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Chapter 1 Design Inputs

Shell Inside Diameter	$D := 8 \cdot ft = 96 \cdot in$
Shell Inside Radius	$R := \frac{D}{2} = 48 \cdot in$
Total Straight Shell Height	$H := 52 \cdot ft + 5 \cdot in = 629\, in$
Design Burial Depth to the Top of the Tank	$h_{bu} := 7 \cdot ft$
Design Water Table	$H_{wt} := D + h_{bu} = 180\, in$
Applied Internal Pressure	$P_{int} := 0 \cdot psi$
Applied External Pressure	$P_{ext} := 0 \cdot psi$
Corrosion Barrier Thk.	$t_{cb} := 0 \cdot in$
Max. Design Temperature	$T_{max} := 100 \cdot F$
Content Specific Gravity	$sg := 1.0$
Water Density:	$\rho_w := 0.0361 \cdot \frac{lb}{in^3}$
FRP Density	$\rho_{frp} := 0.065 \cdot \frac{lb}{in^3}$
Submerged Soil Density	$\rho_{ws} := 70 \cdot \frac{lb}{ft^3}$
Concrete Desity	$\rho_c := 150 \cdot \frac{lb}{ft^3}$

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Design Safety Factor for Sustained Load $F_s := 10$

Design Safety Factor for Transient Load $F_t := 5$

Design Safety Factor for Vacuum $F_{vac} := 2.5$

Chapter 2 Design of Cylindrical Shell

2.1 Shell Properties

Shell Construction Filament Wound

Shell Structure Thk.: $t_s := tsu \cdot in = (0.29)\ in$

Shell & Head Thks, and Stiffener Design Work for Same Diameter Tank with Shorter Shell Length

Shell Total Thk: $t_{stot} := \overrightarrow{(t_s + t_{cb})}$

Shell Mean Radius: $R_m := \overrightarrow{\left(R + \frac{t_s}{2}\right)}$ $R_m = (48.145) \cdot in$

$t_{stot} = (0.29) \cdot in$

Shell Outer Diameter: $D_o := \overrightarrow{(D + 2 \cdot t_{stot})}$

Total Number of Shell Courses $n \equiv 1$ $i \equiv 1 .. n$

Shell Length: $L_s := (H)$ $\sum L_s = 629\ in$ $H = 629\ in$

Property Reduction Factor $\eta := 0.98$

Conservative properties are used. See lamination analysis in App. B

Axial Tensile Modulus

$E_a := (1762000)\cdot\eta\cdot psi = \left(1.727 \times 10^6\right)\cdot psi$

Hoop Tensile Modulus

$E_h := (4402000)\cdot\eta\cdot psi = \left(4.314 \times 10^6\right)\cdot psi$

Axial Flexural Modulus

$E_{af} := (1558000)\cdot\eta\cdot psi = \left(1.527 \times 10^6\right)\cdot psi$

Hoop Flexural Modulus

$E_{hf} := (4588000)\cdot\eta\cdot psi = \left(4.496 \times 10^6\right)\cdot psi$

Axial Hoop Poisson's Ratio

$\upsilon_{ah} := (0.09)$

Hoop Axial Poisson's Ratio

$\upsilon_{ha} := (0.22)$

Shell moment of inertia: $I_s := \overrightarrow{\left[\frac{\pi}{64}\cdot\left[\left(D + 2t_{stot}\right)^4 - D^4\right]\right]}$

Burial Depth to The Bot. of Shell $L_B := \overrightarrow{\left(D + h_{bu}\right)}$

Height of Water Table Above the Bot. of Each Shell Section $h_w := L_B = 180\ in$

2.2 Loads Considered

The following loads will be considered for the structural analysis of the tank:

- Internal pressure
- Lateral earth loads
- Lateral water loads

I. Internal Pressure

Shell internal pressure is a combination of applied pressure and hydrostatic pressure.

Internal Pressure on Shell $P_{s\_ip} := \overrightarrow{\left(P_{int} + \rho_W \cdot sg \cdot D\right)}$ $P_{s\_ip} = 3.466 \cdot psi$

Shell Hoop Stress Due to Internal Pressure $\sigma_{s\_ip} := \overrightarrow{\frac{P_{s\_ip} \cdot R_m}{t_s}}$

$\sigma_{s\_ip} = (575.349) \cdot psi$

Shell Hoop Tensile Strength $\sigma_{h\_al} := 0.01 \cdot E_h$

Shell Hoop Srain Due to Internal Pressure $\varepsilon_{s\_ip} := \overrightarrow{\frac{\sigma_{s\_ip}}{E_h}}$ $\varepsilon_{s\_ip} = \left(1.334 \times 10^{-4}\right)$

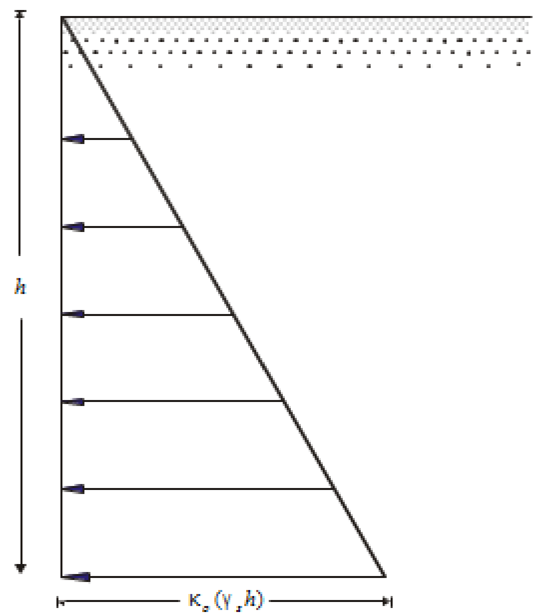
Safety Factor of Shell Under Internal Pressure $SF_{s\_ip} := \overrightarrow{\left(\frac{\sigma_{h\_al}}{\sigma_{s\_ip}}\right)}$ $SF_{s\_ip} = (74.98)$

$checkshellforinternalpressure_i := if\left(SF_{s\_ip_i} \geq 10, "OK", "Inadequate"\right)$

$checkshellforinternalpressure = ("OK")$

II. Earth Load

Ref : Das B.M.; Fundamentals of Geotechnical Engineering, 2000, p.291-295.



The ratio of the horizontal stress to the vertical stress is called the coefficient of earth pressure at rest, κo , or

$$\kappa_o = \frac{\sigma_h}{\sigma_v}$$

Rearranging gives $\sigma_h = \kappa_o \cdot \gamma_s \cdot h$

h = depth of point of interest
γ_s = density of saturated or “moist” soil (Das, page 19)

For granular soils, the coefficient of earth pressure at rest can be represented by the empirical relation.

$$\kappa_o = 1 - \sin(\varphi)$$

φ : soil friction angle

For select backfill material (conforming to the requirements of the Underground Horizontal Tank Installation Instructions Guidelines), we can assume $\varphi_d := 30\,\text{deg}$ for calculation proposes.

Therefore $$\kappa_o := 1 - \sin\left(\frac{\varphi_d}{180} \cdot \pi\right) = 0.5$$

For the subject tank, we have the lateral earth pressure at rest as

$$P_{er\_L} := \kappa_o \cdot \rho_{ws} \cdot L_B$$

III. Lateral Water Load

Height of Water Table Above the Bot. of Shell $h_w = 180 \text{ in}$

Lateral Pressure at Rest Below Ground Water Table $P_{hy} := \rho_w \cdot h_w = 6.498 \cdot psi$

IV. Combined Lateral Load

Combined Pressure Due to Earth Load and Water $P_{s\_ep} := \overrightarrow{\left(P_{hy} + P_{er\_L}\right)}$

$$P_{s\_ep} = 10.144 \cdot psi$$

2.3 Stress Analysis

I. Hoop/Circumferential Crushing

If the tank is in a wet hole, the hydrostatic pressure on the outside of the cylinder produces compressive membrane stresses in the shell if the tank is empty.

The maximum compressive stress in the the cylindrical shell of the system occurs at the bottom of the tank. The expression for these stresses, for the cylinder are given by (Structural Plastics Design Manual, Vol. 2, 1984, ASCE, p. 928-930):

$$\sigma_{s\_c} := \frac{\overrightarrow{P_{s\_ep} \cdot R_m}}{t_s}$$

$tsu \equiv (0.29)$ Shell Structure Thk.

$\sigma_{s\_c} = \left(1.684 \times 10^{3}\right) \cdot psi$

Compressive Strength of Shell $\sigma_{s\_a\_ep} := 20000 \cdot psi$

Safety Factor of Shell Under Combined External Pressure $SF_{s\_ep} := \overrightarrow{\left(\frac{\sigma_{s\_a\_ep}}{\sigma_{s\_c}}\right)}$ $SF_{s\_ep} = (11.876)$

II. Buckling Analysis

The design for underground global buckling is performed according to the methodology detailed in [Moser,A.P.; Buried Pipe Design,1990, pages 65-68]. For this analysis, the cylindrical part of the tank is analyzed for overall buckling against soil and underground water loading, neglecting the constraining end effects of the bottom.

The critical buckling pressure in global buckling mode is given by the modified Luscher formula by Meyerhof and Baike.

