Longitudinal Stresses

In the following equations, D is in inches. The term "$48M_X$" is used for ft-lb or ft-kips. If in.-lb or in.-kips are used, then the term "$4M_X$" should be substituted where "$48M_X$" is used. The allowable stresses S_1E_1 or B may be substituted in the equations for t to determine or verify thickness at any elevation. Compare the stresses or thicknesses required at each elevation against the thickness required for circumferential stress due to internal pressure to determine which one will govern. If there is no external pressure condition, assume the maximum compression will occur when the vessel is not pressurized and the term $P_eD/4t$ will drop out.

$$\sigma_{xt} = \text{tension side} = \frac{P_iD}{4t} + \frac{48M_x}{\pi D^2 t} - \frac{W_h}{\pi Dt}$$

$$\sigma_{xc} = \text{compression side} = (-)\frac{P_eD}{4t} - \frac{48M_x}{\pi D^2 t} - \frac{W_h}{\pi Dt}$$

- *Allowable longitudinal stresses.*

  tension : S_1E_1 =

Elevation	M_x	W_n	D	t	Tension		Compression	
					S_1E_1	σ_{xt}	B	σ_{xc}

Table 4-20
Coefficients for determining period of vibration of free-standing cylindrical shells having varying cross sections and mass distribution

$\frac{h_x}{H}$	α	β	γ	$\frac{h_x}{H}$	α	β	γ	$\frac{h_x}{H}$	α	β	γ
1.00	2.103	8.347	1.000000	0.65	0.3497	2.3365	0.99183	0.30	0.010293	0.16200	0.7914
0.99	2.021	8.121	1.000000	0.64	0.3269	2.2240	0.99065	0.29	0.008769	0.14308	0.7776
0.98	1.941	7.898	1.000000	0.63	0.3052	2.1148	0.98934	0.28	0.007426	0.12576	0.7632
0.97	1.863	7.678	1.000000	0.62	0.2846	2.0089	0.98789	0.27	0.006249	0.10997	0.7480
0.96	1.787	7.461	1.000000	0.61	0.2650	1.9062	0.98630	0.26	0.005222	0.09564	0.7321
0.95	1.714	7.246	0.999999	0.60	0.2464	1.8068	0.98455	0.25	0.004332	0.08267	0.7155
0.94	1.642	7.037	0.999998	0.59	0.2288	1.7107	0.98262	0.24	0.003564	0.07101	0.6981
0.93	1.573	6.830	0.999997	0.58	0.2122	1.6177	0.98052	0.23	0.002907	0.06056	0.6800
0.92	1.506	6.626	0.999994	0.57	0.1965	1.5279	0.97823	0.22	0.002349	0.05126	0.6610
0.91	1.440	6.425	0.999989	0.56	0.1816	1.4413	0.97573	0.21	0.001878	0.04303	0.6413
0.90	1.377	6.227	0.999982	0.55	0.1676	1.3579	0.97301	0.20	0.001485	0.03579	0.6207
0.89	1.316	6.032	0.999971	0.54	0.1545	1.2775	0.97007	0.19	0.001159	0.02948	0.5992
0.88	1.256	5.840	0.999956	0.53	0.1421	1.2002	0.96688	0.18	0.000893	0.02400	0.5769
0.87	1.199	5.652	0.999934	0.52	0.1305	1.1259	0.96344	0.17	0.000677	0.01931	0.5536
0.86	1.143	5.467	0.999905	0.51	0.1196	1.0547	0.95973	0.16	0.000504	0.01531	0.5295
0.85	1.090	5.285	0.999867	0.50	0.1094	0.9863	0.95573	0.15	0.000368	0.01196	0.5044
0.84	1.038	5.106	0.999817	0.49	0.0998	0.9210	0.95143	0.14	0.000263	0.00917	0.4783
0.83	0.988	4.930	0.999754	0.48	0.0909	0.8584	0.94683	0.13	0.000183	0.00689	0.4512
0.82	0.939	4.758	0.999674	0.47	0.0826	0.7987	0.94189	0.12	0.000124	0.00506	0.4231
0.81	0.892	4.589	0.999576	0.46	0.0749	0.7418	0.93661	0.11	0.000081	0.00361	0.3940
0.80	0.847	4.424	0.999455	0.45	0.0678	0.8876	0.93097	0.10	0.000051	0.00249	0.3639
0.79	0.804	4.261	0.999309	0.44	0.0612	0.6361	0.92495	0.09	0.000030	0.00165	0.3327
0.78	0.762	4.102	0.999133	0.43	0.0551	0.5872	0.91854	0.08	0.000017	0.00104	0.3003
0.77	0.722	3.946	0.998923	0.42	0.0494	0.5409	0.91173	0.07	0.000009	0.00062	0.2669
0.76	0.683	3.794	0.998676	0.41	0.0442	0.4971	0.90448	0.06	0.000004	0.00034	0.2323
0.75	0.646	3.845	0.998385	0.40	0.0395	0.4557	0.89679	0.05	0.000002	0.00016	0.1966
0.74	0.610	3.499	0.998047	0.39	0.0351	0.4167	0.88884	0.04	0.000001	0.00007	0.1597
0.73	0.576	3.356	0.997656	0.38	0.0311	0.3801	0.88001	0.03	0.000000	0.00002	0.1218
0.72	0.543	3.217	0.997205	0.37	0.0275	0.3456	0.87088	0.02	0.000000	0.00000	0.0823
0.71	0.512	3.081	0.996689	0.36	0.0242	0.3134	0.86123	0.01	0.000000	0.00000	0.0418
0.70	0.481	2.949	0.998101	0.35	0.0212	0.2833	0.85105	0.	0.	0.	0.
0.69	0.453	2.820	0.995434	0.34	0.0185	0.2552	0.84032				
0.68	0.425	2.694	0.994681	0.33	0.0161	0.2291	0.82901				
0.67	0.399	2.571	0.993834	0.32	0.0140	0.2050	0.81710				
0.88	0.374	2.452	0.992885	0.31	0.0120	0.1826	0.80459				

