Case 2949
Composite Pressure Vessel Consisting of Inner Steel Layered Shell and Outer Reinforced and Prestressed Concrete Shell for Hydrogen Service for Class 2 Section VIII, Division 2

Inquiry: May a composite pressure vessel for hydrogen service consisting of an inner steel layered shell and an outer reinforced and prestressed concrete shell be constructed in accordance with the rules of Section VIII, Division 2, Class 2?

Reply: It is the opinion of the Committee that a composite pressure vessel for hydrogen service consisting of an inner steel layered shell and an outer reinforced and prestressed concrete shell may be constructed in accordance with the rules of Section VIII, Division 2, Class 2, provided the following requirements are met.

1 GENERAL

(a) The maximum design pressure shall be 69 MPa (10,000 psi).

(b) The design temperature is ambient. The maximum ambient temperature and MDMT shall be specified by the user.

(c) An inside austenitic stainless steel liner shall be used in the steel layered shell to act as a barrier for hydrogen penetration. The minimum thickness shall be 6 mm (1/4 in.).

(d) Vent holes shall be provided in the steel-layered shell as

(1) a means for the hydrogen that penetrates the liner to escape to the atmosphere

(2) a monitoring system for the integrity of the steel-layered shell to provide a means for venting any hydrogen that permeates the liner and to provide for a monitoring system for any hydrogen that does escape through the liner.

(e) A shroud, an example of which is shown in Figures 1 and 2, and internal grooves shall be provided on the outside of the steel-layered shell. The edges of the shroud near the hemispherical heads shall be free of weld and

A shroud, an example of which is shown in Figures 1 and 2, shall be provided on the outside of the steel-layered shell. The shroud shall have internal grooves as shown in Figure 3.
shall not be covered by the concrete. The grooves shall be in line with the vent holes to provide means for the hydrogen to escape to the atmosphere.

NOTE: The requirements of Section VIII, Division 3, KD-10 and Section II, Part D, Nonmandatory Appendix A shall be met if any of the pressure-retaining parts are subjected to direct hydrogen contact.

(f) The inner steel vessel shall be designed in accordance with the requirements of Section VIII, Division 2, Part 5. The outer concrete shell shall be designed in accordance with the requirements of ACI 318 (Building Code Requirements for Structural Concrete), ACI 301 (Specifications for Structural Concrete), and ACI 372R (Design and Construction of Circular Wire-and-Strand Wrapped Prestressed Concrete Structures). The stress distribution throughout the steel and concrete shells shall be determined using Lame's thick-shell equation taking into consideration the deformation compatibility between the steel and concrete shells due to pressure, prestress conditions, and any other applied loads.

(g) The inner steel vessel shall be constructed by a fabricator certified in accordance with Section VIII, Division 2, Class 2. The inner steel-layered vessel shall be inspected by an Authorized Inspector (AI).

(h) The outer reinforced and prestressed concrete shell shall be constructed by a fabricator holding an ASME N-type certificate (Class CC). The outer concrete shell, including reinforcing bars and prestress wires, shall be inspected by an ASME Authorized Inspector (AI) qualified in accordance with Section III, Division 2, Nonmandatory Appendix D2-C, Article D2-C-4000. The inspector shall have a “C” (concrete) endorsement.

(i) The Manufacturer's Data Report of the fabricator responsible for the overall steel/concrete vessel and qualified and certified in accordance with the ASME code shall include all documents pertaining to the inner steel-layered vessel, outer prestressed and reinforced concrete shell, and other pertinent components.

(j) This Case number shall be shown on the vessel nameplate and Data Report.

(k) The supports for the completed vessel shall be attached to the heads.
2 INNER STEEL VESSEL (FIGURES 1 AND 2)

(a) The hemispherical heads and the steel-layered shell of the inner steel vessel shall meet all of the requirements of Section VIII, Division 2, Class 2.

(b) The thickness of the steel-layered shell is based on the longitudinal forces in the shell due to internal pressure. If the allowable stress in the hemispherical heads is the same as the allowable stress of the steel-layered shell, then the thickness of the steel-layered shell will be the same as the thickness of the hemispherical heads. All longitudinal forces in the steel-layered shell due to internal pressure shall be transferred directly to the hemispherical heads.

(c) The wrapping process of the steel-layered shell may result in compressive stress on the inside surface of the steel-layered shell that needs to be considered in the overall stress distribution in the shell. The fabricator shall develop a fabrication procedure for measuring such a stress using strain gages in the inside surface of the shell. At a minimum, strain gages shall be installed at four locations around the circumference of the steel-layered shell midway between the heads. A longitudinal and circumferential strain gage rosette shall be installed at each of the four locations in order to calculate the circumferential stress from the measured strains. This procedure is presently not part of the layered vessel rules in Section VIII, Division 2. The circumferential stress distribution in the various layers due to shrinkage of the longitudinal weld seams shall be calculated based on the measured strain in the strain gage. The results from this procedure may be used in subsequent vessels as a basis for calculating stresses without the need for further strain gage instrumentation.

