ENCLOSURE 7

GEH Technical Report

DE-ES-0096 Revision 0

Liner Anchorage Evaluation

Dominion North Anna Unit 3 ESBWR IN-PROCESS STATUS FORM	
Document Title	Liner Anchorage Evaluation
Document Type	Engineering Sheet
Revision ID (if applicable)	0
Author / Responsible Engineer	A. Suzuki (Hitachi-GE Nuclear Energy, Ltd.)
Lead	
Date (Last Update/Revision)	
Document/Work Status e.g. Pending, Active, On-hold, Complete-In Verification, Verified-Waiting eCM	Issued for Use
Specific Cautions To Users e.g. **Enumerate/list specific incomplete content.** **Enumerate/list specific complete but unverified content.** **Enumerate/list key areas of technical uncertainty and parameters impacted.**	
Cross-reference Information e.g. **eDRF or other useful data pointers**	<u>1. Design Inputs</u> 1) Bechtel Topical Report BC-TOP-1, "Containment Building Liner Plate Design Report" 2) ASME B&PV Code Section III, Division 2, Subsection CC 3) ACI 349-01, "Code Requirements for Nuclear Safety Related Concrete Structures and Commentary" 4) A40-4010 (26A6558 R4), "General Civil Design Criteria" 5) GE Document # DE-ES-0017 R3, "Liner Anchorage Evaluation" 6) WG3-T11-DRD-S-0002 (DE-ES-0095 R0), "Structural Design Report for Containment Liner Plate" Verification has been performed in accordance with Hitachi-GE Nuclear Energy QA Program HQA-0005, Rev. 24, ASME B&PV Code, SecIII,Division 2, Subsection CC.

GE PO No.	: 437094586
GE Doc. No.	: -
GE MPL. No.	: -
HTC Doc. No.	: DE-ES-0096
Rev. No.	: -
Sheet No.	: 1 of 50
Issue Date	:
Rev. Date	:

For GE-Hitachi Nuclear Energy

Dominion North Anna Unit 3 ESBWR

Package: RCCV

Title: LINER ANCHORAGE EVALUATION

CLASSIFY	CATEGORY	DISTRIBUTION	COPY	DISTRIBUTION	COPY
1. PLAN	1. FOR APPROVAL				
2. SPECIFICATION	(2) FOR INFORMATION				
3. SPECIFICATION TABLE	3. FOR REVIEW				
4. DESCRIPTION	4. FOR FILE				
(5) CALCULATION REPORT					
6. LIST					
7. PROCEDURE					
8. TEST REPORT					
9. OTHERS					

HITACHI-GE Nuclear Energy,Ltd. - - Nuclear Equipment Design Department		NAME	DATE
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REVISION STATUS SHEET

REV	DESCRIPTION	PREPARED BY	REVIEWED BY	APPROVED BY	ISSUED DATE
0	Initial Issue	(see cover sheet)			

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1. INTRODUCTION

The liner plate anchorage system shall satisfy the force and displacement allowables specified in ASME B&PV Code Sec. III, Div.2, Table CC-3730-1. The evaluation method is consistent with Bechtel Topical Report BC-TOP-1 (Reference 7.1) and ACI 349-01 (Reference 7.3). The load-displacement relationship of liner anchor is based on the idealized bi-linear curve in Reference 7.5. The liner strains to be used for the evaluation of anchor displacement are the strains of liner elements calculated directly from the NASTRAN analysis. Details of the NASTRAN analysis are provided in Section 4.1 of Reference 7.6. Loads and load combinations used to calculate the liner strain are provided in Section 5.2.1 of Reference 7.6. Section 5.4.1 of Reference 7.6 summarizes the maximum and minimum strain demands for liner plates. The evaluated portion is shown in Figures 1-1 through 1-6.

The effect of the fabrication/erection tolerances on the liner anchor displacement is also evaluated in Appendix-1.

2. EVALUATION PORTION

Evaluation portion is as follows. The figure of liner anchor is shown in Reference 7.7. through 7.9.

Drywell top slab (Figure 1-1)

Drywell cylinder (Figure 1-2)

Pedestal cylinder (Figure 1-5)

Pedestal bottom (Figure 1-6)

Wetwell cylinder (Figure 1-3)

Wetwell bottom (Figure 1-4)

(Figures 1-1 through 1-6 are from Reference 7.8 and 7.9)

3. LINER PLATE AND LINER ANCHOR PROPERTIES

3.1 MODULUS OF ELASTICITY

ASME B&PV code Sec. II, Part D, Table TM-1 is applied for modulus of elasticity E of liner plate. E of each materials for each conditions are as follows.

(1) Liner plate material

Carbon steel (SA-516 Gr.70) is applied to DW portion (DW top slab, DW cylinder, Pedestal cylinder, Pedestal bottom). Stainless steel (SA-240 Type 304L) is applied to Wetwell portion (WW cylinder, WW bottom)

(2) Temperature

The temperatures at Category I (test, normal, severe environmental, extreme environmental) and Category II (abnormal, abnormal/severe environmental, abnormal/extreme environmental) for each portions are as follows.

-Category I

DW: To=57°C

WW: To=43°C

-Category II

DW: Ta=171°C

WW (Air phase): Ta=130°C

WW (SC pool): Ta=110°C

(3) Modulus of elasticity

-Carbon steel

E(57°C)=201000MPa

E(171°C)=194000MPa

-Stainless steel

E(43°C)= 193000MPa

E(110°C)=189000MPa

E(130°C)=187000MPa

3.2 SPRING RATIO

Spring ratio R is calculated from Equation (3-1).

$$R = \frac{E \cdot t}{(1-\nu^2) \cdot a} \qquad (3\text{-}1)$$

Here

R : Liner plate spring ratio (N/mm/mm)

E : Modulus of elasticity (MPa)

t : Liner plate thickness (mm)

a : Liner anchor span (mm)

ν : Poisson's ratio=0.3

3.3 LINER PLATE YIELD LOAD

Liner plate yield load F_R is calculated from Equation (3-2).

$$F_R = \sigma'_{xy} \cdot t \qquad (3\text{-}2)$$

Here

F_R : Liner plate yield load (N/mm)

σ'_{xy} : Yield strength in the direction of spring ratio R (MPa)

$$\sigma'_{xy} = \frac{\sigma_y}{\left\{\left(\frac{\varepsilon_y + \nu' \cdot \varepsilon_x}{\varepsilon_x + \nu' \cdot \varepsilon y}\right)^2 - \left(\frac{\varepsilon_y + \nu' \cdot \varepsilon_x}{\varepsilon_x + \nu' \cdot \varepsilon y}\right) + 1\right\}^{\frac{1}{2}}}$$

t : Liner plate thickness (mm)

σ_y : Maximum uniaxial yield strength (MPa)

=390MPa (SA-516 Gr.70)

=340MPa (SA-240 Type 304L)

The yield strength specified in ASME Code Sec. II is lower than these values, however, the lower yield strength provides the smaller value of liner anchor displacement. It is not conservative evaluation, so the maximum value of yield strength is assumed based on the Hitachi practice for ABWR plant in Japan.

ε_x : Strain in the direction of spring ratio R

ε_y : Strain in the direction of perpendicular to ε_x

ν' : Poisson's ratio in the plastic region =0.5

3.4 LINER PLATE FORCED STRAIN LOAD

Liner plate forced strain load F_H is calculated from Equation (3-3).

$$F_H = \frac{E \cdot t}{1-\nu^2} \cdot (\varepsilon_x + \nu \cdot \varepsilon_y) \qquad (3\text{-}3)$$

Here

F_H : Liner plate forced strain load (N/mm)

E : Modulus of elasticity (MPa)

t : Liner plate thickness (mm)

ε_x : Strain in the direction of spring ratio R

ε_y : Strain in the direction of perpendicular to ε_x

ν : Poisson's ratio=0.3

The calculated results of these values for each portions are summarized in Table 3-1.

3.5 LINER ANCHOR LOAD-DISPACEMENT RELATION

The relation of liner anchor load-displacement is from Reference 7.5. This relation is shown in Figure 3-1 for anchor size WT 4x7.5 as shown in Reference 7.7. In order to utilize the available data and to provide more space for placement of RCCV reinforcement, the current anchor size WT 6x8 is replaced by WT 4x7.5.

Furthermore, 50% tolerance is considered for anchor stiffness C as shown below.

Nominal value : C=1603.1 (N/mm/mm)

Lower value : C=800 (N/mm/mm)

Upper value : C=2400 (N/mm/mm)

The elastic displacement limits δ_e corresponding to the each anchor stiffness are calculated from Equation (3-4).

$$\delta_e = \frac{F_e}{C} \qquad (3\text{-}4)$$

Nominal condition : δ_e=0.508 (mm)

Lower condition : δ_e=1.02 (mm)

Upper condition : δ_e=0.339 (mm)

Here

δ_e : Liner anchor elastic displacement limit (mm)

F_e : Liner anchor yield load (N/mm)=814.12 (N/mm)

C : Anchor stiffness (N/mm/mm)

(Values for C and δ_e are from Reference 7.5)

Liner anchor displacement limit for break δ_u is 5.08mm.

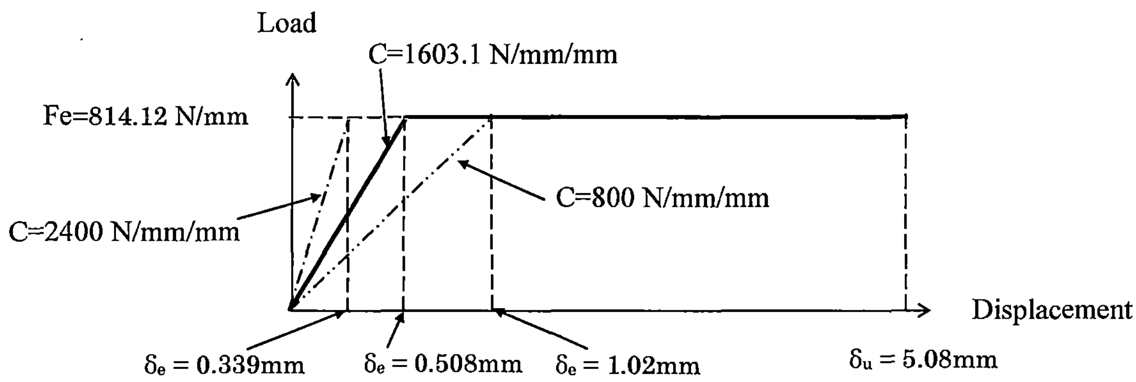


Figure 3-1 Liner anchor load-displacement relation

4. LINER ANCHOR DISPLACEMENT EVALUATION

Liner anchor displacement is evaluated for the highest liner plate forced strain load F_H for each load combination category except wetwell bottom. F_H of wetwell bottom plate is discussed in Section 5.