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compression:

$$A = \frac{0.125t}{R_o}$$

B = from applicable material chart of ASME Code, Section II, Part D, Subpart 3.

Note: Joint efficiency for longitudinal seams in compression is 1.0.

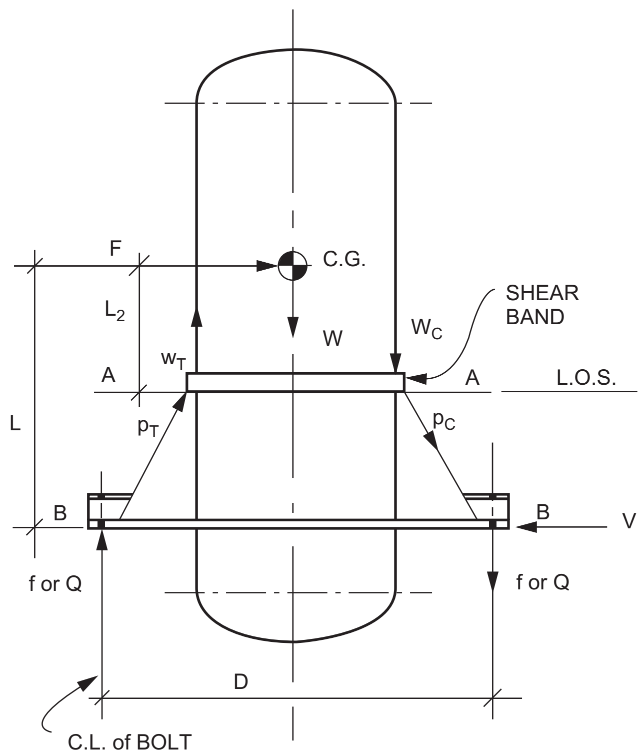
Notes

1. This procedure is for use in determining forces and moments at various planes of uniform and nonuniform vertical pressure vessels.
2. To determine the plate thickness required at any given elevation compare the moments from both wind and seismic at that elevation. The larger of the two should be used. Wind-induced moments may govern the longitudinal loading at one elevation, and seismic-induced moments may govern another.

