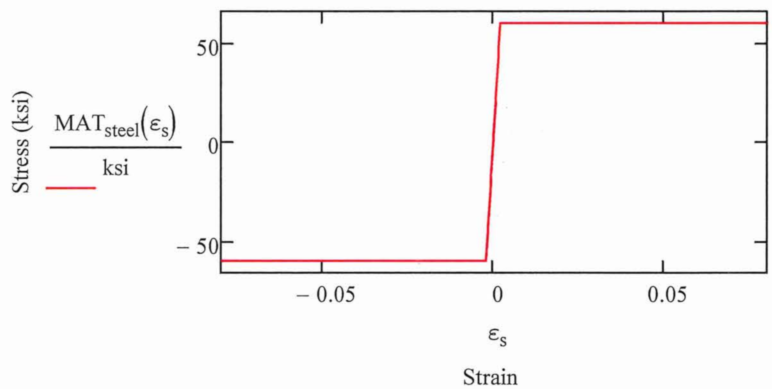
$$MAT_{conc}(\varepsilon) := \begin{cases} 0 & \text{if } \varepsilon > 0 \\ f_c & \text{if } \varepsilon < \dfrac{f_c}{E_c} \\ (E_c \cdot \varepsilon) & \text{otherwise} \end{cases}$$



Steel Material Model

Constitutive model for steel

$$MAT_{steel}(\varepsilon) := \begin{cases} f_y & \text{if } \varepsilon > \dfrac{f_y}{E_s} \\ -f_y & \text{if } \varepsilon < \dfrac{-f_y}{E_s} \\ (E_s \cdot \varepsilon) & \text{otherwise} \end{cases}$$



Concrete Fibers

Number of fibers $\quad Conc_{Num} := 20$

Height of fibers $\quad Conc_H := \dfrac{h}{Conc_{Num}} = 1.2 \cdot in$

Concrete fiber coordinates

$$Conc_y := \left| \begin{array}{l} \text{for } i \in 1..Conc_{Num} \\ \quad ans_i \leftarrow -\dfrac{h}{2} + \dfrac{Conc_H}{2} + (i-1) \cdot Conc_H \\ ans \end{array} \right.$$

Concrete fiber strain

$$Conc_\varepsilon(\varepsilon_{o.conc}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{for } i \in 1..Conc_{Num} \\ \quad ans_i \leftarrow \varepsilon_{o.conc} + \varepsilon - \varphi \cdot Conc_{y_i} \\ ans \end{array} \right.$$

Concrete fiber stress

$$Conc_\sigma(\varepsilon_{o.conc}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{for } i \in 1..Conc_{Num} \\ \quad ans_i \leftarrow MAT_{conc}\left(Conc_\varepsilon(\varepsilon_{o.conc}, \varepsilon, \varphi)_i\right) \\ ans \end{array} \right.$$

Concrete fiber force

$$Conc_F(\varepsilon_{o.conc}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{for } i \in 1..Conc_{Num} \\ \quad ans_i \leftarrow Conc_\sigma(\varepsilon_{o.conc}, \varepsilon, \varphi)_i \cdot (b \cdot Conc_H) \\ ans \end{array} \right.$$

Reinforcement/Steel fibers

Depth to reinforcement fiber

$$Steel_{y_1} := -\left(d - \frac{h}{2}\right) = -8.5 \cdot in$$

$$Steel_{y_2} := d - \frac{h}{2} = 8.5 \cdot in$$

Area of reinforcement fiber

$$Steel_{As_1} := A_s = 0.79 \cdot in^2$$

$$Steel_{As_2} := A_s = 0.79 \cdot in^2$$

Steel fiber strain

$$Steel_\varepsilon(\varepsilon_{o.steel}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{for } i \in 1..Steel_{Num} \\ \quad ans_i \leftarrow \varepsilon_{o.steel} + \varepsilon - \varphi \cdot Steel_{y_i} \\ ans \end{array} \right.$$

Steel fiber stress

$$Steel_\sigma(\varepsilon_{o.steel}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{for } i \in 1..Steel_{Num} \\ \quad ans_i \leftarrow MAT_{steel}\left(Steel_\varepsilon(\varepsilon_{o.steel}, \varepsilon, \varphi)_i\right) \\ ans \end{array} \right.$$

Steel fiber force

$$Steel_F(\varepsilon_{o.steel}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{for } i \in 1..Steel_{Num} \\ \quad ans_i \leftarrow Steel_\sigma(\varepsilon_{o.steel}, \varepsilon, \varphi)_i \cdot Steel_{As_i} \\ ans \end{array} \right.$$

Initial Stress State

Initial stress in concrete

$$\text{Concrete}_{\sigma} := \text{Conc}_{\sigma}(\varepsilon_{o.conc}, 0, 0)$$

$$\text{Concrete}_{\sigma_1} = 0 \cdot \text{ksi}$$

Initial stress in steel

$$\text{Rebar}_{\sigma} := \text{Steel}_{\sigma}(\varepsilon_{o.steel}, 0, 0)$$

$$\text{Rebar}_{\sigma_1} = 0 \cdot \text{ksi}$$

Axial Equilibrium

$$\text{Force}(\varepsilon_{o.conc}, \varepsilon_{o.steel}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{ans1} \leftarrow 0 \\ \text{for } i \in 1 .. \text{Conc}_{\text{Num}} \\ \quad \text{ans1} \leftarrow \text{ans1} + \text{Conc}_F(\varepsilon_{o.conc}, \varepsilon, \varphi)_i \\ \text{ans2} \leftarrow 0 \\ \text{for } i \in 1 .. \text{Steel}_{\text{Num}} \\ \quad \text{ans2} \leftarrow \text{ans2} + \text{Steel}_F(\varepsilon_{o.steel}, \varepsilon, \varphi)_i \\ \text{ans} \leftarrow \text{ans1} + \text{ans2} \end{array} \right.$$

Moment Equilibrium

$$\text{Moment}(\varepsilon_{o.conc}, \varepsilon_{o.steel}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{ans1} \leftarrow 0 \\ \text{for } i \in 1 .. \text{Conc}_{\text{Num}} \\ \quad \text{ans1} \leftarrow \text{ans1} + -1 \cdot \text{Conc}_F(\varepsilon_{o.conc}, \varepsilon, \varphi)_i \cdot \text{Conc}_{y_i} \\ \text{ans2} \leftarrow 0 \\ \text{for } i \in 1 .. \text{Steel}_{\text{Num}} \\ \quad \text{ans2} \leftarrow \text{ans2} + -1 \cdot \text{Steel}_F(\varepsilon_{o.steel}, \varepsilon, \varphi)_i \cdot \text{Steel}_{y_i} \\ \text{ans} \leftarrow \text{ans1} + \text{ans2} \end{array} \right.$$

Solution

Known parameters

Axial force $P := 57.6\text{kip}$

Iteration

Curvature $\phi := 0.0000279 \cdot \frac{1}{\text{in}}$ Requires iteration

Solve for strain at centroid

Axial strain at centroid (initial guess) $x_o := 0.0$

Axial force equilibrium

$$f(x) := \text{Force}(\varepsilon_{o.conc}, \varepsilon_{o.steel}, x, \phi) - P$$

$$\varepsilon_{cent} := \text{root}(f(x_o), x_o) = 1.257 \times 10^{-3}$$

Sectional forces

$$\text{Force}(\varepsilon_{o.conc}, \varepsilon_{o.steel}, \varepsilon_{cent}, \phi) = 57.6 \cdot \text{kip}$$

$$\text{Moment}(\varepsilon_{o.conc}, \varepsilon_{o.steel}, \varepsilon_{cent}, \phi) = 7.697 \cdot \text{kip} \cdot \text{ft}$$

Stress and strain in concrete and steel

Steel fiber stress and strain

$$\text{Rebar}_{\varepsilon} := \text{Steel}_{\varepsilon}(\varepsilon_{o.steel}, \varepsilon_{cent}, \phi) = \begin{pmatrix} 1.494 \times 10^{-3} \\ 1.02 \times 10^{-3} \end{pmatrix}$$

$$\text{Rebar}_{\sigma} := \text{Steel}_{\sigma}(\varepsilon_{o.steel}, \varepsilon_{cent}, \phi) = \begin{pmatrix} 43.333 \\ 29.578 \end{pmatrix} \cdot \text{ksi}$$

$$\text{Steel}_{F}(\varepsilon_{o.steel}, \varepsilon_{cent}, \phi) = \begin{pmatrix} 34.233 \\ 23.367 \end{pmatrix} \cdot \text{kip}$$

$$\text{Concrete}_y := \text{Conc}_y$$

Concrete fiber stress and strain

$$\text{Concrete}_{\varepsilon} := \text{Conc}_{\varepsilon}(\varepsilon_{o.conc}, \varepsilon_{cent}, \phi)$$

$$\text{Concrete}_{\sigma} := \text{Conc}_{\sigma}(\varepsilon_{o.conc}, \varepsilon_{cent}, \phi)$$

Maximum compressive strain in concrete

$$\varepsilon_{max.comp} := \frac{\text{Concrete}_{\varepsilon_{ConcNum}} - \text{Concrete}_{\varepsilon_{ConcNum-1}}}{\text{Conc}_{y_{ConcNum}} - \text{Conc}_{y_{ConcNum-1}}} \cdot \left(\frac{h}{2} - \text{Conc}_{y_{ConcNum-1}}\right) \ldots = 9.223 \times 10^{-4}$$
$$+ \text{Concrete}_{\varepsilon_{ConcNum-1}}$$

Maximum compressive stress in concrete $\sigma_{max.comp} := \text{MAT}_{conc}(\varepsilon_{max.comp}) = 0 \cdot \text{ksi}$

A9. TABLES

Table A1: Stress in rebars at critical locations of CRMAI structure subjected to LC1

Component	Item	Total demands for sustained load (In Situ condition, LC1)		Total stress in steel (ksi)		Maximum compressive stress in concrete (ksi)
		Demand	Location	Rebar 1	Rebar 2	
Walls	Out-of-plane moment (kip-ft/ft)	5.2	East wall, horizontal strip, at the middle of the wall	36.2	26.8	0
	Axial force (kip/ft)	49.8				
Base mat	Out-of-plane moment (kip-ft/ft)	20.8	North-south strip, at intersection with south walls	27.8	26.4	-0.28
	Axial force (kip/ft)	-28.4				

Table A2: Stress in rebars at critical locations of CRMAI structure subjected to LC2

Component	Item	Total demands for sustained loads plus OBE amplified with threshold factor (In Situ condition, LC2)		Total stress in steel (ksi)		Maximum compressive stress in concrete (ksi)
		Demand	Location	Rebar 1	Rebar 2	
Walls	Out-of-plane moment (kip-ft/ft)	7.7	East wall, horizontal strip, at the middle of the wall	43.3	29.6	0
	Axial force (kip/ft)	57.6				
Base mat	Out-of-plane moment (kip-ft/ft)	26.5	North-south strip, at intersection with south walls	39.1	37.3	-0.33
	Axial force (kip/ft)	-32.3				

Example in Section A8

A10. FIGURES

There are no figures.

APPENDIX B

TENSILE STRESS IN REBAR AND CONCRETE OF CONTAINMENT ENCLOSURE BUILDING STRUCTURE

B1. REVISION HISTORY

Revision 0: Initial document.

B2. OBJECTIVE OF CALCULATION

The objective of this calculation is to compute the maximum tensile stress that can form in the rebars and the maximum compressive stress that can form in concrete sections of the Containment Enclosure Building (CEB) structure.

B3. RESULTS AND CONCLUSIONS

Table B1 through B4 summarizes the stress results in rebar and concrete sections of the CEB structure calculated at critical locations. The Maximum tensile stress is 55.6 ksi in the wall at the east side of electrical penetration at Elev. 45 ft subjected to the second in-situ load combination (LC2).

B4. DESIGN DATA / CRITERIA

See Section 4 of the calculation main body (Calc. 150252-CA-02 Rev. 1).

B5. ASSUMPTIONS

B5.1 Justified assumptions

There are no justified assumptions.

B5.2 Unverified assumptions

There are no unverified assumptions.

B6. METHODOLOGY

The critical demands that control the selection of the threshold factor for the CEB structure are out-of-plane moment and axial load interaction at various sections of the wall surface. Finite element analyses were conducted to calculate the axial force and bending moment at these locations due to ASR load [B1].

To calculate the stress in rebars subjected to a combination of axial force and bending moment, sectional analysis based on fiber section method, as explained in calculation main body, is used. The calculation is conducted per 1 foot width of the walls, and each section is discretized into 20 fibers. An example calculation that evaluates the stress in the vertical rebars at the section of the wall on the east side of the electrical penetration and at Elev. 45 ft. is presented in Section B8. The ASR expansion of the CEB wall is included in the analysis to find the initial stress state due to internal ASR alone.

B7. REFERENCES

[B1] Simpson Gumpertz & Heger Inc., *Evaluation of Containment Enclosure Building Structure,* 150252-CA-02 Rev. 1, Waltham, MA, Dec 2017.

[B2] United Engineers & Constructors Inc., Seabrook Station Structural Design Drawings.

B8. COMPUTATION

B8.1. Strain in Steel and Concrete due to Internal ASR expansion

Input Data

ASR expansion

Measured crack index $\varepsilon_{CI} := 0.10 \frac{mm}{m}$

Threshold factor $F_{thr} := 1.3$

Material properties

Compressive strength of concrete $f_c := -4ksi$ Ref. [B1]

Young's modulus of concrete $E_c := 3605ksi$

Yield strength of steel $f_y := 60ksi$

Young's modulus of steel $E_s := 29000ksi$

Geometry

Width of fibers $b := 12in$ Ref. [B2]

Total thickness or height $h := 15in$

Area of concrete $A_c := b \cdot h = 180 \cdot in^2$

Area of tensile reinforcement $A_s := 1.00in^2$

Number of reinforcement in row, e.g. equal to 2 for tensile and compressive $Steel_{Num} := 2$

Depth to reinforcement $d := 15in - 3.60in = 11.4 \cdot in$

Finding the strain in steel and concrete by satisfying compatibility and equilibrium

Initial Guess

Initial mechanical strain in concrete $\varepsilon_{o.conc} := 0$

Initial strain in steel $\varepsilon_{o.steel} := 0$

Given

Compatibility equation $F_{thr} \cdot \varepsilon_{CI} = \varepsilon_{o.steel} - \varepsilon_{o.conc}$

Equilibrium equation $\left(E_c \cdot A_c\right) \cdot \varepsilon_{o.conc} + \left(E_s \cdot A_s \cdot Steel_{Num}\right) \cdot \varepsilon_{o.steel} = 0$

$ans := Find\left(\varepsilon_{o.conc}, \varepsilon_{o.steel}\right)$

Initial strain in concrete and steel

$\varepsilon_{o.conc} := ans_1 = -1.217 \times 10^{-5}$

$\varepsilon_{o.steel} := ans_2 = 1.178 \times 10^{-4}$

B8.2. Sectional Analysis

Input Data

Concrete Material Model

Kent & Park Model

Strain at Peak compressive strength $\varepsilon_{co} := -0.002$

Strain at 50% compressive strength

$$\varepsilon_{50u} := \frac{3 - 0.002 \cdot \dfrac{f_c}{psi}}{\dfrac{f_c}{psi} + 1000} = -3.667 \times 10^{-3}$$

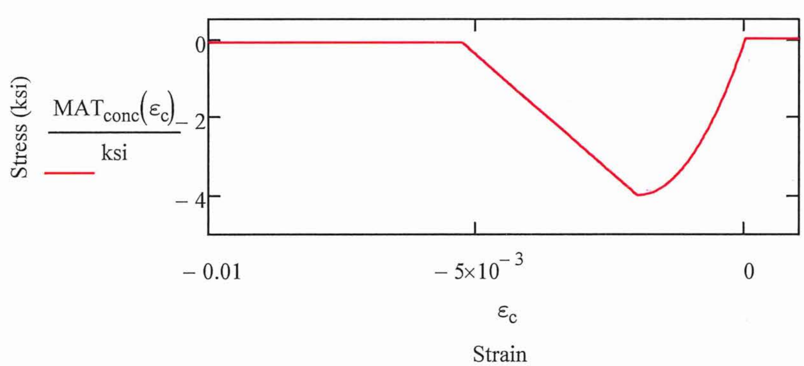
Model parameter

$$Z := \frac{0.5}{\varepsilon_{50u} - \varepsilon_{co}} = -300$$

Residual compressive strength $f_{c.res} := f_c \cdot 0.025 = -100 \cdot psi$

Constitutive model for concrete

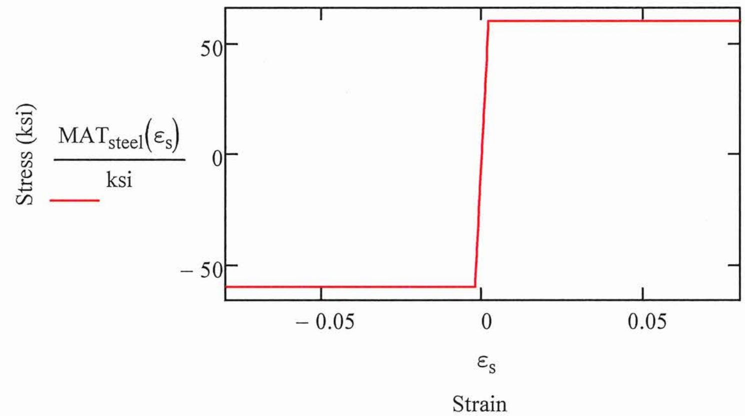
$$MAT_{conc}(\varepsilon) := \begin{cases} \min\left[f_{c.res}, f_c \cdot \left[1 - Z \cdot \left(\varepsilon - \varepsilon_{co}\right)\right]\right] & \text{if } \varepsilon < \varepsilon_{co} \\ f_c \cdot \left[\dfrac{2 \cdot \varepsilon}{\varepsilon_{co}} - \left(\dfrac{\varepsilon}{\varepsilon_{co}}\right)^2\right] & \text{if } \varepsilon_{co} \le \varepsilon < 0 \\ 0 & \text{if } 0 \le \varepsilon \end{cases}$$



Steel Material Model

Constitutive model for steel

$$MAT_{steel}(\varepsilon) := \begin{cases} f_y & \text{if } \varepsilon > \dfrac{f_y}{E_s} \\ -f_y & \text{if } \varepsilon < \dfrac{-f_y}{E_s} \\ (E_s \cdot \varepsilon) & \text{otherwise} \end{cases}$$



Concrete Fibers

Number of fibers

$$Conc_{Num} := 20$$

Height of fibers

$$Conc_H := \frac{h}{Conc_{Num}} = 0.75 \cdot in$$

Concrete fiber coordinates

$$Conc_y := \left| \begin{array}{l} \text{for } i \in 1 .. Conc_{Num} \\ \quad ans_i \leftarrow -\dfrac{h}{2} + \dfrac{Conc_H}{2} + (i-1) \cdot Conc_H \\ ans \end{array} \right.$$

Concrete fiber strain

$$Conc_\varepsilon(\varepsilon_{o.conc}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{for } i \in 1 .. Conc_{Num} \\ \quad ans_i \leftarrow \varepsilon_{o.conc} + \varepsilon - \varphi \cdot Conc_{y_i} \\ ans \end{array} \right.$$

Concrete fiber stress

$$Conc_\sigma(\varepsilon_{o.conc}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{for } i \in 1 .. Conc_{Num} \\ \quad ans_i \leftarrow MAT_{conc}\left(Conc_\varepsilon(\varepsilon_{o.conc}, \varepsilon, \varphi)_i\right) \\ ans \end{array} \right.$$

Concrete fiber force

$$Conc_F(\varepsilon_{o.conc}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{for } i \in 1 .. Conc_{Num} \\ \quad ans_i \leftarrow Conc_\sigma(\varepsilon_{o.conc}, \varepsilon, \varphi)_i \cdot (b \cdot Conc_H) \\ ans \end{array} \right.$$

Reinforcement/Steel fibers

Depth to reinforcement fiber

$$Steel_{y_1} := -\left(d - \frac{h}{2}\right) = -3.9 \cdot in$$

$$Steel_{y_2} := d - \frac{h}{2} = 3.9 \cdot in$$

Area of reinforcement fiber

$$Steel_{As_1} := A_s = 1 \cdot in^2$$

$$Steel_{As_2} := A_s = 1 \cdot in^2$$

Steel fiber strain

$$Steel_{\varepsilon}(\varepsilon_{o.steel}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{for } i \in 1 .. Steel_{Num} \\ \quad ans_i \leftarrow \varepsilon_{o.steel} + \varepsilon - \varphi \cdot Steel_{y_i} \\ ans \end{array} \right.$$

Steel fiber stress

$$Steel_{\sigma}(\varepsilon_{o.steel}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{for } i \in 1 .. Steel_{Num} \\ \quad ans_i \leftarrow MAT_{steel}\left(Steel_{\varepsilon}(\varepsilon_{o.steel}, \varepsilon, \varphi)_i\right) \\ ans \end{array} \right.$$

Steel fiber force

$$Steel_{F}(\varepsilon_{o.steel}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{for } i \in 1 .. Steel_{Num} \\ \quad ans_i \leftarrow Steel_{\sigma}(\varepsilon_{o.steel}, \varepsilon, \varphi)_i \cdot Steel_{As_i} \\ ans \end{array} \right.$$

Initial Stress State

Initial stress in concrete

$$Concrete_{\sigma} := Conc_{\sigma}(\varepsilon_{o.conc}, 0, 0)$$

$$Concrete_{\sigma_1} = -0.049 \cdot ksi$$

Initial stress in steel

$$Rebar_{\sigma} := Steel_{\sigma}(\varepsilon_{o.steel}, 0, 0)$$

$$Rebar_{\sigma_1} = 3.417 \cdot ksi$$

Axial Equilibrium

$$Force(\varepsilon_{o.conc}, \varepsilon_{o.steel}, \varepsilon, \varphi) := \left| \begin{array}{l} ans1 \leftarrow 0 \\ \text{for } i \in 1 .. Conc_{Num} \\ \quad ans1 \leftarrow ans1 + Conc_{F}(\varepsilon_{o.conc}, \varepsilon, \varphi)_i \\ ans2 \leftarrow 0 \\ \text{for } i \in 1 .. Steel_{Num} \\ \quad ans2 \leftarrow ans2 + Steel_{F}(\varepsilon_{o.steel}, \varepsilon, \varphi)_i \\ ans \leftarrow ans1 + ans2 \end{array} \right.$$

Moment Equilibrium

$$\text{Moment}(\varepsilon_{o.conc}, \varepsilon_{o.steel}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{ans1} \leftarrow 0 \\ \text{for } i \in 1..\text{Conc}_{Num} \\ \quad \text{ans1} \leftarrow \text{ans1} + -1 \cdot \text{Conc}_F(\varepsilon_{o.conc}, \varepsilon, \varphi)_i \cdot \text{Conc}_{y_i} \\ \text{ans2} \leftarrow 0 \\ \text{for } i \in 1..\text{Steel}_{Num} \\ \quad \text{ans2} \leftarrow \text{ans2} + -1 \cdot \text{Steel}_F(\varepsilon_{o.steel}, \varepsilon, \varphi)_i \cdot \text{Steel}_{y_i} \\ \text{ans} \leftarrow \text{ans1} + \text{ans2} \end{array} \right.$$