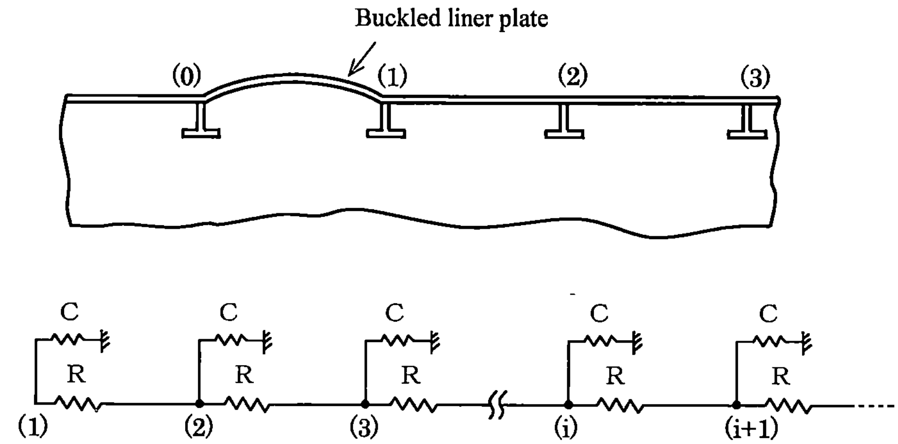
One liner plate section between adjacent liner anchors is assumed to be buckled, and no reaction force comes from this buckled liner plate. (It can be considered some reaction force comes from buckled liner plate, however, this assumption is conservative to evaluate the liner anchor displacement, because this reaction force tends to act to reduce it.)

4.1 CATEGORY I

This load combination category includes test, normal, severe environmental and extreme environmental. In this category, the highest F_H of 683N/mm acts on the wetwell cylinder.

It assumes that all liner anchors and liner plates are within the elastic deformation region.

Figure 4-1 shows the calculation model of anchor displacement evaluation. Here δi represents a displacement of liner anchor of point (i) in Figure 4-1.



Note (i) is the number of anchor from buckled liner plate

Figure 4-1 Calculation model of anchor displacement evaluation

Here

F_H=683 N/mm

R=2672 N/mm/mm

E=193000 MPa

ε_x=-0.000325

ε_y=-0.000595

σ_y=340 MPa

σ'_{xy}=302MPa

t=6.4 mm

F_R=1933 N/mm

F_H<F_R, so liner plate stays in elastic deformation region.

Based on the load balance around point (1) and point (i), following relation can be considered.

$$C \cdot \delta_1 = R \cdot (-\delta_1 + \delta_2) + F_H \tag{4-1}$$

$$R \cdot (-\delta_{i-1} + \delta_i) + F_H + C \cdot \delta_i = R \cdot (-\delta_i + \delta_{i+1}) + F_H \tag{4-2}$$

Here it is assumed that all liner anchors and liner plates are within the elastic deformation region, so the following relation can be considered.

$$\delta_{i+1} = q \cdot \delta_i \tag{4-3}$$

q shall be below 1.0, so that the displacement converges to some value. From Equations (4-1) through (4-3), δ_1 is calculated as follows.

$$q = \left(1 + \frac{C}{2 \cdot R}\right) - \sqrt{\left(1 + \frac{C}{2 \cdot R}\right)^2 - 1}$$
$$\delta_1 = \frac{F_H}{C + R \cdot (1 - q)} \tag{4-4}$$

(1) Nominal anchor stiffness : C=1603.1 N/mm/mm

$$q = \left(1 + \frac{1603.1}{2 \times 2672}\right) - \sqrt{\left(1 + \frac{1603.1}{2 \times 2672}\right)^2 - 1} = 0.46935$$
$$\delta_1 = \frac{683}{1603.1 + 2672 \times (1 - 0.46935)} = 0.226\text{mm}$$

$\delta_1 < \delta_e$=0.508mm, so the assumption is satisfied.

(2) Lower anchor stiffness : C=800 N/mm/mm

$$q = \left(1 + \frac{800}{2 \times 2672}\right) - \sqrt{\left(1 + \frac{800}{2 \times 2672}\right)^2 - 1} = 0.58242$$
$$\delta_1 = \frac{683}{800 + 2672 \times (1 - 0.58242)} = 0.357\text{mm}$$

$\delta_1 < \delta_e$=1.02mm, so the assumption is satisfied.

(3) Upper anchor stiffness : C=2400 N/mm/mm

$$q=\left(1+\frac{2400}{2\times 2672}\right)-\sqrt{\left(1+\frac{2400}{2\times 2672}\right)^2-1}=0.40034$$

$$\delta_1=\frac{683}{2400+2672\times(1-0.40034)}=0.171\text{mm}$$

$\delta_1 < \delta_e$=0.339mm, so the assumption is satisfied.

And δ_1 of all cases are within the allowable of $0.25 \cdot \delta_u$=1.27mm, so the requirement of ASME B&PV Code Sec. III, Div.2, Table CC-3730-1 is satisfied.

4.2 CATEGORY II

This load combination category includes abnormal, abnormal/severe environmental and abnormal/extreme environmental. In this category, the highest F_H of 2881 N/mm acts on the pedestal cylinder. This value is greater than F_R of 2496 N/mm, so liner plate shall yield somewhere.

Here

F_H=2881 N/mm

R=2686 N/mm/mm

F_R=2496 N/mm

(1) Nominal anchor stiffness : C=1603.1 N/mm/mm

Followings are assumed to evaluate liner anchor displacement.

i) Liner anchor No.1 and No.2 are in the plastic deformation region, while No.3 and after are in the elastic deformation region.

ii) Liner plates between liner anchor No.1 and No.5 are in the elastic deformation region. Other plates are in the plastic deformation region. In the plastic deformation region, F_H equals to F_R.

The following simultaneous equations can be considered.

$$F_C = R \cdot \left(-\delta_1 + \delta_2 + \frac{F_H}{R} \right) \quad (4\text{-}5)$$

$$2 \cdot F_C = R \cdot \left(-\delta_2 + \delta_3 + \frac{F_H}{R} \right) \quad (4\text{-}6)$$

$$2 \cdot F_C + C \cdot \delta_3 = R \cdot \left(-\delta_3 + \delta_4 + \frac{F_H}{R} \right) \quad (4\text{-}7)$$

$$R \cdot \left(-\delta_3 + \delta_4 + \frac{F_H}{R} \right) + C \cdot \delta_4 = R \cdot \left(-\delta_4 + \delta_5 + \frac{F_H}{R} \right) \quad (4\text{-}8)$$

$$R \cdot \left(-\delta_4 + \delta_5 + \frac{F_H}{R} \right) + C \cdot \delta_5 = F_R \quad (4\text{-}9)$$

From these simultaneous equations, each anchor displacements are obtained as follows.

δ_1=1.62 mm

δ_2=0.85 mm

δ_3=0.39 mm

δ_4=0.15 mm

δ_5=0.004 mm

Here δ_1 and δ_2 are greater than δe of 0.508 mm, while δ_3 and δ_4 are less than δe, so assumption i) is satisfied.

Liner forced strain load between liner anchor No.4 and No.5, N_R, is calculated as follows and is less than F_R of 2496 N/mm, so assumption ii) is also satisfied.

$$N_R = R \cdot \left(-\delta_4 + \delta_5 + \frac{F_H}{R} \right) = 2686 \times \left(-0.15 + 0.004 + \frac{2881}{2686} \right) = 2489 \text{ N/mm}$$

(2) Lower anchor stiffness : C=800 N/mm/mm

Followings are assumed to evaluate liner anchor displacement.

i) Liner anchor No.1 and No.2 are in the plastic deformation region, while No.3 and after are in the elastic deformation region.

ii) Liner plates between liner anchor No.1 and No.5 are in the elastic deformation region. Other plates are in the plastic deformation region. In the plastic deformation region, F_H equals to F_R.

The following simultaneous equations can be considered.

$$F_C = R \cdot \left(-\delta_1 + \delta_2 + \frac{F_H}{R} \right) \tag{4-10}$$

$$2 \cdot F_C = R \cdot \left(-\delta_2 + \delta_3 + \frac{F_H}{R} \right) \tag{4-11}$$

$$2 \cdot F_C + C \cdot \delta_3 = R \cdot \left(-\delta_3 + \delta_4 + \frac{F_H}{R} \right) \tag{4-12}$$

$$R \cdot \left(-\delta_3 + \delta_4 + \frac{F_H}{R} \right) + C \cdot \delta_4 = R \cdot \left(-\delta_4 + \delta_5 + \frac{F_H}{R} \right) \tag{4-13}$$

$$R \cdot \left(-\delta_4 + \delta_5 + \frac{F_H}{R} \right) + C \cdot \delta_5 = F_R \tag{4-14}$$

From these simultaneous equations, each anchor displacements are obtained as follows.

δ_1=1.85 mm

δ_2=1.08 mm

δ_3=0.61 mm

δ_4=0.33 mm

δ_5=0.14 mm

Here δ_1 and δ_2 are greater than δe of 1.02 mm, while δ_3 through δ_5 are less than δe, so assumption i) is satisfied.

Liner forced strain load between liner anchor No.4 and No.5, N_R, is calculated as follows and is less than F_R of 2496 N/mm, so assumption ii) is also satisfied.

$$N_R = R \cdot \left(-\delta_4 + \delta_5 + \frac{F_H}{R} \right) = 2686 \times \left(-0.33 + 0.14 + \frac{2881}{2686} \right) = 2371 \text{ N/mm}$$

(3) Upper anchor stiffness : C=2400 N/mm/mm

Followings are assumed to evaluate liner anchor displacement.

i) Liner anchor No.1 and No.2 are in the plastic deformation region, while No.3 and after are in the elastic deformation region.

ii) Liner plates between liner anchor No.1 and No.4 are in the elastic deformation region. Other plates are in the plastic deformation region. In the plastic deformation region, F_H equals to F_R.