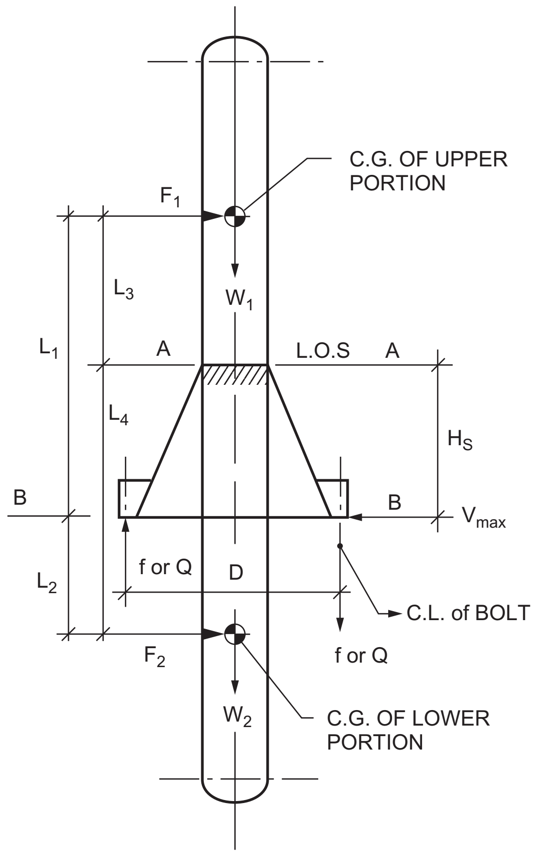
Procedure 4-9: Seismic Design – Vessel on Conical Skirt

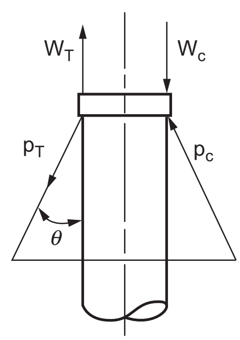
Nomenclature

A = ASME Code strain factor, dimensionless
A_b = Area of base plate supported on steel, in^2
A_t = Area required for one anchor bolt, in^2
A_S = Area of shear band, L_S X t_S, in^2
B_P = Allowable bearing pressure, PSI
D_O = OD of vessel shell, in
D_{SK} = OD of skirt at base plate, in
E = Modulus of elasticity, PSI
F_c = Allowable compressive stress, PSI
f = Load at support points, Lbs
f_P = Bearing pressure, PSI
F_T = Allowable stress, tension, PSI
F_y = Minimum specified yield strength of skirt at design temperature, PSI
F_1 or F_2 = Seismic load for upper or lower portion of vessel
$M_{AA \text{ or } BB}$ = Overturning moment due to earthquake, In-Lbs, at elevation A-A or B-B
M_b = Bending moment, In-Lbs
M_X or M_y = Internal bending moment in base plate, in-lbs
N = Number of support points
N_b = Number of anchor bolts
P = Design pressure, PSIG
p_T, p_C = Load at top of skirt, tension or compression, Lbs/in
Q = Load at support points, Lbs
R_m = Mean radius of shell, in
S = Shell allowable stress, tension, PSI
S_b = Allowable stress, anchor bolts, PSI
t = Thickness of shell, in
t_r = Thickness required, skirt, in
V = Base shear, Lbs
V_{max} = Greater of V_1 or V_2, Lbs
W = Weight, operating, Lbs
W_1 = Weight of vessel, insulation, piping, etc above LOS. Include weight of contents if contents are supported above the LOS. Do not include weight of skirt, Lbs
W_2 = Weight of vessel, insulation, piping, etc., below LOS. Include weight of contents if supported below the LOS. Do not include weight of skirt or base.
w_T, w_C = Uniform load in shell, tension or compression, Lbs/in
ΔT = Temperature differential in skirt; DT – 70° F
λ = Damping Factor
σ_{LT} = Longitudinal tension stress, skirt, PSI
σ_{LC} = Longitudinal compressive stress, skirt, PSI
$\sigma_{\Delta T}$ = Stress in skirt due to ΔT loading, PSI
σ_X = Longitudinal bending stress in shell, PSI
τ_r = Allowable shear stress in shear band, PSI
τ_w = Allowable shear stress in weld, PSI