Solution

Known parameters

Axial force $P := 52.80\text{kip}$

Iteration

Curvature $\phi := 0.000189 \cdot \frac{1}{in}$ Requires iteration

Solve for strain at centroid

Axial strain at centroid (initial guess) $x_o := 0.0$

Axial force equilibrium

$$f(x) := \text{Force}(\varepsilon_{o.conc}, \varepsilon_{o.steel}, x, \phi) - P$$

$$\varepsilon_{cent} := \text{root}(f(x_o), x_o) = 1.063 \times 10^{-3}$$

Sectional forces

$$\text{Force}(\varepsilon_{o.conc}, \varepsilon_{o.steel}, \varepsilon_{cent}, \phi) = 52.8 \cdot \text{kip}$$

$$\text{Moment}(\varepsilon_{o.conc}, \varepsilon_{o.steel}, \varepsilon_{cent}, \phi) = 22.807 \cdot \text{kip} \cdot \text{ft}$$

Stress and strain in concrete and steel

Steel fiber stress and strain

$$\text{Rebar}_\varepsilon := \text{Steel}_\varepsilon(\varepsilon_{o.steel}, \varepsilon_{cent}, \phi) = \begin{pmatrix} 1.918 \times 10^{-3} \\ 4.434 \times 10^{-4} \end{pmatrix}$$

$$\text{Rebar}_\sigma := \text{Steel}_\sigma(\varepsilon_{o.steel}, \varepsilon_{cent}, \phi) = \begin{pmatrix} 55.61 \\ 12.858 \end{pmatrix} \cdot \text{ksi}$$

$$\text{Steel}_F(\varepsilon_{o.steel}, \varepsilon_{cent}, \phi) = \begin{pmatrix} 55.61 \\ 12.858 \end{pmatrix} \cdot \text{kip}$$

$$\text{Concrete}_y := \text{Conc}_y$$

Concrete fiber stress and strain

$$\text{Concrete}_\varepsilon := \text{Conc}_\varepsilon(\varepsilon_{o.conc}, \varepsilon_{cent}, \phi)$$

$$\text{Concrete}_\sigma := \text{Conc}_\sigma(\varepsilon_{o.conc}, \varepsilon_{cent}, \phi)$$

Maximum compressive strain in concrete

$$\varepsilon_{max.comp} := \frac{Concrete_{\varepsilon_{ConcNum}} - Concrete_{\varepsilon_{ConcNum-1}}}{Conc_{y_{ConcNum}} - Conc_{y_{ConcNum-1}}} \cdot \left(\frac{h}{2} - Conc_{y_{ConcNum-1}}\right) \ldots = -3.67 \times 10^{-4}$$
$$+ Concrete_{\varepsilon_{ConcNum-1}}$$

Maximum compressive stress in concrete

$$\sigma_{max.comp} := MAT_{conc}\left(\varepsilon_{max.comp}\right) = -1.333 \cdot ksi$$

B9. TABLES

Table B1. Stress in Rebar and Concrete of Structural Components Subjected to LC1 Standard Case

Comp.	Demand		Location	Total stress in steel (ksi)		Maximum stress and strain in concrete (ksi) [in./in.]
				Rebar 1	Rebar 2	
Wall 36 in.	M = 459.5	(kip-ft/ft)	Wall near foundation. Horz. cut.	27.1	5.60	-2.21 [-6.61e-4]
	P = -141.2	(kip/ft)				
Wall 15 in.	M = 1.94	(kip-ft/ft)	Wall above Elec. Penetration. Horz. cut.	13.2	7.18	0.0 [2.25e-5]
	P = 20.33	(kip/ft)				
Wall 27 in.	M = -39.58	(kip-ft/ft)	Below personal hatch. Vert. cut.	24.6	2.73	-0.71 [-1.88e-4]
	P = 14.07	(kip/ft)				
Wall 27 in.	M = -34.00	(kip-ft/ft)	Side of personal hatch. Vert. cut.	19.5	2.78	-0.57 [-1.49e-4]
	P = 11.05	(kip/ft)				

Table B2. Stress in Rebar and Concrete of Structural Components subjected to LC2 Standard Case

Comp.	Demand		Location	Total stress in steel (ksi)		Maximum stress and strain in concrete (ksi) [in./in.]
				Rebar 1	Rebar 2	
Wall 36 in.	M = 614.7	(kip-ft/ft)	Wall near foundation. Horz. cut.	42.5	1.97	-2.68 [-8.507e-4]
	P = 10.48	(kip/ft)				
Wall 36 in.	M = 432.1	(kip-ft/ft)	Wall near foundation. Horz. cut.	20.6	2.16	-2.48 [-7.69e-4]
	P = -391.3	(kip/ft)				
Wall 15 in.	M =22.81	(kip-ft/ft)	Wall above Elec. Penetration. Horz. cut.	55.6	12.9	-1.33 [-3.67e-4]
	P = 52.80	(kip/ft)				
Wall 15 in.	M = -12.92	(kip-ft/ft)	Wall above Elec. Penetration. Horz. cut.	17.2	3.96	-0.78 [-2.042e-4]
	P = 4.70	(kip/ft)				
Wall 27 in.	M = -6.57	(kip-ft/ft)	Below personal hatch. Vert. cut.	25.9	19.7	0.0 [5.05e-4]
	P = 57.80	(kip/ft)				
Wall 27 in.	M = -92.23	(kip-ft/ft)	Below personal hatch. Vert. cut.	37.0	-1.17	-1.54 [-4.32e-4]
	P = -15.28	(kip/ft)				
Wall 27 in.	M = -1.18	(kip-ft/ft)	Side of personal hatch. Vert. cut.	22.5	21.4	0.0 [6.00e-4]
	P = 55.82	(kip/ft)				
Wall 27 in.	M = -80.76	(kip-ft/ft)	Side of personal hatch. Vert. cut.	27.8	-0.83	-1.29 [-3.55e-4]
	P = -21.38	(kip/ft)				

Table B3. Stress in Rebar and Concrete of Structural Components Subjected to LC1 Standard-Plus Case

Comp.	Demand		Location	Total stress in steel (ksi)		Maximum stress and strain in concrete (ksi) [in./in.]
				Rebar 1	Rebar 2	
Wall 36 in.	M = 459.2	(kip-ft/ft)	Wall near foundation. Horz. cut.	27.1	5.58	-2.21 [-6.61e-4]
	P = -142.2	(kip/ft)				
Wall 15 in.	M = 1.69	(kip-ft/ft)	Wall above Elec. Penetration. Horz. cut.	12.5	7.34	0.0 [4.03e-5]
	P = 19.88	(kip/ft)				
Wall 27 in.	M = -39.25	(kip-ft/ft)	Below personal hatch. Vert. cut.	24.6	2.73	-0.71 [-1.88e-4]
	P = 13.92	(kip/ft)				
Wall 27 in.	M = -33.66	(kip-ft/ft)	Side of personal hatch. Vert. cut.	19.3	2.79	-0.57 [-1.47e-4]
	P = 11.03	(kip/ft)				

Table B4. Stress in Rebar and Concrete of Structural Components Subjected to LC2 Standard-Plus Case

Comp.	Demand		Location	Total stress in steel (ksi)		Maximum stress and strain in concrete (ksi) [in./in.]
				Rebar 1	Rebar 2	
Wall 36 in.	M = 614.4	(kip-ft/ft)	Wall near foundation. Horz. cut.	42.4	1.97	-2.68 [-8.51e-4]
	P = 9.38	(kip/ft)				
Wall 36 in.	M = 431.8	(kip-ft/ft)	Wall near foundation. Horz. cut.	20.6	2.19	-2.48 [-7.67e-4]
	P = -392.3	(kip/ft)				
Wall 15 in.	M =22.45	(kip-ft/ft)	Wall above Elec. Penetration. Horz. cut.	54.9	12.8	-1.32 [-3.62e-4]
	P = 52.29	(kip/ft)				
Wall 15 in.	M = -13.08	(kip-ft/ft)	Wall above Elec. Penetration. Horz. cut.	17.1	3.90	-0.78 [-2.06e-4]
	P = 4.25	(kip/ft)				
Wall 27 in.	M = -6.24	(kip-ft/ft)	Below personal hatch. Vert. cut.	25.9	19.7	0.0 [5.05e-4]
	P = 57.62	(kip/ft)				
Wall 27 in.	M = -91.80	(kip-ft/ft)	Below personal hatch. Vert. cut.	37.0	-1.17	-1.54 [-4.32e-4]
	P = -15.46	(kip/ft)				
Wall 27 in.	M = -0.85	(kip-ft/ft)	Side of personal hatch. Vert. cut.	22.4	21.5	0.0 [6.07e-4]
	P = 55.76	(kip/ft)				
Wall 27 in.	M = -80.25	(kip-ft/ft)	Side of personal hatch. Vert. cut.	27.5	-0.81	-1.29 [-3.52e-4]
	P = -21.39	(kip/ft)				

B9. Figures

There are no figures

APPENDIX C

TENSILE STRESS IN REBARS OF RESIDUAL HEAT REMOVAL EQUIPMENT VAULT STRUCTURE

C1. REVISION HISTORY

Revision 0: Initial document.

C2. OBJECTIVE OF CALCULATION

The objective of this calculation is to compute the maximum tensile stress that can form in the reinforcing steel rebars of Residual Hear Removal Equipment Vault (RHR) structure.

C3. RESULTS AND CONCLUSIONS

Table C1 summarizes the tensile stress in rebars of the RHR structure calculated at critical locations. The maximum tensile stress is 59.5 ksi computed for the vertical rebar of east interior wall at approximate El. (-) 45 ft. and subjected to the second in situ load combination. However, per RHR susceptibility evaluation [C1] and original design calculation [C3], the vertical rebars are not the primary load path. Essentially, the wall were designed to span horizontally. The next highest stress value is 56.5 ksi that is computed for the east exterior wall.

C4. DESIGN DATA / CRITERIA

See Section 4 of the calculation main body (Calc. 160268-CA-06 Rev. 0).

C5. ASSUMPTIONS

C5.1 Justified assumptions

There are no justified assumptions.

C5.2 Unverified assumptions

There are no unverified assumptions.

C6. METHODOLOGY

The most critical stress demand in the horizontal rebars of the RHR structure is primarily due to the axial-flexure interaction along the vertical section cut in the south side of the east exterior wall. The highest stress demand in the vertical rebars of the RHR structure is primarily due to tension in the east and west interior walls.

Finite element analyses are conducted to calculate the axial force and bending moment at critical sections of the structure. The FE model and analysis method are similar to what explained in susceptibility evaluation of RHR structure [C1]. The axial force and bending moments are calculated using the method of section cuts.

Sectional analysis based on fiber section method is used to calculate the stress in the rebars of a section of a wall subjected to a combination of axial force and bending moment, as explained in calculation main body. Each wall section is discretized into 20 fibers of 1 ft width. An example calculation that evaluates the stress in the rebars of the east exterior wall is presented in Section C8. The CI value for the exterior wall was 0.75 mm/m which included in the analysis to find the initial stress state due to internal ASR alone. Zero internal ASR is used for the interior walls.

Figure C1 shows the contour plots of vertical strains in the interior walls due to LC1. The contour plots show that the overall vertical strains are reasonable compared to the yielding strain of rebars (i.e., 0.02% in/in). Localized strain concentration is observed close to the door openings at approximate El. (-) 30 ft. and El. (-) 45 ft.. Ductile distribution of local demands along the width of the interior walls is possible. As a result, localized strain concentration is not of concern.

C7. REFERENCES

[C1] Simpson Gumpertz & Heger Inc., *Evaluation of Residual Heat Removal Equipment Vault,* 160268-CA-06 Rev. 0, Waltham, MA, August 2017.

[C2] United Engineers & Constructors Inc., Seabrook Station Structural Design Drawings.

[C3] United Engineers & Constructors Inc., *Analysis and Design of Vault Walls up to El. 23 ft.*, *PB-30 Calc Rev. 9*, Dec. 2002.

C8. COMPUTATION

C8.1 Strain in Steel and Concrete due to Internal ASR expansion

Input Data

ASR expansion

Measured crack index $\varepsilon_{CI} := 0.75\frac{mm}{m}$

Threshold factor $F_{thr} := 1.0$

Material properties

Ref. [C1]

Compressive strength of concrete $f_c := -3ksi$

Young's modulus of concrete $E_c := 3120ksi$

Yield strength of steel $f_y := 60ksi$

Young's modulus of steel $E_s := 29000ksi$

Geometry

Ref. [C2]

Width of fibers $b := 12in$

Total thickness or height $h := 24in$

Area of concrete $A_c := b \cdot h = 288 \cdot in^2$

Area of tensile reinforcement (#8@9 in.) $A_s := 0.79 \cdot \frac{12}{9} in^2 = 1.053 \cdot in^2$

Number of reinforcement in row, e.g. equal to 2 for tensile and compressive $Steel_{Num} := 2$

Depth to reinforcement $d := 20.5in$

Finding the strain in steel and concrete by satisfying compatibility and equilibrium

Initial Guess

Initial mechanical strain in concrete $\varepsilon_{o.conc} := 0$

Initial strain in steel $\varepsilon_{o.steel} := 0$

Given

Compatibility equation $F_{thr} \cdot \varepsilon_{CI} = \varepsilon_{o.steel} - \varepsilon_{o.conc}$

Equilibrium equation $(E_c \cdot A_c) \cdot \varepsilon_{o.conc} + (E_s \cdot A_s \cdot Steel_{Num}) \cdot \varepsilon_{o.steel} = 0$

$ans := Find(\varepsilon_{o.conc}, \varepsilon_{o.steel})$

Initial strain in concrete and steel $\varepsilon_{o.conc} := ans_1 = -4.775 \times 10^{-5}$

$\varepsilon_{o.steel} := ans_2 = 7.023 \times 10^{-4}$

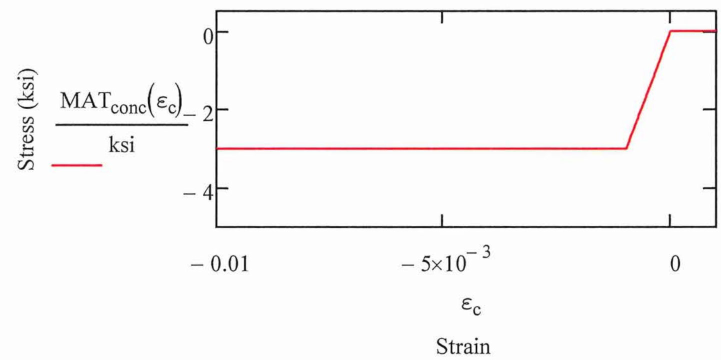
C8.2 Sectional Analysis

Input Data

Concrete Material Model

Constitutive model for concrete

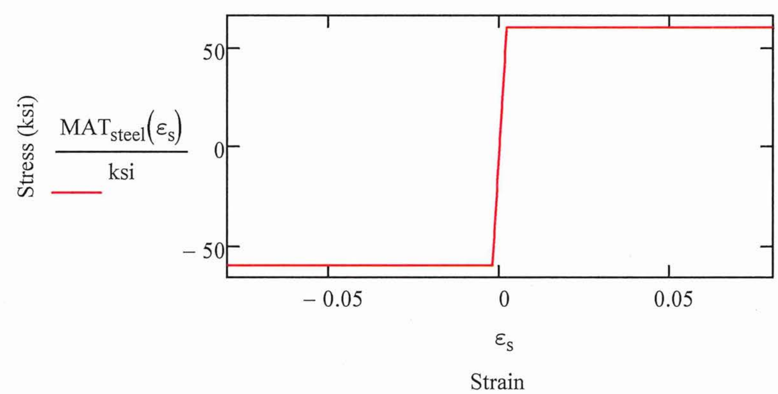
$$MAT_{conc}(\varepsilon) := \begin{cases} 0 & \text{if } \varepsilon > 0 \\ f_c & \text{if } \varepsilon < \dfrac{f_c}{E_c} \\ (E_c \cdot \varepsilon) & \text{otherwise} \end{cases}$$



Steel Material Model

Constitutive model for steel

$$MAT_{steel}(\varepsilon) := \begin{cases} f_y & \text{if } \varepsilon > \dfrac{f_y}{E_s} \\ -f_y & \text{if } \varepsilon < \dfrac{-f_y}{E_s} \\ (E_s \cdot \varepsilon) & \text{otherwise} \end{cases}$$



Concrete Fibers

Number of fibers $Conc_{Num} := 20$

Height of fibers $Conc_H := \frac{h}{Conc_{Num}} = 1.2 \cdot in$

Concrete fiber coordinates

$$Conc_y := \left| \begin{array}{l} \text{for } i \in 1..Conc_{Num} \\ \quad ans_i \leftarrow -\frac{h}{2} + \frac{Conc_H}{2} + (i-1) \cdot Conc_H \\ ans \end{array} \right.$$

Concrete fiber strain

$$Conc_\varepsilon(\varepsilon_{o.conc}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{for } i \in 1..Conc_{Num} \\ \quad ans_i \leftarrow \varepsilon_{o.conc} + \varepsilon - \varphi \cdot Conc_{y_i} \\ ans \end{array} \right.$$

Concrete fiber stress

$$Conc_\sigma(\varepsilon_{o.conc}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{for } i \in 1..Conc_{Num} \\ \quad ans_i \leftarrow MAT_{conc}\left(Conc_\varepsilon(\varepsilon_{o.conc}, \varepsilon, \varphi)_i\right) \\ ans \end{array} \right.$$

Concrete fiber force

$$Conc_F(\varepsilon_{o.conc}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{for } i \in 1..Conc_{Num} \\ \quad ans_i \leftarrow Conc_\sigma(\varepsilon_{o.conc}, \varepsilon, \varphi)_i \cdot (b \cdot Conc_H) \\ ans \end{array} \right.$$

Reinforcement/Steel fibers

Depth to reinforcement fiber

$$Steel_{y_1} := -\left(d - \frac{h}{2}\right) = -8.5 \cdot in$$

$$Steel_{y_2} := d - \frac{h}{2} = 8.5 \cdot in$$

Area of reinforcement fiber

$$Steel_{As_1} := A_s = 1.053 \cdot in^2$$

$$Steel_{As_2} := A_s = 1.053 \cdot in^2$$

Steel fiber strain

$$Steel_\varepsilon(\varepsilon_{o.steel}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{for } i \in 1..Steel_{Num} \\ \quad ans_i \leftarrow \varepsilon_{o.steel} + \varepsilon - \varphi \cdot Steel_{y_i} \\ ans \end{array} \right.$$

Steel fiber stress

$$Steel_\sigma(\varepsilon_{o.steel}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{for } i \in 1..Steel_{Num} \\ \quad ans_i \leftarrow MAT_{steel}\left(Steel_\varepsilon(\varepsilon_{o.steel}, \varepsilon, \varphi)_i\right) \\ ans \end{array} \right.$$

Steel fiber force

$$Steel_F(\varepsilon_{o.steel}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{for } i \in 1..Steel_{Num} \\ \quad ans_i \leftarrow Steel_\sigma(\varepsilon_{o.steel}, \varepsilon, \varphi)_i \cdot Steel_{As_i} \\ ans \end{array} \right.$$

Initial Stress State

Initial stress in concrete

$$\mathrm{Concrete}_{\sigma} := \mathrm{Conc}_{\sigma}(\varepsilon_{o.conc}, 0, 0)$$

$$\mathrm{Concrete}_{\sigma_1} = -0.149 \cdot \mathrm{ksi}$$

Initial stress in steel

$$\mathrm{Rebar}_{\sigma} := \mathrm{Steel}_{\sigma}(\varepsilon_{o.steel}, 0, 0)$$

$$\mathrm{Rebar}_{\sigma_1} = 20.365 \cdot \mathrm{ksi}$$

Axial Equilibrium

$$\mathrm{Force}(\varepsilon_{o.conc}, \varepsilon_{o.steel}, \varepsilon, \varphi) := \left| \begin{array}{l} \mathrm{ans1} \leftarrow 0 \\ \text{for } i \in 1..\mathrm{Conc}_{Num} \\ \quad \mathrm{ans1} \leftarrow \mathrm{ans1} + \mathrm{Conc}_F(\varepsilon_{o.conc}, \varepsilon, \varphi)_i \\ \mathrm{ans2} \leftarrow 0 \\ \text{for } i \in 1..\mathrm{Steel}_{Num} \\ \quad \mathrm{ans2} \leftarrow \mathrm{ans2} + \mathrm{Steel}_F(\varepsilon_{o.steel}, \varepsilon, \varphi)_i \\ \mathrm{ans} \leftarrow \mathrm{ans1} + \mathrm{ans2} \end{array} \right.$$

Moment Equilibrium

$$\mathrm{Moment}(\varepsilon_{o.conc}, \varepsilon_{o.steel}, \varepsilon, \varphi) := \left| \begin{array}{l} \mathrm{ans1} \leftarrow 0 \\ \text{for } i \in 1..\mathrm{Conc}_{Num} \\ \quad \mathrm{ans1} \leftarrow \mathrm{ans1} + -1 \cdot \mathrm{Conc}_F(\varepsilon_{o.conc}, \varepsilon, \varphi)_i \cdot \mathrm{Conc}_{y_i} \\ \mathrm{ans2} \leftarrow 0 \\ \text{for } i \in 1..\mathrm{Steel}_{Num} \\ \quad \mathrm{ans2} \leftarrow \mathrm{ans2} + -1 \cdot \mathrm{Steel}_F(\varepsilon_{o.steel}, \varepsilon, \varphi)_i \cdot \mathrm{Steel}_{y_i} \\ \mathrm{ans} \leftarrow \mathrm{ans1} + \mathrm{ans2} \end{array} \right.$$

Solution

Known parameters

Axial force $P := -35\text{kip}$

Iteration

Curvature $\phi := -0.000072 \cdot \frac{1}{in}$ Requires iteration

Solve for strain at centroid

Axial strain at centroid (initial guess) $x_o := 0.0$

Axial force equilibrium $f(x) := \text{Force}(\varepsilon_{o.conc}, \varepsilon_{o.steel}, x, \phi) - P$

$$\varepsilon_{cent} := \text{root}(f(x_o), x_o) = 3.028 \times 10^{-4}$$

Sectional forces

$$\text{Force}(\varepsilon_{o.conc}, \varepsilon_{o.steel}, \varepsilon_{cent}, \phi) = -35 \cdot \text{kip}$$

$$\text{Moment}(\varepsilon_{o.conc}, \varepsilon_{o.steel}, \varepsilon_{cent}, \phi) = -100.015 \cdot \text{kip} \cdot \text{ft}$$

Stress and strain in concrete and steel

Steel fiber stress and strain

$$\text{Rebar}_\varepsilon := \text{Steel}_\varepsilon(\varepsilon_{o.steel}, \varepsilon_{cent}, \phi) = \begin{pmatrix} 3.931 \times 10^{-4} \\ 1.617 \times 10^{-3} \end{pmatrix}$$

$$\text{Rebar}_\sigma := \text{Steel}_\sigma(\varepsilon_{o.steel}, \varepsilon_{cent}, \phi) = \begin{pmatrix} 11.399 \\ 46.895 \end{pmatrix} \cdot \text{ksi}$$

$$\text{Steel}_F(\varepsilon_{o.steel}, \varepsilon_{cent}, \phi) = \begin{pmatrix} 12.007 \\ 49.396 \end{pmatrix} \cdot \text{kip}$$

$$\text{Concrete}_y := \text{Conc}_y$$

Concrete fiber stress and strain

$$\text{Concrete}_\varepsilon := \text{Conc}_\varepsilon(\varepsilon_{o.conc}, \varepsilon_{cent}, \phi)$$

$$\text{Concrete}_\sigma := \text{Conc}_\sigma(\varepsilon_{o.conc}, \varepsilon_{cent}, \phi)$$