(d) The prestress wires on the outside of the concrete shell will result in compressive stress on the inside surface of the steel-layered shell that needs to be considered in the overall stress distribution in the steel and concrete shell. The fabricator shall develop a fabrication procedure for measuring such a stress. The requirements of Section VIII, Division 3, KF-913 shall be required for the winding procedure of the vessel.

(e) The total tensile stress at any point in the steel-layered shell shall not exceed the limits of equivalent stress given in Section VIII, Division 2, Figure 5.1. Similarly, the compressive stress at any point in the steel-layered shell shall not exceed the allowable compressive stress calculated from Section VIII, Division 2, 4.4.12.

(f) The completed steel-layered shell and welded hemispherical heads of the inner vessel shall be hydrotested to the maximum stress allowed by Section VIII, Division 2 using the thickness of the steel-layered shell as a basis for calculating test pressure. At this stage the hemispherical heads will not be fully stressed due to this intermediate hydrotest. However, they will be fully stressed when
(g) The circumferential weld of layered shell-to-head junction or layered shell-to-layered shell junction shall include a copper chill bar as shown in Figure 4. The space created by the chill bar allows the hydrogen in the weld area to migrate to the layered shell where the vent holes dissipate it to the atmosphere.

This compressive stress is to be added to the compressive stress obtained during the fabrication of the inner steel layered cylinder. The total compressive stress shall be less than the allowable compressive stress of the inner shell liner. Otherwise, adjustments shall be made to the amount of pretension of the prestress wires.

(3) OUTER CONCRETE SHELL (FIGURES 3 AND 4)

(a) The concrete shell material shall meet the requirements of Section III, Division 2; ACI 301; and ACI 372R.

(b) The prestress wire material shall meet the requirements of ASTM A421 (latest edition) low relaxation wire listed in Section III, Division 2, Table D2-1.1.2. Other wires may be used when specified by the user and are listed in Section III, Division 2. Welding is prohibited on A421 wire during the wire-winding manufacturing process.

(c) The reinforcing bars material shall meet the requirements of ASTM A706 (latest edition) as listed in Section III, Division 2, CC-2310. Other reinforcing bars may be used when specified by the user and are listed in Section III, Division 2.

(d) During the prestressing of the outer concrete shell, the compressive stress on the inside surface of the steel-layered shell shall be measured by strain gages installed on the inside surface of the steel-layered shell. The stress distribution in the various layers of the steel-layered shell and the concrete shell due to prestress forces shall be calculated based on the measured strain in the strain gages. The results from this procedure may be used in subsequent vessels as a basis for calculating stresses without the need for further strain gage instrumentation.

(e) The total tensile stress at any point in the outer concrete shell shall not exceed the allowable reinforcing bar stress per prestressed concrete provisions of ACI 318 using the Allowable Stress Design method. Similarly, the compressive stress at any point in the concrete shall not exceed the limits set in ACI 318 for prestressed concrete structures.

(f) A plastic cover shall be placed over the prestressed wires to protect them from the weather. In addition, a metallic shield shall be placed over the plastic to protect the prestressed wires from any damage during shipping or from atmospheric conditions.

4 GENERAL PRELIMINARY DESIGN PROCEDURE

(a) Design of Inner Steel Vessel

(1) Determine the required thicknesses of the vessel hemispherical heads using the rules of Section VIII, Division 2.

(2) Design the head nozzles and any other attachments in the heads.
(3) Determine the required thickness of the steel-layered shell needed to transfer the longitudinal tensile forces due to internal pressure plus any additional tensile loads on the vessel. This thickness is approximately one-half that required for the full MAWP.

(4) Calculate the MAWP for the steel-layered shell using the thickness determined in (3).

(5) Calculate the required thickness of the support skirt or support saddles required for the vessel using an approximate weight of the reinforced concrete outer shell and prestressed wire. The final required thickness will be checked again subsequent to the final design of the concrete shell.

(b) Design of Outer Concrete Shell

(1) The concrete shell and prestress wires shall resist approximately one-half of the MAWP.

(2) The approximate thickness of the concrete shell and the approximate number of layers of the prestressed wires shall be determined by the following procedure:

- (a) Assume a concrete thickness, $t_c$, and an external pressure, $P_o$, on the concrete due to prestress wires.

- (b) Calculate the interface pressure, $P_f$, between the steel and concrete shells due to the design internal pressure, $P_i$, and the assumed external pressure, $P_o$, due to the total number of layers using the deflection compatibility equation: deflection of the outside surface of the steel-layered shell due to $P_i$ and $P_f = \text{deflection of inside surface of concrete shell due to } P_f$ and $P_o$.

\[
\delta_{P_{IPF}} = \delta_{CIPF}\quad (1)
\]

- (c) Calculate the stress in a steel-concrete shell due to the full MAWP. The stress distribution in the steel-layered shell shall be obtained from Lame’s equation using $P_i$ and $P_f$. The stress in the concrete shell shall be obtained from Lame’s equation using $P_f$ and $P_o$. The value of $P_o$ is based on the total number of wire layers.

