WARNING: ALL INDIVIDUALS INTERESTED IN BIDDING ON THIS PROJECT MUST OBTAIN THE FINAL PLANS AND SPECIFICATIONS FROM THE DEPARTMENT MANAGING THE PROJECT OR AS OTHERWISE STATED IN THE ADVERTISEMENT FOR BIDS FOR THE PROJECT. DO NOT USE THE PLANS AND SPECIFICATIONS POSTED ON THE CLERK OF THE BOARD'S WEBSITE FOR BIDDING ON THIS PROJECT.

Modern Custom Fabrication

COMPRESS Pressure Vessel Calculations

Description: SADDLE CALCS

Project: 10K -D5 SUPERVAULT

Saddle #1

ASME Section VIII Division 1, 2001 Edition, A03 Addenda		
Saddle Material	SA 36	
Saddle Construction	Web at edge of rib	
Welded to Vessel	Yes	
Saddle Allowable Stress, S_s	23,760 psi	
Saddle Yield Stress, S_y	36,000 psi	
Foundation Allowable Stress	750 psi	
Design Pressure	Left Saddle	Right Saddle
Operating	2.67 psi	
Test	4.33 psi	
Dimensions		
Right saddle distance to datum	32"	
Tangent To Tangent Length, L	242"	
Saddle separation, L_s	178"	
Vessel Radius, R	64.3125"	
Tangent Distance Left, A_l	31"	
Tangent Distance Right, A_r	33"	
Saddle Height, H_s	68.3125"	
Saddle Contact Angle, θ	126°	
Web Plate Thickness, t_s	0.25"	
Base Plate Length, E	116.5625"	
Base Plate Width, F	11"	
Base Plate Thickness, t_b	0.75"	
Number of Stiffening Ribs, n	6	
Largest Stiffening Rib Spacing, d_i	23.0625"	
Stiffening Rib Thickness, t_w	0.25"	
Saddle Width, b	10"	
Reinforcing Plate		
Thickness, t_p	0.25"	
Width, W_p	16.5"	
Contact Angle, θ_w	138°	
Bolting		
Material	A307	
Bolt Allowable Shear	10,000 psi	
Description	1" coarse threaded	
Corrosion on root	0"	
Anchor Bolts per Saddle	4	
Base coefficient of friction, μ	0.45	
Hole Diameter	1.125"	

Slotted Hole in Which Saddle	Left Saddle	
Slotted Hole Length	1"	
Weight		
	Operating, Corroded	**Hydrotest**
Weight on Left Saddle	39,550 lb	45,256 lb
Weight on Right Saddle	40,449 lb	46,285 lb
Weight of Saddle Pair	1,294 lb	

Notes
(1) Saddle calculations are based on the method presented in "Stresses in Large Cylindrical Pressure Vessels on Two Saddle Supports" by L.P. Zick.

Stress Summary

Load	**Condition**	**Saddle**	**Bending + pressure between saddles (psi)**				**Bending + pressure at the saddle (psi)**			
			S_1 (+)	**allow (+)**	**S_1 (-)**	**allow (-)**	**S_2 (+)**	**allow (+)**	**S_2 (-)**	**allow (-)**
Seismic	Operating	Right Saddle	950	27,840	608	7,027	-52	27,840	-394	7,027
		Left Saddle					288	27,840	-54	7,027
Wind	Operating	Right Saddle	798	27,840	456	7,027	14	27,840	-329	7,027
		Left Saddle					297	27,840	-45	7,027
	Test	Right Saddle	1,067	32,400	512	7,027	179	32,400	-376	7,027
		Left Saddle					503	32,400	-52	7,027
Weight	Operating	Right Saddle	786	23,200	444	5,856	14	23,200	-329	5,856
		Left Saddle					297	23,200	-45	5,856