The following simultaneous equations can be considered.

$$F_C = R \cdot \left(-\delta_1 + \delta_2 + \frac{F_H}{R} \right) \tag{4-15}$$

$$2 \cdot F_C = R \cdot \left(-\delta_2 + \delta_3 + \frac{F_H}{R} \right) \tag{4-16}$$

$$2 \cdot F_C + C \cdot \delta_3 = R \cdot \left(-\delta_3 + \delta_4 + \frac{F_H}{R} \right) \tag{4-17}$$

$$R \cdot \left(-\delta_3 + \delta_4 + \frac{F_H}{R} \right) + C \cdot \delta_4 = F_R \tag{4-18}$$

From these simultaneous equations, each anchor displacements are obtained as follows.

δ_1=1.52 mm

δ_2=0.75 mm

δ_3=0.29 mm

δ_4=0.08 mm

Here δ_1 and δ_2 are greater than δe of 0.339 mm, while δ_3 and δ_4 are less than δe, so assumption i) is satisfied.

Liner forced strain load between liner anchor No.3 and No.4, N_R, is calculated as follows and is less than F_R of 2496 N/mm, so assumption ii) is also satisfied.

$$N_R = R \cdot \left(-\delta_3 + \delta_4 + \frac{F_H}{R} \right) = 2686 \times \left(-0.29 + 0.08 + \frac{2881}{2686} \right) = 2317 \text{ N/mm}$$

And δ_1 of all cases are within the allowable of $0.5 \cdot \delta_u$=2.54 mm, so the requirement of ASME B&PV Code Sec. III, Div.2, Table CC-3730-1 is satisfied.

5. WETWELL BOTTOM LINER ANCHOR DISPACEMENT EVALUATION

Compared to the liner plates discussed in Section 4, the wetwell bottom liner plate is subjected to larger strain demand. This section evaluates the wetwell bottom liner anchor displacement using the liner plate property (thickness and anchor span) provided in Table 5-1.

Due to the need for consideration of negative pressures imposed by the suppression pool hydrodynamic loads, the liner plates on the wetwell bottom slab need to be anchored. The liner anchor pullout evaluation is provided in Section 6.

5.1 CATEGORY I

The highest F_H of 939 N/mm acts on the wetwell bottom.

It assumes that all liner anchors and liner plates are within the elastic deformation region.

Here

F_H=939 N/mm

R=5027 N/mm/mm

E=193000 MPa

ε_x=-0.000591

ε_y=-0.000336

σ_y=340 MPa

σ'_{xy}=367 MPa

t=6.4 mm

F_R=2349 N/mm

F_H<F_R, so liner plate stays in elastic deformation region.

Based on the load balance around point (1) and point (i), following relation can be considered.

$$C \cdot \delta_1 = R \cdot (-\delta_1 + \delta_2) + F_H \quad (5\text{-}1)$$

$$R \cdot (-\delta_{i-1} + \delta_i) + F_H + C \cdot \delta_i = R \cdot (-\delta_i + \delta_{i+1}) + F_H \quad (5\text{-}2)$$

Here it is assumed that all liner anchors and liner plates are within the elastic deformation region, so the following relation can be considered.

$$\delta_{i+1} = q \cdot \delta_i \quad (5\text{-}3)$$

q shall be below 1.0, so that the displacement converges to some value. From Equations (5-1) through (5-3), δ_1 is calculated as follows.

$$q = \left(1 + \frac{C}{2 \cdot R}\right) - \sqrt{\left(1 + \frac{C}{2 \cdot R}\right)^2 - 1}$$
$$\delta_1 = \frac{F_H}{C + R \cdot (1 - q)} \qquad (5\text{-}4)$$

(1) Nominal anchor stiffness : C=1603.1 N/mm/mm

$$q = \left(1 + \frac{1603.1}{2 \times 5027}\right) - \sqrt{\left(1 + \frac{1603.1}{2 \times 5027}\right)^2 - 1} = 0.57266$$
$$\delta_1 = \frac{939}{1603.1 + 5027 \times (1 - 0.57266)} = 0.250\text{mm}$$

$\delta_1 < \delta_e = 0.508$mm, so the assumption is satisfied.

(2) Lower anchor stiffness : C=800 N/mm/mm

$$q = \left(1 + \frac{800}{2 \times 5027}\right) - \sqrt{\left(1 + \frac{800}{2 \times 5027}\right)^2 - 1} = 0.67279$$
$$\delta_1 = \frac{939}{800 + 5027 \times (1 - 0.67279)} = 0.384\text{mm}$$

$\delta_1 < \delta_e = 1.02$mm, so the assumption is satisfied.

(3) Upper anchor stiffness : C=2400 N/mm/mm

$$q = \left(1 + \frac{2400}{2 \times 5027}\right) - \sqrt{\left(1 + \frac{2400}{2 \times 5027}\right)^2 - 1} = 0.50768$$
$$\delta_1 = \frac{939}{2400 + 5027 \times (1 - 0.50768)} = 0.193\text{mm}$$

$\delta_1 < \delta_e = 0.339$mm, so the assumption is satisfied.

And δ_1 of all cases are within the allowable of $0.25 \cdot \delta_u = 1.27$mm, so the requirement of ASME B&PV Code Sec. III, Div.2, Table CC-3730-1 is satisfied.

5.2 CATEGORY II

The highest F_H of 3189 N/mm acts on the wetwell bottom. This value is greater than F_R of 2394 N/mm, so liner plate shall yield somewhere.

Here

F_H=3189 N/mm

R=4923 N/mm/mm

F_R=2394 N/mm

(1) Nominal anchor stiffness : C=1603.1 N/mm/mm

Followings are assumed to evaluate liner anchor displacement.

i) Liner anchor No.1 and No.2 are in the plastic deformation region, while No.3 and after are in the elastic deformation region.

ii) Liner plates between liner anchor No.1 and No.4 are in the elastic deformation region. Other plates are in the plastic deformation region. In the plastic deformation region, F_H equals to F_R.

The following simultaneous equations can be considered.

$$F_C = R \cdot \left(-\delta_1 + \delta_2 + \frac{F_H}{R} \right) \quad (5\text{-}5)$$

$$2 \cdot F_C = R \cdot \left(-\delta_2 + \delta_3 + \frac{F_H}{R} \right) \quad (5\text{-}6)$$

$$2 \cdot F_C + C \cdot \delta_3 = R \cdot \left(-\delta_3 + \delta_4 + \frac{F_H}{R} \right) \quad (5\text{-}7)$$

$$R \cdot \left(-\delta_3 + \delta_4 + \frac{F_H}{R} \right) + C \cdot \delta_4 = F_R \quad (5\text{-}8)$$

From these simultaneous equations, each anchor displacements are obtained as follows.

δ_1=1.14mm

δ_2=0.66mm

δ_3=0.34mm

δ_4=0.14mm

Here δ_1 and δ_2 are greater than δe of 0.508 mm, while δ_3 and δ_4 are less than δe, so assumption i) is satisfied.

Liner forced strain load between liner anchor No.3 and No.4, N_R, is calculated as follows and is less than F_R of 2394N/mm, so assumption ii) is also satisfied.

$$N_R = R \cdot \left(-\delta_3 + \delta_4 + \frac{F_H}{R} \right) = 4923 \cdot \left(-0.34 + 0.14 + \frac{3189}{4923} \right) = 2204 \text{ N/mm}$$

(2) Lower anchor stiffness : C=800 N/mm/mm

Followings are assumed to evaluate liner anchor displacement.

i) Liner anchor No.1 is in the plastic deformation region, while No.2 and after are in the elastic deformation region.

ii) Liner plates between liner anchor No.1 and No.5 are in the elastic deformation region. Other plates are in the plastic deformation region. In the plastic deformation region, F_H equals to F_R.

The following simultaneous equations can be considered.

$$F_C = R \cdot \left(-\delta_1 + \delta_2 + \frac{F_H}{R} \right) \tag{5-9}$$

$$F_C + C \cdot \delta_2 = R \cdot \left(-\delta_2 + \delta_3 + \frac{F_H}{R} \right) \tag{5-10}$$

$$R \cdot \left(-\delta_2 + \delta_3 + \frac{F_H}{R} \right) + C \cdot \delta_3 = R \cdot \left(-\delta_3 + \delta_4 + \frac{F_H}{R} \right) \tag{5-11}$$

$$R \cdot \left(-\delta_3 + \delta_4 + \frac{F_H}{R} \right) + C \cdot \delta_4 = R \cdot \left(-\delta_4 + \delta_5 + \frac{F_H}{R} \right) \tag{5-12}$$

$$R \cdot \left(-\delta_4 + \delta_5 + \frac{F_H}{R} \right) + C \cdot \delta_5 = F_R \tag{5-13}$$

From these simultaneous equations, each anchor displacements are obtained as follows.

δ_1=1.39 mm

δ_2=0.91 mm

δ_3=0.58 mm

δ_4=0.34 mm

δ_5=0.15 mm

Here δ_1 is greater than δe of 1.02 mm, while δ_2 through δ_5 are less than δe, so assumption i) is satisfied.

Liner forced strain load between liner anchor No.4 and No.5, N_R, is calculated as follows and is less than F_R of 2394 N/mm, so assumption ii) is also satisfied.

$$N_R = R \cdot \left(-\delta_4 + \delta_5 + \frac{F_H}{R} \right) = 4923 \cdot \left(-0.34 + 0.15 + \frac{3189}{4923} \right) = 2254 \text{ N/mm}$$

(3) Upper anchor stiffness : C=2400 N/mm/mm

Followings are assumed to evaluate liner anchor displacement.

i) Liner anchor No.1 and No.2 are in the plastic deformation region, while No.3 and after are in the elastic deformation region.

ii) Liner plates between liner anchor No.1 and No.4 are in the elastic deformation region. Other plates are in the plastic deformation region. In the plastic deformation region, F_H equals to F_R.

The following simultaneous equations can be considered.

$$F_C = R \cdot \left(-\delta_1 + \delta_2 + \frac{F_H}{R} \right) \tag{5-14}$$

$$2 \cdot F_C = R \cdot \left(-\delta_2 + \delta_3 + \frac{F_H}{R} \right) \tag{5-15}$$

$$2 \cdot F_C + C \cdot \delta_3 = R \cdot \left(-\delta_3 + \delta_4 + \frac{F_H}{R} \right) \tag{5-16}$$

$$R \cdot \left(-\delta_3 + \delta_4 + \frac{F_H}{R} \right) + C \cdot \delta_4 = F_R \tag{5-17}$$

From these simultaneous equations, each anchor displacements are obtained as follows.