Maximum compressive stress in concrete

$$\sigma_{max.comp} := \text{MAT}_{conc}\left(\text{Concrete}_{\varepsilon_1} + \phi \cdot \frac{\text{Conc}_H}{2}\right) = -1.9 \cdot \text{ksi}$$

C9. TABLES

Table C1: Stress in rebars at critical locations of RHR structure subjected to LC1

Component	Item	Total demands for sustained load (In Situ condition, LC1)		Total stress in steel (ksi)		Maximum compressive stress in concrete (ksi)
		Demand	Location	Rebar 1	Rebar 2	
Wall	Moment about the vertical global axis (kip-ft/ft)	-98.5	East exterior wall, vertical strip, at the approximate El. (-) 30 ft	46.9	11.4	-1.9
	Axial force (kip/ft)	-35.0				
Wall	Moment about the horizontal global axis (kip-ft/ft)	28.6	East interior wall, horizontal strip, at the approximate El. (-) 45 ft	41.6	5.5	0.0
	Axial force (kip/ft)	37.2				
Wall	Moment about the horizontal global axis (kip-ft/ft)	11.0	West interior wall, horizontal strip, at the approximate El. (-) 30 ft	26.5	12.5	0.0
	Axial force (kip/ft)	30.8				

Table C2: Stress in rebars at critical locations of RHR structure subjected to LC2

Component	Item	Total demands for sustained load (In Situ condition, LC1)		Total stress in steel (ksi)		Maximum compressive stress in concrete (ksi)
		Demand	Location	Rebar 1	Rebar 2	
Wall	Moment about the vertical global axis (kip-ft/ft)	-119.5	East exterior wall, vertical strip, at the approximate El. (-) 30 ft	56.5	13.8	-2.1
	Axial force (kip/ft)	-40.8				
Wall	Moment about the horizontal global axis (kip-ft/ft)	33.0	East interior wall, horizontal strip, at the approximate El. (-) 45 ft	59.5	17.7	0.0
	Axial force (kip/ft)	60.9				
Wall	Moment about the horizontal global axis (kip-ft/ft)	13.4	West interior wall, horizontal strip, at the approximate El. (-) 30 ft	36.6	19.6	0.0
	Axial force (kip/ft)	44.4				

C10. FIGURES

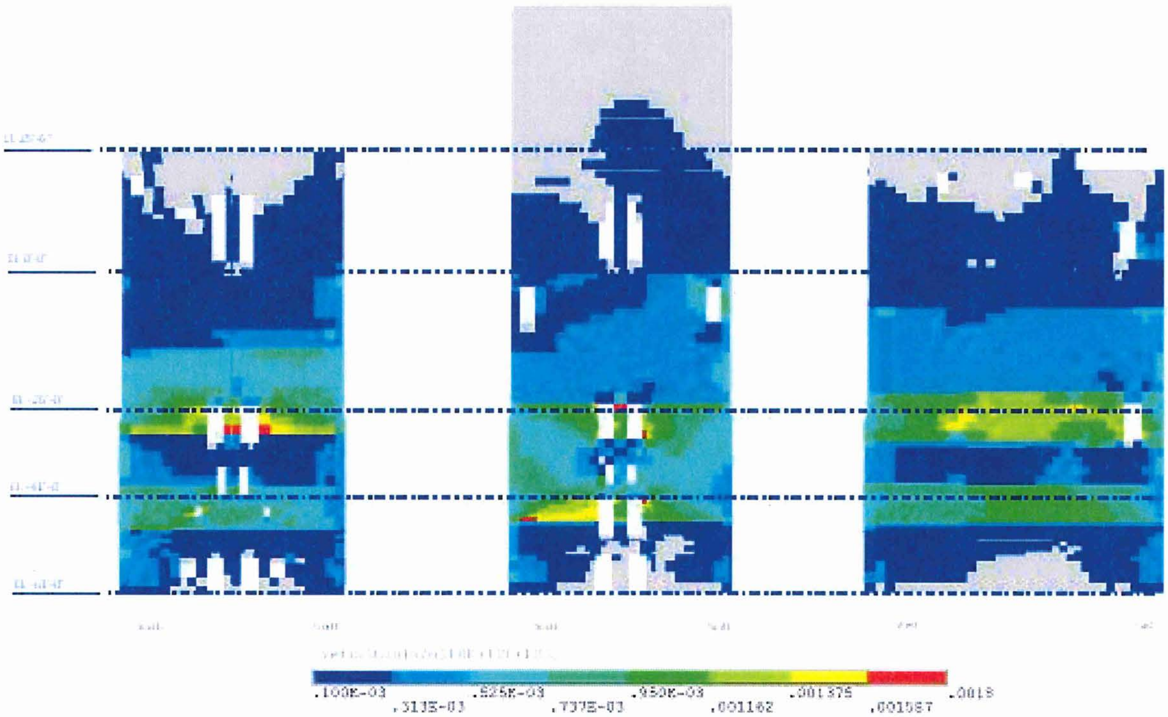


Figure C1: Contour plots of vertical strains in the interior walls due to LC1

APPENDIX D

TENSILE STRESS IN REBARS OF CONDENSATE STORAGE TANK ENCLOSURE STRUCTURE

D1. REVISION HISTORY

Revision 0: Initial document.

D2. OBJECTIVE OF CALCULATION

The objective of this calculation is to compute the maximum tensile stress that can form in the rebars of the Condensate Storage Tank Enclosure (CSTE) structure.

D3. RESULTS AND CONCLUSIONS

Table D1 summarizes the tensile stress in rebars of the CSTE structure calculated at critical locations. The Maximum tensile stress is 26.7 ksi at the bottom of the tank enclosure wall subjected to the second in situ load combination (LC2).

D4. DESIGN DATA / CRITERIA

See Section 4 of the calculation main body (Calc. 160268-CA-03 Rev. 0).

D5. ASSUMPTIONS

D5.1 Justified assumptions

There are no justified assumptions.

D5.2 Unverified assumptions

There are no unverified assumptions.

D6. METHODOLOGY

The critical demands that control the selection of the threshold factor for the CSTE structure are hoop tension at the top of the tank enclosure wall, and vertical moment at the base of the tank enclosure wall. Finite element analyses were conducted to calculate the axial force and bending moment at these locations due to ASR load [D1].

To calculate the stress in rebars subjected to a combination of axial force and bending moment, sectional analysis based on fiber section method, as explained in calculation main body, is used. The calculation is conducted per 1 foot width of the walls, and each section is discretized into 20 fibers. An example calculation that evaluates the stress in the vertical rebars at the base of the tank enclosure wall is presented in Section D8. The ASR expansion of the tank enclosure is included in the analysis to find the initial stress state due to internal ASR alone.

D7. REFERENCES

[D1] Simpson Gumpertz & Heger Inc., *Evaluation of Condensate Storage Tank Enclosure Structure,* 160268-CA-03 Rev. 0, Waltham, MA, Dec 2016.

[D2] United Engineers & Constructors Inc., Seabrook Station Structural Design Drawings.

[D3] United Engineers & Constructors Inc., *Condensate Storage Tank Mat and Wall Reinforcement*, MT-21, Rev. 3, Jan. 1984.

D8. COMPUTATION

D8.1. Strain in Steel and Concrete due to Internal ASR expansion

Input Data

ASR expansion

Measured crack index	$\varepsilon_{CI} := 0.43 \frac{mm}{m}$	
Threshold factor	$F_{thr} := 1.6$	

Material properties

Compressive strength of concrete	$f_c := -4ksi$	Ref. [D1]
Young's modulus of concrete	$E_c := 3605ksi$	
Yield strength of steel	$f_y := 60ksi$	
Young's modulus of steel	$E_s := 29000ksi$	

Geometry

Width of fibers	$b := 12in$	Ref. [D2]
Total thickness or height	$h := 24in$	
Area of concrete	$A_c := b \cdot h = 288 \cdot in^2$	
Area of tensile reinforcement (#11@12 in.)	$A_s := 1.56in^2$	
Number of reinforcement in row, e.g. equal to 2 for tensile and compressive	$Steel_{Num} := 2$	
Depth to reinforcement	$d := 20.3in$	

Finding the strain in steel and concrete by satisfying compatibility and equilibrium

	Initial Guess
Initial mechanical strain in concrete	$\varepsilon_{o.conc} := 0$
Initial strain in steel	$\varepsilon_{o.steel} := 0$
	Given
Compatibility equation	$F_{thr} \cdot \varepsilon_{CI} = \varepsilon_{o.steel} - \varepsilon_{o.conc}$
Equilibrium equation	$(E_c \cdot A_c) \cdot \varepsilon_{o.conc} + (E_s \cdot A_s \cdot Steel_{Num}) \cdot \varepsilon_{o.steel} = 0$
	$ans := Find(\varepsilon_{o.conc}, \varepsilon_{o.steel})$

Initial strain in concrete and steel

$$\varepsilon_{o.conc} := ans_1 = -5.515 \times 10^{-5}$$

$$\varepsilon_{o.steel} := ans_2 = 6.328 \times 10^{-4}$$

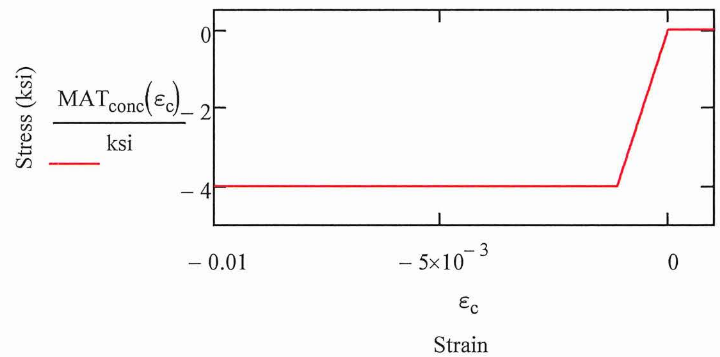
D8.2. Sectional Analysis

Input Data

Concrete Material Model

Constitutive model for concrete

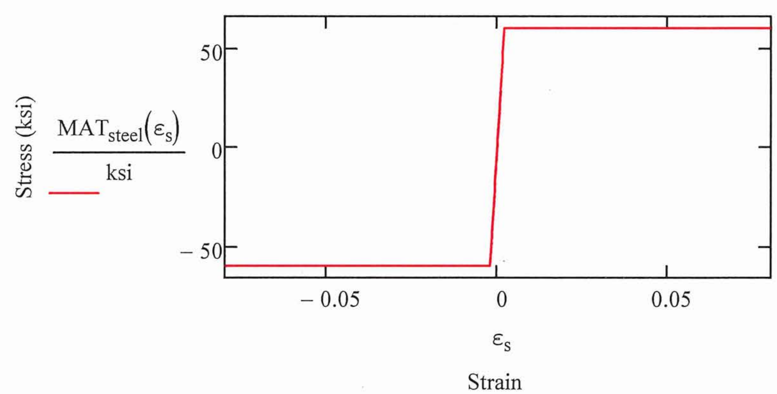
$$MAT_{conc}(\varepsilon) := \begin{vmatrix} 0 \quad \text{if } \varepsilon > 0 \\ f_c \quad \text{if } \varepsilon < \dfrac{f_c}{E_c} \\ (E_c \cdot \varepsilon) \quad \text{otherwise} \end{vmatrix}$$



Steel Material Model

Constitutive model for steel

$$MAT_{steel}(\varepsilon) := \begin{vmatrix} f_y \quad \text{if } \varepsilon > \dfrac{f_y}{E_s} \\ -f_y \quad \text{if } \varepsilon < \dfrac{-f_y}{E_s} \\ (E_s \cdot \varepsilon) \quad \text{otherwise} \end{vmatrix}$$



Concrete Fibers

Number of fibers

$$Conc_{Num} := 20$$

Height of fibers

$$Conc_H := \frac{h}{Conc_{Num}} = 1.2 \cdot in$$

Concrete fiber coordinates

$$Conc_y := \left| \begin{array}{l} \text{for } i \in 1..Conc_{Num} \\ \quad ans_i \leftarrow -\frac{h}{2} + \frac{Conc_H}{2} + (i-1) \cdot Conc_H \\ ans \end{array} \right.$$

Concrete fiber strain

$$Conc_\varepsilon(\varepsilon_{o.conc}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{for } i \in 1..Conc_{Num} \\ \quad ans_i \leftarrow \varepsilon_{o.conc} + \varepsilon - \varphi \cdot Conc_{y_i} \\ ans \end{array} \right.$$

Concrete fiber stress

$$Conc_\sigma(\varepsilon_{o.conc}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{for } i \in 1..Conc_{Num} \\ \quad ans_i \leftarrow MAT_{conc}\left(Conc_\varepsilon(\varepsilon_{o.conc}, \varepsilon, \varphi)_i\right) \\ ans \end{array} \right.$$

Concrete fiber force

$$Conc_F(\varepsilon_{o.conc}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{for } i \in 1..Conc_{Num} \\ \quad ans_i \leftarrow Conc_\sigma(\varepsilon_{o.conc}, \varepsilon, \varphi)_i \cdot (b \cdot Conc_H) \\ ans \end{array} \right.$$

Reinforcement/Steel fibers

Depth to reinforcement fiber

$$Steel_{y_1} := -\left(d - \frac{h}{2}\right) = -8.3 \cdot in$$

$$Steel_{y_2} := d - \frac{h}{2} = 8.3 \cdot in$$

Area of reinforcement fiber

$$Steel_{As_1} := A_s = 1.56 \cdot in^2$$

$$Steel_{As_2} := A_s = 1.56 \cdot in^2$$

Steel fiber strain

$$Steel_\varepsilon(\varepsilon_{o.steel}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{for } i \in 1..Steel_{Num} \\ \quad ans_i \leftarrow \varepsilon_{o.steel} + \varepsilon - \varphi \cdot Steel_{y_i} \\ ans \end{array} \right.$$

Steel fiber stress

$$Steel_\sigma(\varepsilon_{o.steel}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{for } i \in 1..Steel_{Num} \\ \quad ans_i \leftarrow MAT_{steel}\left(Steel_\varepsilon(\varepsilon_{o.steel}, \varepsilon, \varphi)_i\right) \\ ans \end{array} \right.$$

Steel fiber force

$$Steel_F(\varepsilon_{o.steel}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{for } i \in 1..Steel_{Num} \\ \quad ans_i \leftarrow Steel_\sigma(\varepsilon_{o.steel}, \varepsilon, \varphi)_i \cdot Steel_{As_i} \\ ans \end{array} \right.$$

Initial Stress State

Initial stress in concrete

$$\text{Concrete}_{\sigma} := \text{Conc}_{\sigma}\left(\varepsilon_{o.conc}, 0, 0\right)$$

$$\text{Concrete}_{\sigma_1} = -0.199 \cdot \text{ksi}$$

Initial stress in steel

$$\text{Rebar}_{\sigma} := \text{Steel}_{\sigma}\left(\varepsilon_{o.steel}, 0, 0\right)$$

$$\text{Rebar}_{\sigma_1} = 18.353 \cdot \text{ksi}$$

Axial Equilibrium

$$\text{Force}\left(\varepsilon_{o.conc}, \varepsilon_{o.steel}, \varepsilon, \varphi\right) := \left| \begin{array}{l} \text{ans1} \leftarrow 0 \\ \text{for } i \in 1..\text{Conc}_{\text{Num}} \\ \quad \text{ans1} \leftarrow \text{ans1} + \text{Conc}_F\left(\varepsilon_{o.conc}, \varepsilon, \varphi\right)_i \\ \text{ans2} \leftarrow 0 \\ \text{for } i \in 1..\text{Steel}_{\text{Num}} \\ \quad \text{ans2} \leftarrow \text{ans2} + \text{Steel}_F\left(\varepsilon_{o.steel}, \varepsilon, \varphi\right)_i \\ \text{ans} \leftarrow \text{ans1} + \text{ans2} \end{array} \right.$$

Moment Equilibrium

$$\text{Moment}\left(\varepsilon_{o.conc}, \varepsilon_{o.steel}, \varepsilon, \varphi\right) := \left| \begin{array}{l} \text{ans1} \leftarrow 0 \\ \text{for } i \in 1..\text{Conc}_{\text{Num}} \\ \quad \text{ans1} \leftarrow \text{ans1} + -1 \cdot \text{Conc}_F\left(\varepsilon_{o.conc}, \varepsilon, \varphi\right)_i \cdot \text{Conc}_{y_i} \\ \text{ans2} \leftarrow 0 \\ \text{for } i \in 1..\text{Steel}_{\text{Num}} \\ \quad \text{ans2} \leftarrow \text{ans2} + -1 \cdot \text{Steel}_F\left(\varepsilon_{o.steel}, \varepsilon, \varphi\right)_i \cdot \text{Steel}_{y_i} \\ \text{ans} \leftarrow \text{ans1} + \text{ans2} \end{array} \right.$$

Solution

Known parameters

Axial force $P := -12.9\text{kip}$

Iteration

Curvature $\phi := 0.0000266 \cdot \frac{1}{\text{in}}$ Requires iteration

Solve for strain at centroid

Axial strain at centroid (initial guess) $x_o := 0.0$

Axial force equilibrium $f(x) := \text{Force}(\varepsilon_{o.conc}, \varepsilon_{o.steel}, x, \phi) - P$

$$\varepsilon_{cent} := \text{root}(f(x_o), x_o) = 6.778 \times 10^{-5}$$

Sectional forces

$$\text{Force}(\varepsilon_{o.conc}, \varepsilon_{o.steel}, \varepsilon_{cent}, \phi) = -12.9 \cdot \text{kip}$$

$$\text{Moment}(\varepsilon_{o.conc}, \varepsilon_{o.steel}, \varepsilon_{cent}, \phi) = 65.634 \cdot \text{kip} \cdot \text{ft}$$

Stress and strain in concrete and steel

Steel fiber stress and strain

$$\text{Rebar}_{\varepsilon} := \text{Steel}_{\varepsilon}(\varepsilon_{o.steel}, \varepsilon_{cent}, \phi) = \begin{pmatrix} 9.214 \times 10^{-4} \\ 4.799 \times 10^{-4} \end{pmatrix}$$

$$\text{Rebar}_{\sigma} := \text{Steel}_{\sigma}(\varepsilon_{o.steel}, \varepsilon_{cent}, \phi) = \begin{pmatrix} 26.721 \\ 13.916 \end{pmatrix} \cdot \text{ksi}$$

$$\text{Steel}_F(\varepsilon_{o.steel}, \varepsilon_{cent}, \phi) = \begin{pmatrix} 41.685 \\ 21.709 \end{pmatrix} \cdot \text{kip}$$

$$\text{Concrete}_y := \text{Conc}_y$$

Concrete fiber stress and strain

$$\text{Concrete}_{\varepsilon} := \text{Conc}_{\varepsilon}(\varepsilon_{o.conc}, \varepsilon_{cent}, \phi)$$

$$\text{Concrete}_{\sigma} := \text{Conc}_{\sigma}(\varepsilon_{o.conc}, \varepsilon_{cent}, \phi)$$

Maximum compressive strain in concrete

$$\varepsilon_{max.comp} := \frac{\text{Concrete}_{\varepsilon_{ConcNum}} - \text{Concrete}_{\varepsilon_{ConcNum-1}}}{\text{Conc}_{y_{ConcNum}} - \text{Conc}_{y_{ConcNum-1}}} \cdot \left(\frac{h}{2} - \text{Conc}_{y_{ConcNum-1}}\right) \dots + \text{Concrete}_{\varepsilon_{ConcNum-1}} = -3.066 \times 10^{-4}$$

Maximum compressive stress in concrete $\sigma_{max.comp} := \text{MAT}_{conc}(\varepsilon_{max.comp}) = -1.105 \cdot \text{ksi}$

D9. TABLES

Table D1: Stress in rebars at critical locations of CSTE structure subjected to LC1

Component	Item	Total demands for sustained load (In Situ condition, LC1)		Total stress in steel (ksi)		Maximum compressive stress in concrete (ksi)
		Demand	Location	Rebar 1	Rebar 2	
Tank Enclosure Wall	Out-of-plane moment (kip-ft/ft)	0	Top of tank enclosure wall, horizontal direction	16.3	16.3	-0.14
	Axial force (kip/ft)	41.4				
	Out-of-plane moment (kip-ft/ft)	41	Bottom of tank enclosure wall, vertical direction	15.8	8.6	-0.68
	Axial force (kip/ft)	-12.9				

Table D2: Stress in rebars at critical locations of CSTE structure subjected to LC2

Component	Item	Total demands for sustained loads plus OBE amplified with threshold factor (In Situ condition, LC2)		Total stress in steel (ksi)		Maximum compressive stress in concrete (ksi)
		Demand	Location	Rebar 1	Rebar 2	
Tank Enclosure Wall	Out-of-plane moment (kip-ft/ft)	0	Top of tank enclosure wall, horizontal direction	26.0	26.0	-0.23
	Axial force (kip/ft)	66.2				
	Out-of-plane moment (kip-ft/ft)	65.7	Bottom of tank enclosure wall, vertical direction	26.7	13.9	-1.11
	Axial force (kip/ft)	-12.9				

Example in Section D8

D10. FIGURES

There are no figures.

APPENDIX E
TENSILE STRESS IN REBARS OF CONTAINMENT EQUIPMENT HATCH MISSILE SHIELD STRUCTURE

E1. REVISION HISTORY

Revision 0: Initial document.

Revision 1: Revised page E-1 to update Revision history section. Revised page E-2 from Revision 0 to 1 to make editorial correction references to Section A8 to E8.

E2. OBJECTIVE OF CALCULATION

The objective of this calculation is to compute the maximum tensile stress that can form in the rebars of Containment Equipment Hatch Missile Shield (CEHMS) structure.

E3. RESULTS AND CONCLUSIONS

Table E1 summarizes the tensile stress in rebars of the CEHMS structure calculated at critical locations. The maximum tensile stress is 41.2 ksi computed for the eat wing wall at the intersection with the column.

E4. DESIGN DATA / CRITERIA

See Section 4 of the calculation main body (Calc. 160268-CA-02 Rev. 0).

E5. ASSUMPTIONS

E5.1 Justified assumptions

There are no justified assumptions.

E5.2 Unverified assumptions

There are no unverified assumptions.

E6. METHODOLOGY

The critical demand that governed the computation of the threshold factor of CEHMS structure was bending of east wind wall at the intersection with column. At this location the demands are:

- ASR load with threshold factor: M = 168 kip-ft/ft, P = 2.06 kip/ft (Appendix C of Ref. E1)
- Unfactored ASR load: M = 112.1 kip-ft/ft, P = 1.4 kip/ft (threshold factor was 1.5)
- Original unfactored demands excluding the OBE: M = 47.5 kip-ft/ft, P = -9.7 kip/ft (Sheet 30 to 45 of Ref. E3)
- Original unfactored demands including the OBE: M = 143.6 kip-ft/ft, P = -2.72 kip/ft (Sheet 30 to 45 of Ref. E3)

To calculate the stress in rebars subjected to a combination of axial force and bending moment, sectional analysis based on fiber section method, as explained in calculation main body, is used. The calculation is conducted per 1 foot width of the wall, and each section is discretized into 20 fibers. An example calculation that evaluates the stress in rebars of the east wing wall is presented in Section E8. The CI value of the wall was 0.72 mm/m which included in the analysis to find the initial stress state due to internal ASR alone.