Stress Summary

Load	**Condition**	**Saddle**	**Tangential shear (psi)**		**Circumferential stress (psi)**			**Stress over saddle (psi)**		**Splitting (psi)**	
			S_3	**allow**	**S_4 (horns)**	**S_4 (Wear plate)**	**allow (+/-)**	**S_5**	**allow**	**S_6**	**allow**
Seismic	Operating	Right Saddle	2,788	18,560	-19,916	-33,339	34,800	9,006	18,000	2,439	15,840
		Left Saddle	2,776	18,560	-18,231	-30,389	34,800	8,806	18,000	2,385	15,840
Wind	Operating	Right Saddle	2,010	18,560	-14,923	-24,980	34,800	6,748	18,000	1,828	15,840
		Left Saddle	2,081	18,560	-13,662	-22,773	34,800	6,599	18,000	1,787	15,840
	Test	Right Saddle	2,240	25,920	-16,756	-28,049	32,400	7,577	32,400	2,052	32,400
		Left Saddle	2,336	25,920	-15,339	-25,569	32,400	7,409	32,400	2,007	32,400
Weight	Operating	Right Saddle	1,936	18,560	-14,530	-24,323	34,800	6,571	18,000	1,780	15,840
		Left Saddle	2,026	18,560	-13,301	-22,171	34,800	6,425	18,000	1,740	15,840

Seismic base shear on vessel	
Vessel is assumed to be a rigid structure.	
Method of seismic analysis	IBC 2018 ground supported
Vertical seismic accelerations considered	Yes
Force Multiplier	0.3333
Minimum Weight Multiplier	0.2
Importance factor, I_e	1.25
Site Class	D
Short period spectral response acceleration as percent of g, S_s	63.2
1 second spectral response acceleration as percent of g, S_1	24.2
From ASCE Table 11.4-1, F_a	1.2944
From ASCE Table 11.4-2, F_v	1.4
Risk Category (IBC Table 1604.5)	III
Hazardous, toxic, or explosive contents	No
Equations	
$S_{MS} = F_a \cdot S_s$	
$S_{M1} = F_v \cdot S_1$	
$S_{DS} = \left(\frac{2}{3}\right) \cdot S_{MS}$	
$S_{D1} = \left(\frac{2}{3}\right) \cdot S_{M1}$	
$F_p = 0.3 \cdot S_{DS} \cdot W \cdot I_e \cdot 0.7$	
Results	
$S_{MS} = 1.2944 \cdot 0.632$	0.8181
$S_{M1} = 1.4 \cdot 0.242$	0.3388
$S_{DS} = \left(\frac{2}{3}\right) \cdot 0.8181$	0.5454
$S_{D1} = \left(\frac{2}{3}\right) \cdot 0.3388$	0.2259
Seismic Design Category (Section 11.6)	D
$F_p = 0.3 \cdot 0.5454 \cdot 79{,}999 \cdot 1.25 \cdot 0.7$	11,452.71 lb_f

Saddle reactions due to weight + seismic
V_v = vertical seismic force acting on the saddle
V = horizontal seismic shear acting on the saddle (worst case if not slotted)
Seismic longitudinal reaction, Q_l
Seismic transverse reaction, Q_t
Equations
$Q_l = \frac{V \cdot H_s}{L_s} + V_v$
$Q_t = \frac{V \cdot H_s}{R_o \cdot \text{Sin}(\theta \ / \ 2)} + V_v$
$Q = W + \max\left[Q_t, Q_l\right]$
Results

Operating	Right Saddle	$Q_l = \frac{11{,}452.71 \cdot 68.3125}{178} + 8{,}089.8$	12,485.1 lb_f
		$Q_t = \frac{5{,}790.7 \cdot 68.3125}{64.3125 \cdot \text{Sin}(126 \ / \ 2)} + 8{,}089.8$	14,993.08 lb_f
		$Q = 40{,}449 + \max\left[14{,}993.08, 12{,}485.1\right]$	55,442.08 lb_f
	Left Saddle	$Q_l = \frac{11{,}452.71 \cdot 68.3125}{178} + 7{,}910$	12,305.3 lb_f
		$Q_t = \frac{5{,}662 \cdot 68.3125}{64.3125 \cdot \text{Sin}(126 \ / \ 2)} + 7{,}910$	14,659.85 lb_f
		$Q = 39{,}550 + \max\left[14{,}659.85, 12{,}305.3\right]$	54,209.85 lb_f