δ_1=1.06mm

δ_2=0.57mm

δ_3=0.26mm

δ_4=0.06mm

Here δ_1 and δ_2 are greater than δe of 0.339 mm, while δ_3 and δ_4 are less than δe, so assumption i) is satisfied.

Liner forced strain load between liner anchor No.3 and No.4, N_R, is calculated as follows and is less than F_R of 2394 N/mm, so assumption ii) is also satisfied.

$$N_R = R \cdot \left(-\delta_3 + \delta_4 + \frac{F_H}{R} \right) = 4923 \cdot \left(-0.26 + 0.06 + \frac{3189}{4923} \right) = 2204\text{N/mm}$$

And δ_1 of all cases are within the allowable of $0.5 \cdot \delta_u$=2.54 mm, so the requirement of ASME B&PV Code Sec. III, Div.2, Table CC-3730-1 is satisfied.

The allowables can be satisfied with the condition of thin liner plate and narrow liner anchor span.

5.3 EVALUATION RESULTS

The evaluation results are summarized in the Tables 5-2. The requirements for liner anchor displacement are satisfied.

6. LINER ANCHOR PULLOUT EVALUATION

A negative pressure acts on the wetwell portion when hydrodynamic load, such as SRV, CO, CH and combination of them occurs in the suppression pool. Such negative pressure tends to pullout the liner anchors from concrete of RCCV wall. The evaluation for the pullout load is shown below.

6.1 NEGATIVE PRESSURE

The design of wetwell liner anchor shall consider negative pressure loads of CO, CH, SRV and their combinations shown below: (Peak negative pressure (CO, CH, and SRV), DLF, and Wetwell inner pressure are from Reference 7.4.)

Table 6-1 Negative Pressure Load and Load Combination

Load	Peak Negative Pressure (kPag)	DLF *2	Wetwell Inner Pressure (kPag)	Hydrostatic		Total Pressure (kPag)
				Depth (m)	Pressure (kPag)	
Calculation formula	A	B	C	D	E=Dx9.80665	F=AxB+C+E
CO	-186	2	241.3	2.00	19.61	-111
CH	-66	2	241.3	2.00	19.61	129
SRV	-63	2	0	1.38	13.53	-112
CO+SRV *1	-196.4	2	241.3	2.00	19.61	-132
CO+SRV *1	-196.4	2	241.3	5.50	53.94	-98

*1: Peak negative pressure is calculated by SRSS (square root of sum of square) method.

*2: Dynamic Load Factor

In the above table, SRV is category I, and others are category II.

From the results, maximum absolute value of negative pressure, 112kPag for category I and 132kPag for category II, shall be applied for the evaluation of wetwell cylinder portion.

6.2 CONCRETE AND STEEL PROPERTY

The properties of concrete and steel applied to RCCV and liner anchor are as follows.

f_c' : Specified compressive strength of concrete =5000 psi=34.47 MPa

S_y : Yield strength value of SA-36 @ 110°C =224MPa

S_u : Tensile strength value of SA-36 @ 110°C =399MPa

Category I :

F_a equals lesser of $0.67 \cdot F_y$ and $0.33 \cdot F_u$.

$$0.67 \cdot F_y = 0.67 \times 224 \text{ MPa} = 150 \text{ MPa}$$
$$0.33 \cdot F_u = 0.33 \times 399 \text{ MPa} = 131 \text{ MPa}$$
$$F_a = 0.33 \cdot F_u = 131 \text{ MPa}$$

Category II : F_a equals lesser of $0.9 \cdot F_y$ and $0.5 \cdot F_u$.

$$0.9 \cdot F_y = 0.9 \times 224 \text{ MPa} = 201 \text{ MPa}$$
$$0.5 \cdot F_u = 0.5 \times 399 \text{ MPa} = 199 \text{ MPa}$$
$$F_a = 0.5 \cdot F_u = 199 \text{ MPa}$$

6.3 CONCRETE EVALUATION

(1) Cone failure

Tension pullout strength of concrete due to negative hydrodynamic pressure is evaluated per Example A1 of ACI Committee Report ACI 349.2R-97.

Pressure load : q=132 kPa=0.132 MPa

Anchor spacing : a=508 mm

Anchor configuration and dimensions : Figure 6-1

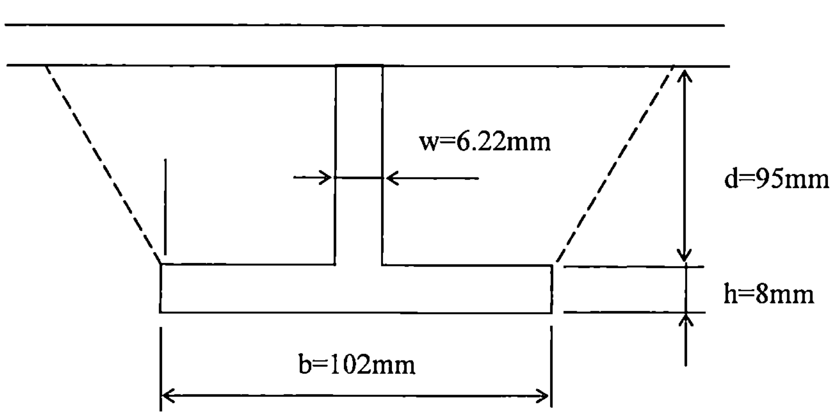


Figure 6-1 Liner Anchor

$fc' = 34.47$ MPa=34.47 N/mm^2

Effective area : $A_{cp} = 2 \times d \cdot tan 35^\circ = 2 \times 95 \times tan 35^\circ = 133 mm^2$

(35° is informed from GE, and used instead of 45°)

Design pullout strength : $P_{dp} = \phi \cdot 0.33 \cdot \sqrt{fc'} \cdot A_{cp}$

Here

ϕ: Strength reduction factor=0.65 ACI 349-01 Appendix B4.4(b)

$P_{dp} = 0.65 \times 0.33 \times \sqrt{34.47} \times 133 = 167 N/mm$

Pullout load P_o due to hydrodynamic negative pressure is as follows.

$P_o = a \cdot q$

Here

a : Liner anchor spacing

q : Hydrodynamic negative pressure

i) Category I

q=112kPa=0.112N/mm^2

P_{oI}=508x0.112=56.9N/mm < P_{dp}=167N/mm

ii) Category II

q=132kPa=0.132N/mm^2

P_{oI}=508x0.132=67.1N/mm < P_{dp}=167N/mm

(2) Bearing on anchor flange

Bearing strength on anchor flange is evaluated in accordance with ACI 349-01 Section 10.17

Design bearing strength : $P_{db} = \phi \cdot 0.85 \cdot fc' \cdot A_1$

Here,

ϕ : Strength reduction factor=0.70 ACI 349-01 Appendix B 4.5.2

A_1 : Loaded area

A_1=b-w=102-6.22=95.78mm^2/mm

P_{db} : 0.70x0.85x34.47x95.78=1964N/mm

i) Category I

P_O : 56.9N/mm< P_{db}=1964N/mm

ii) Category II

P_O =67.1N/mm< P_{db}=1964N/mm

6.4 STEEL ANCHOR EVALUATION

Flange bending and web tension are evaluated due to negative hydrodynamic pressure in accordance with ASME B & PV Code Sec. III.

(1) Flange bending evaluation

It is assumed that the pullout load P_o distributes on flange uniformly. Bending stress σ_b is calculated as follows.

$$\sigma_b = \frac{M}{Z}$$

Here

M : Bending moment

$$M = \frac{1}{8} \cdot (b - w) \cdot P_o$$

Category I: $M = \frac{1}{8} \times (102 - 6.22) \times 56.9 = 681 \quad N \cdot mm / mm$

Category II: $M = \frac{1}{8} \times (102 - 6.22) \times 67.1 = 803 \quad N \cdot mm / mm$

Z : Section modulus of flange = $\frac{h^2}{6} = \frac{8^2}{6} = 10.7 mm^3 / mm$

i) Category I

$\sigma_b = \frac{681}{10.7} = 64$MPa <Fa=0.33 · Fu=131MPa

ii) Category II

$$\sigma_b = \frac{803}{10.7} = 75MPa < \text{Fa=0.5} \cdot \text{Fu=199MPa}$$

(2) Web tension evaluation

Web tensile stress σ_t is calculated as follows.

$$\sigma_t = \frac{P_O}{w}$$

i) Category I

$$\sigma_t = \frac{56.9}{6.22} = 10MPa < \text{Fa=0.33} \cdot \text{Fu=131MPa}$$

ii) Category II

$$\sigma_t = \frac{67.1}{6.22} = 11MPa < \text{Fa=0.5} \cdot \text{Fu=199MPa}$$

6.5 EVALUATION RESULTS

The evaluation results are summarized in the Tables 6-2 and 6-3. The requirements for concrete and steel anchor are satisfied.

7. REFERENCE

7.1 Bechtel Topical Report BC-TOP-1, "Containment Building Liner Plate Design Report"

7.2 ASME B&PV Code Section III, Division 2, Subsection CC

7.3 ACI 349-01, "Code Requirements for Nuclear Safety Related Concrete Structures and Commentary"

7.4 GE MPL # A40-4010 (26A6558 R4), "General Civil Design Criteria"

7.5 GE Document # DE-ES-0017 R3, "Liner Anchorage Evaluation"

7.6 GE Document # WG3-T11-DRD-S-0002 (DE-ES-0095 R0), "Structural Design Report for Containment Liner Plate"

7.7 Hitachi Drawing # 310RB76-127 R2, "RCCV Liner Anchor"

7.8 Hitachi Drawing # 310RB76-128 R1, "RCCV Liner Plate Plans"

7.9 Hitachi Drawing # 310RB76-129 R0, "RCCV Liner Plate Development Elevation"

Table 3-1 Liner Plate Properties

Property			Top slab		DW cylinder	
			Carbon steel		Carbon steel	
			Category I	Category II	Category I	Category II
			57˚C	171˚C	57˚C	171˚C
Thickness	t	mm	6.4		6.4	
Anchor span	a	mm	270		508	
Poisson's ratio	ν	-	0.3		0.3	
Poisson's ratio in the plastic region	ν'	-	0.5		0.5	
Modulus of elasticity	E	MPa (N/mm^2)	201000	194000	201000	194000
Liner plate spring ratio	R	N/mm/mm	5236	5053	2783	2686
Maximum uniaxial yield strength	σy	MPa (N/mm^2)	390		390	
Strain in the direction of spring ratio R	ε_x*	-	-0.000319	-0.001628	-0.000135	-0.001546
Strain in the direction of perpendicular to ε_x	ε_y*	-	-0.000217	-0.001519	-0.000542	-0.001701
Yield strength in the direction of spring ratio R	σ'xy	MPa (N/mm^2)	412	394	295	384
Liner plate yield load	F_R	N/mm	2637	2522	1888	2458
Liner plate forced strain load	F_H	N/mm	543	2843	421	2806

* ε_x and ε_y are the maximum (minimum) strain demands of liner plate determined from WG3-T11-DRD-S-0002. With ε_x and ε_y, σ'_{xy}, F_R, and F_H are calculated using equations in Sections 3.3 and 3.4.