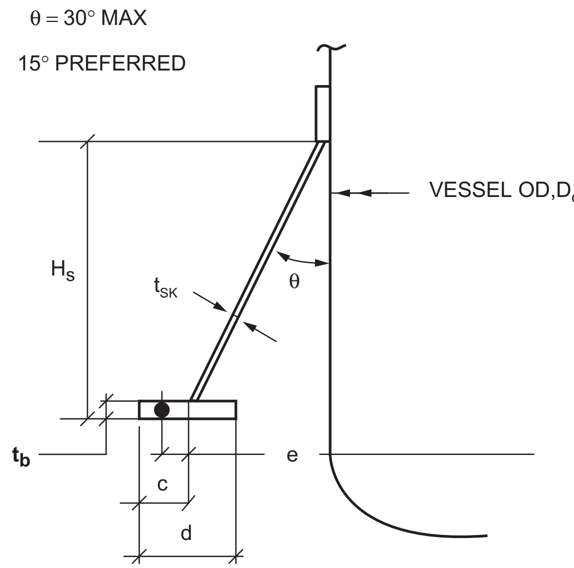


SIMPLE VESSEL DIAGRAM
SEE NOTE 1

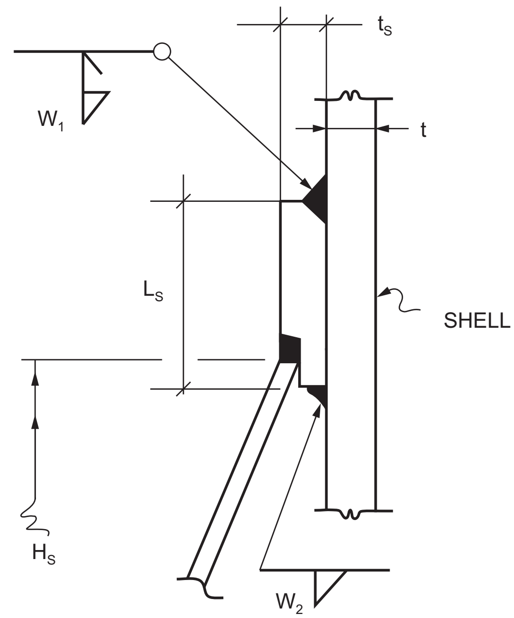




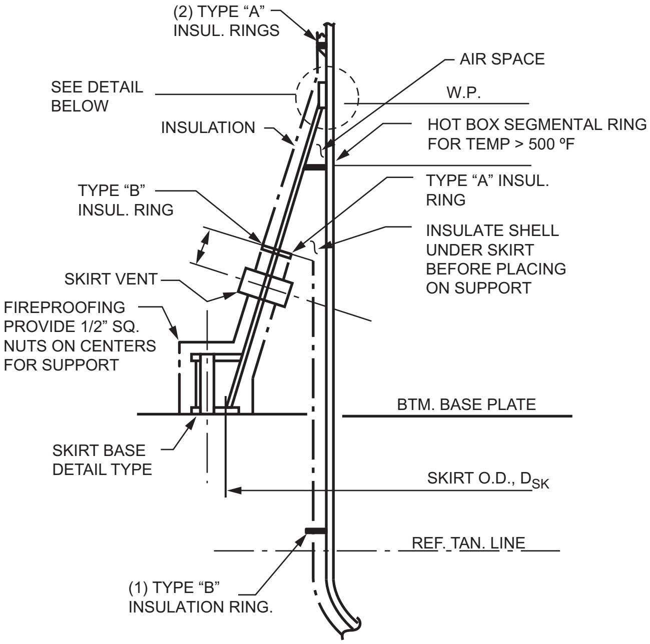
DETAIL OF FORCES



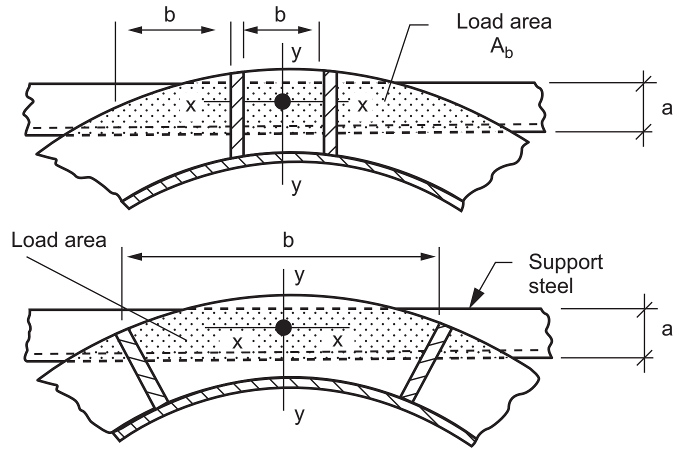
SKIRT DIMENSIONS



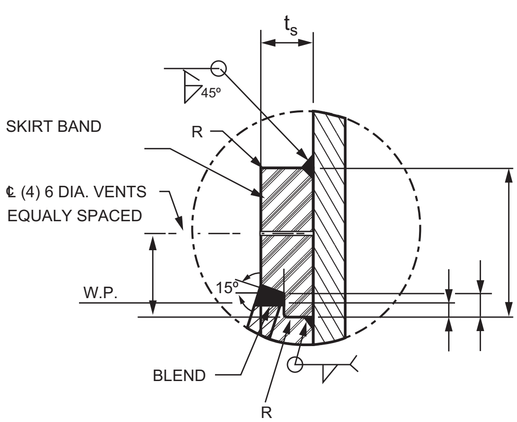
DIMENSIONS OF SHEAR BAND



SKIRT & BASE DETAILS



BASE PLATE LOADING



DETAIL OF SHEAR BAND

Table 4-21
Maximum bending moment in a bearing plate with gussets

a/b	$M_x \begin{bmatrix} x = .5b \\ y = \ell \end{bmatrix}$	$M_y \begin{bmatrix} x = .5b \\ y = 0 \end{bmatrix}$
0	0	$(-).500\ B_p\ l^2$
.333	$.0078\ B_p\ b^2$	$(-).428\ B_p\ \ell^2$
.5	$.0293\ B_p\ b^2$	$(-).319\ B_p\ \ell^2$
.666	$.0558\ B_p\ b^2$	$(-).227\ B_p\ \ell^2$
1.0	$.0972\ B_p\ b^2$	$(-).119\ B_p\ \ell^2$
1.5	$.1230\ B_p\ b^2$	$(-).124\ B_p\ \ell^2$
2.0	$.1310\ B_p\ b^2$	$(-).125\ B_p\ \ell^2$
3.0−∞	$.1330\ B_p\ b^2$	$(-).125\ B_p\ \ell^2$

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From Process Equipment Design, *Table 10.3 (See Note 2.)*

Calculation

Case 1: Simplified Approach (Note 1)

GIVEN:

D = ________ L = ________
F = ________ L_2 = ________
W = ________

Calculate moments;

$M_{AA} = F L_2$

$M_{BB} = F L$

Case 2: Rigorous Approach (Note 2)

GIVEN:

H_S = ________ L_3 = ________
L_4 = ________ W_1 = ________
W_2 = ________ F_1 = ________
F_2 = ________

V_{max} = Greater of F_1 or F_2

M_{max} = Greater of following;

$M_{AA} = F_1 L_3$

Or $= F_2 L_4$

$M_{BB} = (V_{max} H_S) + M_{max}$

$W = W_1 + W_2$

Design of Skirt

- Uniform loads in vessel at ELEV A-A;

$$w_T = \left[(-)W/(\pi D_O)\right] + \left[(4 M_{AA}/(\pi D_O^2)\right]$$
$$w_C = \left[(-)W/(\pi D_O)\right] - \left[(4 M_{AA}/(\pi D_O^2)\right]$$

- Find angle, θ, by layout or calculation;

$$X = .5\,[(D - 2\,e) - (D_O + 2\,t_S)]$$

$$\text{Tan}\,\theta = X/(H_S - t_b)$$

θ = ________

- Uniform load in skirt at ELEV A-A

$p_T = w_T/\text{Cos}\,\theta$
$p_C = w_C/\text{Cos}\,\theta$

- Allowable stress, skirt;

1. Compression, F_C
   Assume a thickness of skirt and calculate;

$A = (.125\,t_{SK})/(.5\,D_{SK})$

$F_C = (A\,E/2) < .5\,F_y$

2. Tension, F_T

S = from ASME II(D) $< .66\,F_y$

$F_T = 1.2\,S$

- Thickness required, skirt, t_r

Tension; $t_r = p_T/F_T$
Comp; $t_r = p_C/F_C$
Use t_{SK} = ________

- Stress due to ΔT

$$\sigma_{\Delta T} = \left[(48\,\Delta T)/(H_S - t_b)\right]\left[D_O\,t_{SK}\right]^{1/2}$$

- Longitudinal stress in skirt due to loadings;

Tension; $\sigma_{LT} = (p_T/t_{SK}) + \sigma_{\Delta T}$
Comp; $\sigma_{LC} = (p_C/t_{SK}) + \sigma_{\Delta T}$

Shear Ring

- Allowable shear stresses;

Ring; $\tau_r = .7\,S$
Weld; $\tau_w = .4\,S$

- Minimum length of shear band, L_{min}

$L_{min} = w_C/\tau_r$

- Size fillet welds, w_1 and w_2

$w = w_1 + w_2$
$w = w_C/(.707\,\tau_w)$
Use $w_1 = w_2$ = ________

- Thickness required for shear band, t_S

$t_S = 2\,w_1$
Use t_S = ________

Base Plate

The base plate thickness depends on how the vessel is supported. The vessel can either have continuous support or partial support. Partial support describes a vessel supported on 4 or 8 points on steel in a structure. Continuous support describes a concrete table top where there is full width, 360° contact between the base plate and the support.

Case A: Full Support

- Maximum load, f
  Note: The maximum loading is assumed to occur at the bolt circle.
  $f = [W/\pi D] \pm [4 M_{BB}/\pi D^2]$
- Bearing pressure, f_P
  $f_P = f/d < B_P$
- Base plate thickness, t_b
  $t_b = C\left[(3 f_P)/(.6 F_y)\right]^{1/2}$

Case B: Partial Support

- Load Q
  $Q = W/N \pm M_{BB}/D$
- Bearing pressure, f_P
  $f_P = Q/A_b$
- Maximum bending moment, M_b, from Table 4-21
  $a/b =$
  $M_b =$ greater of M_X or M_y
- Thickness of base plate, t_b
  $t_b = \left[(6 M_b/.6 F_y)\right]^{1/2}$

Anchor Bolts

- Determine if anchor bolts are required due to uplift
  $N_b A_t = [(48 M_{BB}/D) - W][1/S_b]$

If $N_b A_t$ is negative, then anchor bolts are not required. Use minimum size and maximum spacing for this case.
If $N_b A_t$ is positive then anchor bolts are required.