Modulus of Soil Reaction $E' := 2000 \cdot psi$ SC3 Fine-grained soils with medium to no plasticity (CL, ML, ML–CL), or borderline soil (ML/CL), or any dual symbol or borderline soil beginning with one of these symbols, with ≥30% coarse-grained particles

Moment of Inertia of Tank per Unit Length $I_{s\_un} := Isu \cdot in^{3}$

Buckling Safety Factor $FS_{bu} \equiv 2.5$

Shell Hoop Flexural Modulus $E_{hf} = \left(4.496 \times 10^{6}\right) \cdot psi$

Poisson's Ratio $\upsilon = 0.25$

Critical Buckling Pressure $P_{cr} := \overrightarrow{\left[2 \cdot \sqrt{\frac{E'}{1 - \upsilon^{2}} \cdot \left(\frac{E_{hf} \cdot I_{s\_un}}{R_m^{\ 3}}\right)}\right]}$

$P_{cr} = (263.532) \cdot psi$

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Actual Safety Factor Against Buckling $FS_{bu\_a} := \overrightarrow{\left(\frac{P_{cr}}{P_{s\_ep}}\right)}$ $FS_{bu\_a} = (25.98)$

$checkshellbuckling_i := if\left(FS_{bu\_a_i} \geq FS_{bu}, "OK", "Buckle"\right)$

$checkshellbuckling = ("OK")$

III. Trapezoidal Shell Stiffener Design

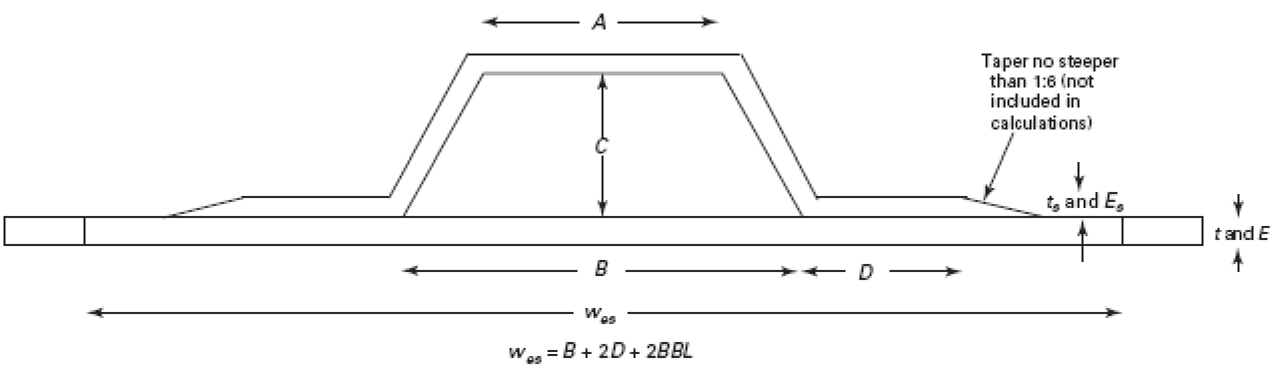
Stiffener Spacing on Shell $Lst := 24 \cdot in$

Max. Design Unsupported Length (This includes 1/3 of head depth) $L_{st\_max} := Lst - 4 \cdot in \cdot 2 = 16\,in$

Required Moment of Inertia of Stiffener

$P_{sti\_q} := \left(P_{s\_ep}\right) = 10.144 \cdot psi$

Fig. NM17-2 Stiffener Moment of Inertia for a Trapezoidal Stiffener



Stiffener Construction: Filament Wound

Stiffener Top Hoop Tensile Modulus: $E_{sr_i} := 14000000 \cdot psi$

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Stiffener Side Hoop Tensile Modulus: $E_{srl_i} := 1400000 \cdot psi$

Stiffener Top FW Thk.: $t_{sr} := (0.24) \cdot in$

Stiffener Side Chop Thk.: $t_{s\_sd} := (0.24) \cdot in$

Shell Outside Diameter: $D_{sh\_o} := \overrightarrow{\left(D + 2 \cdot t_s\right)}$

Stiffener Effective Dimensions: $A_i := 2 \cdot in$ $C_i := 2 \cdot in$ $B_i := 4 \cdot in$ $D_{sr_i} := 2 \cdot in$

Shell Thk: $t_{sh} := t_{stot} = (0.29)\ in$

Shell Hoop Tensile Modulus: $E_{sh} := E_h = \left(4.314 \times 10^6\right) \cdot psi$

$$\phi := \overrightarrow{acos\left[\frac{C}{\sqrt{C^2 + \left(\frac{B - A}{2}\right)^2}}\right]} \qquad \overrightarrow{\left(\phi \cdot \frac{180}{\pi} \cdot deg\right)} = (26.565) \cdot deg \qquad L_{sr} := \overrightarrow{\sqrt{C^2 + \left(\frac{B - A}{2}\right)^2}}$$

Area of Sides: $A_s := \overrightarrow{\left(L_{sr} \cdot t_{s\_sd}\right)}$

Effective Width of Cylinder: $w_{es} := \overrightarrow{\left(B + 2 \cdot D_{sr}\right)}$

Effective Area of Cylinder: $A_c := \overrightarrow{\left(w_{es} \cdot t_{sh}\right)}$

Area of Top: $A_t := \overrightarrow{\left(A \cdot t_{sr}\right)}$

Area of Base: $A_d := \overrightarrow{\left[2 \cdot \left(D_{sr} - t_{s\_sd}\right) \cdot t_{s\_sd}\right]}$

Total Effective Area of Stiffener Excluding Shell: $A_{tot} := \overrightarrow{\left(A_t + A_d + A_s\right)}$

Effective Hoop Modulus of Stiffener and Cylinder: $E_{srh} := \overrightarrow{\dfrac{E_{sh} \cdot A_c + E_{sr} \cdot \left(A_t + A_d\right) + E_{srl} \cdot A_s}{A_c + A_{tot}}} = \left(7.009 \times 10^6\right) \cdot psi$

Required MOI of Ring:

$$I_{sr\_min} := \overrightarrow{\frac{P_{sti\_q} \cdot Lst \cdot D_{sh\_o}^{\ 3}}{24 \cdot E_{srh}}} = (1.304) \cdot in^4$$

Effective CG From Outside of Shell:

$$CG := \overrightarrow{\frac{A_c \cdot \left(\frac{-t_{sh}}{2}\right) + \frac{t_{sr}}{2} \cdot \frac{E_{sr}}{E_{sh}} \cdot A_d + A_s \cdot \frac{C}{2} \cdot \frac{E_{srl}}{E_{sh}} + A_t \cdot \left(C + \frac{t_{sr}}{2}\right) \cdot \frac{E_{sr}}{E_{sh}}}{A_c + A_s \cdot \frac{E_{srl}}{E_{sh}} + \left(A_t + A_d\right) \cdot \frac{E_{sr}}{E_{sh}}}}$$

$CG = (0.511)\ in$

I of Each Side About the Centroid of the Sides:

$$I_{side} := \overrightarrow{\left(\frac{t_{s\_sd} \cdot L_{sr}^{\ 3}}{12} \cdot \cos(\phi)^2 + \frac{L_{sr} \cdot t_{s\_sd}^{\ 3}}{12} \cdot \sin(\phi)^2\right)} = (0.179)\ in^4$$

About the Centroid:

$$I_1 := \overrightarrow{\left(\frac{w_{es} \cdot t_{sh}^{\ 3}}{12} \cdot \frac{E_{sh}}{E_{srh}} + \frac{\frac{E_{srl}}{E_{srh}} \cdot A_d \cdot t_{s\_sd}^{\ 2}}{12} + \frac{E_{srl}}{E_{srh}} \cdot 2 \cdot I_{side} + \frac{\frac{E_{sr}}{E_{srh}} \cdot A_t \cdot t_{sr}^{\ 2}}{12}\right)}$$

$$I_2 := \overrightarrow{\left[t_{sh} \cdot w_{es} \cdot \left(CG + \frac{t_{sh}}{2}\right)^2 \cdot \frac{E_{sh}}{E_{srh}} + A_d \cdot \frac{E_{srl}}{E_{srh}} \cdot \left(CG - \frac{t_{s\_sd}}{2}\right)^2 + A_s \cdot \frac{E_{srl}}{E_{srh}} \cdot \left(\frac{C}{2} - CG\right)^2 + A_t \cdot \frac{E_{sr}}{E_{srh}} \cdot \left(C + \frac{t_{sr}}{2} - CG\right)^2\right]}$$

Effective MOI Considering Different Moduli of Shell and Stiffener: $I_e := \overrightarrow{\left(I_1 + I_2\right)} = (3.236) \cdot in^4$

$checkstiffenerMOI_i := if\left(I_{e_i} \geq I_{sr\_min_i}, \text{"Adequate"}, \text{"Stiffener Inadequate"}\right)$

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checkstiffenerMOI = ("Adequate")

Moment of Inertial of Shell per Inch $\Sigma I_u := \overrightarrow{\left(\frac{I_e}{L_{st\_max}}\right)}$ $\Sigma I_u = (0.202)\cdot in^3$

Stiffener Unit Weight Isu ≡ (0.202)

$W_{stif} := \overrightarrow{\left[\pi\cdot(D_o + 2CG)\cdot\left[A\cdot t_{sr} + (L_{sr} + D_{sr})\cdot t_{s\_sd}\right]\cdot\rho_{frp}\right]}$

Number of Stiffeners on Shell $N_{sr} := (26)$

$W_r := \overrightarrow{(N_{sr}\cdot W_{stif})}$

$W_{stif} = (29.829)\ lb$ $W_r = (775.558)\ lb$

$\Sigma W_r := \sum W_r = 775.558\ lb$

See FEA buckling analysis for shell w/ stiffeners.

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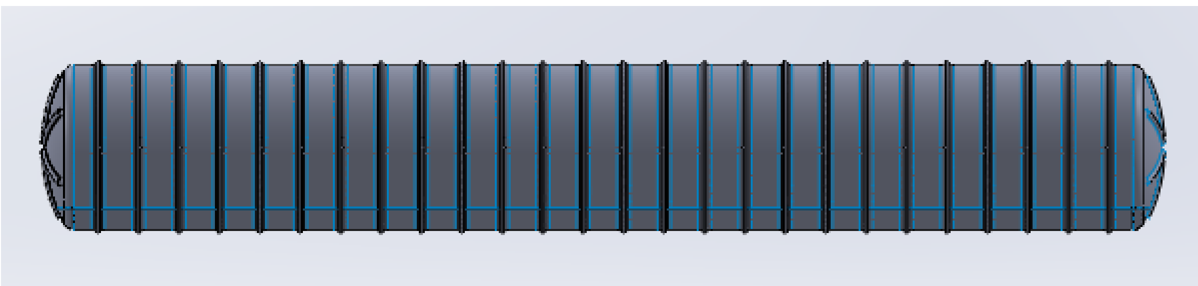
Shell W/ Stiffeners Under External Pressure Finite Element Analysis

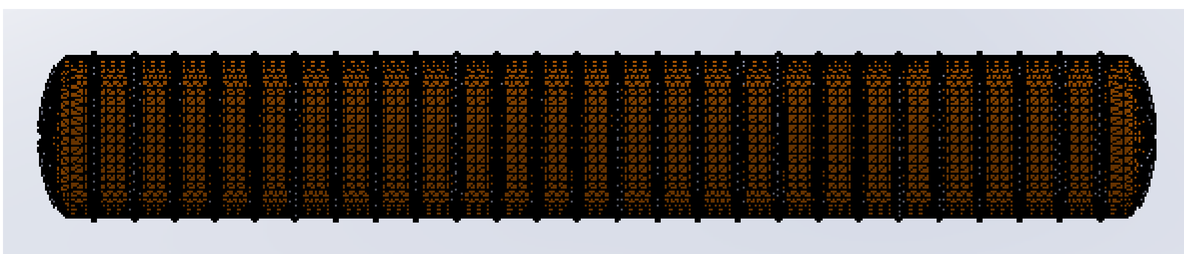
See external pressure calculation in section 2.2 IV.