- (1) Circumferential stress in steel-layered shell

\[
\sigma_{bs} = \frac{P_i R_i^2 + P_f \left(\frac{R_i^2 R_o^2}{R_o^2 - R_i^2}\right) - P_o R_o^2 - P_f \left(\frac{R_o^2 R_i^2}{R_o^2 - R_i^2}\right)}{R_o^2 - R_i^2}
\]

- (2) Circumferential stress in concrete shell

\[
\sigma_{bc} = \frac{P_i R_i^2 + P_f \left(\frac{R_i^2 R_o^2}{R_o^2 - R_i^2}\right) - P_o R_o^2 - P_o \left(\frac{R_o^2 R_i^2}{R_o^2 - R_i^2}\right)}{R_o^2 - R_i^2}
\]

- (d) If the tensile stress in the steel-layered shell or the concrete shell exceeds the allowable, then the thickness of the concrete shell and/or the value of $P_o$ shall be adjusted until the stresses are within the allowable stress.
INCREASE A

(a) The thickness of the outer concrete shell and the amount of external pressure exerted by the prestress wire are obtained by trial and error [1]. Three design criteria must be satisfied in choosing the concrete thickness and amount of external pressure. The first is the compressive stress in the concrete due to prestressing and the compressive stress in the steel shell due to prestressing and wrapping must not exceed the allowable compressive stress of the concrete and steel, respectively. The second criterion is the tensile stress in the steel shell due to internal pressure must not exceed the allowable stress and the stress in the concrete must remain in compression. And the third criterion is the stress in the steel shell due to hydrostatic testing must remain within the allowable stress and any tension in the concrete shell needs to be resisted by reinforcing bars.

In order to determine the stresses in the steel and concrete, compatibility equations need to be formulated. This is accomplished by defining the radial deflection, $\delta$, of any thick shell due to internal and external pressure as

$$\delta = [R_i^2 \left( \frac{P_i - P_o}{R_o^2 - R_i^2} \right) (1 - 2 \mu) + \left( P_i - P_o \right) \frac{R_i^2}{R_o^2} (1 + \mu)]/[E \cdot R \cdot (R_o^2 - R_i^2)]$$

(1)

When an internal pressure, $P_i$, is applied at the inside surface of a steel-concrete composite shell, an interface pressure, $P_o$, is developed at the interface between the outside surface of the steel cylinder and the inside surface of the concrete cylinder. The magnitude of this interface pressure is determined by the following compatibility equation

$$\delta_{opp} = \delta_{opp} = \delta_{opp} - \delta_{opp}$$

(2)

Where,

$\delta_{opp}$ = deflection of steel cylinder at outside surface due to internal pressure.

$\delta_{opp}$ = deflection of steel cylinder at outside surface due to interface pressure.

$\delta_{opp}$ = deflection of concrete cylinder at inside surface due to interface pressure.

$\delta_{opp}$ = deflection of concrete cylinder at inside surface due to outside pressure.

Substituting Eq.(1) into Eq.(2), rearranging terms, and using the terminology of Figure 7 results in

$$P_i = (P_i K_s + P_o K_o) \left/ \left( K_2 + K_3 + K_4 \right) \right.$$  

(3)

Where,

$$K_1 = \left[ \frac{E_s \left( R_i^2 - R_o^2 \right)}{E_c \left( R_o^2 - R_i^2 \right)} \right]$$

$$K_2 = K_1 \left[ R_o^2 (1 - 2 \mu) + R_i^2 (1 + \mu) \right]$$

$$K_3 = R_i^2 \left( 1 - 2 \mu \right)$$

$$K_4 = R_i^2 \left( 1 + \mu \right)$$

$$K_5 = R_o^2 \left( 2 - \mu \right)$$

$$K_6 = K_1 R_o^2 \left( 2 - \mu \right)$$

Once the value of $P_i$ is obtained from Eq.(3), then the circumferential stress in the steel cylinder is obtained from Lame’s equation as [2]

$$\sigma_{o} = \left( P_i R_o^2 - P_o R_i^2 \right)$$

$$\left( P_i - P_o \right) \left( R_o^2 / R_i^2 \right)$$

$$\left( R_o^2 - R_i^2 \right)$$

(4)

While the circumferential stress in the concrete cylinder is given by

$$\sigma_{o} = \left( P_i R_o^2 - P_o R_i^2 \right)$$

$$\left( P_i - P_o \right) \left( R_o^2 / R_i^2 \right)$$

$$\left( R_o^2 - R_i^2 \right)$$

(5)

The above equations are used repeatedly as the thickness of the concrete and values of external pressure are adjusted to meet the design conditions. When the thickness of the concrete and the value external pressure are found satisfactory then the number of prestress layers is calculated as shown next.