E7. REFERENCES

[E1] Simpson Gumpertz & Heger Inc., *Evaluation of Containment Equipment Hatch Missile Shield structure,* 160268-CA-02 Rev. 0, Waltham, MA, Oct 2016.

[E2] United Engineers & Constructors Inc., Seabrook Station Structural Design Drawings.

[E3] United Engineers & Constructors Inc., *Equipment Hatch Shield Wall*, *CE-6-Calc Rev. 3*, Aug. 1998.

E8. COMPUTATION

E8.1. Strain in Steel and Concrete due to Internal ASR expansion

Input Data

ASR expansion

Measured crack index	$\varepsilon_{CI} := 0.72 \frac{mm}{m}$	
Threshold factor	$F_{thr} := 1.5$	

Material properties

Compressive strength of concrete	$f_c := -3ksi$	Ref. [E1]
Young's modulus of concrete	$E_c := 3120ksi$	
Yield strength of steel	$f_y := 60ksi$	
Young's modulus of steel	$E_s := 29000ksi$	

Geometry

Width of fibers	$b := 12in$	Ref. [E2]
Total thickness or height	$h := 42in$	
Area of concrete	$A_c := b \cdot h = 504 \cdot in^2$	
Area of tensile reinforcement (#11@6 in.)	$A_s := 2 \cdot 1.56in^2$	
Number of reinforcement in row, e.g. equal to 2 for tensile and compressive	$Steel_{Num} := 2$	
Depth to reinforcement	$d := 36.88in$	

Finding the strain in steel and concrete by satisfying compatibility and equilibrium

	Initial Guess
Initial mechanical strain in concrete	$\varepsilon_{o.conc} := 0$
Initial strain in steel	$\varepsilon_{o.steel} := 0$
	Given
Compatibility equation	$F_{thr} \cdot \varepsilon_{CI} = \varepsilon_{o.steel} - \varepsilon_{o.conc}$
Equilibrium equation	$(E_c \cdot A_c) \cdot \varepsilon_{o.conc} + (E_s \cdot A_s \cdot Steel_{Num}) \cdot \varepsilon_{o.steel} = 0$
	$ans := Find(\varepsilon_{o.conc}, \varepsilon_{o.steel})$

Initial strain in concrete and steel

$$\varepsilon_{o.conc} := ans_1 = -1.115 \times 10^{-4}$$

$$\varepsilon_{o.steel} := ans_2 = 9.685 \times 10^{-4}$$

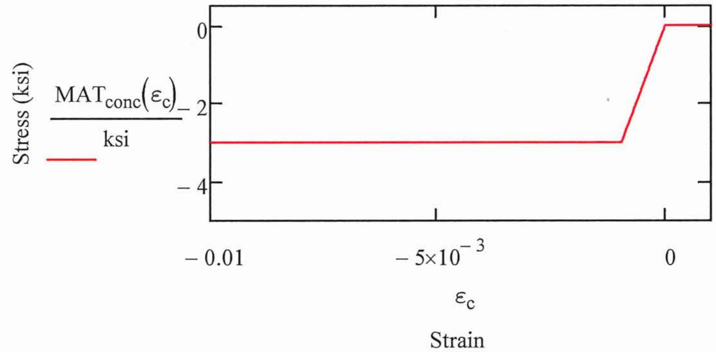
E8.2. Sectional Analysis

Input Data

Concrete Material Model

Constitutive model for concrete

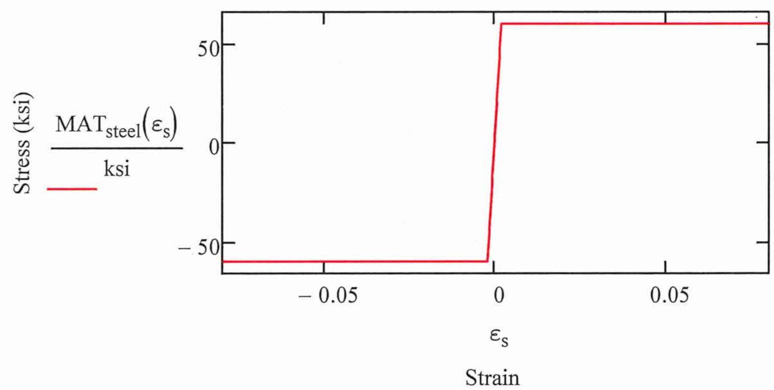
$$MAT_{conc}(\varepsilon) := \begin{cases} 0 & \text{if } \varepsilon > 0 \\ f_c & \text{if } \varepsilon < \dfrac{f_c}{E_c} \\ (E_c \cdot \varepsilon) & \text{otherwise} \end{cases}$$



Steel Material Model

Constitutive model for steel

$$MAT_{steel}(\varepsilon) := \begin{cases} f_y & \text{if } \varepsilon > \dfrac{f_y}{E_s} \\ -f_y & \text{if } \varepsilon < \dfrac{-f_y}{E_s} \\ (E_s \cdot \varepsilon) & \text{otherwise} \end{cases}$$



Concrete Fibers

Number of fibers $\quad Conc_{Num} := 20$

Height of fibers $\quad Conc_H := \frac{h}{Conc_{Num}} = 2.1 \cdot in$

Concrete fiber coordinates

$$Conc_y := \left| \begin{array}{l} \text{for } i \in 1..Conc_{Num} \\ \quad ans_i \leftarrow -\frac{h}{2} + \frac{Conc_H}{2} + (i-1) \cdot Conc_H \\ ans \end{array} \right.$$

Concrete fiber strain

$$Conc_\varepsilon(\varepsilon_{o.conc}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{for } i \in 1..Conc_{Num} \\ \quad ans_i \leftarrow \varepsilon_{o.conc} + \varepsilon - \varphi \cdot Conc_{y_i} \\ ans \end{array} \right.$$

Concrete fiber stress

$$Conc_\sigma(\varepsilon_{o.conc}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{for } i \in 1..Conc_{Num} \\ \quad ans_i \leftarrow MAT_{conc}\left(Conc_\varepsilon(\varepsilon_{o.conc}, \varepsilon, \varphi)_i\right) \\ ans \end{array} \right.$$

Concrete fiber force

$$Conc_F(\varepsilon_{o.conc}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{for } i \in 1..Conc_{Num} \\ \quad ans_i \leftarrow Conc_\sigma(\varepsilon_{o.conc}, \varepsilon, \varphi)_i \cdot (b \cdot Conc_H) \\ ans \end{array} \right.$$

Reinforcement/Steel fibers

Depth to reinforcement fiber

$$Steel_{y_1} := -\left(d - \frac{h}{2}\right) = -15.88 \cdot in$$

$$Steel_{y_2} := d - \frac{h}{2} = 15.88 \cdot in$$

Area of reinforcement fiber

$$Steel_{As_1} := A_s = 3.12 \cdot in^2$$

$$Steel_{As_2} := A_s = 3.12 \cdot in^2$$

Steel fiber strain

$$Steel_\varepsilon(\varepsilon_{o.steel}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{for } i \in 1..Steel_{Num} \\ \quad ans_i \leftarrow \varepsilon_{o.steel} + \varepsilon - \varphi \cdot Steel_{y_i} \\ ans \end{array} \right.$$

Steel fiber stress

$$Steel_\sigma(\varepsilon_{o.steel}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{for } i \in 1..Steel_{Num} \\ \quad ans_i \leftarrow MAT_{steel}\left(Steel_\varepsilon(\varepsilon_{o.steel}, \varepsilon, \varphi)_i\right) \\ ans \end{array} \right.$$

Steel fiber force

$$Steel_F(\varepsilon_{o.steel}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{for } i \in 1..Steel_{Num} \\ \quad ans_i \leftarrow Steel_\sigma(\varepsilon_{o.steel}, \varepsilon, \varphi)_i \cdot Steel_{As_i} \\ ans \end{array} \right.$$

Initial Stress State

Initial stress in concrete

$$\mathrm{Concrete}_{\sigma} := \mathrm{Conc}_{\sigma}\left(\varepsilon_{o.conc}, 0, 0\right)$$

$$\mathrm{Concrete}_{\sigma_1} = -0.348 \cdot \mathrm{ksi}$$

Initial stress in steel

$$\mathrm{Rebar}_{\sigma} := \mathrm{Steel}_{\sigma}\left(\varepsilon_{o.steel}, 0, 0\right)$$

$$\mathrm{Rebar}_{\sigma_1} = 28.088 \cdot \mathrm{ksi}$$

Axial Equilibrium

$$\mathrm{Force}\left(\varepsilon_{o.conc}, \varepsilon_{o.steel}, \varepsilon, \varphi\right) := \left| \begin{array}{l} \mathrm{ans1} \leftarrow 0 \\ \text{for } i \in 1 .. \mathrm{Conc}_{Num} \\ \quad \mathrm{ans1} \leftarrow \mathrm{ans1} + \mathrm{Conc}_F\left(\varepsilon_{o.conc}, \varepsilon, \varphi\right)_i \\ \mathrm{ans2} \leftarrow 0 \\ \text{for } i \in 1 .. \mathrm{Steel}_{Num} \\ \quad \mathrm{ans2} \leftarrow \mathrm{ans2} + \mathrm{Steel}_F\left(\varepsilon_{o.steel}, \varepsilon, \varphi\right)_i \\ \mathrm{ans} \leftarrow \mathrm{ans1} + \mathrm{ans2} \end{array} \right.$$

Moment Equilibrium

$$\mathrm{Moment}\left(\varepsilon_{o.conc}, \varepsilon_{o.steel}, \varepsilon, \varphi\right) := \left| \begin{array}{l} \mathrm{ans1} \leftarrow 0 \\ \text{for } i \in 1 .. \mathrm{Conc}_{Num} \\ \quad \mathrm{ans1} \leftarrow \mathrm{ans1} + -1 \cdot \mathrm{Conc}_F\left(\varepsilon_{o.conc}, \varepsilon, \varphi\right)_i \cdot \mathrm{Conc}_{y_i} \\ \mathrm{ans2} \leftarrow 0 \\ \text{for } i \in 1 .. \mathrm{Steel}_{Num} \\ \quad \mathrm{ans2} \leftarrow \mathrm{ans2} + -1 \cdot \mathrm{Steel}_F\left(\varepsilon_{o.steel}, \varepsilon, \varphi\right)_i \cdot \mathrm{Steel}_{y_i} \\ \mathrm{ans} \leftarrow \mathrm{ans1} + \mathrm{ans2} \end{array} \right.$$

Solution

Known parameters

Axial force $P := -0.7\text{kip}$

Iteration

Curvature $\phi := 0.00002285 \cdot \frac{1}{\text{in}}$ Requires iteration

Solve for strain at centroid

Axial strain at centroid (initial guess) $x_o := 0.0$

Axial force equilibrium

$$f(x) := \text{Force}(\varepsilon_{o.conc}, \varepsilon_{o.steel}, x, \phi) - P$$

$$\varepsilon_{cent} := \text{root}(f(x_o), x_o) = 1.037 \times 10^{-4}$$

Sectional forces

$$\text{Force}(\varepsilon_{o.conc}, \varepsilon_{o.steel}, \varepsilon_{cent}, \phi) = -0.7 \cdot \text{kip}$$

$$\text{Moment}(\varepsilon_{o.conc}, \varepsilon_{o.steel}, \varepsilon_{cent}, \phi) = 311.755 \cdot \text{kip} \cdot \text{ft}$$

Stress and strain in concrete and steel

Steel fiber stress and strain

$$\text{Rebar}_{\varepsilon} := \text{Steel}_{\varepsilon}(\varepsilon_{o.steel}, \varepsilon_{cent}, \phi) = \begin{pmatrix} 1.435 \times 10^{-3} \\ 7.094 \times 10^{-4} \end{pmatrix}$$

$$\text{Rebar}_{\sigma} := \text{Steel}_{\sigma}(\varepsilon_{o.steel}, \varepsilon_{cent}, \phi) = \begin{pmatrix} 41.618 \\ 20.572 \end{pmatrix} \cdot \text{ksi}$$

$$\text{Steel}_F(\varepsilon_{o.steel}, \varepsilon_{cent}, \phi) = \begin{pmatrix} 129.848 \\ 64.186 \end{pmatrix} \cdot \text{kip}$$

$$\text{Concrete}_y := \text{Conc}_y$$

Concrete fiber stress and strain

$$\text{Concrete}_{\varepsilon} := \text{Conc}_{\varepsilon}(\varepsilon_{o.conc}, \varepsilon_{cent}, \phi)$$

$$\text{Concrete}_{\sigma} := \text{Conc}_{\sigma}(\varepsilon_{o.conc}, \varepsilon_{cent}, \phi)$$

Maximum compressive strain in concrete

$$\varepsilon_{max.comp} := \frac{\text{Concrete}_{\varepsilon_{ConcNum}} - \text{Concrete}_{\varepsilon_{ConcNum-1}}}{\text{Conc}_{y_{ConcNum}} - \text{Conc}_{y_{ConcNum-1}}} \cdot \left(\frac{h}{2} - \text{Conc}_{y_{ConcNum-1}}\right) \ldots + \text{Concrete}_{\varepsilon_{ConcNum-1}} = -4.876 \times 10^{-4}$$

Maximum compressive stress in concrete

$$\sigma_{max.comp} := \text{MAT}_{conc}(\varepsilon_{max.comp}) = -1.521 \cdot \text{ksi}$$

E9. TABLES

Table E1: Stress in rebars at critical locations of CEHMS structure subjected to LC1

Component	Item	Total demands for sustained load (In Situ condition, LC1)		Total stress in steel (ksi)		Maximum compressive stress in concrete (ksi)
		Demand	Location	Rebar 1	Rebar 2	
East wing walls	Out-of-plane moment (kip-ft/ft)	159.6	East wing wall, at intersection with column	23.4	15.0	-0.78
	Axial force (kip/ft)	-8.3				

Table E2: Stress in rebars at critical locations of CEHMS structure subjected to LC2

Component	Item	Total demands for sustained loads plus OBE amplified with threshold factor (In Situ condition, LC2)		Total stress in steel (ksi)		Maximum compressive stress in concrete (ksi)
		Demand	Location	Rebar 1	Rebar 2	
East wing wall	Out-of-plane moment (kip-ft/ft)	311.6	East wall, horizontal strip, at the middle of the wall	41.6	20.8	-1.52
	Axial force (kip/ft)	-0.7				

Example in Section E8

E10. FIGURES

There are no figures.

APPENDIX F

TENSILE STRESS IN REBARS OF CONTAINMENT ENCLOSURE VENTILATION AREA

F1. REVISION HISTORY

Revision 0: Initial document.

F2. OBJECTIVE OF CALCULATION

The objective of this calculation is to compute the maximum tensile stress that can form in the rebars of Containment Enclosure Ventilation Area (CEVA) structure.

F3. RESULTS AND CONCLUSIONS

Table F1 summarizes the tensile stress in rebars of the CEVA structure calculated at critical locations. The maximum tensile stress is 44.0 ksi computed for the rebars of the base slab along east-west direction.

F4. DESIGN DATA / CRITERIA

See Section 4 of the calculation main body (Calc. 160268-CA-05 Rev. 0).

F5. ASSUMPTIONS

F5.1 Justified assumptions

There are no justified assumptions.

F5.2 Unverified assumptions

There are no unverified assumptions.

F6. METHODOLOGY

The critical demand that governed the computation of the threshold factor of CEVA structure was bending moment of the base slab in Area 3 subjected to seismic load combinations that act parallel to east-west direction [F1]. The original calculation of CEVA structure [F3] does not provide unfactored demand values; therefore, in this evaluation, the factored load is conservatively divided by the minimum load factor in the load combination and used in calculating rebar stress:

- ASR load with threshold factor: M = 28.7 kip-ft/ft P = 0 (Appendix C of Ref. F1)
- Unfactored ASR load: M = 9.56 kip-ft/ft, P = 0 (threshold factor was 3.0)
- Original unfactored demands incxluding the OBE: M = 77/1.4 = 55 kip-ft/ft, P = 2.44/1.4 = 1.43 kip/ft (Sheet 16 of Ref. F3). Note that the value of 1.4 was the load factor applied to the dead load in the combination (minimum load factor)

To calculate the stress in rebars subjected to a combination of axial force and bending moment, sectional analysis based on fiber section method, as explained in calculation main body, is used. The calculation is conducted per 1 foot width, and each section is discretized into 20 fibers. An example calculation that evaluates the stress in rebars of the base slab is presented in Section F8. The CI value of all components was set equal to 0.31 mm/m which included in the analysis to find the initial stress state due to internal ASR alone.

F7. REFERENCES

[F1] Simpson Gumpertz & Heger Inc., *Evaluation of Containment Enclosure Ventilation Area,* 160268-CA-05 Rev. 0, Waltham, MA, Mar. 2017.

[F2] United Engineers & Constructors Inc., Seabrook Station Structural Design Drawings.

[F3] United Engineers & Constructors Inc., *Containment Enclosure Ventilation Area*, *EM-33-Calc Rev. 4*, Jan. 1986.

F8. COMPUTATION

F8.1. Strain in Steel and Concrete due to Internal ASR expansion

Input Data

ASR expansion

Measured crack index $\varepsilon_{CI} := 0.31 \frac{mm}{m}$

Threshold factor $F_{thr} := 3$

Material properties

Compressive strength of concrete $f_c := -3ksi$ Ref. [F1]

Young's modulus of concrete $E_c := 3120ksi$

Yield strength of steel $f_y := 60ksi$

Young's modulus of steel $E_s := 29000ksi$

Geometry

Width of fibers $b := 12in$ Ref. [F2]

Total thickness or height $h := 30in$

Area of concrete $A_c := b \cdot h = 360 \cdot in^2$

Area of tensile reinforcement (#9@12 in.) $A_s := 1in^2$

Number of reinforcement in row, e.g. equal to 2 for tensile and compressive $Steel_{Num} := 2$

Depth to reinforcement $d := 26.4in$

Finding the strain in steel and concrete by satisfying compatibility and equilibrium

Initial Guess

Initial mechanical strain in concrete $\varepsilon_{o.conc} := 0$

Initial strain in steel $\varepsilon_{o.steel} := 0$

Given

Compatibility equation $F_{thr} \cdot \varepsilon_{CI} = \varepsilon_{o.steel} - \varepsilon_{o.conc}$

Equilibrium equation $(E_c \cdot A_c) \cdot \varepsilon_{o.conc} + (E_s \cdot A_s \cdot Steel_{Num}) \cdot \varepsilon_{o.steel} = 0$

$ans := Find(\varepsilon_{o.conc}, \varepsilon_{o.steel})$

Initial strain in concrete and steel

$\varepsilon_{o.conc} := ans_1 = -4.567 \times 10^{-5}$

$\varepsilon_{o.steel} := ans_2 = 8.843 \times 10^{-4}$

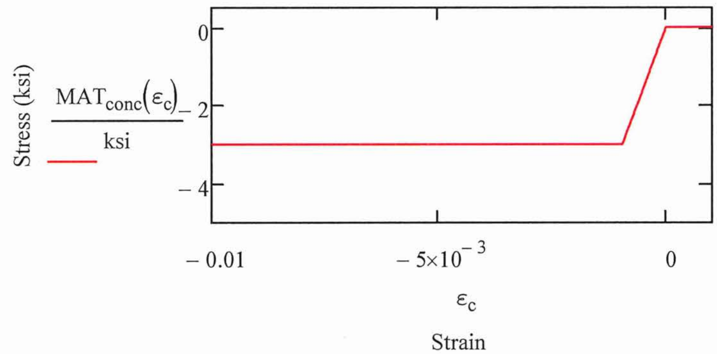
F8.2. Sectional Analysis

Input Data

Concrete Material Model

Constitutive model for concrete

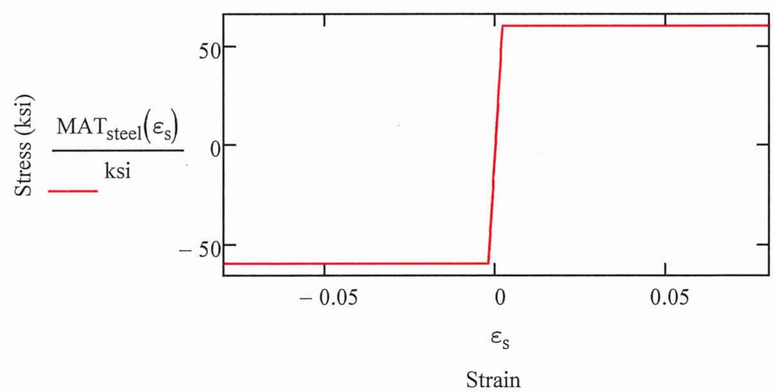
$$MAT_{conc}(\varepsilon) := \begin{vmatrix} 0 \text{ if } \varepsilon > 0 \\ f_c \text{ if } \varepsilon < \dfrac{f_c}{E_c} \\ (E_c \cdot \varepsilon) \text{ otherwise} \end{vmatrix}$$



Steel Material Model

Constitutive model for steel

$$MAT_{steel}(\varepsilon) := \begin{vmatrix} f_y \text{ if } \varepsilon > \dfrac{f_y}{E_s} \\ -f_y \text{ if } \varepsilon < \dfrac{-f_y}{E_s} \\ (E_s \cdot \varepsilon) \text{ otherwise} \end{vmatrix}$$



Concrete Fibers

Number of fibers $Conc_{Num} := 20$

Height of fibers $Conc_H := \dfrac{h}{Conc_{Num}} = 1.5 \cdot in$

Concrete fiber coordinates

$$Conc_y := \left| \begin{array}{l} \text{for } i \in 1 .. Conc_{Num} \\ \quad ans_i \leftarrow -\dfrac{h}{2} + \dfrac{Conc_H}{2} + (i-1) \cdot Conc_H \\ ans \end{array} \right.$$

Concrete fiber strain

$$Conc_{\varepsilon}(\varepsilon_{o.conc}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{for } i \in 1 .. Conc_{Num} \\ \quad ans_i \leftarrow \varepsilon_{o.conc} + \varepsilon - \varphi \cdot Conc_{y_i} \\ ans \end{array} \right.$$

Concrete fiber stress

$$Conc_{\sigma}(\varepsilon_{o.conc}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{for } i \in 1 .. Conc_{Num} \\ \quad ans_i \leftarrow MAT_{conc}\left(Conc_{\varepsilon}(\varepsilon_{o.conc}, \varepsilon, \varphi)_i\right) \\ ans \end{array} \right.$$

Concrete fiber force

$$Conc_F(\varepsilon_{o.conc}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{for } i \in 1 .. Conc_{Num} \\ \quad ans_i \leftarrow Conc_{\sigma}(\varepsilon_{o.conc}, \varepsilon, \varphi)_i \cdot (b \cdot Conc_H) \\ ans \end{array} \right.$$