Saddle reactions due to weight + wind	
Wind longitudinal reaction, Q_l	
Wind transverse reaction, Q_t	
Wind pressure, P_w	16.7223 psf
Equations	
$V_{wt} = P_w \cdot G \cdot \left(C_{f(\text{shell})} \cdot (\text{Projected shell area}) + C_{f(\text{saddle})} \cdot (\text{Projected saddle area})\right)$	
$V_{we} = P_w \cdot G \cdot \left(\frac{C_{f(\text{shell})} \cdot \pi \cdot R_o^2}{144} + C_{f(\text{saddle})} \cdot (\text{Projected saddle area})\right)$	
$Q_t = \frac{V_{wt} \cdot H_s}{R_o \cdot \text{Sin}(\theta \ / \ 2)}$	
$Q_l = \frac{V_{we} \cdot H_s}{L_s}$	
$Q = W + \max\left[Q_t, Q_l\right]$	
Results	

		$V_{wt} = 16.72 \cdot 0.85 \cdot (0.57 \cdot 112.0229 + 2 \cdot 0.2778)$	915.5 lb_f

Operating	Right Saddle	$V_{we} = 16.72 \cdot 0.85 \cdot \left(\frac{0.5 \cdot \pi \cdot 64.3125^{\ 2}}{144} + 2 \cdot 12.0398 \right)$	983.57 lb_f
		$Q_t = \frac{915.5 \cdot 68.3125}{64.3125 \cdot \text{Sin}(126 \ / \ 2)}$	1,091.4 lb_f
		$Q_l = \frac{983.57 \cdot 68.3125}{178}$	377.47 lb_f
		$Q = 40{,}449 + \max\ [1{,}091.4, 377.47]$	41,540.4 lb_f
	Left Saddle	$V_{wt} = 16.72 \cdot 0.85 \cdot (0.57 \cdot 110.2364 + 2 \cdot 0.2778)$	901.03 lb_f
		$V_{we} = 16.72 \cdot 0.85 \cdot \left(\frac{0.5 \cdot \pi \cdot 64.3125^{\ 2}}{144} + 2 \cdot 12.0398 \right)$	983.57 lb_f
		$Q_t = \frac{901.03 \cdot 68.3125}{64.3125 \cdot \text{Sin}(126 \ / \ 2)}$	1,074.14 lb_f
		$Q_l = \frac{983.57 \cdot 68.3125}{178}$	377.47 lb_f
		$Q = 39{,}550 + \max\ [1{,}074.14, 377.47]$	40,624.14 lb_f
Test	Right Saddle	$V_{wt} = 5.52 \cdot 0.85 \cdot (0.57 \cdot 112.0229 + 2 \cdot 0.2778)$	302.12 lb_f
		$V_{we} = 5.52 \cdot 0.85 \cdot \left(\frac{0.5 \cdot \pi \cdot 64.3125^{\ 2}}{144} + 2 \cdot 12.0398 \right)$	324.58 lb_f
		$Q_t = \frac{302.12 \cdot 68.3125}{64.3125 \cdot \text{Sin}(126 \ / \ 2)}$	360.16 lb_f
		$Q_l = \frac{324.58 \cdot 68.3125}{178}$	124.57 lb_f
		$Q = 46{,}285 + \max\ [360.16, 124.57]$	46,645.16 lb_f
	Left Saddle	$V_{wt} = 5.52 \cdot 0.85 \cdot (0.57 \cdot 110.2364 + 2 \cdot 0.2778)$	297.34 lb_f
		$V_{we} = 5.52 \cdot 0.85 \cdot \left(\frac{0.5 \cdot \pi \cdot 64.3125^{\ 2}}{144} + 2 \cdot 12.0398 \right)$	324.58 lb_f
		$Q_t = \frac{297.34 \cdot 68.3125}{64.3125 \cdot \text{Sin}(126 \ / \ 2)}$	354.47 lb_f
		$Q_l = \frac{324.58 \cdot 68.3125}{178}$	124.57 lb_f
		$Q = 45{,}256 + \max\ [354.47, 124.57]$	45,610.47 lb_f

Longitudinal stress between saddles (Seismic, Operating, left saddle loading and geometry govern)

$$S_1 = \pm \frac{3 \cdot K_1 \cdot Q \cdot (L \ / \ 12)}{\pi \cdot R^2 \cdot t} = \frac{3 \cdot 0.6001 \cdot 54{,}209.85 \cdot (242 \ / \ 12)}{\pi \cdot 64.1875^{\ 2} \cdot 0.25} = 608 \ \text{psi}$$

$$S_p = \frac{P \cdot R}{2 \cdot t} = \frac{2.67 \cdot 64.0625}{2 \cdot 0.25} = 342 \ \text{psi}$$