The external pressure $P_o$ calculated above is provided by the prestress wires. The wires are placed spirally with no space between them. For ease of calculations an effective thickness is determined by smearing the wire area over one inch of shell length to come up with an equivalent thickness per inch of length

$$t_w = (\pi d^2/4) / (1/d) = \pi d/4$$

(6)

The external pressure on the shell provided by a layer of wires is

$$P_o = S_w t_w / R_o$$

(7)

Where, $R_o$ = outside radius of the concrete shell for the first layer of wires and $R_o$ = outside radius of the concrete shell plus $t_w$ for the second layer of wires, etc.
(b) The equations for calculating the stress in the concrete and steel inner shell due placing the first layer of prestress wires are given below. When the second layer of prestress wire is placed, a second set of calculations is performed. However, the stress in the steel and concrete shells imposed by the first set of wires is now reduced due to the added second layer which reduces the tensile stress in the first layer. This reduction has to be accounted for as the process proceeds from one prestress layer to the other.

The pertinent equations needed for the analysis are based on Eqs. (1), (4), and (5) and the details shown in Figure 8. The derivation of the equations is shown below.

In Figure 8, the outer steel layer shown represents the prestressing wires that are already in place and \( p_0 \) is the pressure on them from a new additional wire. The two unknowns in the figure are interface pressures \( p_1 \) and \( p_2 \). These are obtained from the deflection, \( \delta \), compatibility equations

\[
\begin{align*}
\text{\textit{\delta of the outer surface of the inner steel shell}} &= \text{\textit{\delta of the inner surface of the concrete shell}} \\
\end{align*}
\]

Substituting Eq. (1) into Eq. (8), rearranging terms, and using the terminology of Figure 8 results in

\[
P_1(C_1 + C_2) - C_3P_2 = C_4
\]

Similarly,

\[
\text{\textit{\delta of the outer surface of the concrete shell}} = \text{\textit{\delta of the inner surface of the outer steel shell}}
\]

Substituting Eqs. (1) into Eq. (10), rearranging terms, and using the terminology of Figure 8 gives

\[
C_3P_1 - P_2(C_6 + C_7) = C_8
\]

Solving Eqs. (9) and (11) for \( p_1 \) and \( p_2 \) results in

\[
P_1 = \frac{C_{12}}{C_{12}} \quad \text{and} \quad P_2 = \frac{C_8}{C_{10}}
\]

Where,

\[
C_2 = (R_1^2 - R_2^2)(R_1)[(R_2^2 + R_1^2) + \mu(R_2^2 - R_1^2)]
\]

\[
C_3 = 2(R_1^2 - R_3^2)R_1R_2
\]

\[
C_4 = 2(E/E_I)(R_2^2 - R_1^2)p_1R_1R_2
\]

\[
C_5 = 2(R_0^2 - R_2^2)R_1R_2
\]

\[
C_6 = (R_0^2 - R_2^2)(R_2)[(R_2^2 + R_1^2) - \mu(R_2^2 - R_1^2)]
\]

\[
C_7 = (E/E_I)(R_2^2 - R_1^2)(R_2)[(R_0^2 + R_2^2) + \mu(R_0^2 - R_2^2)]
\]

\[
C_8 = -2(E/E_I)(R_2^2 - R_1^2)p_0R_2R_2
\]

\[
C_9 = C_6(C_1 + C_2) - C_4C_5
\]

\[
C_{10} = C_3C_5 - (C_1 + C_2)(C_6 + C_7)
\]

\[
C_{11} = C_4 + (C_3C_9/C_{10})
\]

\[
C_{12} = C_1 + C_2
\]

Equations (4), (5) and (12) are used to obtain the stress in the inner steel shell, the concrete shell, and the prestress wires.
CASE (continued)

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(e) Calculate the interface pressure, \( P_f \), between the steel and concrete shells due to assumed external pressure, \( P_o \), and letting \( P_f = 0 \) using the deflection compatibility equation.

\[
\text{deflection of the outside surface of the steel-layered shell due to } P_f = \text{deflection of inside surface of the concrete shell due to } P_f \text{ and } P_o
\]

(f) Calculate the compressive stress in a steel-concrete shell due to \( P_o \). If the compressive stress in the steel-layered shell or the concrete shell exceeds the allowable stress, then the thickness of the concrete shell and/or the value of \( P_o \) shall be adjusted until the compressive stresses are within the allowable stress.

(g) The thickness, \( t_c \), and pressure, \( P_o \), determined from the steps above will be finalized when a detailed stress distribution analysis is performed.

5 DETAILED STRESS ANALYSIS

The actual stress distribution in the steel and concrete shells is obtained as follows:

(a) The stress distribution in the steel-layered shell wall due to weld shrinkage of the steel layers during fabrication shall be obtained from strain gages installed circumferentially and longitudinally on the inside surface of the steel-layered shell. The longitudinal and circumferential strains at the inside surface of the steel-layered shell shall be obtained and recorded after welding each layer, and the corresponding stress shall be calculated from the following equations:

\[
\sigma_l = \left( \frac{E}{1-\mu^2} \right) (\epsilon_l + \mu \epsilon_t)
\]

\[
\sigma_t = \left( \frac{E}{1-\mu^2} \right) (\epsilon_t + \mu \epsilon_l)
\]

(b) The interface pressure on the cylinder due to weld shrinkage of any layer shall be obtained from Lame's equation using \( P_f \) and \( P_o \).

\[
\sigma_f = \frac{P_f R_o^2 + P_l \left( \frac{R_f^2 R_o^2}{R_o^2} \right) - P_o R_o^2 - P_l \left( \frac{R_f^2 R_o^2}{r^2} \right)}{R_o^2 - R_f^2}
\]

(c) From the equivalent pressure, the stress distribution in the rest of the layers shall be obtained from \( \sigma_f \), eq. (7).