Tank is simply supported at the bot. 180 deg. surface.

Buckling analysis is run to investigate the safety factor against buckling for the shell and stiffeners assembly



Solid Model



Meshed Model

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Buckling Safety Factors For Shell + Stiffeners Assembly

"Mode No."	"Buckling Factor of Safety"
1	3.2011
2	3.2071
3	3.3664
4	3.3731
5	3.4237

Greater than min. buckling factor 2.5, OK.

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Chapter 3 Dished Heads

Head Construction	Hand Layup
Head Configuration	ASME F & D
Head Straight Flange Length	$sf_{th} := 1.5 \cdot in$
Head Structural Thk.	$t_{th} := 0.31 \cdot in$
Head Total Thk.	$t_{th\_tot} := t_{th} + t_{cb} = 0.31 \cdot in$
Tensile Modulus	$E_{th} := 1500 \cdot ksi$
Tensile Strength	$S_{th} := 15 \cdot ksi$
Flexural Modulus	$E_{th\_f} := 1000 \cdot ksi$
Ultimate Flexural Strength	$S_{th\_f} := 22 \cdot ksi$
Poisson's Ratio	$\upsilon \equiv 0.25$
Design Factor For Pressure	$F_s = 10$
Design Factor For Vacuum and Combined Load	$F_{vac} = 2.5$

3.1 Head Design for Pressure

Head Construction: Hand Layup

Head Design Pressure: $P_{H\_ip} := P_{s\_ip} = 3.466 \cdot psi$

Head Inside Dish Radius: $R_c := 96 \cdot in$

Head Inside Knuckle Radius: $r_c := 6 \cdot in$

Minimum Required thk. For Pressure: $t_{h\_ip} := \dfrac{0.885 P_{H\_ip} \cdot R_c}{\dfrac{S_{th}}{F_s}} = 0.196\ in$

$checkheadthkip := if\left(t_{th\_tot} \geq t_{h\_ip}, \text{"OK"}, \text{"Increase head thk."}\right) = \text{"OK"}$

3.2 Design of Head to Shell Joint

Joint Tensile Modulus: $E_j := E_{th}$

Secondary Bond Shear Strength: $\tau_j := 2000 \cdot psi$

Left & Right Head to Shell Joint

Min. Req'd Joint Thk.: $t_{jH\_min} := \dfrac{P_{H\_ip} \cdot \left(\dfrac{D}{2} + t_{s_1}\right)}{\left(0.001 \cdot E_j\right)} = 0.112\ in$

Design Joint Thk.: $t_{jH} := t_{th} = 0.31\ in$

Min. Req'd Joint Length: $$L_{jH\_min} := \frac{P_{H\_ip} \cdot \left(\frac{D}{2} + t_{s_1}\right)}{2 \cdot \frac{\tau_j}{F_s}} = 0.418\ \text{in}$$

Design Joint length: See detail. in Appendix A

3.3 Head Design for External Loads

Design Max External Pressure $P_{H\_ep} := P_{s\_ep} = 10.144 \cdot \text{psi}$

Finite Element Analysis of Dished Heads

Applied Load : - Gravity

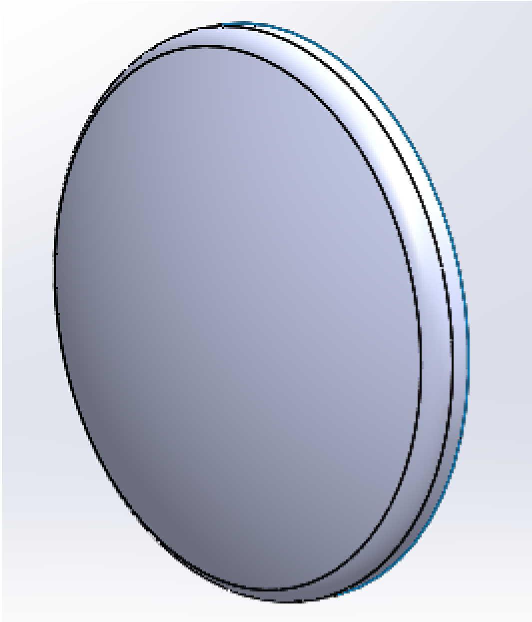
- External Water Pressure

- Soil Load

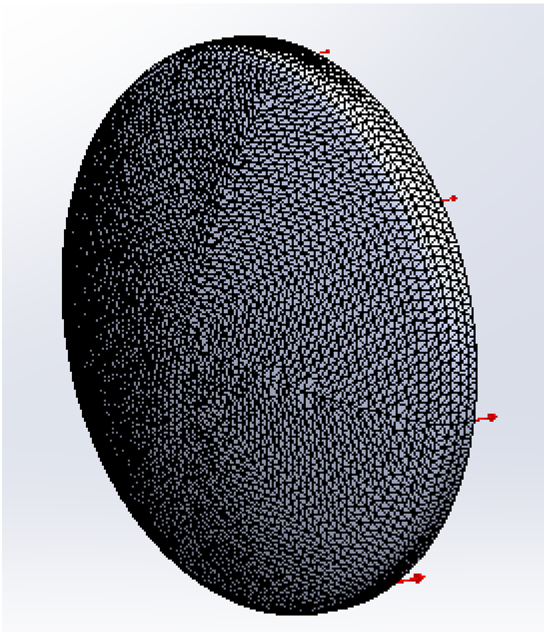
Boundary Condition: Fixed around the perimeter of the top head. (For simplicity of analysis.)

Finite element analysis is performed based on the load and boundary conditions as stated above and material properties and thks specified in the previous sections of thie report. Solidworks 2012 Simulation is used for this analysis.