Maximum tensile stress $S_{1t} = S_1 + S_p$ = 950 psi
Maximum compressive stress (shut down) $S_{1c} = S_1$ = 608 psi

Tensile stress is acceptable ($\leq 1.2 \cdot S \cdot E = 27{,}840 \;\; \text{psi}$)

Compressive stress is acceptable ($\leq 1.2 \cdot S_c = 7{,}027 \;\; \text{psi}$)

Longitudinal stress at the right saddle (Seismic, Operating)

$$L_e = \frac{2 \cdot H_l}{3} + L + \frac{2 \cdot H_r}{3} = \frac{2 \cdot 4.5678}{3} + 242 + \frac{2 \cdot 4.5678}{3} = 248.0903 \;\; \text{in}$$

Seismic vertical acceleration coefficient $m = 1.397 \cdot 0.1432 = 0.2$

$$w = \frac{W_t \cdot (1 + m)}{L_e} = \frac{79{,}999 \cdot (1 + 0.2)}{248.0903} = 386.95 \;\; \text{lb}_f/\text{in}$$

Bending moment at the right saddle:

$$M_q = w \cdot \left(\frac{2 \cdot H_r \cdot A_r}{3} + \frac{A_r^2}{2} - \frac{R^2 - H_r^2}{4} \right)$$

$$= 386.95 \cdot \left(\frac{2 \cdot 4.5678 \cdot 33}{3} + \frac{33^2}{2} - \frac{64.3125^{\,2} - 4.5678^{\,2}}{4} \right)$$

$$= -148{,}518.6 \;\; \text{lb}_f\text{-in}$$

$$S_2 = \pm \frac{M_q \cdot K_1{}'}{\pi \cdot R^2 \cdot t} = \frac{-148{,}518.6 \cdot 8.5944}{\pi \cdot 64.1875^{\,2} \cdot 0.25} = -394 \;\; \text{psi}$$

$$S_p = \frac{P \cdot R}{2 \cdot t} = \frac{2.67 \cdot 64.0625}{2 \cdot 0.25} = 342 \;\; \text{psi}$$

Maximum tensile stress $S_{2t} = S_2 + S_p$ = -52 psi
Maximum compressive stress (shut down) $S_{2c} = S_2$ = -394 psi

Tensile stress is acceptable ($\leq 1.2 \cdot S = 27{,}840 \;\; \text{psi}$)

Compressive stress is acceptable ($\leq 1.2 \cdot S_c = 7{,}027 \;\; \text{psi}$)

Longitudinal stress at the right saddle (Weight, Operating)

$$L_e = \frac{2 \cdot H_l}{3} + L + \frac{2 \cdot H_r}{3} = \frac{2 \cdot 4.5678}{3} + 242 + \frac{2 \cdot 4.5678}{3} = 248.0903 \;\; \text{in}$$

$$w = \frac{W_t}{L_e} = \frac{79{,}999}{248.0903} = 322.46 \;\; \text{lb}_f/\text{in}$$

Bending moment at the right saddle:

$$M_q = w \cdot \left(\frac{2 \cdot H_r \cdot A_r}{3} + \frac{A_r^2}{2} - \frac{R^2 - H_r^2}{4} \right)$$

$$= 322.46 \cdot \left(\frac{2 \cdot 4.5678 \cdot 33}{3} + \frac{33^2}{2} - \frac{64.3125^{\,2} - 4.5678^{\,2}}{4} \right)$$

$$= -123{,}765.5 \;\; \text{lb}_f\text{-in}$$

$$S_2 = \pm \frac{M_q \cdot K_1{}'}{\pi \cdot R^2 \cdot t} = \frac{-123{,}765.5 \cdot 8.5944}{\pi \cdot 64.1875^{\,2} \cdot 0.25} = -329 \;\; \text{psi}$$

$$S_p = \frac{P \cdot R}{2 \cdot t} = \frac{2.67 \cdot 64.0625}{2 \cdot 0.25} = 342 \;\; \text{psi}$$