(d) The stress distribution in the steel layers and concrete shell due to prestressing the concrete shall be obtained by the same procedure outlined above.
(a) Welding of the longitudinal seams of any individual layer in a layered shell causes shrinkage of the welds. This shrinkage results in locked-in residual tensile stress in the individual layer being welded and compressive stress in the layers underneath it. These secondary stresses are normally ignored in commercially fabricated layered vessels since they do not contribute to the stress calculations for determining the required thickness of the layered shell. However, they are important in the steel-concrete composite vessel since they must be combined with the stresses obtained from the prestressing wires on the outside surface of the concrete as well as the stress due to internal pressure in order to obtain the full stress pattern needed for design. The compressive stress in the inner layer due to weld shrinkage of the longitudinal welds of the outer layers is obtained from strain gage rosettes attached to the inside surface of the inner layer. The pertinent equations for calculating the stress from measured strain are

$$\sigma_0 = \left[ E/(1-\mu_s^2) \right] (e_0 + \mu_s \varepsilon_0) \quad (16)$$

$$\sigma_t = \left[ E/(1-\mu_s^2) \right] (e_t + \mu_s \varepsilon_t) \quad (17)$$

(b) The stress distribution in the steel layered shell due to weld shrinkage of the longitudinal welds of the layers can be formulated from deflection compatibility equations and the stress results obtained from Equations (16) and (17) for the inner layer. The stress pattern through the wall of a layered cylinder due to shrink fitting the layers (autofrettaging) is based on the details shown in Figure 9 as well as the derivations and experimental verifications given by [3].

Define \( t_0 \) as the thickness of the outer layer being shrunk and \( t_1 \) as the thickness of all layers underneath it. Also, define \( R_0 \) and \( R_1 \) as the outside and inside radii of the layer being shrunk and \( R_o \) and \( R_i \) as the outside and inside radii of all layers underneath it as shown in Figure 9. Define \( "w" \) as the width of the weld seam in the outer layer and \( "n" \) as the number of weld seams in the outer layer. Define \( p_i \) as the interface pressure between the outer layer and all layers underneath it.

The deflection of the inside surface of a cylinder due to internal and external pressure is given by [2]

$$\delta_i = \left[ R_i p_i (R_o^2 + R_i^2) + \mu_s R_i p_i (R_o^2 - R_i^2) - 2p_0 R_i R_o^2 \right] / E_i (R_o^2 - R_i^2) \quad (18)$$

Similarly, the deflection of the outside surface of a cylinder due to internal and external pressure is given by [2]

$$\delta_o = \left[ 2p_1 R_i^2 R_o - R_o p_o (R_o^2 + R_i^2) + \mu_s R_o p_o (R_o^2 - R_i^2) \right] / E_i (R_o^2 - R_i^2) \quad (19)$$

The shrinkage due to welding of seam \( "w" \) in the outer layer is given by

$$\delta_w = (K)(w) \quad (20)$$

The value of the weld shrink factor \( K \) in Equation (20) depends on many variables such as weld width and thickness, weld process, and number of weld passes. The value of \( K \) is obtained by trial and error as explained below.

The inward radial deflection of the outer layer due to weld shrinkage of seam \( "w" \) is expressed as

$$\Delta_w = \frac{\delta_w n}{(2\pi)} \quad (21)$$

The compatibility equation between layer \( t_o \) and layer \( t_i \) is given by

$$\Delta_w - \Delta_o = \Delta_i \quad (22)$$

From Eq.(18), the deflection of the inside surface of outer layer to due \( t_o \) interface pressure \( p_i \) is
\[ \Delta_1 = (P_f R_f) \left[ R_0^2 (1+\mu_b) + R_f^2 (1-\mu_b) \right] / E_s (R_0^2 - R_f^2) \]  \hspace{1cm} \text{(23)}

Similarly, from Eq.(19), the deflection of the outside surface of inner layer t_i due to interface pressure \( p_f \) is
\[ \Delta_0 = (P_f R_f) \left[ R_f^2 (-1+\mu_b) - R_i^2 (1-\mu_b) \right] / E_s (R_i^2 - R_f^2) \]  \hspace{1cm} \text{(24)}

Substituting Eqs.(20), (21), (23), and (24) into Eq.(22) and solving for the unknown interface pressure \( p_f \) gives
\[ p_f = K_3 / [R_f (K_1 - K_2)] \]  \hspace{1cm} \text{(25)}

Where,
\[ K_1 = R_0^2 (1+\mu_b) + R_f^2 (1-\mu_b) / [R_0^2 - R_f^2] \]
\[ K_2 = R_i^2 (-1+\mu_b) - R_i^2 (1+\mu_b) / [R_i^2 - R_f^2] \]
\[ K_3 = (E_s K) / (2\pi) \]

The above derivations are based on the following assumptions
The width \( "w" \) of the weld seams is the same in all layers.
Weld parameters such as voltage, amperes, speed, etc. are constant from weld to weld such that the shrinkage constant \( K \) does not vary from weld to weld or layer to layer.
The number of welds \( "n" \) in each layer is constant throughout the layers.
The modulus of elasticity, \( E_s \), is the same for all layers.