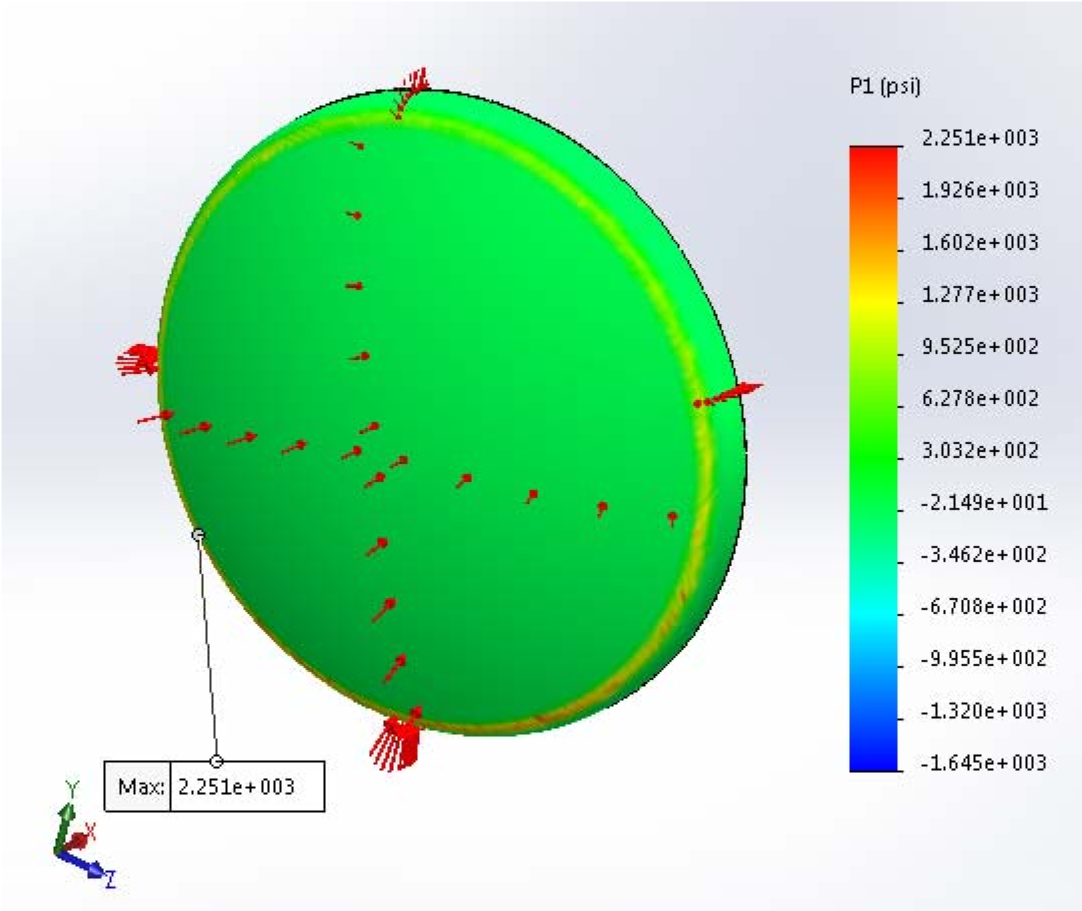
FEA Solid Model



Meshed Model

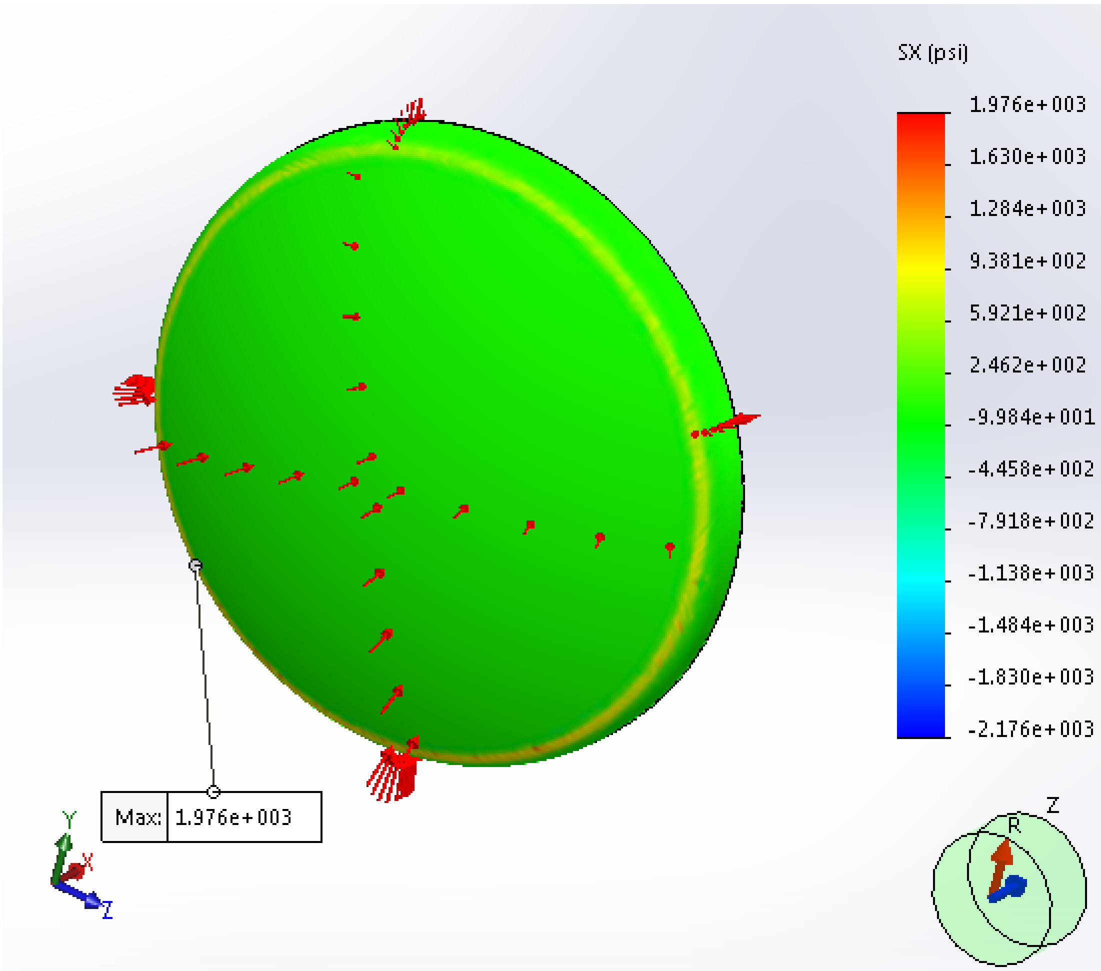


1st Principal Stress



Tank head is under external pressure. Max. allowable compressive stress in type II hand layup laminate is 20,000 psi / 3 = 6,667 psi. Max. 1st principal stress in the head is 2,251 psi. Buckling analysis is run to evaluate the head's stability under external loads.

X - Stress


SX (psi)
1.976e+003
1.630e+003
1.284e+003
9.381e+002
5.921e+002
2.462e+002
-9.984e+001
-4.458e+002
-7.918e+002
-1.138e+003
-1.484e+003
-1.830e+003
-2.176e+003
Max: 1.976e+003
Y
X
Z
R
Z

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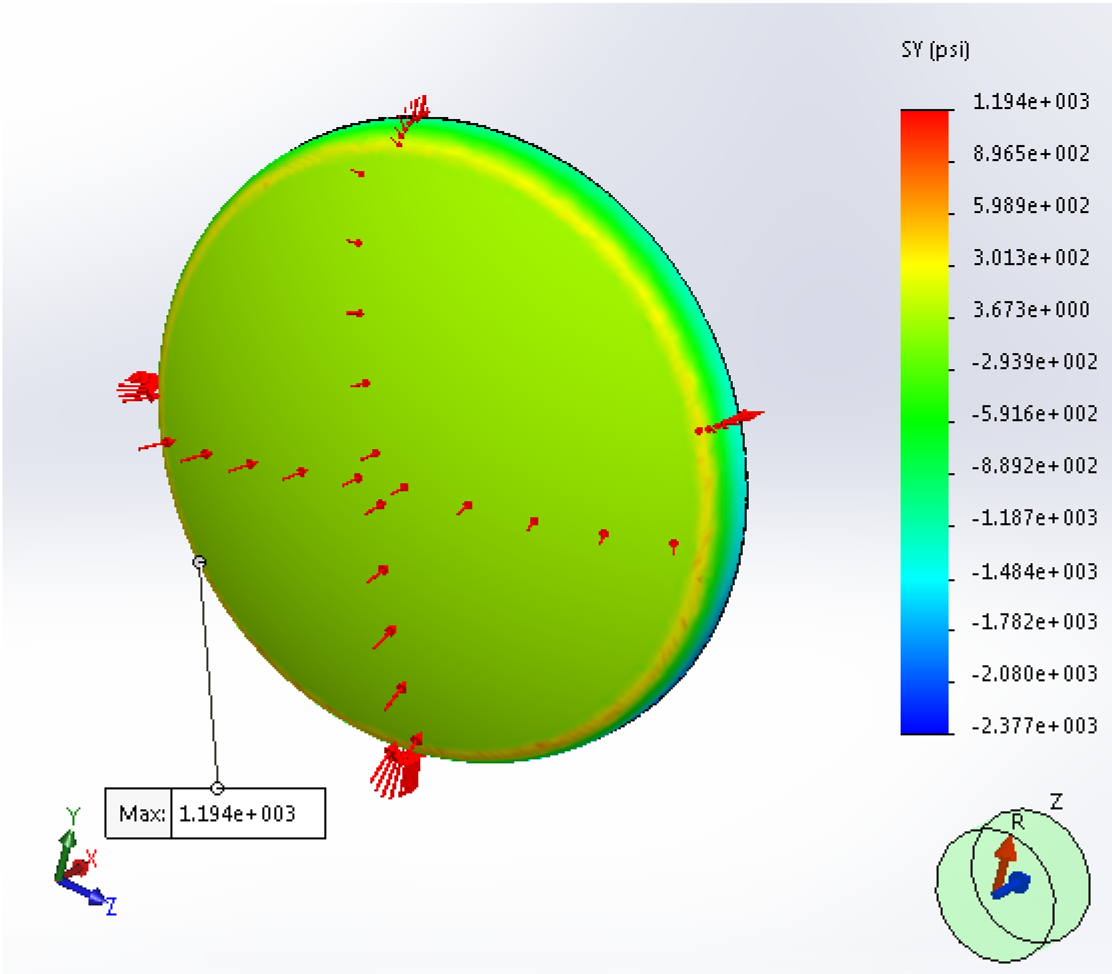
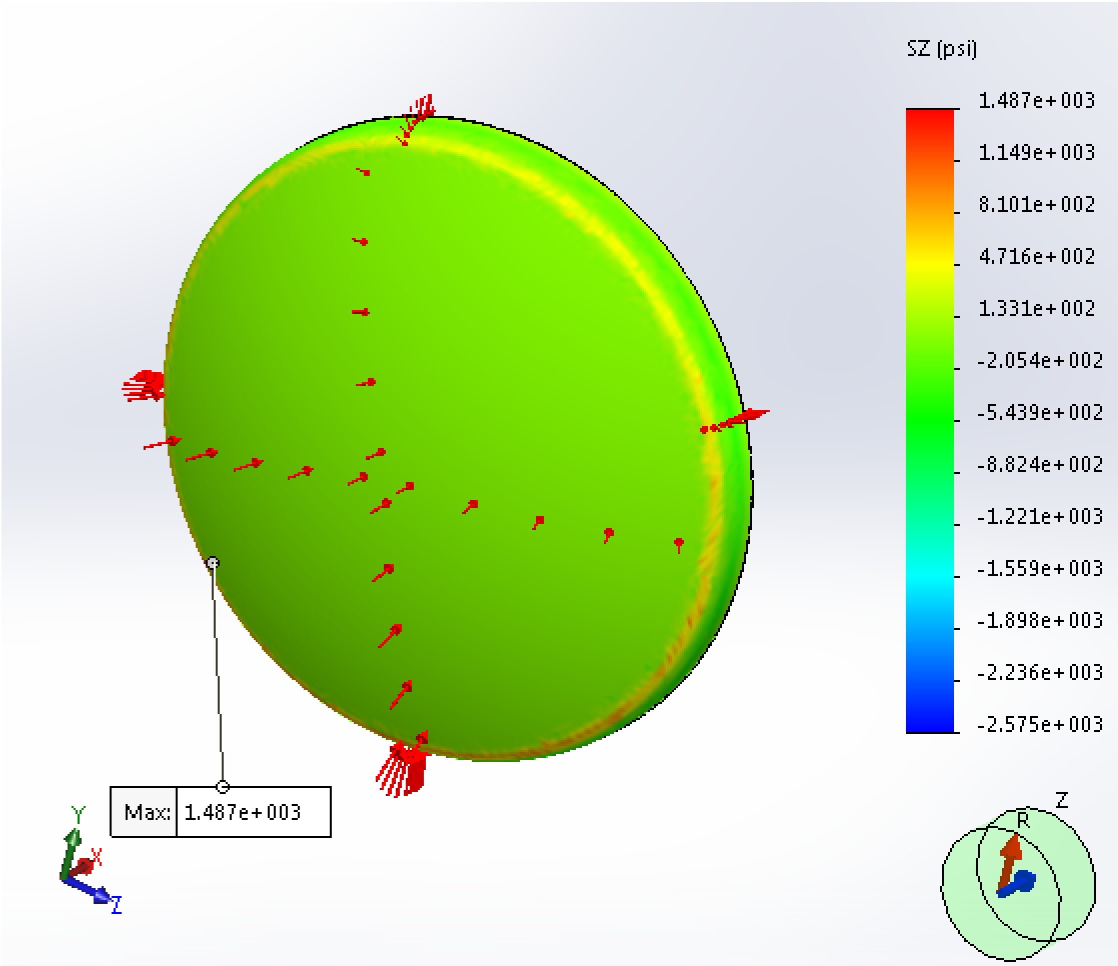
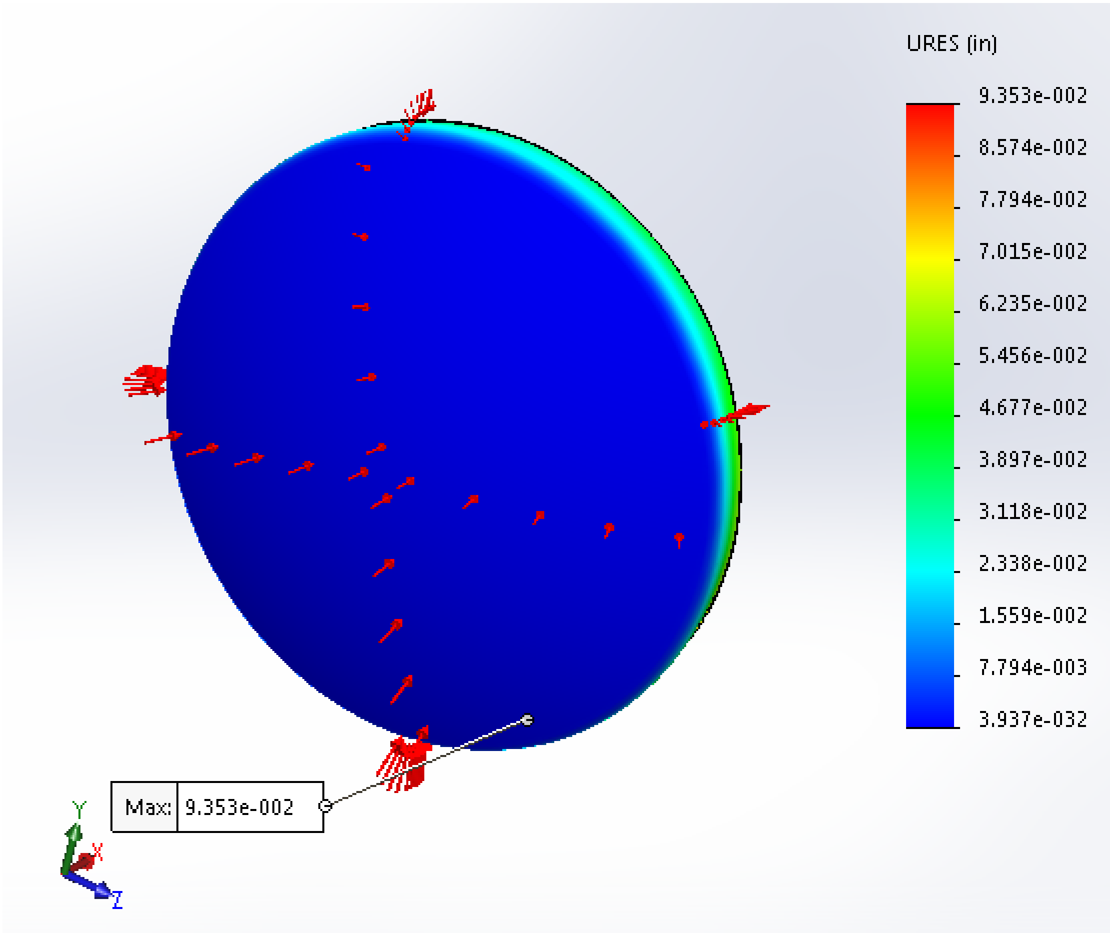
Y - Stress