Maximum tensile stress $S_{2t} = S_2 + S_p$ = 14 psi
Maximum compressive stress (shut down) $S_{2c} = S_2$ = -329 psi

Tensile stress is acceptable ($\leq S = 23{,}200 \;\; \text{psi}$)

Compressive stress is acceptable ($\leq S_c = 5{,}856 \;\; \text{psi}$)

Tangential shear stress in the shell (right saddle, Seismic, Operating)

$$Q_{shear} = Q - w \cdot \left(A_r + \frac{2 \cdot H_r}{3}\right) = 55{,}442.08 - 386.95 \cdot \left(33 + \frac{2 \cdot 4.5678}{3}\right) = 41{,}494.36 \;\; \text{lb}_f$$

$$S_3 = \frac{K_{2.2} \cdot Q_{shear}}{R \cdot t} = \frac{1.078 \cdot 41{,}494.36}{64.1875 \cdot 0.25} = 2{,}788 \;\; \text{psi}$$

Tangential shear stress is acceptable ($\leq 0.8 \cdot S = 18{,}560 \;\; \text{psi}$)

Circumferential stress at the right saddle horns (Seismic, Operating)

$$S_4 = \frac{-Q}{4 \cdot (t + t_p) \cdot \left(b + 1.56 \cdot \sqrt{R_o \cdot t}\right)} - \frac{12 \cdot K_3 \cdot Q \cdot R}{L \cdot \left(t^2 + t_p^2\right)}$$
$$= \frac{-55{,}442.08}{4 \cdot (0.25 + 0.25) \cdot \left(10 + 1.56 \cdot \sqrt{64.3125 \cdot 0.25}\right)} - \frac{12 \cdot 0.0129 \cdot 55{,}442.08 \cdot 64.1875}{242 \cdot \left(0.25^2 + 0.25^2\right)}$$
$$= -19{,}916 \;\; \text{psi}$$

Circumferential stress at saddle horns is acceptable ($\leq 1.5 \cdot S_a = 34{,}800 \;\; \text{psi}$)

Circumferential stress at the right saddle wear plate horns (Seismic, Operating)

$$S_4 = \frac{-Q}{4 \cdot t \cdot \left(b + 1.56 \cdot \sqrt{R_o \cdot t}\right)} - \frac{12 \cdot K_3 \cdot Q \cdot R}{L \cdot t^2}$$
$$= \frac{-55{,}442.08}{4 \cdot 0.25 \cdot \left(10 + 1.56 \cdot \sqrt{64.3125 \cdot 0.25}\right)} - \frac{12 \cdot 0.0106 \cdot 55{,}442.08 \cdot 64.1875}{242 \cdot 0.25^2}$$
$$= -33{,}339 \;\; \text{psi}$$

Circumferential stress at wear plate horns is acceptable ($\leq 1.5 \cdot S_a = 34{,}800 \;\; \text{psi}$)

Ring compression in shell over right saddle (Seismic, Operating)

$$S_5 = \frac{K_5 \cdot Q}{(t + t_p) \cdot \left(t_s + 1.56 \cdot \sqrt{R_o \cdot t_c}\right)}$$
$$= \frac{0.7388 \cdot 55{,}442.08}{(0.25 + 0.25) \cdot \left(0.25 + 1.56 \cdot \sqrt{64.3125 \cdot 0.5}\right)}$$
$$= 9{,}006 \;\; \text{psi}$$

Ring compression in shell is acceptable ($\leq 0.5 \cdot S_y = 18{,}000 \;\; \text{psi}$)

Saddle splitting load (right, Seismic, Operating)

Area resisting splitting force = Web area + wear plate area

$A_e = H_{eff} \cdot t_s + t_p \cdot W_p = 3 \cdot 0.25 + 0.25 \cdot 16.5$ = 4.875 in^2

$$S_6 = \frac{K_8 \cdot Q}{A_e} = \frac{0.2145 \cdot 55{,}442.08}{4.875} = 2{,}439 \;\; \text{psi}$$

Stress in saddle is acceptable $\left(\leq \frac{2}{3} \cdot S_s = 15{,}840 \;\; \text{psi}\right)$

Shear stress in anchor bolting, one end slotted

Maximum seismic or wind base shear $= 11{,}452.71 \ \ \mathrm{lb}_f$

Thermal expansion base shear $= W \cdot \mu$ = 40,197*0.45 $= 18{,}088.65 \ \ \mathrm{lb}_f$