- Area required, A_t
  $A_t = [(48 M_{BB}/D) - W][1/N_b S_b]$

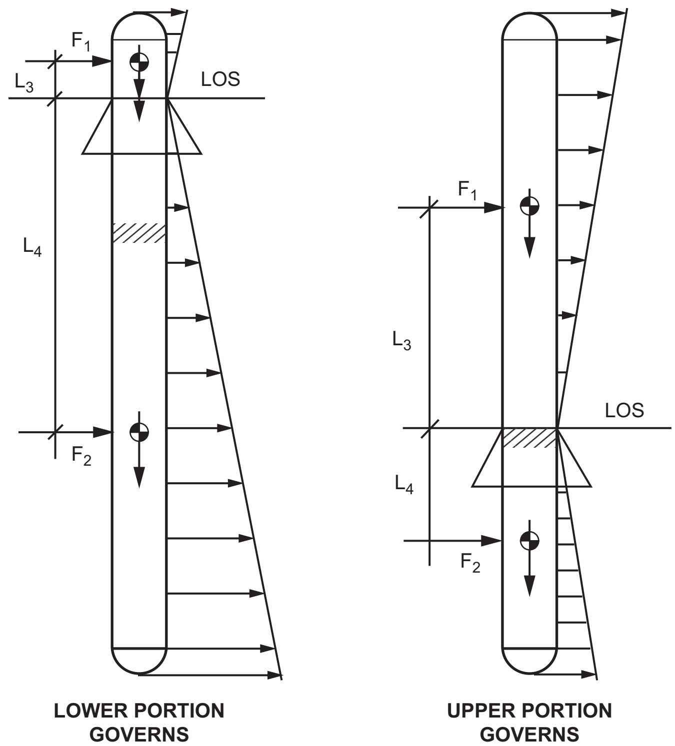
Use $N_b =$ _________
$d_b =$ _________

Longitudinal Stress in Shell due to Shear Band

- Cross sectional area of shear band, A_S
  $A_S = L_S t_S$
- Damping Factor, λ
  $\lambda = 1.285/(R_m t)^{1/2}$
- Bending moment in shell, M
  $M = [P/2 \lambda^2][A_S/(A_S + t L_S + 2 t/\lambda)]$
- Longitudinal bending stress in shell, σ_X
  $\sigma_X = 6 M/t^2$

Notes

1. The "Simplified Approach" is valid for average size vessels where $L/D < 5$ and the support point is near the C.G. of the vessel. The simplified approach applies the full seismic force at the C.G. of the vessel.
2. The "Rigorous Approach" is for vessel where $L/D > 5$ or the vessel is supported near the top or bottom of the vessel. In such cases the simplified approach may not be adequate. In this case the vessel is divided into two parts; the upper and lower part. The division between the upper and lower part is the line of support.
3. A third approach, not shown here, would be to determine the loadings by determining the shear and moments at each weld plane for each part of the vessel. This procedure is illustrated in Procedure 4-8.
4. The upper weight, W_1, will produce a compressive force in the shell equal to W_1 / A, where A is the cross sectional area of the vessel.
5. The lower weight, W_2, will produce a tensile force in the vessel shell equal to W_2 / A. This would be additive to effects due to internal pressure.
6. The effects of the unbalanced inward (or outward) load on the shell to cone junction should be evaluated for circumferential membrane and bending stresses, as well as longitudinal bending stresses.



M_{max} = GREATER OF ...

$M_{AA} = F_1 L_3$

Or $F_2 L_4$

$M_{BB} = (V_{max} H_s) + M_{max}$

V_{max} = Greater of F_1 or F_2

Figure 4-39. Vessel supported on conical skirt (Influence of support positioning).