(c) The actual interface pressure \( p_f \) in Eq.(25) is based on a selected value of constant \( K \). Once the pressure \( p_f \) is known then the circumferential stresses in the outer and inner cylinders are obtained from the following equations
Due to external pressure \( P_o \),
\[ \sigma_0 = \left[ -P_o R_0^2 - P_o \left( R_i^2 R_o^2 / R_i^2 \right) \right] / (R_o^2 - R_i^2) \]  \hspace{1cm} \text{(26)}

Due to internal pressure \( P_i \),
\[ \sigma_0 = \left[ P_i R_i^2 + P_i \left( R_i^2 R_o^2 / R_i^2 \right) \right] / (R_o^2 - R_i^2) \]  \hspace{1cm} \text{(27)}

The value of \( K \) in Equation (25) is determined as follows:
The values of circumferential compressive stress in the inner layer due to wrapping each of the outer layers as obtained from the strain gage readings and Equations (16) and (17) are plotted as shown in Figure 10.
A value of \( K \) between 0.05 and 0.50 is assumed.
Equations (25) through (27) are solved for each welded outer layer and the resultant curve based on an assumed value of \( K \) is plotted as shown in Figure 10.
If the curve from the equations does not match the actual data then a new value of \( K \) is assumed and the procedure is continued until a satisfactory curve is obtained.
Once the value of \( K \) is established, then the stress distribution in the various layers due to the wrapping process is determined from Equations (25) through (27). Figure 11 shows a typical stress distribution in the layered shell due to wrapping stress.
The wrapping stress in the various layers is added to the stress in these layers due to prestressing the concrete outer shell and stress due to internal pressure to obtain the overall stress pattern in the shell.
(e) The stress in the steel-layered shell due to internal pressure plus steel layer weld shrinkage plus concrete prestressing plus any concrete shrinkage shall be calculated from (b), eq. (7). The tensile and compressive stresses shall not exceed the allowable stress, S.

(f) The stress in the concrete shell due to internal pressure plus concrete prestressing shall be calculated from (b), eq. (7). The tensile and compressive stresses shall be within the allowable values specified by ACI 318 for prestressed concrete structures.

(g) At the design stage, consideration must be given to hydrotecting. During final hydrotecting, excessive tensile stress may occur in the concrete. Such condition will require use of reinforcing bars in the concrete to resist tensile forces in accordance with ACI 318.

(h) Long-range creep relaxation of the concrete shall be taken into account when calculating stresses in the steel-layered shell and outer concrete shell due to prestressing and internal pressure per the prestressed concrete provisions of ACI 318, ACI 209R (Prediction of Creep, Shrinkage, and Temperature Effects in Concrete Structures), and Concrete International Journal, June 1979, “Estimating Prestress Losses” by Zia, Preston, Scott, and Workman, pages 32–38.

(i) Fatigue evaluation shall be considered in the overall analysis of the vessel in accordance with Section VIII, Division 2 and ACI 376 (Code Requirements for Design and Construction of Concrete Structures for Containment of Refrigerated Liquefied Gases and Commentary).

(k) Low temperature evaluation of various components shall be considered in the overall analysis of the vessel.
(g) Discontinuity Stress between Head And Steel-Concrete Shell

The discontinuity forces are shown in Figure 12. Total unknown forces are $H_1$, $H_2$, $H_3$, $M_1$, $M_2$, and $P_t$. The six equations (two equilibrium and four compatibility) required to solve these six unknown forces are

$$H_1 - H_2 - H_3 = 0 \quad (28)$$

$$M_1 - M_2 = 0 \quad (29)$$

$$\delta_h = \delta_h \quad (30)$$

$$\delta = \delta \quad (31)$$

$$\theta = \theta \quad (32)$$

$$\theta = \theta \quad (33)$$

**Head equations**

$$\delta_h = \delta_{hpi} - \delta_{hm1} + \delta_{hm1} \quad (34)$$

$$\theta_h = \theta_{hp1} + \theta_{hm1} - \theta_{hm1} \quad (35)$$

Where,

$$\delta_{hpi} = \text{radial deflection of head due to internal pressure } P_t, \quad \delta_{hm1} = \text{radial deflection of head due to shear force } H_1, \quad \delta_{hm1} = \text{radial deflection of head due to bending moment } M_1.$$

$$\theta_{hpi} = \text{rotation of head due to internal pressure } P_t, \quad \theta_{hm1} = \text{rotation of head due to shear force } H_1, \quad \theta_{hm1} = \text{rotation of head due to bending moment } M_1.$$