Table 3-1 Liner Plate Properties (Continued)

Property			Pedestal cylinder	
			Carbon steel	
			Category I	Category II
			57°C	171°C
Thickness	t	mm	6.4	
Anchor span	a	mm	508	
Poisson's ratio	ν	-	0.3	
Poisson's ratio in the plastic region	ν'	-	0.5	
Modulus of elasticity	E	MPa (N/mm^2)	201000	194000
Liner plate spring ratio	R	N/mm/mm	2783	2686
Maximum uniaxial yield strength	σy	MPa (N/mm^2)	390	
Strain in the direction of spring ratio R	ε_x*	-	-0.000322	-0.001622
Strain in the direction of perpendicular to ε_x	ε_y*	-	-0.000339	-0.001633
Yield strength in the direction of spring ratio R	σ'xy	MPa (N/mm^2)	387	390
Liner plate yield load	F_R	N/mm	2477	2496
Liner plate forced strain load	F_H	N/mm	599	2881

* ε_x and ε_y are the maximum (minimum) strain demands of liner plate determined from WG3-T11-DRD-S-0002. With ε_x and ε_y, σ'_{xy}, F_R, and F_H are calculated using equations in Sections 3.3 and 3.4.

Table 3-1 Liner Plate Properties (Continued)

Property			Pedestal bottom		WW cylinder (Air)	
			Carbon steel		Stainless steel	
			Category I	Category II	Category I	Category II
			57°C	171°C	43°C	130°C
Thickness	t	mm	6.4		6.4	
Anchor span	a	mm	508		508	
Poisson's ratio	ν	-	0.3		0.3	
Poisson's ratio in the plastic region	ν'	-	0.5		0.5	
Modulus of elasticity	E	MPa (N/mm^2)	201000	194000	193000	187000
Liner plate spring ratio	R	N/mm/mm	2783	2686	2672	2589
Maximum uniaxial yield strength	σy	MPa (N/mm^2)	390		340	
Strain in the direction of spring ratio R	ε_x*	-	-0.000221	-0.000323	-0.000325	-0.001600
Strain in the direction of perpendicular to ε_x	ε_y*	-	-0.000206	-0.000340	-0.000595	-0.001615
Yield strength in the direction of spring ratio R	σ'xy	MPa (N/mm^2)	394	387	302	339
Liner plate yield load	F_R	N/mm	2522	2477	1933	2170
Liner plate forced strain load	F_H	N/mm	400	580	683	2741

* ε_x and ε_y are the maximum (minimum) strain demands of liner plate determined from WG3-T11-DRD-S-0002. With ε_x and ε_y, σ'_{xy}, F_R, and F_H are calculated using equations in Sections 3.3 and 3.4.

Table 3-1 Liner Plate Properties (Continued)

Property			WW cylinder (SP)	
			Stainless steel	
			Category I	Category II
			43°C	110°C
Thickness	t	mm	6.4	
Anchor span	a	mm	508	
Poisson's ratio	ν	-	0.3	
Poisson's ratio in the plastic region	ν'	-	0.5	
Modulus of elasticity	E	MPa (N/mm^2)	193000	189000
Liner plate spring ratio	R	N/mm/mm	2672	2617
Maximum uniaxial yield strength	σy	MPa (N/mm^2)	340	
Strain in the direction of spring ratio R	ε_x*	-	-0.000325	-0.001600
Strain in the direction of perpendicular to ε_x	ε_y*	-	-0.000595	-0.001615
Yield strength in the direction of spring ratio R	σ'xy	MPa (N/mm^2)	302	339
Liner plate yield load	F_R	N/mm	1933	2170
Liner plate forced strain load	F_H	N/mm	683	2771

* ε_x and ε_y are the maximum (minimum) strain demands of liner plate determined from WG3-T11-DRD-S-0002. With ε_x and ε_y, σ'_{xy}, F_R, and F_H are calculated using equations in Sections 3.3 and 3.4.

Table 5-1 Wetwell Bottom Liner Plate

Property			WW bottom	
			Stainless steel	
			Category I	Category II
			43°C	110°C
Thickness	t	mm	6.4	
Anchor span	a	mm	270	
Poisson's ratio	ν	-	0.3	
Poisson's ratio in the plastic region	ν'	-	0.5	
Modulus of elasticity	E	MPa (N/mm^2)	193000	189000
Liner plate spring ratio	R	N/mm/mm	5027	4923
Maximum uniaxial yield strength	σy	MPa (N/mm^2)	340	
Strain in the direction of spring ratio R	ε_x*	-	-0.000591	-0.002110
Strain in the direction of perpendicular to ε_x	ε_y*	-	-0.000336	-0.000963
Yield strength in the direction of spring ratio R	σ'xy	MPa (N/mm^2)	367	374
Liner plate yield load	F_R	N/mm	2349	2394
Liner plate forced strain load	F_H	N/mm	939	3189

* ε_x and ε_y are the maximum (minimum) strain demands of liner plate determined from WG3-T11-DRD-S-0002. With ε_x and ε_y, σ'_{xy}, F_R, and F_H are calculated using equations in Sections 3.3 and 3.4.

Table 5-2 Summary of Liner Anchor Displacement Evaluation

Location	Anchor Stiffness	Category I		Category II	
		Displacement (mm)	Allowable (mm)	Displacement (mm)	Allowable (mm)
Wetwell Cylinder	Nominal	0.226	1.27	-	2.54
	Lower	0.357		-	
	Upper	0.171		-	
Pedestal Cylinder	Nominal	-		1.62	
	Lower	-		1.85	
	Upper	-		1.52	
Wetwell Bottom	Nominal	0.250		1.14	
	Lower	0.384		1.39	
	Upper	0.193		1.06	

Table 6-2 Summary of Liner Anchor Pullout Evaluation (Concrete)

Failure Mode	Category I		Category II	
	Load (N/mm)	Allowable (N/mm)	Load (N/mm)	Allowable (N/mm)
Cone Failure	56.9	167	67.1	167
Bearing on Flange	56.9	1964	67.1	1964

Table 6-3 Summary of Liner Anchor Pullout Evaluation (Steel)

Location	Stress Type	Category I		Category II	
		Stress (MPa)	Allowable (MPa)	Load (MPa)	Allowable (MPa)
Flange	Bending	64	131	75	199
Web	Tension	10		11	