Z - Stress


SZ (psi)
1.487e+003
1.149e+003
8.101e+002
4.716e+002
1.331e+002
-2.054e+002
-5.439e+002
-8.824e+002
-1.221e+003
-1.559e+003
-1.898e+003
-2.236e+003
-2.575e+003
Max: 1.487e+003
Y
X
Z
R
Z

Resultant Displacement



Less than 0.75", OK.

Note : Deflection is exaggerated by 50 times for clarity.

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Buckling Safety Factor

"Mode No."	"Buckling Factor of Safety"
1	2.5228
2	2.5326
3	2.5509
4	2.5731
5	2.7976

Greater than 2.5. OK.

BLF Value (factor of safety)	Buckling Status	Notes
1 < BLF	Buckling not predicted	The applied loads are less than the estimated critical loads. Buckling is not expected.
0 < BLF < 1	Buckling predicted	The applied loads exceed the estimated critical loads. Buckling is expected.
BLF = 1	Buckling predicted	The applied loads are exactly equal to the estimated critical loads. Buckling is expected.
BLF = -1	Buckling not predicted	The buckling occurs when the directions of the applied loads are all reversed. For example, if a bar is under tensile load, the BLF should be negative. The bar will never buckle.
-1 < BLF < 0	Buckling not predicted	Buckling is predicted if you reverse all loads.
BLF < -1	Buckling not predicted	Buckling is not expected even if you reverse all loads.

Chapter 4 Component Weight

Weight of Each Head: $W_H := Wt_{torihead}(\rho_{frp}, r_c, R, R_c, 0, t_{th})$

$W_H = 175.043lb$

Head Depth: $$h_H := R_c - \left[(R_c - r_c)\cdot\cos\left(\operatorname{asin}\left(\frac{\frac{D}{2} - r_c}{R_c - r_c}\right)\right)\right]$$

$h_H = 16.401\ in$

Weight of Shell: $W_S := \rho_{frp}\cdot\pi\cdot D\cdot H\cdot\left|t_{stot}\right| = 3.576\times 10^3\ lb$

$W_S = 3.576\times 10^3\ lb$

Top Head Volume: $V_{L\_H} := f\_volts(r_c, R, R_c, 0) = 314.542\cdot gal$

Tank Volume (Flooded): $V_L := 2V_{L\_H} + \pi\cdot R^2\cdot H$

$V_L = 2.034\times 10^4\ gal$

Content Weight: $W_L := \rho_c\cdot V_L = 4.078\times 10^5\ lb$

Extra FRP Dead Weight (Covers joints, nozzles, and repads etc.) $W_{ad1} := 1000\cdot lb$

Total Weight Multiplication Factor: $\eta := 1.15$

Total FRP Tank Weight: $W_{FRP} := \left|W_S + 2 \cdot W_H + W_{ad1} + W_r\right| \cdot \eta = 6.557 \times 10^3 \, lb$

Total FRP + Content Weight: $W_T := W_{FRP} + W_L = 4.144 \times 10^5 \, lb$

Chapter 5 Buoyancy Design

1. Buoyant force acting on the underground tank is equal to the weight of fluid which the tank displaces.

2. Tank tank w/ stiffeners' weights, soil load above the tank within the friction angle, and the weight of the concrete deadman attached to the tank are used to resist buoyancy.

Buoyancy Design Safety Factor $SF_{by} \equiv 1.2$

Saturated Backfill Material Density $\rho_{fil} := 70 \cdot \frac{lb}{ft^3}$

Projected Area $A_{prj} := D \cdot H = 6.038 \times 10^4 \cdot in^2$

Estimated Weight of Tank Used to Counteract Buoyancy $W_{by\_ww} := W_{FRP} = 6.557 \times 10^3 \, lb$

Total Volume of Water Displaced $V_{h2o} := V_L = 2.034 \times 10^4 \, gal$

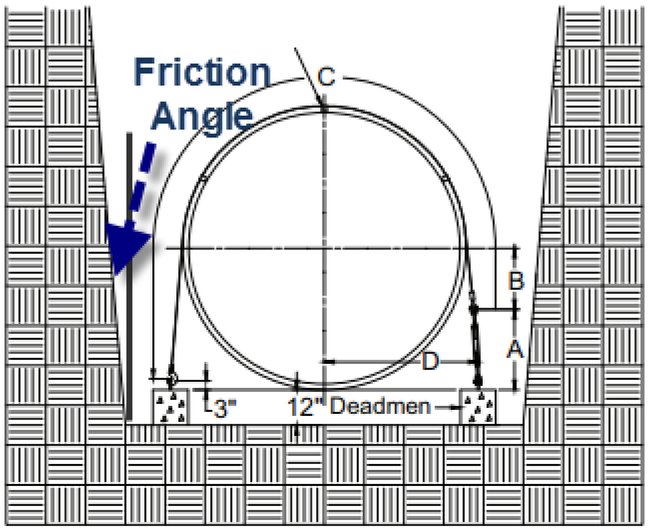
Total Weight of Water Displaced $W_{h2o} := \rho_w \cdot V_{h2o} = 1.696 \times 10^5 \cdot lb$

Design Buoyancy Force $F_{by} := W_{h2o} \cdot SF_{by} = 2.035 \times 10^5 \cdot lb$

Min. Backfill Height $d_{bk} := 3 \cdot ft$

Soil Friction Angle (Estimated) $\phi := 20 \cdot deg$

$$\phi_r := \frac{\phi}{180 \cdot deg} \cdot \pi = 0.349$$



Soil friction angle must be verified by end user. Ecavate area must be greater than 20 degree area. All excavated in situ soil must be replaced with primary backfill material. Back fill soil must be even and uniform in every direction.

Base Area $a_b := D \cdot H$

Height $h := d_{bk} + \frac{D}{2} = 7 \cdot ft$

$$\Delta := h \cdot \tan(\phi_r) = 30.573\ in$$

Top Area $a_t := (D + 2 \cdot \Delta)(H + 2 \cdot \Delta) = 1.085 \times 10^5\ in^2$

Concrete Deadmen Qty $N_d := 6$

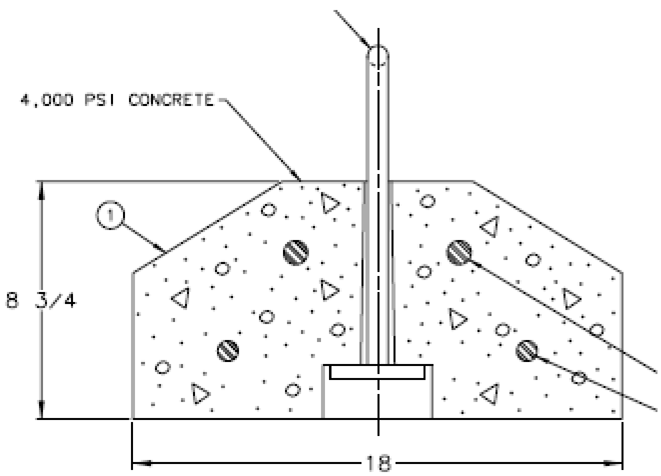
Concrete Deadmen Length $L_d := 16 \cdot ft$

Unit Weight $w_d := 2400 \cdot lb$

Concrete Deadmen Width $b_d := 18 \cdot in$

Total Concrete Deadmen Weight When Submerged $W_d := N_d \cdot w_d \cdot \frac{\rho_c - \rho_w}{\rho_c} = 8.411 \times 10^3\ lb$

Soil Above Deadmen Below Tank C.L. $V_{d\_sl} := N_d \cdot L_d \cdot b_d \cdot \frac{D}{2} = 576 \cdot ft^3$



Volume of Backfill and Soil Above Tank Used to Counteract Buoyancy $V_s := \frac{h}{3} \cdot \left(a_t + a_b + \sqrt{a_t \cdot a_b}\right) - \frac{1}{4} \cdot \pi \cdot D^2 \cdot H \cdot \frac{1}{2} = 2.73 \times 10^3 \cdot ft^3$

Backfill Weight $W_{bk} := \left(V_s + V_{d\_sl}\right) \cdot \rho_{fil} = 2.314 \times 10^5\ lb$

Weight of Concrete Required To Hold Down the Tank When Totally Submerged $W_{c\_r} := F_{by} - W_{by\_ww} - W_{bk} = -3.443 \times 10^4 \cdot lb$

checkbuoyancy := if$\left(W_d \geq W_{c_r}\right.$, "Adequate" , "Additional Weight Req'd" $\left.\right)$ = "Adequate"

See concrete deadmen design sketch in Appendix A.