Corroded root area for a 1" coarse threaded bolt $= 0.551 \ \ \mathrm{in}^2$ (4 per saddle)

Bolt shear stress = $\dfrac{18{,}088.65}{0.551 \cdot 1 \cdot 4} = 8{,}207 \ \ \mathrm{psi}$

Anchor bolt stress is acceptable (≤ 10,000 psi)

Shear stress in anchor bolting, transverse

Maximum seismic or wind base shear $= 11{,}452.71 \ \ \mathrm{lb}_f$

Corroded root area for a 1" coarse threaded bolt $= 0.551 \ \ \mathrm{in}^2$ (4 per saddle)

Bolt shear stress = $\dfrac{11{,}452.71}{0.551 \cdot 2 \cdot 4} = 2{,}598 \ \ \mathrm{psi}$

Anchor bolt stress is acceptable (≤ 10,000 psi)

Web plate buckling check (Escoe pg 251)

Allowable compressive stress S_c = min(23,760 , 3,942) = 3,942 psi

$$S_c = \frac{K_i \cdot \pi^2 \cdot E}{12 \cdot \left(1 - 0.3^{\,2}\right) \cdot \left(\frac{d_i}{t_s}\right)^2} = \frac{1.28 \cdot \pi^2 \cdot 29\mathrm{E}{+}06}{12 \cdot \left(1 - 0.3^{\,2}\right) \cdot \left(\frac{23.0625}{0.25}\right)^2} = 3{,}942 \ \ \mathrm{psi}$$

Allowable compressive load on the saddle

$$b_e = \frac{d_i \cdot t_s}{(d_i \cdot t_s) + 2 \cdot t_w \cdot (b - 1)} = \frac{23.0625 \cdot 0.25}{(23.0625 \cdot 0.25) + 2 \cdot 0.25 \cdot (10 - 1)} = 0.5616$$

$$F_b = n \cdot (A_s + 2 \cdot b_e \cdot t_s) \cdot S_c = 6 \cdot (2.4375 + 2 \cdot 0.5616 \cdot 0.25) \cdot 3{,}942 = 64{,}299.04 \ \ \mathrm{lb}_f$$

Saddle loading of 56,089.08 $\mathrm{lb_f}$ is ≤ F_b; satisfactory.

Primary bending + axial stress in the saddle due to end loads (assumes one saddle slotted)

$$\sigma_b = \frac{V \cdot (H_s - x_o) \cdot y}{I} + \frac{Q}{A} = \frac{11{,}452.71 \cdot (68.3125 - 52.1145) \cdot 5.975}{196.32} + \frac{55{,}442.08}{43.2764} = 6{,}927 \ \ \mathrm{psi}$$

The primary bending + axial stress in the saddle ≤ S_s = 23,760 psi; satisfactory.

Secondary bending + axial stress in the saddle due to end loads (includes thermal expansion, assumes one saddle slotted)

$$\sigma_b = \frac{V \cdot (H_s - x_o) \cdot y}{I} + \frac{Q}{A} = \frac{29{,}541.36 \cdot (68.3125 - 52.1145) \cdot 5.975}{196.32} + \frac{54{,}209.85}{43.2764} = 15{,}816 \ \ \mathrm{psi}$$

The secondary bending + axial stress in the saddle ≤ 2*S_y = 72,000 psi; satisfactory.

Saddle base plate thickness check (Roark sixth edition, Table 26, case 7a)

where $a = 23.0625, b = 10.75 \ \ \mathrm{in}$

$$t_b = \sqrt{\frac{\beta_1 \cdot q \cdot b^2}{1.5 \cdot S_a}} = \sqrt{\frac{1.8979 \cdot 44 \cdot 10.75^{\,2}}{1.5 \cdot 23{,}760}} = 0.5189 \ \ \mathrm{in}$$

The base plate thickness of 0.75 in is adequate.

Foundation bearing check

$$S_f = \frac{Q_{\max}}{F \cdot E} = \frac{56{,}089.08}{11 \cdot 116.5625} = 44 \ \ \mathrm{psi}$$

Concrete bearing stress ≤ 750 psi ; satisfactory.