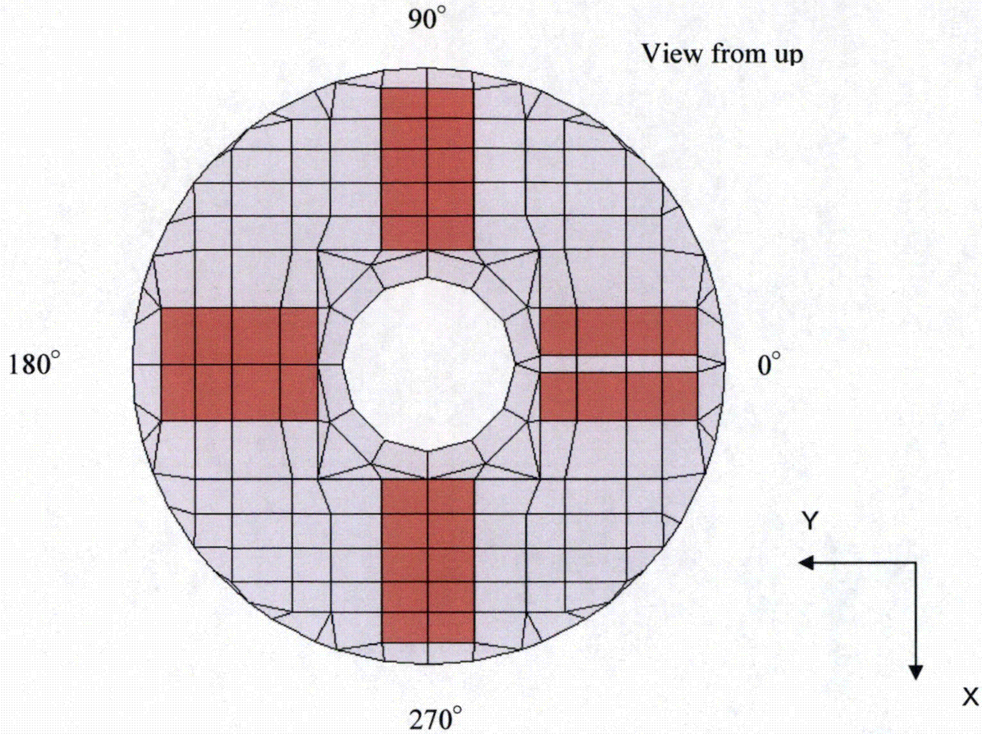


Figure 1-1 Evaluated Portion of Top Slab

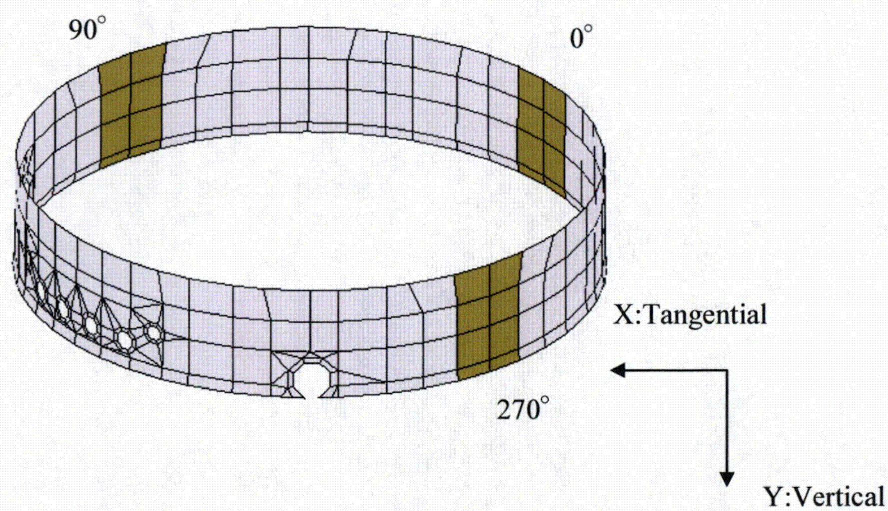


Figure 1-2 Evaluated Portion of Upper Drywell Cylinder

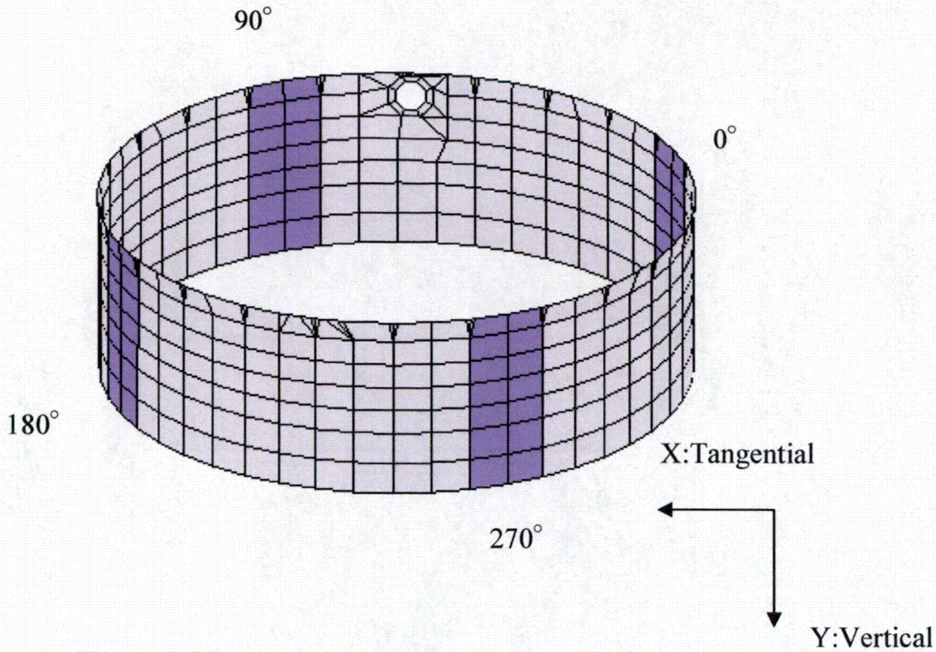


Figure 1-3 Evaluated Portion of Wetwell Cylinder

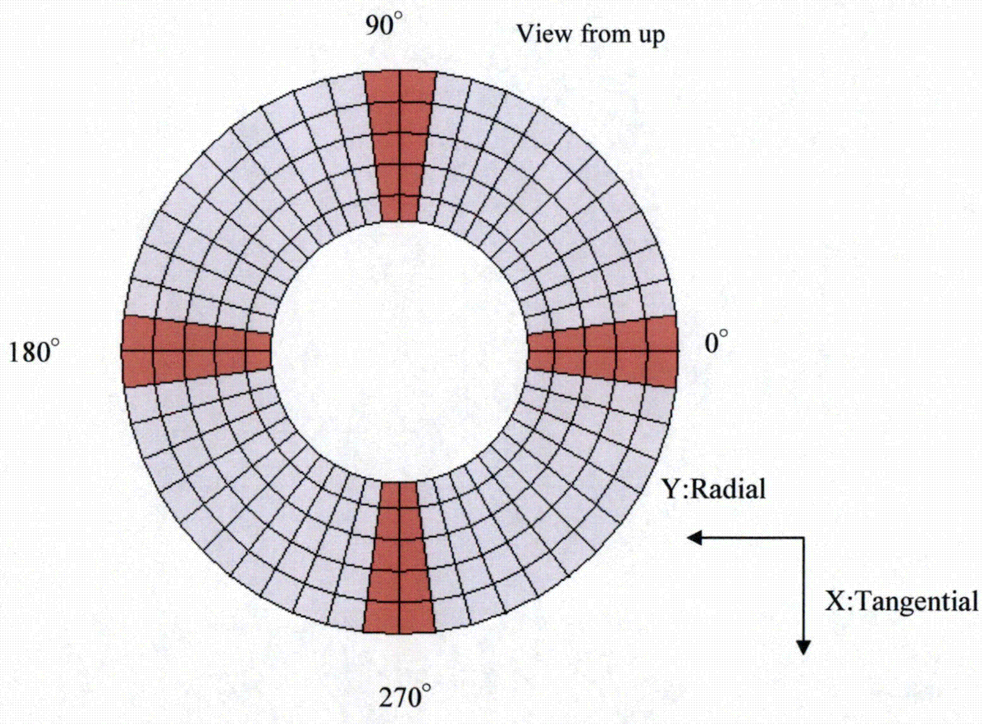


Figure 1-4 Evaluated Portion of Wetwell Bottom

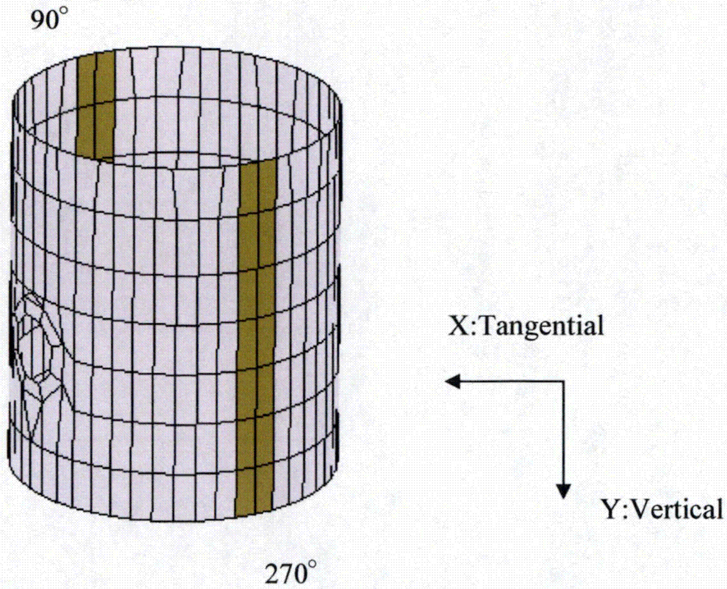


Figure 1-5 Evaluated Portion of Pedestal Cylinder

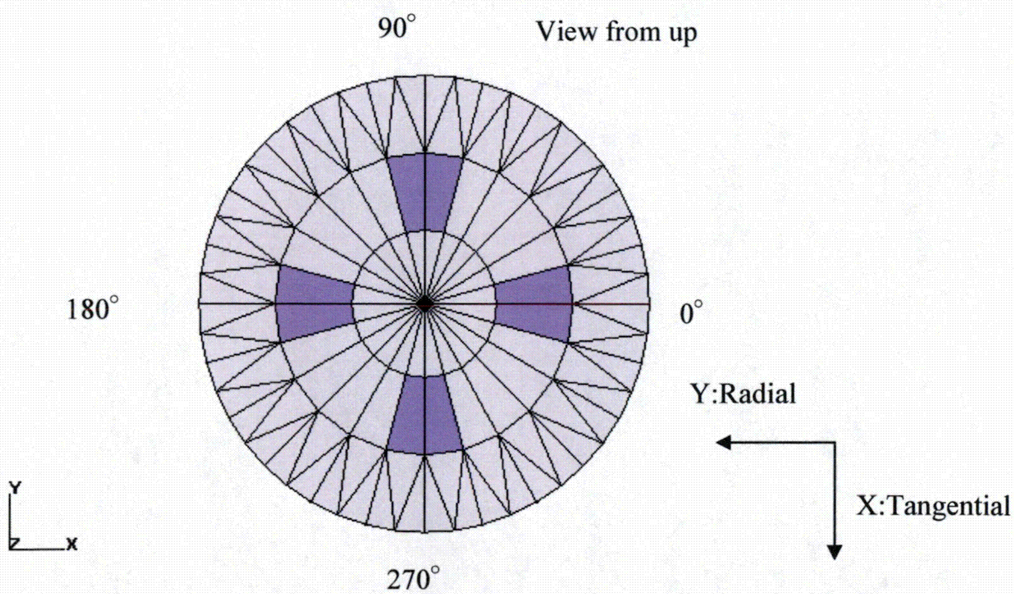


Figure 1-6 Evaluated Portion of Pedestal Bottom

APPENDIX-1: EFFECT OF THE FABRICATION/ERECTION TOLERANCES ON THE LINER ANCHOR DISPLACEMENT

A1. INTRODUCTION

It is considered that the fabrication/erection tolerances will affect the liner anchor evaluation. These effects are evaluated in this Appendix.

A2. FABRICATION/ERECTION TOLERANCES

The evaluated fabrication/erection tolerances are liner plate thickness and liner anchor spacing. The tolerances of them are specified as follows:

(1) Liner plate thickness

The nominal liner thickness is 6.4mm. In accordance with ASME SA20, largest permissible tolerance over the specified is 1.016 mm (0.04 inch) for the carbon steel liner. In accordance with ASME SA480, the largest permissible tolerance over the specified thickness is 1.27 mm (0.05 inch) for the stainless steel liner. SA 20 tolerance under specified thickness of 0.254 mm (0.01 inch) has been used for both carbon and stainless steel.

Therefore following thicknesses are considered in this evaluation.

i) Carbon steel liner plate

Nominal thickness: 6.4 mm

Maximum thickness: 7.416 mm

Minimum thickness: 6.146 mm

ii) Stainless steel liner plate

Nominal thickness: 6.4 mm

Maximum thickness: 7.67 mm

Minimum thickness: 6.146 mm

(2) Liner anchor spacing

The nominal sizes of liner anchor spacing are 508 mm and 270 mm. The effect of 10mm tolerance is considered. Therefore the following spacing variations are considered.

i) Nominal 508 mm, maximum 518 mm, minimum 498 mm

ii) Nominal 270 mm, maximum 280 mm, minimum 260 mm

A3. EFFECT OF TOLERANCE ON LINER ANCHOR EVALUATION

A3.1 LINER ANCHOR DISPLACEMENT

(1) Evaluation of lower bound variation

It is considered that the thinner liner thickness and narrower liner anchor spacing reduce the liner anchor displacement because of the following reasons.