Chapter 6 Lifting Lug Design

Lifting Lug are Attached by Hoop Filament Wound Glass

A36 C.S. = Lifting Lug Material

$W_{FRP} = 6557\,lb$ = Total Empty Tank Weight

$N_L := 4$ = Number of Lift Lugs

$t_{lug} := 0.375 \cdot in$ = Thickness of Backing Plate

$w_L := 8 \cdot in$ = Width of Backing Plate

$h_L := 10 \cdot in$ = Height of Backing Plate

$e_{lift} := 1.5 \cdot in$ = Eccentricity

$S_v := 2000 \cdot psi$ = FRP Shear Strength

$S_a := 15000 \cdot psi$ = FRP Axial Tensile Strength

$S_h := 30000 \cdot psi$ = FRP Hoop Tensile Strength

$t_{o1} := 0.40 \cdot in$ = Hoop Overwind Thk.

$\lambda := 1.5$ = Design Factor

A36 C.S. = Lug Material

Material properties from ASME Section II part D for ambient temperature.

	Es	Sy	Su
A36	29000 ksi	36 ksi	58 ksi
304 S.S.	29000 ksi	30 ksi	75 ksi
316S.S.	29000 ksi	30 ksi	75 ksi

Lug Eastic Modulus $Ecs := 29000 \cdot ksi$

Lug Yield Strength $Fy_{lug} := 36 \cdot ksi$

Lug Ultimate Tensile Strength $Fu_{lug} := 58 \cdot ksi$

CALCULATIONS

Reinforcement pad thickness $t_p := 0.043 in \cdot 5 = 0.215 in$ (All Mat Construction)

Reinforcement pad height $L_p := h_L + 6 \cdot in = 16 in$

Reinforcement pad width $w_p := w_L + 6 \cdot in = 14 in$

Pad + shell thickness $t_{ps} := t_p + t_{sh} = (0.505)\, in$

Load per lug $F_{lift} := \frac{\lambda \cdot W_{FRP}}{N_L} = 2.459 \times 10^3\, lb$

Bending moment per lug $M_L := F_{lift} \cdot e_{lift} = 3.688 \times 10^3\, in \cdot lb$

Unit radial load on overwrap $W_{max} := \frac{3 \cdot F_{lift} \cdot e_{lift}}{w_L^2} = 172.883 \frac{lb}{in}$

Total radial load due to lug moment $P_L := \frac{W_{max} \cdot w_L}{2} = 691.533\, lb$

Overwind mean radius $R_o := R + t_{ps} = (48.505)\, in$

Hoop overwind load $T_{tl} := \frac{P_L \cdot R_o}{h_L} = \left(3.354 \times 10^3\right) lb$

Hoop overwind tensile stress $\sigma_o := \dfrac{T_{tl}}{h_L \cdot t_{o1}} = (838.57)\cdot psi$ OK

Shear across vessel wall $\tau_o := \dfrac{P_L}{t_{ps} \cdot h_L} = (136.937)\cdot psi$ OK

Coefficient of bending in vessel wall: $\beta_L := \dfrac{1.28}{\sqrt{R_o \cdot t_{ps}}} = 0.259\,\dfrac{1}{in}$

Poisson's ratio $\upsilon = 0.25$

Unit radial loading $P_{star} := \dfrac{P_L}{h_L} = 69.153\,\dfrac{lb}{in}$

Bending loads:

$$M_{ax.L} := \frac{P_{star}}{4 \cdot \beta_L} = 66.847\,lb$$

$$M_{hp.L} := \upsilon \cdot M_{ax.L} = 16.712\,lb$$

Loads due to pressure:
Zero during lift

$$N_{axL} := 0$$

$$N_{hpL} := 0$$

Bending stress on shell, psi:

$$\sigma_{ax.L} := \frac{6 \cdot M_{ax.L}}{t_{ps}^{2}} + \frac{N_{axL}}{t_{ps}} = \left(1.573 \times 10^{3}\right)\cdot psi$$

$$\sigma_{hp.L} := \frac{6 \cdot M_{hp.L}}{t_{ps}^{2}} + \frac{N_{hpL}}{t_{ps}} = (393.179)\cdot psi$$

Safety factor for bending:

$$\frac{S_a}{\sigma_{ax.L}} = (9.538) \quad > 3 \text{ OK}$$

$$\frac{S_h}{\sigma_{hp.L}} = (76.301) \quad > 3 \text{ OK}$$

LIFTING RING STRESS CHECK

Diameter of Ring Rod $d_{bolt} := 0.5 \cdot in$

Ring Outside Diameter $od_{ring} := 1.25 \cdot 2 \cdot in = 2.5\, in$

Ring Inside Diameter $id_{ring} := 1.5 \cdot in$

Diameter of Pin $d_{pin} := 0.75 \cdot in$

$\phi_{gross} := .90$ $\Omega_{gross} := 1.67$

$\phi_{net} := .75$ $\Omega_{net} := 2$

Shear lag factor $U := 1$ table D3.1

Net area $An := 0.141 \cdot in^2$

Tensile rupture in net area $Ft_{net} := \frac{Fu_{lug}}{\Omega_{net}}$

$Vcap_1 := Ft_{net} \cdot An \cdot U$ $Vcap_1 = 4.089 \times 10^3\, lb$

AISC(13th ed.), sect. J7 bearing strength

$\phi_{brg} := .75$ $\Omega_{brg} := 2$ LRFD

$Allow_{mushrooming} :=$ "yes"

Allowable bearing stress: $F_{brg} := 1.8 \cdot \frac{Fy_{lug}}{\Omega_{brg}}$

Projected bearing area: $A_{brg} := d_{pin} \cdot d_{bolt}$

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Allowable load for bearing: $Vcap_2 := \begin{cases} F_{brg} \cdot A_{brg} & \text{if } Allow_{mushrooming} = \text{"no"} \\ Vcap_1 & \text{if } Allow_{mushrooming} = \text{"yes"} \end{cases}$ $Vcap_2 = 4.089 \times 10^3\ lb$

AISC(13th ed.), sect. J4-2 Strength of connecting elements in shear

shear yeilding $\phi_{sy} := 1$ $\Omega_{sy} := 1.5$

Net shear area: $Anv_{sr} := 2 \cdot \frac{1}{4} \cdot \pi \cdot d_{bolt}^2$

shear rupture $\phi_{sr} := .75$ $\Omega_{sr} := 2$

Net area subject to shear: $Anv_{sr} := Anv_{sr}$

$Rn_{sr} := 0.6 \cdot Fu_{lug} \cdot Anv_{sr}$

$Vcap_3 := \frac{Rn_{sr}}{\Omega_{sr}}$ $Vcap_3 = 6.833 \times 10^3\ lb$

AISC(13th ed.), sect. J4-3 Block shear strength

Block Shear $\phi_{sb} := .75$ $\Omega_{sb} := 2$ $U_{bs} := 1$ tension is uniform

Net area subject to tension $A_{nt} := An$

Net area subject to shear $A_{nv} := Anv_{sr}$

$Rn_{sb} := \min\left(0.6 \cdot Fu_{lug} \cdot A_{nv} + U_{bs} \cdot Fu_{lug} \cdot A_{nt}\right)$ AISC(13th ed.), J4-5

$Vcap_4 := \frac{Rn_{sb}}{\Omega_{sb}}$ $Vcap_4 = 1.092 \times 10^4\ lb$

AISC(13th ed.), sect. D5

tensile rupture $\quad \phi_{tr} := .75 \quad \Omega_{tr} := 2$

$Pn_{tr} = 2 \cdot thk \cdot b_{eff} \cdot Fu_{lug}$

$b_{eff} := d_{bolt}$

$b_{eff} = 0.5\,in$

$Vcap_5 := 2 \cdot An \cdot \frac{Fu_{lug}}{\Omega_{tr}} \qquad Vcap_5 = 8.178 \times 10^3\,lb$

$$Vcap = \begin{pmatrix} 4.089 \times 10^3 \\ 4.089 \times 10^3 \\ 6.833 \times 10^3 \\ 1.092 \times 10^4 \\ 8.178 \times 10^3 \end{pmatrix} lb \qquad \frac{\min(Vcap)}{F_{lift}} = 1.663$$

must be greater than 1

Chapter 7 Opening Reinforcement

Reference: RTP-1 3A-700 - 730

$P_{int} = 0.0$	= Design Pressure
d_n	= Nozzle Diameter
h_n	= Nozzle Elevation
P_n	= Pressure at Nozzle Centerline
t_r	= Required Reinforcement Thickness
D_r	= Required Reinforcement Diameter
t_n	= Nozzle Neck Thickness
t_i	= Inside Bond Thickness
t_o	= Outside Bond Thickness
$H = 629\ \text{in}$	= Max Liquid Level
$S_r := S_{th}$	= Strength of Reinforcement Laminate
$sg = 1.00$	= Specific Gravity of Tank Contents

7.1 Shell Nozzle Opening Reinforcement

$$d_n := \begin{pmatrix} 4 \\ 24 \\ 30 \end{pmatrix} \cdot \text{in} \qquad h_n := \begin{pmatrix} 96 \\ 96 \\ 96 \end{pmatrix} \cdot \text{in} \qquad \Delta h := \overrightarrow{\left(D - h_n\right)} \qquad \Delta h = \begin{pmatrix} 1.748 \times 10^{-14} \\ 1.748 \times 10^{-14} \\ 1.748 \times 10^{-14} \end{pmatrix} \text{in}$$

$$k := 1 .. \text{last}\left(d_n\right)$$

Calculate Pressure at Each Nozzle:

$$P_{n_k} := P_{int} + \Delta h_k \cdot sg \cdot \rho_{ws} \qquad P_n = \begin{pmatrix} 0.00 \\ 0.00 \\ 0.00 \end{pmatrix} \cdot \text{psi}$$

Calculate Reinforcement Diameter:

$$D_{r_k} := \overrightarrow{\text{if}\left[\left(d_{n_k}\right) > 6 \cdot \text{in}, \left(2 \cdot d_{n_k}\right), \left(d_{n_k} + 6 \cdot \text{in}\right)\right]}$$

Required Cutout Reinforcement Dia.: $D_r = \begin{pmatrix} 10 \\ 48 \\ 60 \end{pmatrix} \cdot in$

Calculate Coefficient "K":

$K_{n_k} := if\left[d_{n_k} < 6 \cdot in, \left(\frac{d_{n_k}}{6 \cdot in}\right), 1.0\right]$ $K_n = \begin{pmatrix} 0.67 \\ 1.00 \\ 1.00 \end{pmatrix}$

Calculate Coefficient "M":

Laminate type: type := "X" (X for filament wound, I and II for HLU)

Hoop tensile strength for shell: $\sigma_{u_k} := 0.01 \cdot E_{h_1}$

Factor M $M_{r_k} := \begin{cases} 1 & \text{if } type = "I" \vee type = "II" \\ \frac{\sigma_{u_k}}{15000 \cdot psi} & \text{otherwise} \end{cases}$

Calculated Structural Thk: $T_{c_k} := t_{s_1}$

Theoretical Structural Wall Thk.: $T_t := T_c$

Factor V $V_k := \frac{1}{2}$ (pressure governs V=1, vacuum governs V=1/2)

Calculate Reinforcement Thickness:

$$t_{r_k} := V_k \cdot M_{r_k} \cdot K_{n_k} \cdot T_{t_k} - M_{r_k} \cdot \left(T_{c_k} - T_{t_k}\right)$$

$$t_{r_k} := \overrightarrow{if\left(t_{r_k} \geq 0.19 \cdot in, t_{r_k}, 0.19 \cdot in\right)}$$

Required Reinforcement Thickness: **Use Reinforcment Thickness:**

$$t_r = \begin{pmatrix} 0.278 \\ 0.417 \\ 0.417 \end{pmatrix} \cdot in \qquad t_{rd} := \begin{pmatrix} 0.31 \\ 0.43 \\ 0.43 \end{pmatrix} \cdot in$$

Reinforcement should be made of type II laminate with mat and woven roving.