Reinforcement/Steel fibers

Depth to reinforcement fiber

$$Steel_{y_1} := -\left(d - \frac{h}{2}\right) = -11.4 \cdot in$$

$$Steel_{y_2} := d - \frac{h}{2} = 11.4 \cdot in$$

Area of reinforcement fiber

$$Steel_{As_1} := A_s = 1 \cdot in^2$$

$$Steel_{As_2} := A_s = 1 \cdot in^2$$

Steel fiber strain

$$Steel_{\varepsilon}(\varepsilon_{o.steel}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{for } i \in 1 .. Steel_{Num} \\ \quad ans_i \leftarrow \varepsilon_{o.steel} + \varepsilon - \varphi \cdot Steel_{y_i} \\ ans \end{array} \right.$$

Steel fiber stress

$$Steel_{\sigma}(\varepsilon_{o.steel}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{for } i \in 1 .. Steel_{Num} \\ \quad ans_i \leftarrow MAT_{steel}\left(Steel_{\varepsilon}(\varepsilon_{o.steel}, \varepsilon, \varphi)_i\right) \\ ans \end{array} \right.$$

Steel fiber force

$$Steel_F(\varepsilon_{o.steel}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{for } i \in 1 .. Steel_{Num} \\ \quad ans_i \leftarrow Steel_{\sigma}(\varepsilon_{o.steel}, \varepsilon, \varphi)_i \cdot Steel_{As_i} \\ ans \end{array} \right.$$

Initial Stress State

Initial stress in concrete

$$\text{Concrete}_\sigma := \text{Conc}_\sigma(\varepsilon_{o.conc}, 0, 0)$$

$$\text{Concrete}_{\sigma_1} = -0.142 \cdot \text{ksi}$$

Initial stress in steel

$$\text{Rebar}_\sigma := \text{Steel}_\sigma(\varepsilon_{o.steel}, 0, 0)$$

$$\text{Rebar}_{\sigma_1} = 25.646 \cdot \text{ksi}$$

Axial Equilibrium

$$\text{Force}(\varepsilon_{o.conc}, \varepsilon_{o.steel}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{ans1} \leftarrow 0 \\ \text{for } i \in 1..\text{Conc}_{Num} \\ \quad \text{ans1} \leftarrow \text{ans1} + \text{Conc}_F(\varepsilon_{o.conc}, \varepsilon, \varphi)_i \\ \text{ans2} \leftarrow 0 \\ \text{for } i \in 1..\text{Steel}_{Num} \\ \quad \text{ans2} \leftarrow \text{ans2} + \text{Steel}_F(\varepsilon_{o.steel}, \varepsilon, \varphi)_i \\ \text{ans} \leftarrow \text{ans1} + \text{ans2} \end{array} \right.$$

Moment Equilibrium

$$\text{Moment}(\varepsilon_{o.conc}, \varepsilon_{o.steel}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{ans1} \leftarrow 0 \\ \text{for } i \in 1..\text{Conc}_{Num} \\ \quad \text{ans1} \leftarrow \text{ans1} + -1 \cdot \text{Conc}_F(\varepsilon_{o.conc}, \varepsilon, \varphi)_i \cdot \text{Conc}_{y_i} \\ \text{ans2} \leftarrow 0 \\ \text{for } i \in 1..\text{Steel}_{Num} \\ \quad \text{ans2} \leftarrow \text{ans2} + -1 \cdot \text{Steel}_F(\varepsilon_{o.steel}, \varepsilon, \varphi)_i \cdot \text{Steel}_{y_i} \\ \text{ans} \leftarrow \text{ans1} + \text{ans2} \end{array} \right.$$

Solution

Known parameters

Axial force $P := 1.74\text{kip}$

Iteration

Curvature $\phi := 0.0000353 \cdot \frac{1}{\text{in}}$ Requires iteration

Solve for strain at centroid

Axial strain at centroid (initial guess) $x_o := 0.0$

Axial force equilibrium $f(x) := \text{Force}(\varepsilon_{o.conc}, \varepsilon_{o.steel}, x, \phi) - P$

$$\varepsilon_{cent} := \text{root}(f(x_o), x_o) = 2.299 \times 10^{-4}$$

Sectional forces

$$\text{Force}(\varepsilon_{o.conc}, \varepsilon_{o.steel}, \varepsilon_{cent}, \phi) = 1.74 \cdot \text{kip}$$

$$\text{Moment}(\varepsilon_{o.conc}, \varepsilon_{o.steel}, \varepsilon_{cent}, \phi) = 83.675 \cdot \text{kip} \cdot \text{ft}$$

Stress and strain in concrete and steel

Steel fiber stress and strain

$$\text{Rebar}_{\varepsilon} := \text{Steel}_{\varepsilon}(\varepsilon_{o.steel}, \varepsilon_{cent}, \phi) = \begin{pmatrix} 1.517 \times 10^{-3} \\ 7.118 \times 10^{-4} \end{pmatrix}$$

$$\text{Rebar}_{\sigma} := \text{Steel}_{\sigma}(\varepsilon_{o.steel}, \varepsilon_{cent}, \phi) = \begin{pmatrix} 43.982 \\ 20.642 \end{pmatrix} \cdot \text{ksi}$$

$$\text{Steel}_{F}(\varepsilon_{o.steel}, \varepsilon_{cent}, \phi) = \begin{pmatrix} 43.982 \\ 20.642 \end{pmatrix} \cdot \text{kip}$$

$$\text{Concrete}_y := \text{Conc}_y$$

Concrete fiber stress and strain

$$\text{Concrete}_{\varepsilon} := \text{Conc}_{\varepsilon}(\varepsilon_{o.conc}, \varepsilon_{cent}, \phi)$$

$$\text{Concrete}_{\sigma} := \text{Conc}_{\sigma}(\varepsilon_{o.conc}, \varepsilon_{cent}, \phi)$$

Maximum compressive strain in concrete

$$\varepsilon_{max.comp} := \frac{\text{Concrete}_{\varepsilon_{ConcNum}} - \text{Concrete}_{\varepsilon_{ConcNum-1}}}{\text{Conc}_{y_{ConcNum}} - \text{Conc}_{y_{ConcNum-1}}} \cdot \left(\frac{h}{2} - \text{Conc}_{y_{ConcNum-1}}\right) \ldots = -3.453 \times 10^{-4}$$
$$+ \text{Concrete}_{\varepsilon_{ConcNum-1}}$$

Maximum compressive stress in concrete

$$\sigma_{max.comp} := \text{MAT}_{conc}(\varepsilon_{max.comp}) = -1.077 \cdot \text{ksi}$$

F9. TABLES

Table F1: Stress in rebars at critical locations of CEVA structure subjected to LC1

Component	Item	Total demands for sustained load (In Situ condition, LC1)		Total stress in steel (ksi)		Maximum compressive stress in concrete (ksi)
		Demand	Location	Rebar 1	Rebar 2	
Base slab	Out-of-plane moment (kip-ft/ft)	64.5*	Base slab at Area 3	32.8	5.1	-0.89
	Axial force (kip/ft)	1.74*				

**These demands are computed conservatively by including OBE and dividing the total factor demand by the minimum load factor in the load combination in the original design calculation.*

Table F2: Stress in rebars at critical locations of CEVA structure subjected to LC2

Component	Item	Total demands for sustained load (In Situ condition, LC1)		Total stress in steel (ksi)		Maximum compressive stress in concrete (ksi)
		Demand	Location	Rebar 1	Rebar 2	
Base slab	Out-of-plane moment (kip-ft/ft)	83.7	Base slab at Area 3	44.0	20.6	-1.08
	Axial force (kip/ft)	1.74				

Example in Section F8

F10. FIGURES

There are no figures.

APPENDIX G

TENSILE STRESS IN REBARS OF STAGE 1 ELECTRICAL MANHOLES

G1. REVISION HISTORY

Revision 0: Initial document.

Revision 1: Revised pages G-1 and G-2 from Revision 0 to 1 to update references of calculation revision from A to 0. Revised page G-1 to update Revision history section.

G2. OBJECTIVE OF CALCULATION

The objective of this calculation is to compute the maximum tensile stress that can form in the rebars of the Stage 1 Electrical Manhole (EMH) structures.

G3. RESULTS AND CONCLUSIONS

Table G1 summarizes the tensile stress in rebars of the EMH calculated at critical locations. The maximum tensile stress is 27 ksi in EMH W13/W15 subjected to the second in situ load combination (LC2).

G4. DESIGN DATA / CRITERIA

See Section 4 of the calculation main body (Calc. 160268-CA-12 Rev. 0).

G5. ASSUMPTIONS

G5.1 Justified assumptions

There are no justified assumptions.

G5.2 Unverified assumptions

There are no unverified assumptions.

G6. METHODOLOGY

The critical demands that control rebar tension in the Stage 1 EMH are horizontal moment and horizontal tension in EMH W13 and W15. Finite element analyses were conducted to calculate the axial force and bending moment at these locations due to ASR load [G1].

To calculate the stress in rebars subjected to a combination of axial force and bending moment, sectional analysis based on fiber section method, as explained in calculation main body, is used. The calculation is conducted per 1 foot width of the walls, and each section is discretized into 20 fibers. An example calculation that evaluates the stress in the horizontal rebars in the walls of EMH W13 and W15 is presented in Section G8. The ASR expansion of the EMH is included in the analysis to find the initial stress state due to internal ASR alone.

G7. REFERENCES

[G1] Simpson Gumpertz & Heger Inc., *Evaluation of Seismic Category I Electrical Manholes – Stage 1,* 160268-CA-12 Rev. 0, Waltham, MA, Jan 2018.

[G2] United Engineers & Constructors Inc., Seabrook Station Structural Design Drawings.

G8. COMPUTATION

G8.1. Strain in Steel and Concrete due to Internal ASR expansion

Input Data

ASR expansion

Measured crack index $\varepsilon_{CI} := 0.25 \frac{mm}{m}$

Threshold factor $F_{thr} := 3.7$

Material properties

Compressive strength of concrete $f_c := -3ksi$ Ref. [G1]

Young's modulus of concrete $E_c := 3120ksi$

Yield strength of steel $f_y := 60ksi$

Young's modulus of steel $E_s := 29000ksi$

Geometry

Width of fibers $b := 12in$ Ref. [G2]

Total thickness or height $h := 18in$

Area of concrete $A_c := b \cdot h = 216 \cdot in^2$

Area of tensile reinforcement (#6@12 in.) $A_s := 0.44in^2$

Number of reinforcement in row, e.g. equal to 2 for tensile and compressive $Steel_{Num} := 2$

Depth to reinforcement $d := 15.625in$

Finding the strain in steel and concrete by satisfying compatibility and equilibrium

Initial Guess

Initial mechanical strain in concrete $\varepsilon_{o.conc} := 0$

Initial strain in steel $\varepsilon_{o.steel} := 0$

Given

Compatibility equation $F_{thr} \cdot \varepsilon_{CI} = \varepsilon_{o.steel} - \varepsilon_{o.conc}$

Equilibrium equation $\left(E_c \cdot A_c\right) \cdot \varepsilon_{o.conc} + \left(E_s \cdot A_s \cdot Steel_{Num}\right) \cdot \varepsilon_{o.steel} = 0$

$ans := Find\left(\varepsilon_{o.conc}, \varepsilon_{o.steel}\right)$

Initial strain in concrete and steel

$\varepsilon_{o.conc} := ans_1 = -3.375 \times 10^{-5}$

$\varepsilon_{o.steel} := ans_2 = 8.913 \times 10^{-4}$

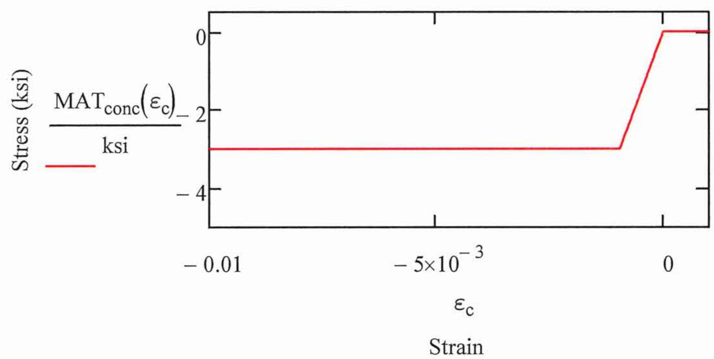
G8.2. Sectional Analysis

Input Data

Concrete Material Model

Constitutive model for concrete

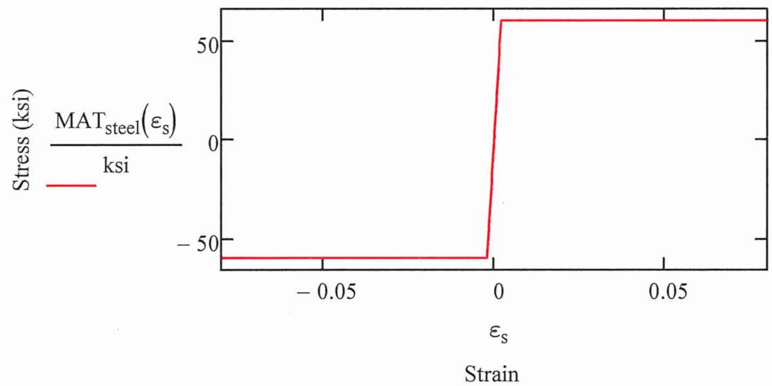
$$MAT_{conc}(\varepsilon) := \begin{cases} 0 & \text{if } \varepsilon > 0 \\ f_c & \text{if } \varepsilon < \dfrac{f_c}{E_c} \\ (E_c \cdot \varepsilon) & \text{otherwise} \end{cases}$$



Steel Material Model

Constitutive model for steel

$$MAT_{steel}(\varepsilon) := \begin{cases} f_y & \text{if } \varepsilon > \dfrac{f_y}{E_s} \\ -f_y & \text{if } \varepsilon < \dfrac{-f_y}{E_s} \\ (E_s \cdot \varepsilon) & \text{otherwise} \end{cases}$$



Concrete Fibers

Number of fibers $Conc_{Num} := 20$

Height of fibers $Conc_H := \dfrac{h}{Conc_{Num}} = 0.9 \cdot in$

Concrete fiber coordinates

$$Conc_y := \left| \begin{array}{l} \text{for } i \in 1..Conc_{Num} \\ \quad ans_i \leftarrow -\dfrac{h}{2} + \dfrac{Conc_H}{2} + (i-1) \cdot Conc_H \\ ans \end{array} \right.$$

Concrete fiber strain

$$Conc_\varepsilon(\varepsilon_{o.conc}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{for } i \in 1..Conc_{Num} \\ \quad ans_i \leftarrow \varepsilon_{o.conc} + \varepsilon - \varphi \cdot Conc_{y_i} \\ ans \end{array} \right.$$

Concrete fiber stress

$$Conc_\sigma(\varepsilon_{o.conc}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{for } i \in 1..Conc_{Num} \\ \quad ans_i \leftarrow MAT_{conc}\left(Conc_\varepsilon(\varepsilon_{o.conc}, \varepsilon, \varphi)_i\right) \\ ans \end{array} \right.$$

Concrete fiber force

$$Conc_F(\varepsilon_{o.conc}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{for } i \in 1..Conc_{Num} \\ \quad ans_i \leftarrow Conc_\sigma(\varepsilon_{o.conc}, \varepsilon, \varphi)_i \cdot (b \cdot Conc_H) \\ ans \end{array} \right.$$

Reinforcement/Steel fibers

Depth to reinforcement fiber

$$Steel_{y_1} := -\left(d - \frac{h}{2}\right) = -6.625 \cdot in$$

$$Steel_{y_2} := d - \frac{h}{2} = 6.625 \cdot in$$

Area of reinforcement fiber

$$Steel_{As_1} := A_s = 0.44 \cdot in^2$$

$$Steel_{As_2} := A_s = 0.44 \cdot in^2$$

Steel fiber strain

$$Steel_\varepsilon(\varepsilon_{o.steel}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{for } i \in 1..Steel_{Num} \\ \quad ans_i \leftarrow \varepsilon_{o.steel} + \varepsilon - \varphi \cdot Steel_{y_i} \\ ans \end{array} \right.$$

Steel fiber stress

$$Steel_\sigma(\varepsilon_{o.steel}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{for } i \in 1..Steel_{Num} \\ \quad ans_i \leftarrow MAT_{steel}\left(Steel_\varepsilon(\varepsilon_{o.steel}, \varepsilon, \varphi)_i\right) \\ ans \end{array} \right.$$

Steel fiber force

$$Steel_F(\varepsilon_{o.steel}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{for } i \in 1..Steel_{Num} \\ \quad ans_i \leftarrow Steel_\sigma(\varepsilon_{o.steel}, \varepsilon, \varphi)_i \cdot Steel_{As_i} \\ ans \end{array} \right.$$

Initial Stress State

Initial stress in concrete

$$\text{Concrete}_\sigma := \text{Conc}_\sigma\left(\varepsilon_{\text{o.conc}}, 0, 0\right)$$

$$\text{Concrete}_{\sigma_1} = -0.105 \cdot \text{ksi}$$

Initial stress in steel

$$\text{Rebar}_\sigma := \text{Steel}_\sigma\left(\varepsilon_{\text{o.steel}}, 0, 0\right)$$

$$\text{Rebar}_{\sigma_1} = 25.846 \cdot \text{ksi}$$

Axial Equilibrium

$$\text{Force}\left(\varepsilon_{\text{o.conc}}, \varepsilon_{\text{o.steel}}, \varepsilon, \varphi\right) := \left| \begin{array}{l} \text{ans1} \leftarrow 0 \\ \text{for } i \in 1 .. \text{Conc}_{\text{Num}} \\ \quad \text{ans1} \leftarrow \text{ans1} + \text{Conc}_F\left(\varepsilon_{\text{o.conc}}, \varepsilon, \varphi\right)_i \\ \text{ans2} \leftarrow 0 \\ \text{for } i \in 1 .. \text{Steel}_{\text{Num}} \\ \quad \text{ans2} \leftarrow \text{ans2} + \text{Steel}_F\left(\varepsilon_{\text{o.steel}}, \varepsilon, \varphi\right)_i \\ \text{ans} \leftarrow \text{ans1} + \text{ans2} \end{array} \right.$$

Moment Equilibrium

$$\text{Moment}\left(\varepsilon_{\text{o.conc}}, \varepsilon_{\text{o.steel}}, \varepsilon, \varphi\right) := \left| \begin{array}{l} \text{ans1} \leftarrow 0 \\ \text{for } i \in 1 .. \text{Conc}_{\text{Num}} \\ \quad \text{ans1} \leftarrow \text{ans1} + -1 \cdot \text{Conc}_F\left(\varepsilon_{\text{o.conc}}, \varepsilon, \varphi\right)_i \cdot \text{Conc}_{y_i} \\ \text{ans2} \leftarrow 0 \\ \text{for } i \in 1 .. \text{Steel}_{\text{Num}} \\ \quad \text{ans2} \leftarrow \text{ans2} + -1 \cdot \text{Steel}_F\left(\varepsilon_{\text{o.steel}}, \varepsilon, \varphi\right)_i \cdot \text{Steel}_{y_i} \\ \text{ans} \leftarrow \text{ans1} + \text{ans2} \end{array} \right.$$

Solution

Known parameters

Axial force $P := -4.4\text{kip}$

Iteration

Curvature $\phi := 0.0000065 \cdot \frac{1}{\text{in}}$ Requires iteration

Solve for strain at centroid

Axial strain at centroid (initial guess) $x_o := 0.0$

Axial force equilibrium

$$f(x) := \text{Force}(\varepsilon_{o.conc}, \varepsilon_{o.steel}, x, \phi) - P$$

$$\varepsilon_{cent} := \text{root}(f(x_o), x_o) = -4.655 \times 10^{-6}$$

Sectional forces

$$\text{Force}(\varepsilon_{o.conc}, \varepsilon_{o.steel}, \varepsilon_{cent}, \phi) = -4.4 \cdot \text{kip}$$

$$\text{Moment}(\varepsilon_{o.conc}, \varepsilon_{o.steel}, \varepsilon_{cent}, \phi) = 9.679 \cdot \text{kip} \cdot \text{ft}$$

Stress and strain in concrete and steel

Steel fiber stress and strain

$$\text{Rebar}_\varepsilon := \text{Steel}_\varepsilon(\varepsilon_{o.steel}, \varepsilon_{cent}, \phi) = \begin{pmatrix} 9.297 \times 10^{-4} \\ 8.435 \times 10^{-4} \end{pmatrix}$$

$$\text{Rebar}_\sigma := \text{Steel}_\sigma(\varepsilon_{o.steel}, \varepsilon_{cent}, \phi) = \begin{pmatrix} 26.96 \\ 24.462 \end{pmatrix} \cdot \text{ksi}$$

$$\text{Steel}_F(\varepsilon_{o.steel}, \varepsilon_{cent}, \phi) = \begin{pmatrix} 11.862 \\ 10.763 \end{pmatrix} \cdot \text{kip}$$

$$\text{Concrete}_y := \text{Conc}_y$$

Concrete fiber stress and strain

$$\text{Concrete}_\varepsilon := \text{Conc}_\varepsilon(\varepsilon_{o.conc}, \varepsilon_{cent}, \phi)$$

$$\text{Concrete}_\sigma := \text{Conc}_\sigma(\varepsilon_{o.conc}, \varepsilon_{cent}, \phi)$$

Maximum compressive strain in concrete

$$\varepsilon_{max.comp} := \frac{\text{Concrete}_{\varepsilon_{ConcNum}} - \text{Concrete}_{\varepsilon_{ConcNum-1}}}{\text{Conc}_{y_{ConcNum}} - \text{Conc}_{y_{ConcNum-1}}} \cdot \left(\frac{h}{2} - \text{Conc}_{y_{ConcNum-1}}\right) \dots = -9.69 \times 10^{-5}$$
$$+ \text{Concrete}_{\varepsilon_{ConcNum-1}}$$

Maximum compressive stress in concrete $\sigma_{max.comp} := \text{MAT}_{conc}(\varepsilon_{max.comp}) = -0.302 \cdot \text{ksi}$

G9. TABLES

Table G1: Stress in rebars at critical locations of EMH subjected to LC1

Component	Item	Total demands for sustained load (In Situ condition, LC1)		Total stress in steel (ksi)		Maximum compressive stress in concrete (ksi)
		Demand	Location	Rebar 1	Rebar 2	
EMH W13/W15	Out-of-plane moment (kip-ft/ft)	7.4	W13/W15 wall	11.2	5.6	-0.28
	Axial force (kip/ft)	-3.2				

Table G2: Stress in rebars at critical locations of EMH subjected to LC2

Component	Item	Total demands for sustained loads plus OBE amplified with threshold factor (In Situ condition, LC2)		Total stress in steel (ksi)		Maximum compressive stress in concrete (ksi)
		Demand	Location	Rebar 1	Rebar 2	
EMH W13/W15	Out-of-plane moment (kip-ft/ft)	9.3	W13/W15 wall	27.0	24.5	-0.30
	Axial force (kip/ft)	-4.4				

Example in Section G8

G10. FIGURES

There are no figures.

APPENDIX H

EVALUATING THE PERFORMANCE OF A SIMPLE ELASTO-PLASTIC MATERIAL MODEL FOR CONCRETE TO BE USED FOR EVALUATION OF REBAR STRESS

H1. REVISION HISTORY

Revision 0: Initial document.

H2. OBJECTIVE OF CALCULATION

The objective of this calculation is to compare the rebar stresses computed by using two different using constitutive models for concrete, and justify the at the simple material model provides a satisfactory results.