-Thinner liner makes anchor reaction load lower.

-Wider liner anchor spacing makes liner spring ratio lower, and lower liner spring ratio needs larger anchor displacement to release the liner strain.

To demonstrate above expectation, the following evaluations are performed considering the lower bound variations for liner thickness and liner anchor spacing separately. Category II of pedestal cylinder with the lower anchor stiffness is selected as the evaluation case.

The liner plate properties are summarized in Table A3-1.

a. Minimum thickness t=6.146mm

Here

F_H=2767 N/mm

R=2579 N/mm/mm

F_R=2397 N/mm

Followings are assumed to evaluate liner anchor displacement.

i) Liner anchor No.1 is in the plastic deformation region, while No.2 and after are in the elastic deformation region.

ii) Liner plates between liner anchor No.1 and No.5 are in the elastic deformation region. Other plates are in the plastic deformation region. In the plastic deformation region, F_H equals to F_R.

The following simultaneous equations can be considered.

$$F_C = R \cdot \left(-\delta_1 + \delta_2 + \frac{F_H}{R} \right) \quad \text{(A3-1)}$$

$$F_C + C \cdot \delta_2 = R \cdot \left(-\delta_2 + \delta_3 + \frac{F_H}{R} \right) \quad \text{(A3-2)}$$

$$R \cdot \left(-\delta_2 + \delta_3 + \frac{F_H}{R} \right) + C \cdot \delta_3 = R \cdot \left(-\delta_3 + \delta_4 + \frac{F_H}{R} \right) \quad \text{(A3-3)}$$

$$R \cdot \left(-\delta_3 + \delta_4 + \frac{F_H}{R} \right) + C \cdot \delta_4 = R \cdot \left(-\delta_4 + \delta_5 + \frac{F_H}{R} \right) \quad \text{(A3-4)}$$

$$R \cdot \left(-\delta_4 + \delta_5 + \frac{F_H}{R} \right) + C \cdot \delta_5 = F_R \quad \text{(A3-5)}$$

From these simultaneous equations, each anchor displacements are obtained as follows.

δ_1=1.77 mm

δ_2=1.01 mm

δ_3=0.56 mm

δ_4=0.29 mm

δ_5=0.11 mm

Here δ_1 is greater than δe of 1.02 mm, while δ_2 through δ_5 are less than δe, so assumption i) is satisfied.

Liner forced strain load between liner anchor No.4 and No.5, N_R, is calculated as follows and is less than F_R of 2397 N/mm, so assumption ii) is also satisfied.

$$N_R = R \cdot \left(-\delta_4 + \delta_5 + \frac{F_H}{R} \right) = 2579 \times \left(-0.29 + 0.11 + \frac{2767}{2579} \right) = 2303 \text{ N/mm}$$

The maximum displacement of 1.77mm is less than 1.85mm of nominal thickness case, therefore it is confirmed that upper bound consideration in the liner thickness is conservative evaluation.

b. Minimum liner anchor spacing a=498mm

Here

F_H=2881 N/mm

R=2740 N/mm/mm

F_R=2496 N/mm

Followings are assumed to evaluate liner anchor displacement.

i) Liner anchor No.1 and No.2 are in the plastic deformation region, while No.3 and after are in the elastic deformation region.

ii) Liner plates between liner anchor No.1 and No.6 are in the elastic deformation region. Other plates are in the plastic deformation region. In the plastic deformation region, F_H equals to F_R.

The following simultaneous equations can be considered.

$$F_C = R \cdot \left(-\delta_1 + \delta_2 + \frac{F_H}{R} \right) \qquad \text{(A3-6)}$$

$$2 \cdot F_C = R \cdot \left(-\delta_2 + \delta_3 + \frac{F_H}{R} \right) \qquad \text{(A3-7)}$$

$$2 \cdot F_C + C \cdot \delta_3 = R \cdot \left(-\delta_3 + \delta_4 + \frac{F_H}{R} \right) \qquad \text{(A3-8)}$$

$$R \cdot \left(-\delta_3 + \delta_4 + \frac{F_H}{R} \right) + C \cdot \delta_4 = R \cdot \left(-\delta_4 + \delta_5 + \frac{F_H}{R} \right) \qquad \text{(A3-9)}$$

$$R \cdot \left(-\delta_4 + \delta_5 + \frac{F_H}{R} \right) + C \cdot \delta_5 = R \cdot \left(-\delta_5 + \delta_6 + \frac{F_H}{R} \right) \qquad \text{(A3-10)}$$

$$R \cdot \left(-\delta_5 + \delta_6 + \frac{F_H}{R} \right) + C \cdot \delta_6 = F_R \qquad \text{(A3-11)}$$

From these simultaneous equations, each anchor displacements are obtained as follows.

δ_1=1.82 mm

δ_2=1.07 mm

δ_3=0.61 mm

δ_4=0.33 mm

δ_5=0.145 mm

δ_6=0.003 mm

Here δ_1 and δ_2 are greater than δe of 1.02 mm, while δ_3 through δ_6 are less than δe, so assumption i) is satisfied.

Liner forced strain load between liner anchor No.5 and No.6, N_R, is calculated as follows and is less than F_R of 2496 N/mm, so assumption ii) is also satisfied.

$$N_R = R \cdot \left(-\delta_5 + \delta_6 + \frac{F_H}{R} \right) = 2740 \times \left(-0.145 + 0.003 + \frac{2881}{2740} \right) = 2492 \text{ N/mm}$$

The maximum displacement of 1.82mm is less than 1.85mm of nominal liner anchor spacing case, therefore it is confirmed that upper bound consideration in the liner anchor spacing is conservative evaluation.

(2) Evaluation of upper bound variation

Based on the above evaluation, it is considered as the worst case to combine the upper bound variations of liner thickness and liner anchor spacing.

The lower anchor stiffness gives the largest anchor displacement in the case of nominal thickness and liner anchor spacing (see Sections 4, 5 and Table 6-1), therefore the lower anchor stiffness case for each location is evaluated for the upper bound variation.

The liner plate properties are summarized in Table A3-2.

a. Wetwell cylinder (Category I)

Here

F_H=819 N/mm

R=3140 N/mm/mm

C=800 N/mm/mm

E=193000 MPa

ε_x=-0.000325

ε_y=-0.000595

σ_y=340 MPa

σ'_{xy}=302 MPa

t=7.67 mm

a=518 mm

F_R=2316 N/mm

F_H<F_R, so liner plate stays in elastic deformation region.

$$q = \left(1 + \frac{C}{2 \cdot R}\right) - \sqrt{\left(1 + \frac{C}{2 \cdot R}\right)^2 - 1} = \left(1 + \frac{800}{2 \times 3140}\right) - \sqrt{\left(1 + \frac{800}{2 \times 3140}\right)^2 - 1} = 0.60681$$

$$\delta_1 = \frac{F_H}{C + R \cdot (1 - q)} = \frac{819}{800 + 3140 \times (1 - 0.60681)} = 0.403\text{mm}$$

$\delta_1 < \delta_e$=1.02mm, so the assumption is satisfied.

And δ_1 is within the allowable of $0.25 \cdot \delta_u$=1.27mm, so the requirement of ASME B&PV Code Sec. III, Div.2, Table CC-3730-1 is satisfied.

b. Pedestal cylinder (Category II)

Here

F_H=3339 N/mm

R=3052 N/mm/mm

F_R=2892 N/mm

C=800 N/mm/mm

Followings are assumed to evaluate liner anchor displacement.

i) Liner anchor No.1 and No.2 are in the plastic deformation region, while No.3 and after are in the elastic deformation region.

ii) Liner plates between liner anchor No.1 and No.6 are in the elastic deformation region. Other plates are in the plastic deformation region. In the plastic deformation region, F_H equals to F_R.

The following simultaneous equations can be considered.

$$F_C = R \cdot \left(-\delta_1 + \delta_2 + \frac{F_H}{R}\right) \quad \text{(A3-12)}$$

$$2 \cdot F_C = R \cdot \left(-\delta_2 + \delta_3 + \frac{F_H}{R} \right) \quad \text{(A3-13)}$$

$$2 \cdot F_C + C \cdot \delta_3 = R \cdot \left(-\delta_3 + \delta_4 + \frac{F_H}{R} \right) \quad \text{(A3-14)}$$

$$R \cdot \left(-\delta_3 + \delta_4 + \frac{F_H}{R} \right) + C \cdot \delta_4 = R \cdot \left(-\delta_4 + \delta_5 + \frac{F_H}{R} \right) \quad \text{(A3-15)}$$

$$R \cdot \left(-\delta_4 + \delta_5 + \frac{F_H}{R} \right) + C \cdot \delta_5 = R \cdot \left(-\delta_5 + \delta_6 + \frac{F_H}{R} \right) \quad \text{(A3-16)}$$

$$R \cdot \left(-\delta_5 + \delta_6 + \frac{F_H}{R} \right) + C \cdot \delta_6 = F_R \quad \text{(A3-17)}$$

From these simultaneous equations, each anchor displacements are obtained as follows.

δ_1=2.20 mm

δ_2=1.37 mm

δ_3=0.81 mm

δ_4=0.46 mm

δ_5=0.24 mm

δ_6=0.07 mm

Here δ_1 and δ_2 are greater than δe of 1.02 mm, while δ_3 through δ_6 are less than δe, so assumption i) is satisfied.