and where,

$$\beta_s = \frac{\sqrt{3(1-\mu_s^2)}}{(R_s t_s)^{0.25}}$$

and

$$D_s = E_s t_s^3/[12(1-\mu_s^2)]$$

**Concrete shell equations**

$$\delta_s = \delta_{sp1} - \delta_{sp2} + \delta_{sp2} \quad (36)$$

$$\theta_s = \theta_{sp1} + \theta_{sp2} - \theta_{sp2} \quad (37)$$

Where,

$$\delta_{sp1} = \text{radial deflection of steel shell due to internal pressure } P_t, \quad \delta_{sp2} = \text{radial deflection of steel shell due to interface pressure } P_t,$$

$$\delta_{sp2} = \text{radial deflection of steel shell due to shear force } H_2, \quad \delta_{sp2} = \text{radial deflection of steel shell due to bending moment } M_2.$$

$$\theta_{sp1} = \text{rotation of steel shell due to internal pressure } P_t, \quad \theta_{sp2} = \text{rotation of steel shell due to external pressure } P_t.$$

$$\theta_{sp2} = \text{rotation of steel shell due to shear force } H_2, \quad \theta_{sp2} = \text{rotation of steel shell due to bending moment } M_2.$$

and where,

$$\beta_s = \frac{3(1-\mu_s^2)}{(R_s t_s)^{0.25}}$$
\[ \theta_{\text{rot}} = \text{rotation of concrete shell due to shear force } H_3, \]
\[ = H_3 / (2 \beta_c^2 D_c) \]
and where,
\[ \beta_c = [3(1-\mu_c^2)] / (R_c t_c^2)^{0.25} \]
and
\[ D_c = E_c t_c^3 / [12(1-\mu_c^2)] \]

Substituting Equations (34) through (39) into Equations (28) through (33) and rearranging terms results in the following six simultaneous equations, written in matrix form, and can be solved for the unknowns \( H_1, H_2, H_3, M_1, M_2, \) and \( P_f. \)

\[
[K][F] = [C] \tag{40}
\]

Where,
\[
[K] = \begin{bmatrix}
1 & -1 & -1 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & -1 & 0 \\
c_1 & c_2 & 0 & -c_3 & c_4 & -c_5 \\
0 & c_2 & -c_7 & 0 & c_4 & -c_8 \\
-c_3 & c_4 & 0 & c_{10} & c_{11} & 0 \\
0 & c_4 & -c_{12} & 0 & c_{11} & 0
\end{bmatrix}
\]
\[
[F] = \begin{bmatrix}
H_1 \\
H_2 \\
H_3 \\
M_1 \\
M_2 \\
P_f
\end{bmatrix}
\]
\[
[C] = \begin{bmatrix}
0 \\
0 \\
c_6 \\
c_9 \\
0
\end{bmatrix}
\]

and,
\[ c_1 = 2 R_n \lambda / (E_n t_n) \]
\[ c_2 = 1 / (2 \beta_c^2 D_c) \]
\[ c_3 = 2 \lambda^2 / (E_n t_n) \]
\[ c_4 = 1 / (2 \beta_c^2 D_c) \]
\[ c_5 = R_c^2 / (E_c t_c) \]
\[ c_6 = P_f [R_n^2 (1-\mu_n)/(2 E_n t_n) - R_c^2 (1-\mu_c^2)/(E_c t_c)] \]
\[ c_7 = 1 / (2 \beta_c^2 D_c) \]
\[ c_8 = R_c^2 / (E_c t_c) + R_c^2 / (E_c t_c) \]
\[ c_9 = -P_f [R_n^2 (1-\mu_n)/(2 E_n t_n) - P_o R_c^2 / (E_c t_c)] \]
\[ c_{10} = 4 \lambda^2 / (E_n R_n t_n) \]
\[ c_{11} = 1 / (\beta_c D_c) \]
\[ c_{12} = 1 / (2 \beta_c^2 D_c) \]

Once the unknown forces are calculated from Eq.(40), the stresses are then determined from the following equations

**Steel head**

Longitudinal stress
\[ S_L = P_f R_n / 2 t_n + 6 M_2 / t_n^2 \] \( \tag{41} \)

Circumferential stress
\[ S_C = \delta_n E_n / R_n + (\mu_n) (6 M_2 / t_n^2) \] \( \tag{42} \)

**Layered steel shell**

Longitudinal stress
\[ S_L = P_f R_n / 2 t_n + 6 M_2 / t_n^2 \] \( \tag{43} \)

Circumferential stress
\[ S_C = \delta_n E_n / R_n + (\mu_n) (6 M_2 / t_n^2) \] \( \tag{44} \)

**Concrete shell**

Longitudinal stress
\[ S_L = 0 \] \( \tag{45} \)

Circumferential stress
\[ S_C = \delta_c E_c / R_c \] \( \tag{46} \)