H3. RESULTS AND CONCLUSIONS

The stress in rebars are computed using two constitutive models for concrete. The stress in rebars obtained using both models are very close indicating the simple model captures the concrete behavior satisfactorily. This is due to steel ratios in the components of Seabrook structures which is less than the maximum ratio allowed by the code. Therefore concrete crushing and post-linear response of the concrete does not impact the response noticeably.

CRMAI:

- Stress in Rebar 1: 39.1 (simple model, Appendix A) and 39.01 (accurate model)
- Stress in Rebar 2: 37.3 (simple model, Appendix A) and 37.16 (accurate model)
- Stress in concrete: -0.33 (simple model, Appendix A) and -0.328 (accurate model)

CEHMS:

- Stress in Rebar 1: 41.6 (simple model, Appendix E) and 42.1 (accurate model)
- Stress in Rebar 2: 20.8 (simple model, Appendix E) and 19.3 (accurate model)
- Stress in concrete: -1.5 (simple model, Appendix E) and -1.4 (accurate model)

H4. DESIGN DATA / CRITERIA

There are no design data.

H5. ASSUMPTIONS

H5.1 Justified assumptions

There are no justified assumptions.

H5.2 Unverified assumptions

There are no unverified assumptions.

H6. METHODOLOGY

Stress in rebars at the base mat of CRMAI and at the east wing wall of CEHMS structures are computed using a more accurate constitutive model of Kent and Park [H4] in compression, and the results are compared with the stresses obtained from the simple model as explained in the main body. The stresses in rebars from the simple model are provided in Appendix A and E for CRMAI and CEHMS structures respectively. Section H8 provides a sample calculation for rhe base mat of CRMAI structures.

H7. REFERENCES

[H1] Simpson Gumpertz & Heger Inc., *Evaluation of Control Room Makeup Air Intake structure,* 160268-CA-08 Rev. 0, Waltham, MA, May 2017.

[H2] United Engineers & Constructors Inc., Seabrook Station Structural Design Drawings.

[H3] United Engineers & Constructors Inc., *Design of Makeup Air Intake Structure*, *MT-28-Calc Rev. 2*, Feb. 1984.

[H4] Dudley. C. Kent, and Robert Park, Flexural members with confined concrete, ASCE Journal of Structural Division, 97 (ST7), 1969-1990, 1971.

H8. COMPUTATION

H8.1. Strain in Steel and Concrete due to Internal ASR expansion

Input Data

ASR expansion

Measured crack index $\varepsilon_{CI} := 0.99\dfrac{mm}{m}$

Threshold factor $F_{thr} := 1.4$

Material properties

Compressive strength of concrete $f_c := -3ksi$ Ref. [H1]

Young's modulus of concrete $E_c := 3120ksi$

Yield strength of steel $f_y := 60ksi$

Young's modulus of steel $E_s := 29000ksi$

Geometry

Width of fibers $b := 12in$ Ref. [H2]

Total thickness or height $h := 36in$

Area of concrete $A_c := b \cdot h = 432 \cdot in^2$

Area of tensile reinforcement (#8@12 in.) $A_s := 0.79in^2$

Number of reinforcement in row, e.g. equal to 2 for tensile and compressive $Steel_{Num} := 2$

Depth to reinforcement $d := 32.5in$

Finding the strain in steel and concrete by satisfying compatibility and equilibrium

Initial Guess

Initial mechanical strain in concrete $\varepsilon_{o.conc} := 0$

Initial strain in steel $\varepsilon_{o.steel} := 0$

Given

Compatibility equation $F_{thr} \cdot \varepsilon_{CI} = \varepsilon_{o.steel} - \varepsilon_{o.conc}$

Equilibrium equation $(E_c \cdot A_c) \cdot \varepsilon_{o.conc} + (E_s \cdot A_s \cdot Steel_{Num}) \cdot \varepsilon_{o.steel} = 0$

$ans := Find(\varepsilon_{o.conc}, \varepsilon_{o.steel})$

Initial strain in concrete and steel $\varepsilon_{o.conc} := ans_1 = -4.557 \times 10^{-5}$

$\varepsilon_{o.steel} := ans_2 = 1.34 \times 10^{-3}$

H8.2. Sectional Analysis

Input Data

Concrete Material Model

Kent & Park Model

Strain at Peak compressive strength $\varepsilon_{co} := -0.002$

Strain at 50% compressive strength

$$\varepsilon_{50u} := \frac{3 - 0.002 \cdot \frac{f_c}{psi}}{\frac{f_c}{psi} + 1000} = -4.5 \times 10^{-3}$$

Model parameter

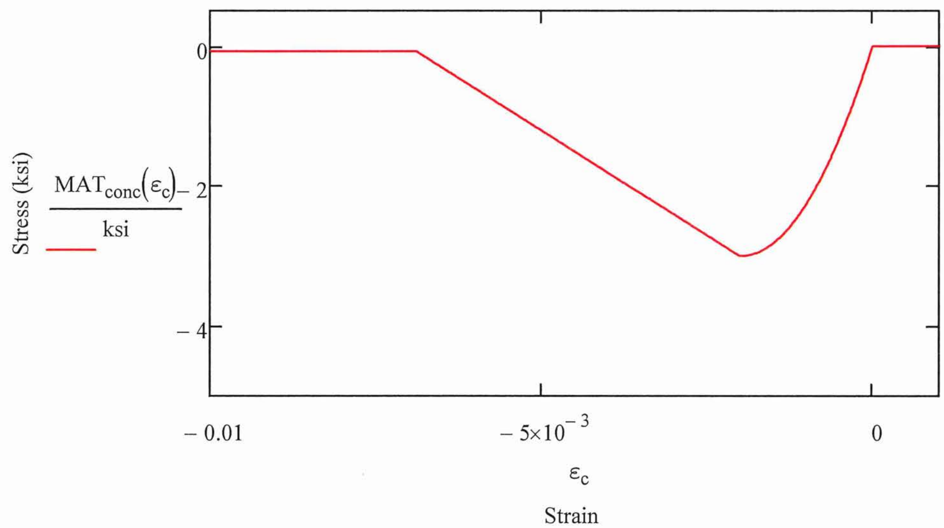
$$Z := \frac{0.5}{\varepsilon_{50u} - \varepsilon_{co}} = -200$$

Residual compressive strength

$$f_{c.res} := f_c \cdot 0.025 = -75 \cdot psi$$

Constitutive model for concrete

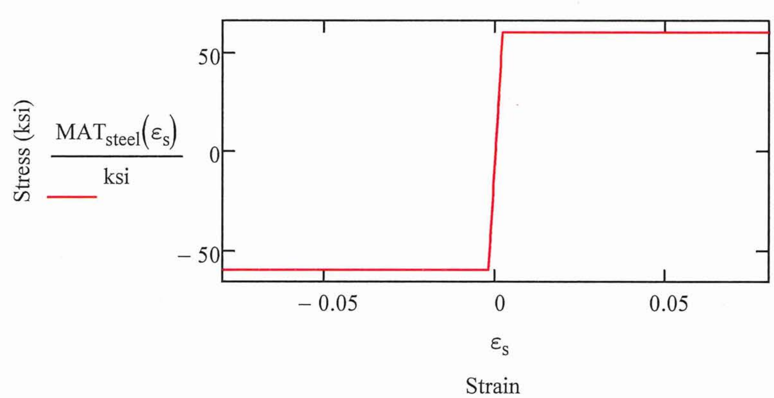
$$MAT_{conc}(\varepsilon) := \begin{cases} \min\left[f_{c.res}, f_c \cdot \left[1 - Z \cdot \left(\varepsilon - \varepsilon_{co}\right)\right]\right] & \text{if } \varepsilon < \varepsilon_{co} \\ f_c \cdot \left[\frac{2 \cdot \varepsilon}{\varepsilon_{co}} - \left(\frac{\varepsilon}{\varepsilon_{co}}\right)^2\right] & \text{if } \varepsilon_{co} \le \varepsilon < 0 \\ 0 & \text{if } 0 \le \varepsilon \end{cases}$$



Steel Material Model

Constitutive model for steel

$$MAT_{steel}(\varepsilon) := \begin{cases} f_y & \text{if } \varepsilon > \frac{f_y}{E_s} \\ -f_y & \text{if } \varepsilon < \frac{-f_y}{E_s} \\ \left(E_s \cdot \varepsilon\right) & \text{otherwise} \end{cases}$$



Concrete Fibers

Number of fibers $\quad Conc_{Num} := 20$

Height of fibers $\quad Conc_H := \dfrac{h}{Conc_{Num}} = 1.8 \cdot in$

Concrete fiber coordinates

$$Conc_y := \left| \begin{array}{l} \text{for } i \in 1..Conc_{Num} \\ \quad ans_i \leftarrow -\dfrac{h}{2} + \dfrac{Conc_H}{2} + (i-1) \cdot Conc_H \\ ans \end{array} \right.$$

Concrete fiber strain

$$Conc_\varepsilon(\varepsilon_{o.conc}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{for } i \in 1..Conc_{Num} \\ \quad ans_i \leftarrow \varepsilon_{o.conc} + \varepsilon - \varphi \cdot Conc_{y_i} \\ ans \end{array} \right.$$

Concrete fiber stress

$$Conc_\sigma(\varepsilon_{o.conc}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{for } i \in 1..Conc_{Num} \\ \quad ans_i \leftarrow MAT_{conc}\left(Conc_\varepsilon(\varepsilon_{o.conc}, \varepsilon, \varphi)_i\right) \\ ans \end{array} \right.$$

Concrete fiber force

$$Conc_F(\varepsilon_{o.conc}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{for } i \in 1..Conc_{Num} \\ \quad ans_i \leftarrow Conc_\sigma(\varepsilon_{o.conc}, \varepsilon, \varphi)_i \cdot (b \cdot Conc_H) \\ ans \end{array} \right.$$

Reinforcement/Steel fibers

Depth to reinforcement fiber

$$Steel_{y_1} := -\left(d - \frac{h}{2}\right) = -14.5 \cdot in$$

$$Steel_{y_2} := d - \frac{h}{2} = 14.5 \cdot in$$

Area of reinforcement fiber

$$Steel_{As_1} := A_s = 0.79 \cdot in^2$$

$$Steel_{As_2} := A_s = 0.79 \cdot in^2$$

Steel fiber strain

$$Steel_\varepsilon(\varepsilon_{o.steel}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{for } i \in 1..Steel_{Num} \\ \quad ans_i \leftarrow \varepsilon_{o.steel} + \varepsilon - \varphi \cdot Steel_{y_i} \\ ans \end{array} \right.$$

Steel fiber stress

$$Steel_\sigma(\varepsilon_{o.steel}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{for } i \in 1..Steel_{Num} \\ \quad ans_i \leftarrow MAT_{steel}\left(Steel_\varepsilon(\varepsilon_{o.steel}, \varepsilon, \varphi)_i\right) \\ ans \end{array} \right.$$

Steel fiber force

$$Steel_F(\varepsilon_{o.steel}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{for } i \in 1..Steel_{Num} \\ \quad ans_i \leftarrow Steel_\sigma(\varepsilon_{o.steel}, \varepsilon, \varphi)_i \cdot Steel_{As_i} \\ ans \end{array} \right.$$

Initial Stress State

Initial stress in concrete

$$\text{Concrete}_\sigma := \text{Conc}_\sigma(\varepsilon_{o.conc}, 0, 0)$$

$$\text{Concrete}_{\sigma_1} = -0.135 \cdot \text{ksi}$$

Initial stress in steel

$$\text{Rebar}_\sigma := \text{Steel}_\sigma(\varepsilon_{o.steel}, 0, 0)$$

$$\text{Rebar}_{\sigma_1} = 38.873 \cdot \text{ksi}$$

Axial Equilibrium

$$\text{Force}(\varepsilon_{o.conc}, \varepsilon_{o.steel}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{ans1} \leftarrow 0 \\ \text{for } i \in 1..\text{Conc}_{Num} \\ \quad \text{ans1} \leftarrow \text{ans1} + \text{Conc}_F(\varepsilon_{o.conc}, \varepsilon, \varphi)_i \\ \text{ans2} \leftarrow 0 \\ \text{for } i \in 1..\text{Steel}_{Num} \\ \quad \text{ans2} \leftarrow \text{ans2} + \text{Steel}_F(\varepsilon_{o.steel}, \varepsilon, \varphi)_i \\ \text{ans} \leftarrow \text{ans1} + \text{ans2} \end{array} \right.$$

Moment Equilibrium

$$\text{Moment}(\varepsilon_{o.conc}, \varepsilon_{o.steel}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{ans1} \leftarrow 0 \\ \text{for } i \in 1..\text{Conc}_{Num} \\ \quad \text{ans1} \leftarrow \text{ans1} + -1 \cdot \text{Conc}_F(\varepsilon_{o.conc}, \varepsilon, \varphi)_i \cdot \text{Conc}_{y_i} \\ \text{ans2} \leftarrow 0 \\ \text{for } i \in 1..\text{Steel}_{Num} \\ \quad \text{ans2} \leftarrow \text{ans2} + -1 \cdot \text{Steel}_F(\varepsilon_{o.steel}, \varepsilon, \varphi)_i \cdot \text{Steel}_{y_i} \\ \text{ans} \leftarrow \text{ans1} + \text{ans2} \end{array} \right.$$

Solution

Known parameters

Axial force $P := -32.3\text{kip}$

Iteration

Curvature $\phi := 0.0000022 \cdot \frac{1}{\text{in}}$ Requires iteration

Solve for strain at centroid

Axial strain at centroid (initial guess) $x_o := 0.0$

Axial force equilibrium

$$f(x) := \text{Force}(\varepsilon_{o.conc}, \varepsilon_{o.steel}, x, \phi) - P$$

$$\varepsilon_{cent} := \text{root}(f(x_o), x_o) = -2.724 \times 10^{-5}$$

Sectional forces

$$\text{Force}(\varepsilon_{o.conc}, \varepsilon_{o.steel}, \varepsilon_{cent}, \phi) = -32.3 \cdot \text{kip}$$

$$\text{Moment}(\varepsilon_{o.conc}, \varepsilon_{o.steel}, \varepsilon_{cent}, \phi) = 26.431 \cdot \text{kip} \cdot \text{ft}$$

Stress and strain in concrete and steel

Steel fiber stress and strain

$$\text{Rebar}_{\varepsilon} := \text{Steel}_{\varepsilon}(\varepsilon_{o.steel}, \varepsilon_{cent}, \phi) = \begin{pmatrix} 1.345 \times 10^{-3} \\ 1.281 \times 10^{-3} \end{pmatrix}$$

$$\text{Rebar}_{\sigma} := \text{Steel}_{\sigma}(\varepsilon_{o.steel}, \varepsilon_{cent}, \phi) = \begin{pmatrix} 39.008 \\ 37.158 \end{pmatrix} \cdot \text{ksi}$$

$$\text{Steel}_{F}(\varepsilon_{o.steel}, \varepsilon_{cent}, \phi) = \begin{pmatrix} 30.816 \\ 29.354 \end{pmatrix} \cdot \text{kip}$$

$$\text{Concrete}_{y} := \text{Conc}_{y}$$

Concrete fiber stress and strain

$$\text{Concrete}_{\varepsilon} := \text{Conc}_{\varepsilon}(\varepsilon_{o.conc}, \varepsilon_{cent}, \phi)$$

$$\text{Concrete}_{\sigma} := \text{Conc}_{\sigma}(\varepsilon_{o.conc}, \varepsilon_{cent}, \phi)$$

Maximum compressive strain in concrete

$$\varepsilon_{max.comp} := \frac{\text{Concrete}_{\varepsilon_{ConcNum}} - \text{Concrete}_{\varepsilon_{ConcNum-1}}}{\text{Conc}_{y_{ConcNum}} - \text{Conc}_{y_{ConcNum-1}}} \cdot \left(\frac{h}{2} - \text{Conc}_{y_{ConcNum-1}}\right) \ldots = -1.124 \times 10^{-4}$$
$$+ \text{Concrete}_{\varepsilon_{ConcNum-1}}$$

Maximum compressive stress in concrete $\sigma_{max.comp} := \text{MAT}_{conc}(\varepsilon_{max.comp}) = -0.328 \cdot \text{ksi}$

H9. TABLES

There are no tables.

H10. FIGURES

There are no figures.

APPENDIX I

TENSILE STRESS IN REBARS OF WEST PIPE CHASE STRUCTURE

I1. REVISION HISTORY

Revision 0: Initial document.

Revision 1: Revised pages I-1 and I-2 from Revision 0 to 1 to update references of calculations revision from A to 0. Revised I-1 to update Revision history section.

I2. OBJECTIVE OF CALCULATION

The objective of this calculation is to compute the maximum tensile stress that can form in the rebars of the West Pipe Chase (WPC) structure.

I3. RESULTS AND CONCLUSIONS

Table I1 summarizes the tensile stress in rebars of the WPC structure calculated at critical locations. The Maximum tensile stress is 44 ksi at the base of the WPC north wall subjected to the second in situ load combination (LC2).

I4. DESIGN DATA / CRITERIA

See Section 4 of the calculation main body (Calc. 170443-CA-04 Rev. 0).

I5. ASSUMPTIONS

I5.1 Justified assumptions

There are no justified assumptions.

I5.2 Unverified assumptions

There are no unverified assumptions.

I6. METHODOLOGY

The critical demands that control rebar tension in the WPC structure are horizontal moment and horizontal tension near the base of the WPC north wall. Finite element analyses were conducted to calculate the axial force and bending moment at these locations due to ASR load [I1].

To calculate the stress in rebars subjected to a combination of axial force and bending moment, sectional analysis based on fiber section method, as explained in calculation main body, is used. The calculation is conducted per 1 foot width of the walls, and each section is discretized into 20 fibers. An example calculation that evaluates the stress in the horizontal rebars at the base of the WPC north wall is presented in Section I8. The ASR expansion of the WPC north wall is included in the analysis to find the initial stress state due to internal ASR alone.

I7. REFERENCES

[I1] Simpson Gumpertz & Heger Inc., *Evaluation of the Main Steam and Feedwater West Pipe Chase and Personnel Hatch Structures,* 170443-CA-04 Rev. 0, Waltham, MA, Jan 2018.

[I2] United Engineers & Constructors Inc., Seabrook Station Structural Design Drawings.

[I3] United Engineers & Constructors Inc., *Analysis and Design of MS&FW Pipe Chase - West*, EM-20, Rev. 7, February 1986

I8. COMPUTATION

I8.1. Strain in Steel and Concrete due to Internal ASR expansion

Input Data

ASR expansion

Measured crack index $\varepsilon_{CI} := 0.24 \frac{mm}{m}$

Threshold factor $F_{thr} := 1.0$

Material properties

Compressive strength of concrete $f_c := -3ksi$ Ref. [I1]

Young's modulus of concrete $E_c := 3120ksi$

Yield strength of steel $f_y := 60ksi$

Young's modulus of steel $E_s := 29000ksi$

Geometry

Width of fibers $b := 12in$ Ref. [I2]

Total thickness or height $h := 24in$

Area of concrete $A_c := b \cdot h = 288 \cdot in^2$

Area of tensile reinforcement (#11@12 in.) $A_s := 1.56in^2$

Number of reinforcement in row, e.g. equal to 2 for tensile and compressive $Steel_{Num} := 2$

Depth to reinforcement $d := 20.3in$

Finding the strain in steel and concrete by satisfying compatibility and equilibrium

Initial Guess

Initial mechanical strain in concrete $\varepsilon_{o.conc} := 0$

Initial strain in steel $\varepsilon_{o.steel} := 0$

Given

Compatibility equation $F_{thr} \cdot \varepsilon_{CI} = \varepsilon_{o.steel} - \varepsilon_{o.conc}$

Equilibrium equation $\left(E_c \cdot A_c\right) \cdot \varepsilon_{o.conc} + \left(E_s \cdot A_s \cdot Steel_{Num}\right) \cdot \varepsilon_{o.steel} = 0$

$ans := Find\left(\varepsilon_{o.conc}, \varepsilon_{o.steel}\right)$

Initial strain in concrete and steel

$$\varepsilon_{o.conc} := ans_1 = -2.196 \times 10^{-5}$$

$$\varepsilon_{o.steel} := ans_2 = 2.18 \times 10^{-4}$$

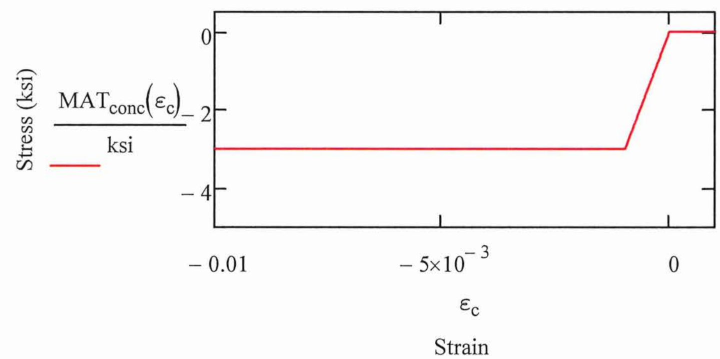
I8.2. Sectional Analysis

Input Data

Concrete Material Model

Constitutive model for concrete

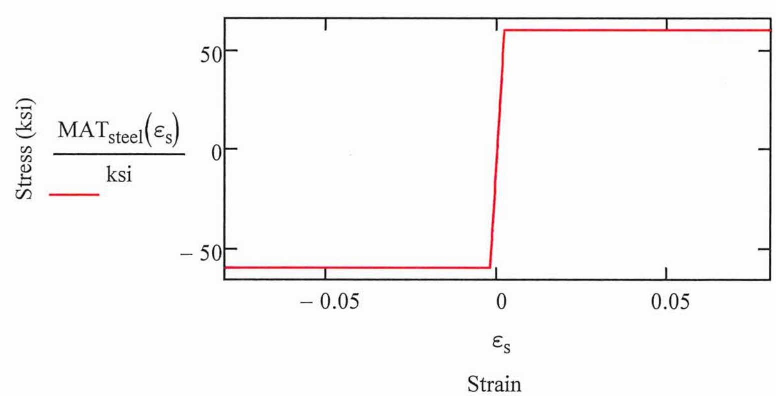
$$MAT_{conc}(\varepsilon) := \begin{cases} 0 & \text{if } \varepsilon > 0 \\ f_c & \text{if } \varepsilon < \dfrac{f_c}{E_c} \\ (E_c \cdot \varepsilon) & \text{otherwise} \end{cases}$$



Steel Material Model

Constitutive model for steel

$$MAT_{steel}(\varepsilon) := \begin{cases} f_y & \text{if } \varepsilon > \dfrac{f_y}{E_s} \\ -f_y & \text{if } \varepsilon < \dfrac{-f_y}{E_s} \\ (E_s \cdot \varepsilon) & \text{otherwise} \end{cases}$$



Concrete Fibers

Number of fibers $Conc_{Num} := 20$

Height of fibers $Conc_H := \frac{h}{Conc_{Num}} = 1.2 \cdot in$

Concrete fiber coordinates
$$Conc_y := \left| \begin{array}{l} \text{for } i \in 1..Conc_{Num} \\ \quad ans_i \leftarrow -\frac{h}{2} + \frac{Conc_H}{2} + (i-1) \cdot Conc_H \\ ans \end{array} \right.$$