Liner forced strain load between liner anchor No.5 and No.6, N_R, is calculated as follows and is less than F_R of 2892 N/mm, so assumption ii) is also satisfied.

$$N_R = R \cdot \left(-\delta_5 + \delta_6 + \frac{F_H}{R} \right) = 3052 \times \left(-0.24 + 0.07 + \frac{3339}{3052} \right) = 2820 \text{ N/mm}$$

And δ_1 is within the allowable of $0.5 \cdot \delta_u$=2.54 mm, so the requirement of ASME B&PV Code Sec. III, Div.2, Table CC-3730-1 is satisfied.

c. Wetwell bottom (Category I and II)

c-1. Category I

Here

F_H=1125 N/mm

R=5810 N/mm/mm

C=800 N/mm/mm

E=193000 MPa

ε_x=-0.000591

ε_y=-0.000336

σ_y=340 MPa

σ'_{xy}=367 MPa

t=7.67 mm

a=280 mm

F_R=2815 N/mm

F_H<F_R, so liner plate stays in elastic deformation region.

$$q=\left(1+\frac{C}{2\cdot R}\right)-\sqrt{\left(1+\frac{C}{2\cdot R}\right)^2-1}=\left(1+\frac{800}{2\times 5810}\right)-\sqrt{\left(1+\frac{800}{2\times 5810}\right)^2-1}=0.69144$$

$$\delta_1=\frac{F_H}{C+R\cdot(1-q)}=\frac{1125}{800+5810\times(1-0.69144)}=0.434\text{mm}$$

δ_1 <δ_e=1.02mm, so the assumption is satisfied.

And δ_1 is within the allowable of $0.25\cdot\delta_u$=1.27mm, so the requirement of ASME B&PV Code Sec. III, Div.2, Table CC-3730-1 is satisfied.

c-2 Category II

Here

F_H=3821 N/mm

R=5689 N/mm/mm

F_R=2869 N/mm

C=800 N/mm/mm

Followings are assumed to evaluate liner anchor displacement.

i) Liner anchor No.1 and No.2 are in the plastic deformation region, while No.3 and after are in the elastic deformation region.

ii) Liner plates between liner anchor No.1 and No.6 are in the elastic deformation region. Other plates are in the plastic deformation region. In the plastic deformation region, F_H equals to F_R.

The following simultaneous equations can be considered.

$$F_C = R \cdot \left(-\delta_1 + \delta_2 + \frac{F_H}{R} \right) \tag{A3-18}$$

$$2 \cdot F_C = R \cdot \left(-\delta_2 + \delta_3 + \frac{F_H}{R} \right) \tag{A3-19}$$

$$2 \cdot F_C + C \cdot \delta_3 = R \cdot \left(-\delta_3 + \delta_4 + \frac{F_H}{R} \right) \tag{A3-20}$$

$$R \cdot \left(-\delta_3 + \delta_4 + \frac{F_H}{R} \right) + C \cdot \delta_4 = R \cdot \left(-\delta_4 + \delta_5 + \frac{F_H}{R} \right) \tag{A3-21}$$

$$R \cdot \left(-\delta_4 + \delta_5 + \frac{F_H}{R} \right) + C \cdot \delta_5 = R \cdot \left(-\delta_5 + \delta_6 + \frac{F_H}{R} \right) \tag{A3-22}$$

$$R \cdot \left(-\delta_5 + \delta_6 + \frac{F_H}{R} \right) + C \cdot \delta_6 = F_R \tag{A3-23}$$

From these simultaneous equations, each anchor displacements are obtained as follows.

δ_1=1.66 mm

δ_2=1.13 mm

δ_3=0.75 mm

δ_4=0.47 mm

δ_5=0.26 mm

δ_6=0.077 mm

Here δ_1 and δ_2 are greater than δe of 1.02 mm, while δ_3 through δ_6 are less than δe, so assumption i) is satisfied.

Liner forced strain load between liner anchor No.5 and No.6, N_R, is calculated as follows and is less than F_R of 2869 N/mm, so assumption ii) is also satisfied.

$$N_R = R \cdot \left(-\delta_5 + \delta_6 + \frac{F_H}{R} \right) = 5689 \times \left(-0.26 + 0.077 + \frac{3821}{5689} \right) = 2780 \text{ N/mm}$$

And δ_1 is within the allowable of $0.5 \cdot \delta_u = 2.54$ mm, so the requirement of ASME B&PV Code Sec. III, Div.2, Table CC-3730-1 is satisfied.

A3.2 LINER ANCHOR PULLOUT EVALUATION

In the liner anchor pullout evaluation, the liner anchor spacing affects the load for concrete and stress for steel. Here these loads and stresses are evaluated using upper bound of a=518mm instead of nominal a=508mm for Section 6 evaluation.

(1) Concrete evaluation

a. Cone failure

i) Category I

$q = 112\text{kPa} = 0.112\text{N/mm}^2$

$P_{ol} = 518 \times 0.112 = 58.1\text{N/mm} < P_{dp} = 167\text{N/mm}$

ii) Category II

$q = 132\text{kPa} = 0.132\text{N/mm}^2$

$P_{ol} = 518 \times 0.132 = 68.4\text{N/mm} < P_{dp} = 167\text{N/mm}$

b. Bearing on anchor flange

i) Category I

P_O : $58.1\text{N/mm} < P_{db} = 1964\text{N/mm}$

ii) Category II

P_O : $68.4\text{N/mm} < P_{db} = 1964\text{N/mm}$

(2) Steel anchor evaluation

a. Flange bending evaluation

Category I : $M = \frac{1}{8} \times (102 - 6.22) \times 58.1 = 696 \quad \text{N} \cdot \text{mm/mm}$

Category II: $M = \frac{1}{8} \times (102 - 6.22) \times 68.4 = 819 \quad N \cdot mm / mm$

Z : Section modulus of flange = $\frac{h^2}{6} = \frac{8^2}{6} = 10.7 mm^3 / mm$

i) Category I

$\sigma_b = \frac{696}{10.7} = 65 MPa < Fa = 0.33 \cdot Fu = 131 MPa$

ii) Category II

$\sigma_b = \frac{819}{10.7} = 77 MPa < Fa = 0.5 \cdot Fu = 199 MPa$

b. Web tension evaluation

i) Category I

$\sigma_t = \frac{58.1}{6.22} = 10 MPa < Fa = 0.33 \cdot Fu = 131 MPa$

ii) Category II

$\sigma_t = \frac{68.4}{6.22} = 11 MPa < Fa = 0.5 \cdot Fu = 199 MPa$

A4 EVALUATION RESULTS

The evaluation results considering upper bound of the fabrication/erection tolerances of liner plate thickness and liner anchor spacing are summarized in the Tables A4-1 through A4-3. The requirements for liner anchor displacement and anchor pullout load are satisfied.

Table A3-1 Liner Plate Properties-Lower Bound Variation

Property			Pedestal cylinder Carbon steel Category II 171°C	
Thickness	t	mm	6.146	6.4
Anchor span	a	mm	508	498
Poisson's ratio	ν	-	0.3	
Poisson's ratio in the plastic region	ν'	-	0.5	
Modulus of elasticity	E	MPa (N/mm^2)	194000	
Liner plate spring ratio	R	N/mm/mm	2579	2740
Maximum uniaxial yield strength	σy	MPa (N/mm^2)	390	
Strain in the direction of spring ratio R	ε_x	-	-0.001622	
Strain in the direction of perpendicular to ε_x	ε_y	-	-0.001633	
Yield strength in the direction of spring ratio R	σ'xy	MPa (N/mm^2)	390	
Liner plate yield load	F_R	N/mm	2397	2496
Liner plate forced strain load	F_H	N/mm	2767	2881

Table A3-2 Liner Plate Properties-Upper Bound Variation

Property			WW cylinder (Air)	Pedestal cylinder
			Stainless steel	Carbon steel
			Category I	Category II
			43°C	171°C
Thickness	t	mm	7.67	7.416
Anchor span	a	mm	518	518
Poisson's ratio	ν	-	0.3	0.3
Poisson's ratio in the plastic region	ν'	-	0.5	0.5
Modulus of elasticity	E	MPa (N/mm^2)	193000	194000
Liner plate spring ratio	R	N/mm/mm	3140	3052
Maximum uniaxial yield strength	σy	MPa (N/mm^2)	340	390
Strain in the direction of spring ratio R	ε_x	-	-0.000325	-0.001622
Strain in the direction of perpendicular to ε_x	ε_y	-	-0.000595	-0.001633
Yield strength in the direction of spring ratio R	σ'xy	MPa (N/mm^2)	302	390
Liner plate yield load	F_R	N/mm	2316	2892
Liner plate forced strain load	F_H	N/mm	819	3339

A3-2 Liner Plate Properties-Upper Bound Variation (Continued)

Property			Modified WW bottom	
			Stainless steel	
			Category I	Category II
			43°C	110°C
Thickness	t	mm	7.67	
Anchor span	a	mm	280	
Poisson's ratio	ν	-	0.3	
Poisson's ratio in the plastic region	ν'	-	0.5	
Modulus of elasticity	E	MPa (N/mm^2)	193000	189000
Liner plate spring ratio	R	N/mm/mm	5810	5689
Maximum uniaxial yield strength	σy	MPa (N/mm^2)	340	
Strain in the direction of spring ratio R	ε_x	-	-0.000591	-0.002110
Strain in the direction of perpendicular to ε_x	ε_y	-	-0.000336	-0.000963
Yield strength in the direction of spring ratio R	σ'xy	MPa (N/mm^2)	367	374
Liner plate yield load	F_R	N/mm	2815	2869
Liner plate forced strain load	F_H	N/mm	1125	3821

Table A4-1 Summary of Liner Anchor Displacement Evaluation

Location	Liner Thickness (mm)	Anchor Spacing (mm)	Anchor Stiffness (N/mm/mm)	Category I		Category II	
				Displacement (mm)	Allowable (mm)	Displacement (mm)	Allowable (mm)
Wetwell Cylinder	7.67 (Max.)	518 (Max.)	800 (Lower)	0.403	1.27	-	2.54
Pedestal Cylinder	7.416 (Max.)	518 (Max.)	800 (Lower)	-		2.20	
Wetwell Bottom	7.67 (Max.)	280 (Max.)	800 (Lower)	0.434		1.66	

Table A4-2 Summary of Liner Anchor Pullout Evaluation (Concrete)

Failure Mode	Anchor Spacing (mm)	Category I		Category II	
		Load (N/mm)	Allowable (N/mm)	Load (N/mm)	Allowable (N/mm)
Cone Failure	518 (Max.)	58.1	167	68.4	167
Bearing on		58.1	1964	68.4	1964

Table A4-3 Summary of Liner Anchor Pullout Evaluation (Steel)

Location	Stress Type	Anchor Spacing (mm)	Category I		Category II	
			Stress (MPa)	Allowable (MPa)	Load (MPa)	Allowable (MPa)
Flange	Bending	518 (Max.)	65	131	77	199
Web	Tension		10		11	