Shell Nozzle Opening Reinforcement Summary

$$d_n = \begin{pmatrix} 4 \\ 24 \\ 30 \end{pmatrix} \cdot in \qquad D_r = \begin{pmatrix} 10 \\ 48 \\ 60 \end{pmatrix} \cdot in \qquad t_{rd} = \begin{pmatrix} 0.31 \\ 0.43 \\ 0.43 \end{pmatrix} \cdot in$$

7.2 Head Nozzle Reinforcement

$d_{nc} := (4) \cdot in$ $h_{Lc} := (0) \cdot in$ $\Delta h_{Lc} := D - h_{Lc}$ $\Delta h_{Lc} = (96)\ in$

$m := 1 .. last(d_{nc})$ $last(d_{nc}) = 1$

Calculate Pressure At Each Nozzle:

$$P_{nc_m} := P_{int} + \rho_c \cdot \Delta h_{Lc_m}$$

$$P_{nc} = (8.333) \cdot psi$$

Calculate Reinforcement Diameter:

$$D_{rc_m} := \overrightarrow{if\left[\left(d_{nc_m}\right) > 6 \cdot in, \left(2 \cdot d_{nc_m}\right), \left(d_{nc_m} + 6 \cdot in\right)\right]}$$

Calculate Coefficient "K":

$$K_{nc_m} := if\left[d_{nc_m} < 6 \cdot in, \left(\frac{d_{nc_m}}{6 \cdot in}\right), 1.0\right] \qquad K_{nc} = (0.667)$$

Calculate Coefficient "M":

Laminate type: $type_c := \text{"II"}$

Factor M $M_{rc_m} := 1$

Calculated structural thk: $T_{sc_m} := t_{th}$

Theoretical structural thk: $T_{tc_m} := T_{sc_m}$

$V_{rc_m} := \frac{1}{2}$ (pressure governs V=1, vacuum/bending governs V=1/2)

Calculate Reinforcement Thickness:

$t_{rc_m} := V_{rc_m} \cdot M_{rc_m} \cdot K_{nc_m} \cdot T_{tc_m}$

$t_{rc_m} := \overrightarrow{\text{if}\left(t_{rc_m} \geq 0.19 \cdot \text{in}, t_{rc_m}, 0.19 \cdot \text{in}\right)}$ $t_{rc} = (0.19) \cdot \text{in}$

Design Repad Thk.: $t_{rc\_d} := (0.19) \cdot \text{in}$

Repad Width $w_{rc_m} := \begin{cases} 8 \cdot \text{in} & \text{if } \frac{D_{rc_m} - d_{nc_m}}{2} > 8 \cdot \text{in} \\ \frac{D_{rc_m} - d_{nc_m}}{2} & \text{otherwise} \end{cases}$ $w_{rc} = (3)\ \text{in}$

Design Repad Width $w_{rc\_d} := w_{rc} = (3)\ \text{in}$

Top Head Nozzle Reinforcement Summary

$d_{nc} = (4) \cdot \text{in}$ $t_{rc\_d} = (0.19) \cdot \text{in}$ $w_{rc\_d} = (3) \cdot \text{in}$

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Appendix A Design Summaries and Sketches

Tank Inside Diameter.................................. $D = 96 \cdot in$

Straight Shell Length.................................. $H = 629 \cdot in$

Shell Total Thk.. $t_{stot} = (0.29) \cdot in$

Left/Right Head Combined Thk..................... $t_{th\_tot} = 0.31 \cdot in$

Tank Empty Weight.................................... $W_{FRP} = 6.557 \times 10^3\ lb$

Lamination Sequence

Left & Right Heads	0.31" -3(M,R)M,M
Shell	0.29" - 2(2FW,U),FW

Nomenclature For Lamination Sequence:

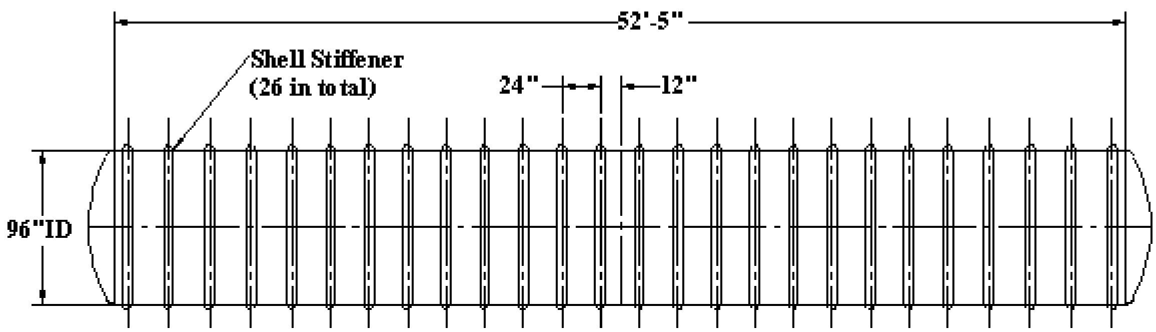
FW = 0.05" @ 89 deg. winding angle, 1 cycle of filament wound glass
c = 0.02", 1 layer interspersed chopped strand glass, 0.7 oz/ft2
C*** = 1 layer of chopped strand glass - *** indicates thk. of layer in mils (C025 = 0.025")
C = 0.043", 1 layer chopped strand glass, 1.5 oz/ft2
M = 0.043", 1 layer chopped strand glass mat, 1.5 oz/ft2
R = 0.033", 1 layer woven roving, 24 oz/sq. yd.
U = 0.02", 1 layer unidirectional roving

Shell Stiffener Layout

Total Stiffener Weight $\Sigma W_r = 775.558\ \text{lb}$

Total # of Stiffeners $N_{sr} = (26)$

Stiffener Spacing $Lst = 24\ \text{in}$



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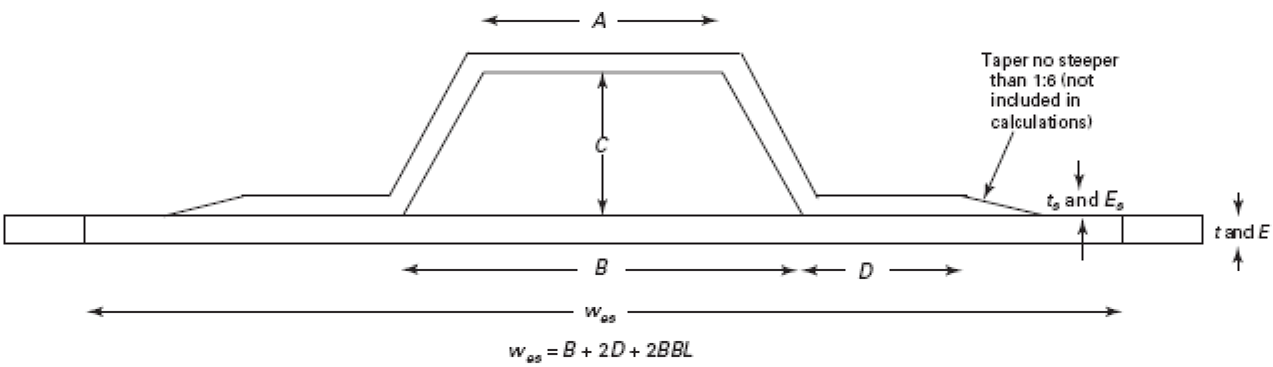
Note : Bottom 180 deg. section of the tank is fully supported. See customer installation manual.