Concrete fiber strain
$$Conc_\varepsilon(\varepsilon_{o.conc}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{for } i \in 1..Conc_{Num} \\ \quad ans_i \leftarrow \varepsilon_{o.conc} + \varepsilon - \varphi \cdot Conc_{y_i} \\ ans \end{array} \right.$$

Concrete fiber stress
$$Conc_\sigma(\varepsilon_{o.conc}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{for } i \in 1..Conc_{Num} \\ \quad ans_i \leftarrow MAT_{conc}\left(Conc_\varepsilon(\varepsilon_{o.conc}, \varepsilon, \varphi)_i\right) \\ ans \end{array} \right.$$

Concrete fiber force
$$Conc_F(\varepsilon_{o.conc}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{for } i \in 1..Conc_{Num} \\ \quad ans_i \leftarrow Conc_\sigma(\varepsilon_{o.conc}, \varepsilon, \varphi)_i \cdot (b \cdot Conc_H) \\ ans \end{array} \right.$$

Reinforcement/Steel fibers

Depth to reinforcement fiber
$$Steel_{y_1} := -\left(d - \frac{h}{2}\right) = -8.3 \cdot in$$
$$Steel_{y_2} := d - \frac{h}{2} = 8.3 \cdot in$$

Area of reinforcement fiber
$$Steel_{As_1} := A_s = 1.56 \cdot in^2$$
$$Steel_{As_2} := A_s = 1.56 \cdot in^2$$

Steel fiber strain
$$Steel_\varepsilon(\varepsilon_{o.steel}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{for } i \in 1..Steel_{Num} \\ \quad ans_i \leftarrow \varepsilon_{o.steel} + \varepsilon - \varphi \cdot Steel_{y_i} \\ ans \end{array} \right.$$

Steel fiber stress
$$Steel_\sigma(\varepsilon_{o.steel}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{for } i \in 1..Steel_{Num} \\ \quad ans_i \leftarrow MAT_{steel}\left(Steel_\varepsilon(\varepsilon_{o.steel}, \varepsilon, \varphi)_i\right) \\ ans \end{array} \right.$$

Steel fiber force
$$Steel_F(\varepsilon_{o.steel}, \varepsilon, \varphi) := \left| \begin{array}{l} \text{for } i \in 1..Steel_{Num} \\ \quad ans_i \leftarrow Steel_\sigma(\varepsilon_{o.steel}, \varepsilon, \varphi)_i \cdot Steel_{As_i} \\ ans \end{array} \right.$$

Initial Stress State

Initial stress in concrete

$Concrete_{\sigma} := Conc_{\sigma}(\varepsilon_{o.conc}, 0, 0)$

$Concrete_{\sigma_1} = -0.069 \cdot ksi$

Initial stress in steel

$Rebar_{\sigma} := Steel_{\sigma}(\varepsilon_{o.steel}, 0, 0)$

$Rebar_{\sigma_1} = 6.323 \cdot ksi$

Axial Equilibrium

$$Force(\varepsilon_{o.conc}, \varepsilon_{o.steel}, \varepsilon, \varphi) := \left| \begin{array}{l} ans1 \leftarrow 0 \\ \text{for } i \in 1 .. Conc_{Num} \\ \quad ans1 \leftarrow ans1 + Conc_F(\varepsilon_{o.conc}, \varepsilon, \varphi)_i \\ ans2 \leftarrow 0 \\ \text{for } i \in 1 .. Steel_{Num} \\ \quad ans2 \leftarrow ans2 + Steel_F(\varepsilon_{o.steel}, \varepsilon, \varphi)_i \\ ans \leftarrow ans1 + ans2 \end{array} \right.$$

Moment Equilibrium

$$Moment(\varepsilon_{o.conc}, \varepsilon_{o.steel}, \varepsilon, \varphi) := \left| \begin{array}{l} ans1 \leftarrow 0 \\ \text{for } i \in 1 .. Conc_{Num} \\ \quad ans1 \leftarrow ans1 + -1 \cdot Conc_F(\varepsilon_{o.conc}, \varepsilon, \varphi)_i \cdot Conc_{y_i} \\ ans2 \leftarrow 0 \\ \text{for } i \in 1 .. Steel_{Num} \\ \quad ans2 \leftarrow ans2 + -1 \cdot Steel_F(\varepsilon_{o.steel}, \varepsilon, \varphi)_i \cdot Steel_{y_i} \\ ans \leftarrow ans1 + ans2 \end{array} \right.$$

Solution

Known parameters

Axial force $P := 19.1\text{kip}$

Iteration

Curvature $\phi := 0.0000024 \cdot \frac{1}{in}$ Requires iteration

Solve for strain at centroid

Axial strain at centroid (initial guess) $x_o := 0.0$

Axial force equilibrium

$$f(x) := Force(\varepsilon_{o.conc}, \varepsilon_{o.steel}, x, \phi) - P$$

$$\varepsilon_{cent} := root(f(x_o), x_o) = 3.004 \times 10^{-5}$$

Sectional forces

$$Force(\varepsilon_{o.conc}, \varepsilon_{o.steel}, \varepsilon_{cent}, \phi) = 19.1 \cdot kip$$

$$Moment(\varepsilon_{o.conc}, \varepsilon_{o.steel}, \varepsilon_{cent}, \phi) = 3.784 \cdot kip \cdot ft$$

Stress and strain in concrete and steel

Steel fiber stress and strain

$$Rebar_{\varepsilon} := Steel_{\varepsilon}(\varepsilon_{o.steel}, \varepsilon_{cent}, \phi) = \begin{pmatrix} 2.68 \times 10^{-4} \\ 2.282 \times 10^{-4} \end{pmatrix}$$

$$Rebar_{\sigma} := Steel_{\sigma}(\varepsilon_{o.steel}, \varepsilon_{cent}, \phi) = \begin{pmatrix} 7.772 \\ 6.617 \end{pmatrix} \cdot ksi$$

$$Steel_F(\varepsilon_{o.steel}, \varepsilon_{cent}, \phi) = \begin{pmatrix} 12.124 \\ 10.322 \end{pmatrix} \cdot kip$$

$$Concrete_y := Conc_y$$

Concrete fiber stress and strain

$$Concrete_{\varepsilon} := Conc_{\varepsilon}(\varepsilon_{o.conc}, \varepsilon_{cent}, \phi)$$

$$Concrete_{\sigma} := Conc_{\sigma}(\varepsilon_{o.conc}, \varepsilon_{cent}, \phi)$$

Maximum compressive strain in concrete

$$\varepsilon_{max.comp} := \frac{Concrete_{\varepsilon_{ConcNum}} - Concrete_{\varepsilon_{ConcNum-1}}}{Conc_{y_{ConcNum}} - Conc_{y_{ConcNum-1}}} \cdot \left(\frac{h}{2} - Conc_{y_{ConcNum-1}}\right) \ldots = -2.072 \times 10^{-5}$$
$$+ Concrete_{\varepsilon_{ConcNum-1}}$$

Maximum compressive stress in concrete $\sigma_{max.comp} := MAT_{conc}(\varepsilon_{max.comp}) = -0.065 \cdot ksi$

I9. TABLES

Table I1: Stress in rebars at critical locations of WPC structure subjected to LC1

Component	Item	Total demands for sustained load (In Situ condition, LC1)		Total stress in steel (ksi)		Maximum compressive stress in concrete (ksi)
		Demand	Location	Rebar 1	Rebar 2	
WPC North Wall	Out-of-plane moment (kip-ft/ft)	3.8	Base of wall, horizontal direction	7.8	6.6	-0.07
	Axial force (kip/ft)	19.1				

Example in Section I8

Table I2: Stress in rebars at critical locations of WPC structure subjected to LC2

Component	Item	Total demands for sustained loads plus OBE amplified with threshold factor (In Situ condition, LC2)		Total stress in steel (ksi)		Maximum compressive stress in concrete (ksi)
		Demand	Location	Rebar 1	Rebar 2	
WPC North Wall	Out-of-plane moment (kip-ft/ft)	78.8	Base of wall, horizontal direction	44.4	8.0	-1.36
	Axial force (kip/ft)	34.4				

I10. FIGURES

There are no figures.

APPENDIX J

COMPUTER RUN IDENTIFICATION LOG

SIMPSON GUMPERTZ & HEGER
Engineering of Structures and Building Enclosures

Client: NextEra Energy Seabrook **Page** 1 **of** 4

Project: Evaluation of maximum stress in rebars of Seabrook structures

Project No.: 170444 **Subcontract No.:** N/A **Calculation No.:** RAI-D8 Attachment 2

Run No.	Title	Program/Ver.[A]	Hardware	Date	Files	
1	CRMAI subjected to unfactored load (sustained loading) including ASR load	ANSYS 15.0 Structural	Cluster3g[B]	10/12/2017	Note C	
2	CRMAI subjected to unfactored load (sustained loading) plus OBE including ASR load that has been amplified by threshold factor	ANSYS 15.0 Structural	Cluster3g[B]	10/12/2017	Note C	
3	CEB Standard Case subjected to unfactored loads (sustained loading) including ASR and OBE. For OBE load case, ASR loads are amplified by threshold factor.	ANSYS 15.0 Structural	Cluster3g[B]	11/22/2017	Note C	
4	CEB Standard-Plus Case subjected to unfactored loads (sustained loading) including ASR and OBE. For OBE load case, ASR loads are amplified by threshold factor.	ANSYS 15.0 Structural	Cluster3g[B]	11/22/2017	Note C	
5	RHR subjected to unfactored sustained loads (i.e., non ASR loads), unfactored ASR loads, and unfactored seismic loads considering unit acceleration (i.e., 1 g).	ANSYS 15.0 Structural	Cluster3g[B]	10/12/2017	Note C	
6	CSTE subjected to ASR load	ANSYS 15.0 Structural	Cluster3g[B]	11/11/2016	Note C	

SIMPSON GUMPERTZ & HEGER

Engineering of Structures
and Building Enclosures

PROJECT NO: 170444

DATE: Dec. 2017

CLIENT: NextEra Energy Seabrook

BY: MR. M. Gargari

SUBJECT: Evaluation of maximum stress in rebars of Seabrook structures

VERIFIER: A.T. Sarawit

Run No.	Title	Program/Ver.[A]	Hardware	Date	Files	
7	WPC/PH subjected to ASR load	ANSYS 15.0 Structural	Cluster3g[B]	11/09/2017	Note C	

Notes:

A ANSYS 15.0 Structural is QA verified

B Cluster3g information is provided below:
Model: Compute Blade E55A2
Serial Number: 4600E70 T201000293
Manufacturer: American Megatrends Inc.
Operating System: Microsoft Windows NT Server 6.2 (x64)

C Input and output files for ANSYS computer runs are listed in Table J1.

Table J1. Input and output files for ANSYS computer runs

Run No.	Input Files[A]	Output Files[A]
1	CRMAI_SUS.db[B]	CRMAI_SUS.rst
2	CRMAI_SUS_OBE.db[B]	CRMAI_SUS_OBE.rst
3	SR_Rebar_Stress_A10_r0.db[B]	SR_Rebar_Stress_A10_r0.lxx
4	SR_Rebar_Stress_B7_r0.db[B]	SR_Rebar_Stress_B7_r0.lxx
5	<u>Non ASR Loads</u> • RHR_ILC_02.db • RHR_ILC_03.db • RHR_ILC_05.db • RHR_ILC_16.db <u>ASR Loads</u> • RHR_ILC_09.db • RHR_ILC_10.db <u>Seismic 1g</u> • RHR_ILC_06.db • RHR_ILC_07.db • RHR_ILC_08.db • RHR_ILC_13.db • RHR_ILC_14.db	<u>Non ASR Loads</u> • RHR_ILC_02.rst • RHR_ILC_03.rst • RHR_ILC_05.rst • RHR_ILC_16.rst <u>ASR Loads</u> • RHR_ILC_09.rst • RHR_ILC_10.rst <u>Seismic 1g</u> • RHR_ILC_06.rst • RHR_ILC_07.rst • RHR_ILC_08.rst • RHR_ILC_13 rst • RHR_ILC_14.rst
6	CST_024.db[C]	CST_024.rst
7	WPC.db[C]	WPC.rst

Notes:

A Input and output files are provided on RAI-Attachment-CD. File type descriptions are as follows.
*.db = ANSYS database file containing the model (nodes, elements, properties, boundary conditions, loads, etc.).
*.rst = ANSYS result file containing forces, moments, reactions, displacements, etc.
*.lxx = ANSYS load case file containing forces, moments, reactions, displacements, and other structural response output for load cases and load combinations.

B Each structure has been analyzed for two load combination as follows:
- D + L + E + To + Sa (In-situ condition, LC1)
- D + L + E + T_o + E_o + He + $F_{THR}.S_a$ (In-situ condition plus seismic load, LC2)

C Each structure is analyzed for ASR load only. The original design demands are extracted from original design calculation.

D The description of the input and output files for Run No. 5 is following:
RHR_ILC_02: Self-Weight:
RHR_ILC_03: Hydrostatic Pressure Outside
RHR_ILC_05: Live Load
RHR_ILC_06: Seismic North-South with 1g acceleration
RHR_ILC_07: Seismic East-West with 1g acceleration
RHR_ILC_08: Seismic Vertical with 1g acceleration
RHR_ILC_09: In structure ASR

RHR_ILC_10: Concrete fill
RHR_ILC_13: Seismic South-North with 1g acceleration
RHR_ILC_14: Seismic West-East with 1g acceleration
RHR_ILC_16: Backfill Soil Static Pressure

Enclosure 5 to SBK-L-18074

Simpson Gumpertz & Heger calculations supporting the response provided to RAI D10 regarding cracked section properties used for the evaluation of the RHR vault and Spent fuel pool walls.

SIMPSON GUMPERTZ & HEGER

Engineering of Structures
and Building Enclosures

PROJECT NO. 170444

DATE 31 May 2018

CLIENT NextEra Energy Seabrook

BY Georgios Tsampras

SUBJECT Verification of cracked section properties: RHR structure

CHECKED BY MR. M. Gargari

Calculation attachment
Flexural Cracking of 2 ft. thick east exterior wall

1.0 Revision History

Revision 0. Initial document.

2.0 Objective of Calculation

The objective of this calculation attachment is to verify current cracked section properties used for the evaluation of the Residual Heat Removal (RHR) structure east exterior wall when considering ASR loading pre-compressive effect on the cracking moment calculation and to determine if such results affect negatively the current results for the evaluation of the RHR.

3.0 Assumptions

No assumptions are considered in this calculation attachment.

4.0 Methodology

The highest demand-to-capacity (D/C) ratio in the RHR walls is reported at the east exterior wall due to interaction of horizontal axial compression and bending about the vertical axis (see Appendix E of 160268-CA-06 [1]). Therefore, RHR east exterior wall is selected for the verification.

In Appendix E of 160268-CA-06 [1] Section E6.4.1 the bending moment demand was calculated considering uncracked section properties for bending about the vertical axis. In Appendix E of 160268-CA-06 Section E6.4.3 [1] the effective moment of inertia of cracked concrete is calculated according to ACI318-14 Table 6.6.3.1.1(b) [2] considering the factored moment and axial load demands. The ratio of effective over gross moment of inertia calculated in Appendix E of 160268-CA-06 Section E6.4.3 [1] is compared with the ratio of effective over gross moment of inertia calculated considering the modified ACI 318-71 Eqn 9-4 [3, 4] including the compressive stress due to ASR expansion effects.

5.0 Results and Conclusions

The effective moment of inertia of cracked concrete calculated in Appendix E of 160268-CA-06 [1] Section E6.4.3 is equal to 35% of the gross moment of inertia of uncracked concrete. The effective moment of inertia of cracked concrete calculated using the modified ACI 318-71 Eqn 9-4 [3, 4] including the compressive stress due to ASR expansion effects is equal to 23% of the gross moment of inertia of uncracked concrete. Thus, the demands are expected to reduce when the modified ACI 318-71 Eqn 9-4 [3, 4] is used to calculate the effective moment of inertia. As a result, the evaluation of the RHR structure presented in160268-CA-06 is conservative and it is not affected.

6.0 Computations

Below are the demands at the support of the East exterior wall - 2 ft thick wall between El. (-) 32 ft to (-) 40 ft with uncracked section properties in flexure about the vertical axis from Section E6.4.1 160268-CA-06 [1].

Horizontal axial load due to 1.0Sa $N_{B01} := 4.8031E+02 \cdot \frac{lbf}{in}$

Horizontal axial load due to 1.4D+ 1.7L+1.7E $N_{C02} := -5.6331E+03 \cdot \frac{lbf}{in}$

ASR effects load combination multiplier $SFSa := 1.6$

Threshold factor $k_{th} := 1.2$

Total horizontal axial load $N_{sup\_u\_2} := N_{C02} + k_{th} \cdot SFSa \cdot N_{B01} = -4.7109 \times 10^{3} \cdot \frac{lbf}{in}$

Bending Moment about the vertical axis due to 1.0Sa $M_{B01} := -1.1382E+05 \cdot \frac{lbf \cdot in}{in}$

Bending Moment about the vertical axis due to 1.4D+ 1.7L+1.7E $M_{C02} := -2.4120E+04 \cdot \frac{lbf \cdot in}{in}$

Total bending Moment about the vertical axis $M_{sup\_u\_2} := M_{C02} + k_{th} \cdot SFSa \cdot M_{B01} = -242.6544 \cdot kip \cdot \frac{ft}{ft}$

Calculation of effective moment of inertia of cracked concrete using the modified ACI 318-71 Eqn 9-4 [3, 4] including the compressive stress due to ASR expansion effects.

Wall thickness $t_w := 2ft$

Gross moment of inertia of uncracked concrete $I_g := \frac{t_w^{3}}{12} = 1.152 \times 10^{3} \cdot \frac{in^4}{in}$

One foot long section width $b := 12in$

Compressive stress due to compressive load $_c := \frac{-N_{sup\_u\_2}}{b} = 392.5754\,psi$

Concrete Strength $f_c := 3000psi$

Cracking stress $f_r := 7.5 \cdot \sqrt{f_c \cdot psi} = 410.7919\,psi$

Size of reinforcing bar in the wall at the section cut

$A_{rb} :=$

#8
#9
#10
#11

Reinforcing bar area

$$\left(A_{rb} \cdot in^2\right) = 0.79 \cdot in^2$$

Reinforcing bar spacing

$$(s := 9in)$$

Total reinforcing bar area per length in the wall at the location of the section cut

$$A_s := \frac{\left(A_{rb} \cdot in^2\right)}{\frac{s}{b}} = 1.0533 \cdot in^2$$

Depth of concrete section

$$d := 20.5in$$

Steel modulus

$$E_s := 29000ksi$$

Concrete modulus

$$E_c := 57000 \cdot \sqrt{f_c \cdot psi}$$

Ratio of steel modulus over concrete modulus

$$\left(n := \frac{E_s}{E_c} = 9.2889\right)$$

$$B := \frac{b}{n \cdot A_s} = 1.2265 \cdot in^{-1}$$

$$kd := \frac{\left(\sqrt{2 \cdot d \cdot B + 1} - 1\right)}{B} = 5.0237 \cdot in$$

Cracked moment of inertia

$$I_{cr} := \frac{\frac{b \cdot kd^3}{3} + n \cdot A_s \cdot (d - kd)^2}{b} = 237.5526 \cdot \frac{in^4}{in}$$

Cracking moment

Reference [4]

$$M_{cr} := \frac{I_g \cdot \left(f_r + \ _c\right)}{\frac{t_w}{2}} = 77.1233 \cdot \frac{kip \cdot ft}{ft}$$

Effective cracked moment of inertia [ACI 318-71 Eqn 9-4] (defined as a function of Ma)

$$I_{crsup\_MD} := \left(\frac{M_{cr}}{\left|M_{sup\_u\_2}\right|}\right)^3 \cdot I_g + \left[1 - \left(\frac{M_{cr}}{\left|M_{sup\_u\_2}\right|}\right)^3\right] \cdot I_{cr} = 266.9122 \cdot \frac{in^4}{in}$$

$$\frac{I_{crsup\_MD}}{I_g} = 0.2317$$

7.0 References

[1] Simpson Gumpertz & Heger Inc., Appendix E: Evaluation of Residual Heat Removal Equipment Vault, Report 160268-CA-06, August 2017, Waltham, Revision 0

[2] American Concrete Institute, Building Code Requirements for Structural Concrete and Commentary, ACI 318-14, 2014

[3] American Concrete Institute, Building Code Requirements for Structural Concrete and Commentary, ACI 318-71, 1972

[4] Simpson Gumpertz & Heger Inc., Methodology for the analysis of seismic category I structures with concrete affected by Alkali-Silica Reaction, Methodology Document 170444-MD-01, Waltham, Revision 1

Calculation Attachment
Flexural Cracking of 6ft Thick SFP Walls

1.0 Revision History

Revision 0. Initial document.

2.0 Objective of Calculation

The objective of this calculation attachment is to verify the cracked section properties used for the evaluation of the Spent Fuel Pool (SFP) walls in the Fuel Storage Building (FSB) when taking into account the ASR pre-compression effect has on delaying the onset of flexural cracking and determine if such effect negatively impact the current FSB evaluation results.

3.0 Assumptions

No assumptions are considered in this calculation attachment.

4.0 Methodology

The highest demand-to-capacity (D/C) ratio in the SFP walls is reported at the north wall due to interaction of vertical axial compression and bending about the horizontal axis. This SFP north wall is selected for the verification. For completeness, cracked section properties of this SFP north wall due to interaction of horizontal axial compression and bending about the vertical axis are also verified. The highest D/C ratio due to bending about horizontal axis is 0.9 and corresponds to load combination C03 (Table 10, Calculation 160268-CA-09). The highest D/C ratio due to bending about vertical axis is 0.5 and corresponds to load combination C03. Load combination C03 considers an ASR load factor of 2.0 and a threshold factor of 1.2 to account for potential future ASR expansion.

Field inspection of accessible SFP walls show that they are already cracked. Cracking can be initiated by factors other than flexural loads, such as thermal gradients. Original design calculation for the SFP mat and walls uses fully-cracked moment of inertia (Icr) for the calculation of demands due to thermal gradients in the SFP walls.

The ratio of Icr to the gross moment of inertia (Ig) is 0.13 when evaluating bending about the horizontal axis. The ratios of the effective moment of inertia (Ie) to Ig corresponding to the un-cracked section moment due to operational and accidental thermal gradients are 0.15 and 0.14, respectively. The above results justify the use of Icr in the original design calculation for the evaluation of temperature bending demands about the horizontal axis in the SPF walls.

The ratio of Icr to Ig is 0.09 when evaluating bending about the vertical axis. The ratios of Ie to Ig corresponding to the un-cracked section moment due to operational and accidental thermal gradients are 0.11 and 0.10, respectively. The above results justify the use of Icr in the original design calculation for the evaluation of temperature bending demands about the vertical axis in the SPF walls.

The evaluation of the SFP walls in CA-09 is performed based on a ratio of Ie to Ig of 0.25. To verify the use of this ratio, the cracking moment (Mcr) is re-calculated taking into account the ASR pre-compression effect has on delaying the onset of flexural cracking. The Ie to Ig ratio is then calculated based on this re-calculated Mcr for the un-cracked section moment due to operational and accidental thermal gradients.

5.0 Results and Conclusions

The ratios of Ie to Ig about the horizontal axis due to operational and accidental thermal gradients when taking into account the ASR loading pre-compressive effect due to load combination C03 are 0.16 and 0.15, respectively. These ratio values do not exceed the used ratio value of 0.25.