Where,
\[ \delta_n = (1/E_n t_n) \left[ (0.5) (P_f R_n^2 (1-\mu_n) - 2 H_3 R_n \lambda + 2 M_1 \lambda^2) \right] \]
\[ \delta_c = (P_f R_n^2 (1-\mu_n)/(E_c t_c) - (P_f R_n^2)/(E_c t_c)) + H_3 / (2 \beta_c^2 D_c) + M_2 / (2 \beta_c^2 D_c) \]
\[ \delta_c = (P_f R_c^2)/(E_c t_c) - (P_o R_c^2)/(E_c t_c) + H_3 / (2 \beta_c^2 D_c) \]

\[ C_6 = P_f [R_n^2 (1-\mu_n)/(2 E_n t_n) - R_c^2 (1-\mu_c^2)/(E_c t_c)] \]
\[ C_7 = 1 / (2 \beta_c^2 D_c) \]
6 FINAL HYDROTESTING

The completed vessel shall be hydrotected in accordance with Section VIII, Division 2, 8.2. The final hydrotest shall be witnessed by an Authorized Inspector.

7 NOMENCLATURE

\[ E = \text{modulus of elasticity} \]
\[ \text{MAWP} = \text{maximum allowable working pressure} \]
\[ \text{MDMT} = \text{minimum design metal temperature} \]
\[ P_f = \text{interface pressure} \]
\[ P_i = \text{internal pressure} \]
\[ P_o = \text{outside pressure} \]
\[ r = \text{radius at any location} \]
\[ r_f = \text{interface radius between steel-layered shell and concrete shell} \]
\[ R_i = \text{inside radius} \]
\[ R_o = \text{outside radius} \]
\[ S = \text{allowable stress} \]
\[ t_c = \text{thickness of concrete} \]
\[ \delta_{cwp} = \text{deflection of concrete shell due to interface pressure, } P_f, \text{ and outside pressure, } P_o \]
\[ \delta_{spf} = \text{deflection of steel shell due to internal pressure, } P_i, \text{ and interface pressure, } P_f \]
\[ \varepsilon_L = \text{strain in the longitudinal direction} \]
\[ \varepsilon_\theta = \text{strain in the circumferential direction} \]
\[ \mu = \text{Poisson's ratio} \]
\[ \sigma_L = \text{longitudinal stress} \]
\[ \sigma_\theta = \text{circumferential stress at any location} \]
\[ \sigma_{oc} = \text{circumferential stress at any location in the concrete shell} \]
\[ \sigma_{os} = \text{circumferential stress at any location in the steel layered shell} \]
8 REFERENCES


The following is a partial list of various publications referenced in the ACI documents in this code case

AMERICAN ASSOCIATION OF STATE HIGHWAY AND TRANSPORTATION OFFICIALS (AASHTO)

AASHTO M 182 (2005; R 2009) Standard Specification for Burlap Cloth Made from Jute or Kenaf and Cotton Mats

AMERICAN CONCRETE INSTITUTE INTERNATIONAL (ACI)


ACI 301 (2010; Errata 2011) Specifications for Structural Concrete

ACI 318 (2011; Errata 1 2011; Errata 2 2012; Errata 3-4 2013) Building Code Requirements for Structural Concrete and Commentary

ACI 347 (2004; Errata 2008; Errata 2012) Guide to Formwork for Concrete


ACI/MCP-1 (2013) Manual of Concrete Practice Part 1


ACI/MCP-3 (2013) Manual of Concrete Practice Part 3

ACI/MCP-4 (2013) Manual of Concrete Practice Part 4
AMERICAN WATER WORKS ASSOCIATION (AWWA)
AWWA C300 (2011) Reinforced Concrete Pressure Pipe, Steel-Cylinder Type
AWWA C301 (2007) Prestressed Concrete Pressure Pipe, Steel-Cylinder Type

AMERICAN WELDING SOCIETY (AWS)
AWS D1.4/D1.4M (2011) Structural Welding Code - Reinforcing Steel

ASTM INTERNATIONAL (ASTM)


ASTM C192/C192M (2013a) Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory

ASTM C295/C295M (2012) Petrographic Examination of Aggregates for Concrete

ASTM C311/C311M (2013) Sampling and Testing Fly Ash or Natural Pozzolans for Use as a Mineral Admixture in Portland-Cement Concrete


ASTM C618 (2012a) Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete


ASTM F844 (2007a; R 2013) Washers, Steel, Plain (Flat), Unhardened for General Use
Figure 1. Example of Streel-Layered Vessel

Figure 2. Detail of Head-to-Steel Layered Shell Junction

NOTES:
(1) This weld shall be made after the hydrostatic test. Do not weld to layer.
(2) Longitudinal grooves: the orientation of these grooves shall be placed directly above the vent holes.
Figure 3. Shroud for the Vent Holes in the Layered Steel Shell

Figure 4. Head-to-Layered Shell Detail
Figure 5. Example of Outer Concrete Shell

Figure 6. Details of Concrete Reinforcement
Figure 7. Steel-Concrete Composite Shell

Figure 8. Steel-Concrete-Steel Interaction
Figure 9. Layered Vessel

Figure 10. Stress from Strain Gage Measurements Versus Stress from Assumed Value of K
Figure 11. Wrapping Stress Distribution Through Thickness

Figure 12. Head-to-Shell Forces