Shell Stiffener Detail

Fig. NM17-2 Stiffener Moment of Inertia for a Trapezoidal Stiffener

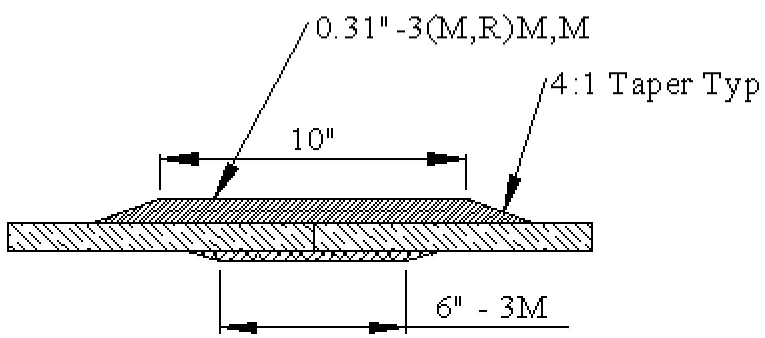


A = (2) in   B = (4) in   C = (2) in D_{sr} = (2) in

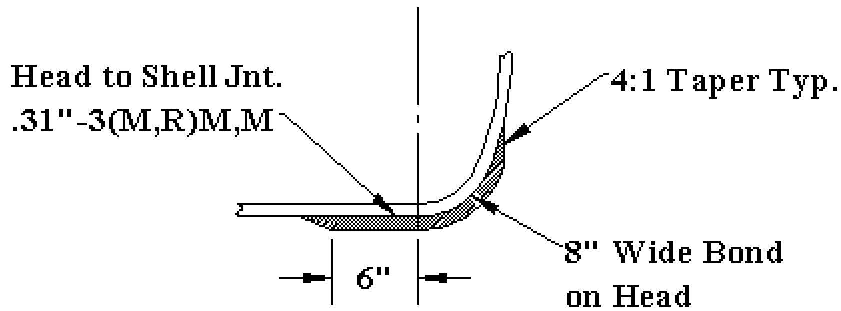
Stiffener Thk.: t_{sr} = (0.24) in

0.24" - 3C,U,2C

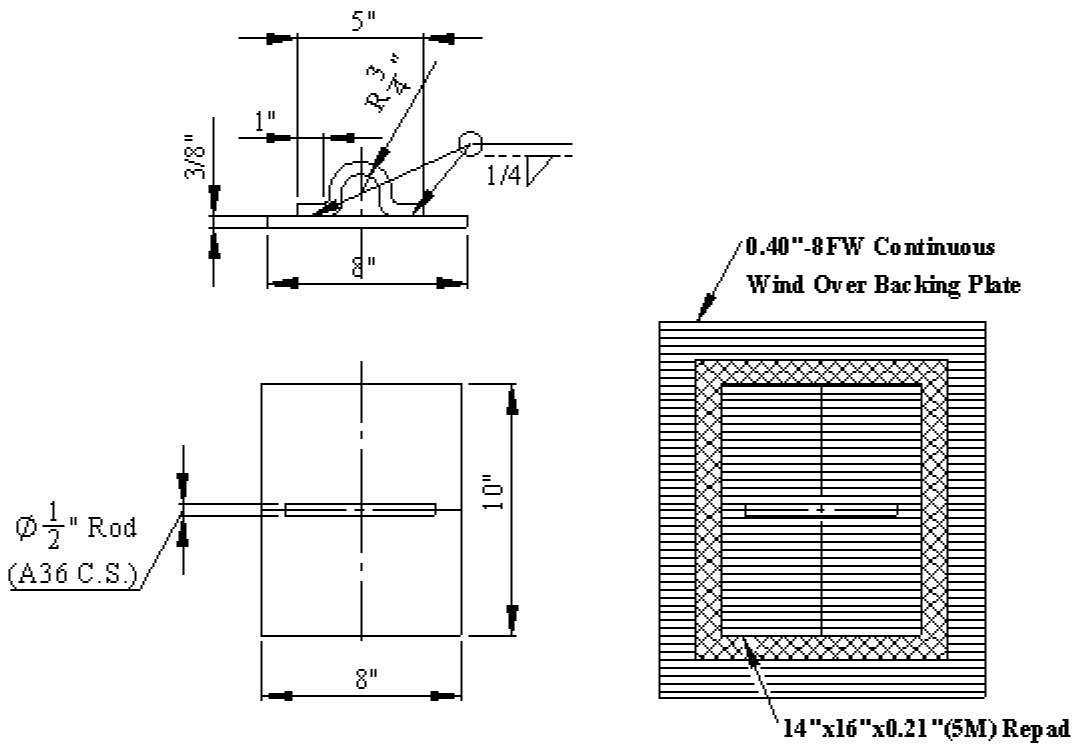
Shell to Shell Joint Detail



Head to Shell Joint Detail



Lifting Lugs



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Nozzle Opening Reinforcement

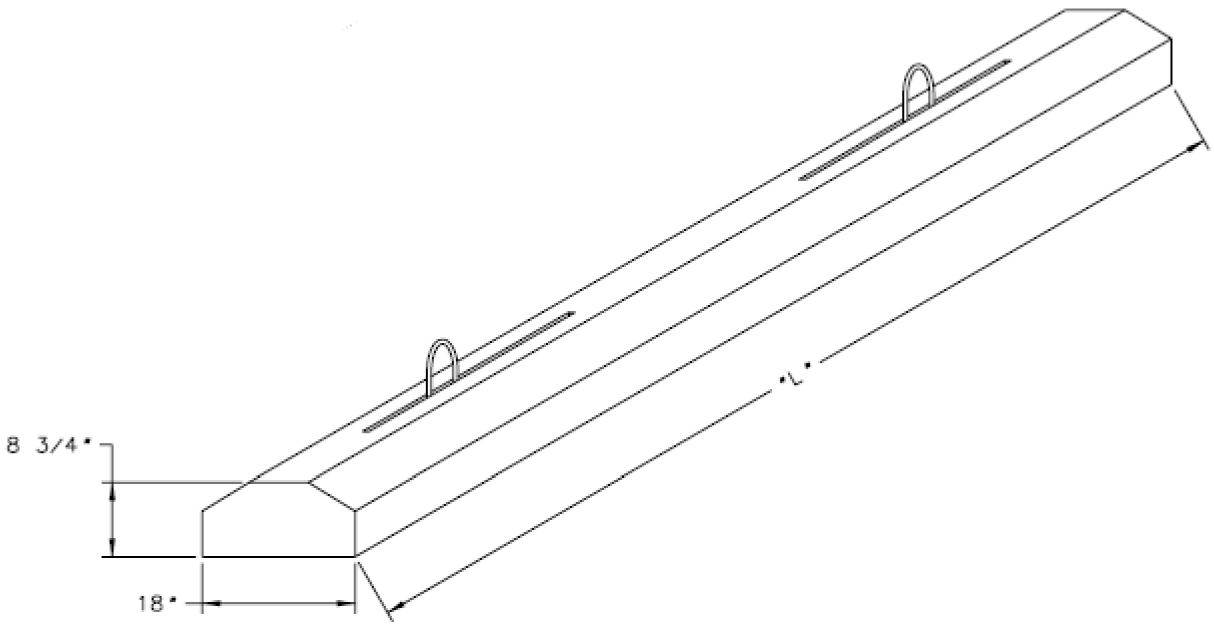
Shell Nozzle Opening Reinforcement Summary

$d_n = \begin{pmatrix} 4 \\ 24 \\ 30 \end{pmatrix} \cdot in$ $\quad D_r = \begin{pmatrix} 10 \\ 48 \\ 60 \end{pmatrix} \cdot in$ $\quad t_{rd} = \begin{pmatrix} 0.31 \\ 0.43 \\ 0.43 \end{pmatrix} \cdot in$

Top Head Nozzle Reinforcement Summary

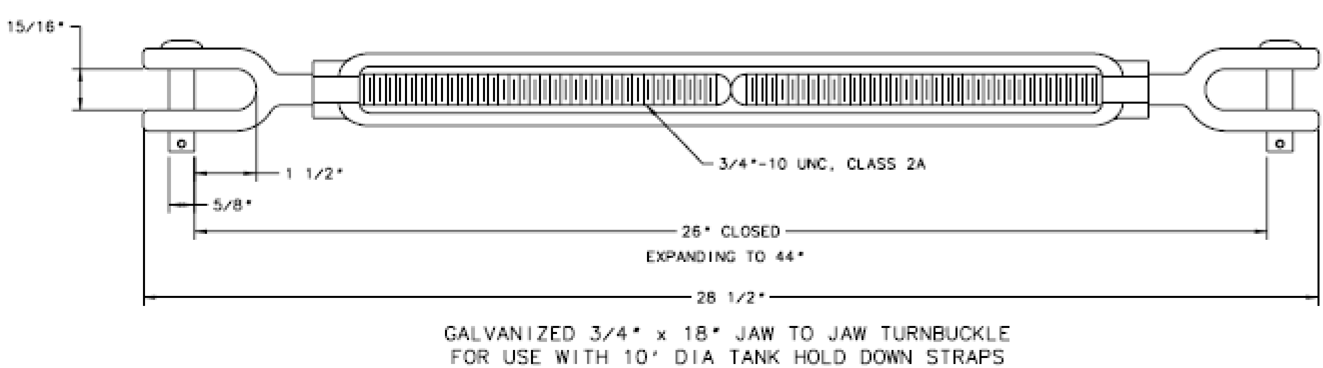
$d_{nc} = (4) \cdot in$ $\quad t_{rc\_d} = (0.19) \cdot in$ $\quad w_{rc\_d} = (3) \cdot in$

Concrete Deadmen Design



18" wide x 8 3/4" tall x 16' long; 6 req'd

Turnbuckle Selection



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Appendix B Lamination Analysis Using Trilam

Stypol DCPD Resin used for construction of tank. Trilam analysis uses iso resin which has similar mechanical properties.

Laminate Sequence Shell

Layer	Thickness	Reinforcmen	Reinforcmen	Orientation	Reinforcment	Matrix
	in	%wt	oz/sq ft	Degrees		
1	0.025	65.4	2.38	89.0	E Glass Roving	isophthalic
2	0.025	65.4	2.38	-89.0	E Glass Roving	isophthalic
3	0.025	65.4	2.38	89.0	E Glass Roving	isophthalic
4	0.025	65.4	2.38	-89.0	E Glass Roving	isophthalic
5	0.020	62.8	1.76	0.0	Uni-Glass	isophthalic
6	0.025	65.4	2.38	89.0	E Glass Roving	isophthalic
7	0.025	65.4	2.38	-89.0	E Glass Roving	isophthalic
8	0.025	65.4	2.38	89.0	E Glass Roving	isophthalic
9	0.025	65.4	2.38	-89.0	E Glass Roving	isophthalic
10	0.020	62.8	1.76	0.0	Uni-Glass	isophthalic
11	0.025	65.4	2.38	89.0	E Glass Roving	isophthalic
12	0.025	65.4	2.38	-89.0	E Glass Roving	isophthalic

Laminate Properties Shell

```
Tensile                                          Modulus
       - Longitudinal                            = 1762203  psi
       - Transverse                              = 4402197  psi
       - Normal                                  = 1294388  psi

Flexural
       - Longitudinal                            = 1558983  psi
       - Transverse                              = 4588138  psi

Shear
       - L-T (Inplane)                           = 383223  psi
       - L-N                                     = 475898  psi
       - T-N                                     = 397226  psi

Poisson ratios - Load direction / Strain direction
 - L/T = 0.09          - T/L = 0.22
 - L/N = 0.30          - N/L = 0.22
 - T/N = 0.32          - N/T = 0.09

Neutral axis (measured from the centroid)
       - Longitudinal                            = 0.006  in
       - Transverse                              = -0.003  in

Thermal expansion coefficient
       - Longitudinal                            = 14.89E-06  /F
       - Transverse                              = 52.04E-07  /F
       - Normal                                  = 24.09E-06  /F

Specific heat        = 0.197  Btu/lb F

Thermal conductance  = 6.611  Btu/hr sq ft F

Laminate weight      = 2.74  lb/sq ft

Reinforcement Wt.    = 1.78  lb/sq ft

Total reinforcement  = 65.03%  % by weight

Laminate density     = 0.066  lb/cu in

Laminate thickness   = 0.290  in
```