The ratios of Ie to Ig about the vertical axis due to operational and accidental thermal gradients when taking into account the ASR loading pre-compressive effect due to load combination C03 are 0.30 and 0.21, respectively. The ratio value due operational thermal gradient slightly exceed the used ratio value of 0.25. The associated current D/C ratio is 0.5. Section 6.3 estimates the corresponding D/C ratio when Ie/Ig has a value of 0.30. The moment demand is estimated by amplifying the current moment demand by the ratio of Ie/Ig value of 0.30 to Ie/Ig value of 0.25. The updated D/C ratio is calculated as 0.6.

Based on the above results, it is concluded that accounting for the ASR loading pre-compression effect in calculating the Mcr does not impact negatively the current results for the evaluation of the FSB.

6.0 Computations

6.1 Bending About Horizontal Axis

Inputs

Section properties are obtained from Page I-06 of Calculation 160268-CA-09 Appendix I

thickness of cross section	$h := (6\cdot 12)\text{in} = 6\,\text{ft}$
depth to reinforcement	$d := h - 3.5\text{in} - 1.128\text{in} - \frac{1.41\text{in}}{2} = 66.7\cdot\text{in}$
unit width	$b := 1\text{ft}$
concrete compressive strength	$fpc := 3000\text{psi}$
area of tension steel (#11 @ 12 in)	$As := 1.56\text{in}^2$
yield strength of tension steel	$fy := 60000\text{psi}$
concrete elastic modulus	$Ec := 3120000\text{psi}$
steel elastic modulus	$Es := 29000000\text{psi}$

ASR Loading Demands

The controlling combination load for the evaluation of the SFP North Wall is C03 (Section Cut 40 in Table 10, Calculation 160268-CA-09). Factored ASR axial compression demand and including the threshold factor of 1.2 applied in the vertical direction of the SFP north wall are obtained from FSB_UC model of the FSB (Section 6.2, Calculation 160268-CA-09). Axial compression demand due to the thermal gradient is not considered since the wall is free to translate in the upward direction.

Threshold factor	$TF := 1.2$
ASR loading factor of 2.0 for combination load C03 and affected by 20% reduction in ASR load (Table 6 of Methodology Document170444-MD-01)	$ASR\_F := 1.6$

Unfactored ASR compression force. $P_u := 3737.5 \frac{lbf}{in} = 44.9 \cdot \frac{kip}{ft}$

Factored ASR compressive stress due to combination load C03 $f_{initial} := \frac{ASR\_F \cdot TF \cdot P_u}{h} = 100 \, psi$

Temperature Loading Demands

The temperature moment demands for the un-cracked section of the wall are calculated based on thermal gradients defined in the original design calculation for the SFP mat and walls (FB-17) and considering fixed-fixed boundary conditions. Modeling as fixed-pinned boundary conditions leads to bending demands that are up to 1.5 times larger than that obtained using fixed-fixed boundary conditions. Therefore, the use of fixed-fixed boundary conditions for bending about the horizontal direction is conservative.

Operational Temperature:

Temperature at top $T_t := 175 \cdot \ {}^\circ F$

Temperature at bottom $T_b := -10 \cdot \ {}^\circ F$

Coefficient of Thermal Expansion for concrete $:= 5.5 \cdot 10^{-6} \cdot \left(\frac{1}{{}^\circ F}\right)$

Gross moment of inertia $Ig := \frac{b \cdot h^3}{12} = 3.732 \times 10^5 \cdot in^4$

Operational thermal moment based on un-cracked section $M_{tgo} := \frac{Ec \cdot (Ig) \cdot \ \cdot \left(\frac{T_t - T_b}{2}\right)}{0.5 \cdot h} = 1371.4 \cdot kip \cdot ft$

Accidental Temperature:

Temperature at top $T_t := 212 \cdot \ {}^\circ F$

Temperature at bottom $T_b := -10 \cdot \ {}^\circ F$

Accidental thermal moment based on un-cracked section $M_{tga} := \frac{Ec \cdot (Ig) \cdot \ \cdot \left(\frac{T_t - T_b}{2}\right)}{0.5 \cdot h} = 1645.7 \cdot kip \cdot ft$

Determine M_{cr}

Ratio of steel to concrete elastic moduli $n := \mathrm{round}\left(\frac{Es}{Ec}\right) = 9$

modulus of rupture [ACI 318-71 Section 9.5.2.2] $fr := 7.5 \cdot \sqrt{\frac{fpc}{psi}} \cdot psi = 410.792 \cdot psi$

Cracking moment [ACI 318-71 Eqn 9-5] $Mcr := \frac{(fr + f_{initial}) \cdot Ig}{0.5 \cdot h} = 441 \cdot kip \cdot ft$

Compute Cracked Moment of Inertia

Distance to neutral axis of cracked section

$$kd := \left(\sqrt{1 + \frac{2b \cdot d}{n \cdot As}} - 1\right) \cdot \frac{n \cdot As}{b} = 11.375 \cdot in$$

Fully cracked moment of inertia

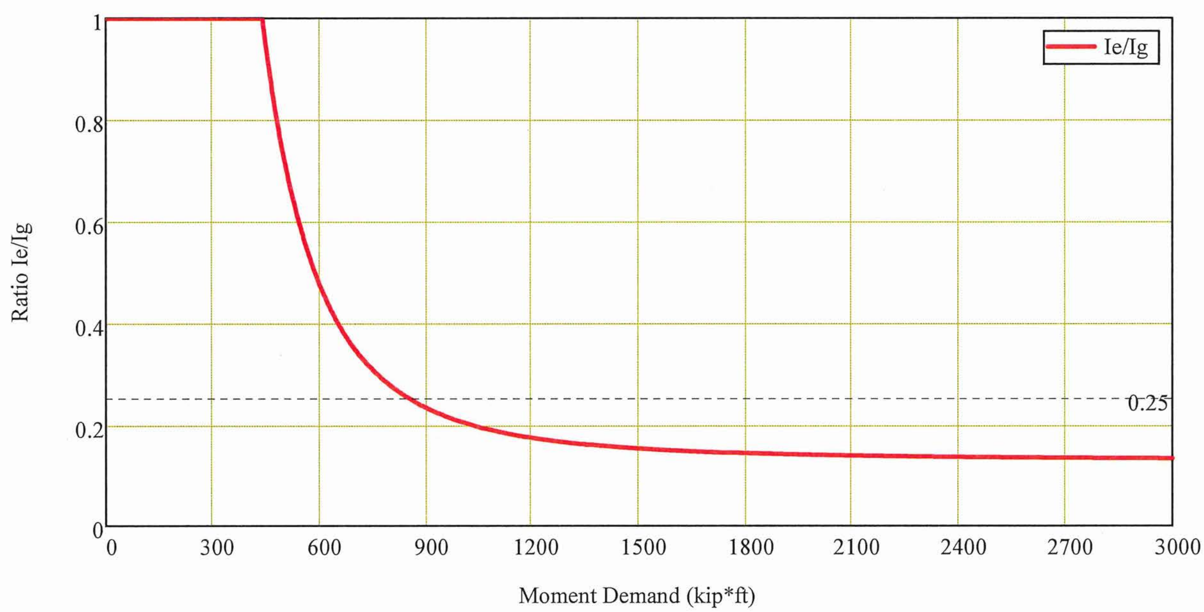
$$Icr := \frac{b \cdot kd^3}{3} + n \cdot As \cdot (d - kd)^2 = 4.881 \times 10^4 \cdot in^4$$

Ratio of fully cracked moment of inertia to gross moment of inertia

$$\frac{Icr}{Ig} = 0.131$$

Effective cracked moment of inertia [ACI 318-71 Eqn 9-4] (defined as a function of Ma)

$$Ie(Ma\_in) := \min\left[\left(\frac{Mcr}{|Ma\_in|}\right)^3 \cdot Ig + \left[1 - \left(\frac{Mcr}{|Ma\_in|}\right)^3\right] \cdot Icr, Ig\right]$$



Ie / Ig Ratio for Bending about Horizontal Axis

Ie/Ig Ratio at Uncracked Section Temperature Moment Demand

Ratio of effective moment of inertia to gross moment of inertia at moment demand for an un-cracked section due to operational temperature.

$$\frac{Ie(M_{tgo})}{Ig} = 0.16$$

Ratio of effective moment of inertia to gross moment of inertia at moment demand for an un-cracked section due to accidental temperature.

$$\frac{Ie(M_{tga})}{Ig} = 0.15$$

6.2 Bending About Vertical Axis

Inputs

Section properties are obtained from Page I-03 of Calculation 160268-CA-09 Appendix I

depth to reinforcement $$d := h - 3.5in - \frac{1.128in}{2} = 67.9\cdot in$$

area of tension steel (#9 @ 12in) $$As := 1.00in^2$$

ASR Loading Demands

The controlling combination load for the evaluation of the SFP North Wall is C03 (Section Cut 38 in Table 10, Calculation 160268-CA-09). Factored ASR axial compression demand and including the threshold factor of 1.2 applied in the horizontal direction of the SFP north wall are obtained from FSB_UC model of the FSB (Section 6.2, Calculation 160268-CA-09). Axial compression demand due to the thermal gradient is not considered. The restraint and inward pressure effects due to ASR expansion of the concrete backfill at the west side of the north wall leads to large axial compression demands. Including the axial compression demand due to temperature is considered to double-count the compressive effect and thus too conservative since its effect is only developed due to the restraint effect of the concrete backfill.

Unfactored ASR compression force. $$P_u := 21098\frac{lbf}{in} = 253.2\cdot\frac{kip}{ft}$$

ASR compressive stress due to combination load C03 $$f_{initial} := \frac{ASR\_F\cdot TF\cdot P_u}{h} = 563\ psi$$

Temperature Loading Demands

The temperature moment demands for the un-cracked section of the wall are calculated based on thermal gradients defined in the original design calculation for the SFP mat and walls (FB-17) and considering fixed-fixed boundary conditions. Fixed boundary conditions for bending about vertical axis are judged adequate due to the restraint effects of the thick west wall of the SFP and north wall of the cask loading pool. Therefore, the same temperature moment demands considered in the evaluation for bending about the horizontal axis are used.

Determine M_{cr}

Cracking moment [ACI 318-71 Eqn 9-5] $$Mcr := \frac{(fr + f_{initial})\cdot Ig}{0.5\cdot h} = 841\cdot kip\cdot ft$$

Compute Cracked Moment of Inertia

Distance to neutral axis of cracked section $$kd := \left(\sqrt{1 + \frac{2b\cdot d}{n\cdot As}} - 1\right)\cdot\frac{n\cdot As}{b} = 9.373\cdot in$$

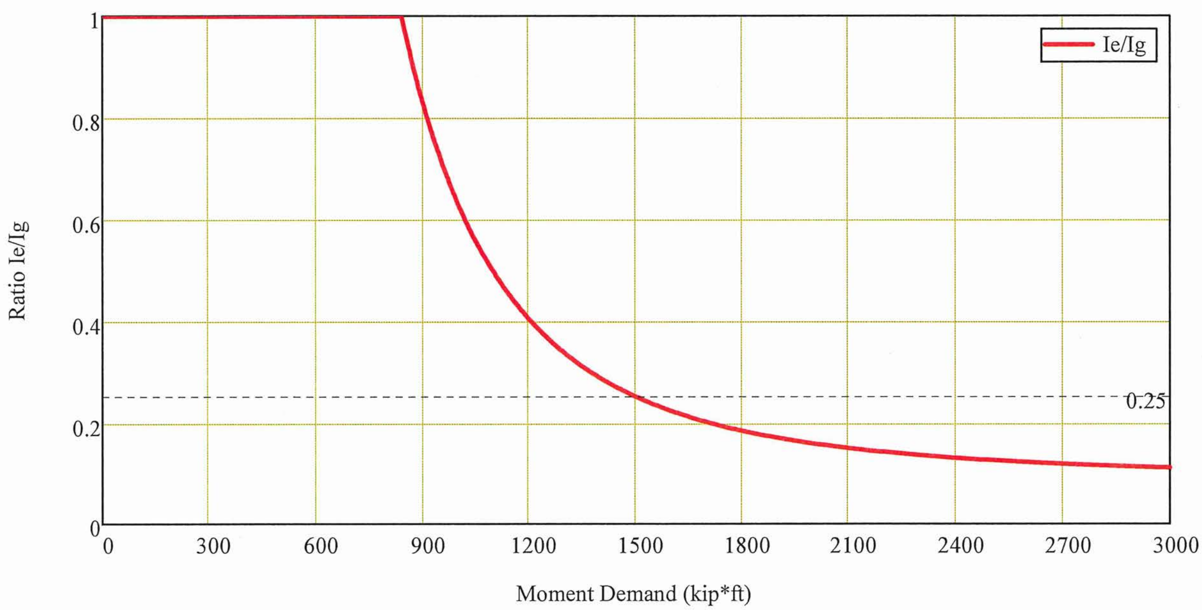
Fully cracked moment of inertia $$Icr := \frac{b\cdot kd^3}{3} + n\cdot As\cdot(d - kd)^2 = 3.416\times 10^4\cdot in^4$$

Ratio of fully cracked moment of inertia to gross moment of inertia

$$\frac{Icr}{Ig} = 0.092$$

Effective cracked moment of inertia [ACI 318-71 Eqn 9-4] (defined as a function of Ma)

$$Ie(Ma\_in) := \min\left[\left(\frac{Mcr}{|Ma\_in|}\right)^3 \cdot Ig + \left[1 - \left(\frac{Mcr}{|Ma\_in|}\right)^3\right] \cdot Icr, Ig\right]$$



Ie / Ig Ratio for Bending about Vertical Axis

Ie/Ig Ratio at Uncracked Section Temperature Moment Demand

Ratio of effective moment of inertia to gross moment of inertia at moment demand for an un-cracked section due to operational temperature.

$$\frac{Ie(M_{tgo})}{Ig} = 0.3$$

Ratio of effective moment of inertia to gross moment of inertia at moment demand for an un-cracked section due to accidental temperature.

$$\frac{Ie(M_{tga})}{Ig} = 0.21$$

6.3 Evaluation of D/C Ratio for Bending about Vertical Axis in the SFP North Wall

Axial compression demands in the horizontal direction and bending demands about the vertical direction in the SFP north wall are obtained from FSB_FC model of the FSB. The demands correspond to Section Cut 38. (Section 6.2, Calculation 160268-CA-09).

Unfactored ASR axial compression demand $P_{ASR} := 17793\frac{lbf}{in} = 213.5\cdot\frac{kip}{ft}$

Unfactored ASR bending demand $M_{ASR} := 359990\frac{lbf\cdot in}{in} = 360\cdot\frac{kip\cdot ft}{ft}$

Factored ASR axial compression load due to combination load C03 $P_{ASR\_C03} := ASR\_F\cdot TF\cdot P_{ASR} = 410\cdot\frac{kip}{ft}$

Factored ASR bending demand due to combination load C03 $M_{ASR\_C03} := ASR\_F\cdot TF\cdot M_{ASR} = 691\cdot\frac{kip\cdot ft}{ft}$

Factored axial tension load due to combination load C03 w/o ASR loading $P_{C03} := -94.808\frac{lbf}{in} = -1.1\cdot\frac{kip}{ft}$

Factored bending demand due to combination load C03 w/o ASR loading (opposite to ASR moment) $M_{C03} := -13921\frac{lbf\cdot in}{in} = -13.9\cdot\frac{kip\cdot ft}{ft}$

Factored axial compression load due to combination load C03 $P_{uC03} := P_{ASR\_C03} + P_{C03} = 408.8\cdot\frac{kip}{ft}$

Factored bending demand due to combination load C03 $M_{uC03} := M_{ASR\_C03} + M_{C03} = 677.3\cdot\frac{kip\cdot ft}{ft}$

Amplification factor for M_{uC03}. The amplification factor to estimate the moment demand when accounting for the ASR loading compressive effect ($f_{initial}$) is conservatively calculated by the factor between the ratios of the effective moment of inertia Ie with and without $f_{initial}$. $I_{amp} := \frac{0.30}{0.25} = 1.2$

Factored amplified bending demand due to combination load C03 $M_{uC03\_amp} := I_{amp}\cdot\left(M_{uC03}\right) = 812.7\cdot\frac{kip\cdot ft}{ft}$

PM capacity diagram file (From spColumn with adjusted capacity factors) PMD := "0072_0083_0083_0406_0406.PMD"

Load PM capacity diagram for section cut 38 PM_File := READFILE(PMD, "delimited")

Extract PM capacity curve

$$PM\_CapM := \mathrm{submatrix}(PM\_File, 2, \mathrm{rows}(PM\_File), 1, 1)\cdot\frac{kip\cdot ft}{ft}$$

$$PM\_CapP := \mathrm{submatrix}(PM\_File, 2, \mathrm{rows}(PM\_File), 2, 2)\cdot\frac{kip}{ft}$$

Compression capacity

$$Pn := 0.7\cdot 0.80\cdot\left[0.85\cdot fpc\cdot\left(h - 2\frac{As}{b}\right) + 2\frac{As}{b}\cdot fy\right] = 1298.1\cdot\frac{kip}{ft}$$

Cap axial compression to the design limit.

$$PM\_CapP\_capped := \left|\begin{array}{l} retval_{\mathrm{rows}(PM\_CapP)} \leftarrow 0 \\ \text{for } rowi \in 1..\mathrm{rows}(PM\_CapP) \\ \quad retval_{rowi} \leftarrow \min\left(PM\_CapP_{rowi}, Pn\right) \\ retval \end{array}\right.$$

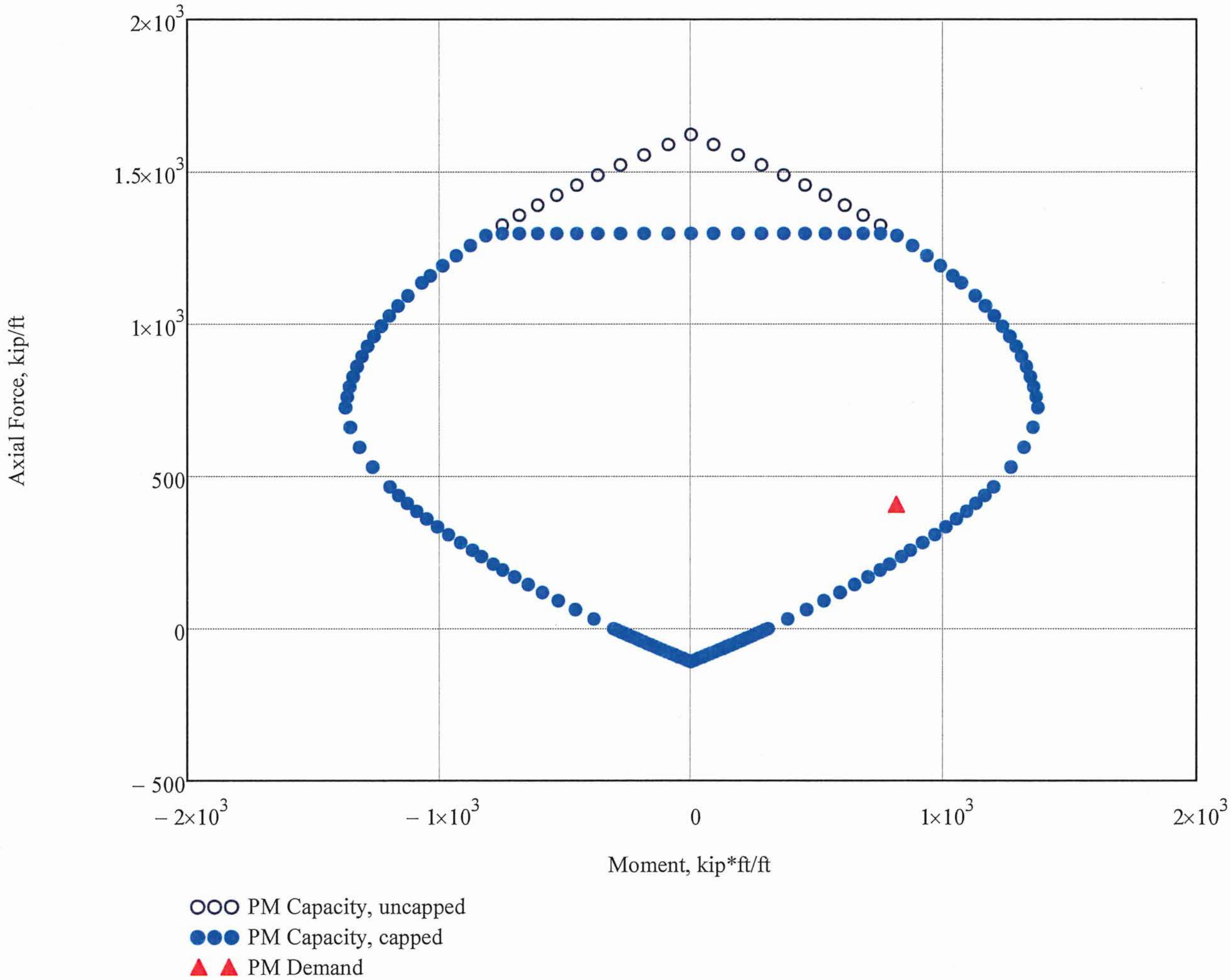
Demand point:

$$PM\_DM := M_{uC03\_amp} = 812.712\cdot\frac{kip\cdot ft}{ft}$$

$$PM\_DP := P_{uC03} = 408.813\cdot\frac{kip}{ft}$$

Compute DCR for PM Interaction

$$DCR_{PM} := \left|\begin{array}{l} demandAngle \leftarrow \mathrm{angle}\left[\frac{PM\_DM}{\left(\frac{kip\cdot ft}{ft}\right)}, \frac{PM\_DP}{\left(\frac{kip}{ft}\right)}\right] \\ best\_P \leftarrow 0.0 \\ best\_M \leftarrow 0.0 \\ best\_AngleDelta \leftarrow 99999 \\ \text{for } ci \in 1..\mathrm{rows}(PM\_CapP\_capped) \\ \quad \left|\begin{array}{l} thisAngle \leftarrow \mathrm{angle}\left[\frac{PM\_CapM_{ci}}{\left(\frac{kip\cdot ft}{ft}\right)}, \frac{PM\_CapP\_capped_{ci}}{\left(\frac{kip}{ft}\right)}\right] \\ angleDelta \leftarrow thisAngle - demandAngle \\ \text{if } |angleDelta| < best\_AngleDelta \\ \quad \left|\begin{array}{l} best\_AngleDelta \leftarrow |angleDelta| \\ best\_P \leftarrow PM\_CapP\_capped_{ci} \\ best\_M \leftarrow PM\_CapM_{ci} \end{array}\right. \end{array}\right. \\ demandLength \leftarrow \sqrt{\left[\frac{PM\_DM}{\left(\frac{kip\cdot ft}{ft}\right)}\right]^2 + \left[\frac{PM\_DP}{\left(\frac{kip}{ft}\right)}\right]^2} \\ capacityLength \leftarrow \sqrt{\left[\frac{best\_M}{\left(\frac{kip\cdot ft}{ft}\right)}\right]^2 + \left[\frac{best\_P}{\left(\frac{kip}{ft}\right)}\right]^2} \\ \text{return } \frac{demandLength}{capacityLength} \end{array}\right. = 0.6$$



Axial Force Moment Interaction Diagram for Section 38