Procedure 4-10: Design of Horizontal Vessel on Saddles [1,3,14,15]

Notation

A_r = cross-sectional area of composite ring stiffener, $in.^2$
E = joint efficiency
E_1 = modulus of elasticity, psi
C_h = seismic factor
I_1 = moment of inertia of ring stiffener, $in.^4$
t_w = thickness of wear plate, in.
t_s = thickness of shell, in.
t_h = thickness of head, in.
Q = total load per saddle (including piping loads, wind or seismic reactions, platforms, operating liquid, etc.) lb
W_o = operating weight of vessel, lb
M_1 = longitudinal bending moment at saddles, in.-lb
M_2 = longitudinal bending moment at midspan, in.-lb
S = allowable stress, tension, psi
S_c = allowable stress, compression, psi
S_{1-14} = shell, head, and ring stresses, psi
K_{1-9} = coefficients
F_L = longitudinal force due to wind, seismic, expansion, contraction, etc., lb
F_T = transverse force, wind or seismic, lb
σ_x = longitudinal stress, internal pressure, psi
σ_ϕ = circumferential stress, internal pressure, psi

σ_e = longitudinal stress, external pressure, psi
σ_s = circumferential stress in stiffening ring, psi
σ_h = latitudinal stress in head due to internal pressure, psi
F_y = minimum yield stress, shell, psi
P = internal pressure, psi
P_e = external pressure, psi
K_s = pier spring rate,
μ = friction coefficient
y = pier deflection, in.

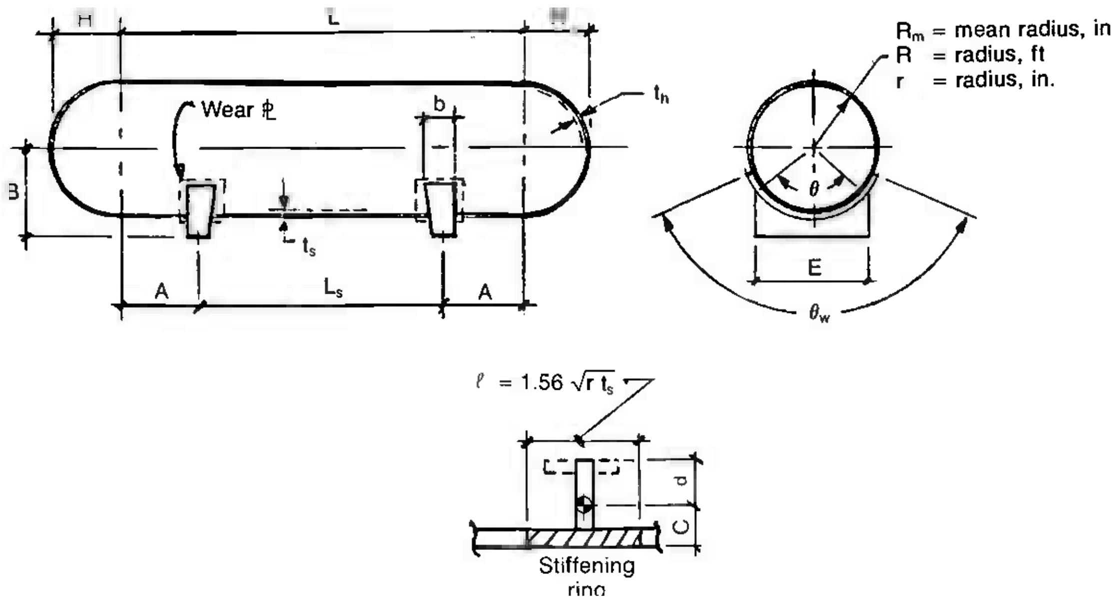


Figure 4-40. Typical dimensions for a horizontal vessel supported on two saddles.

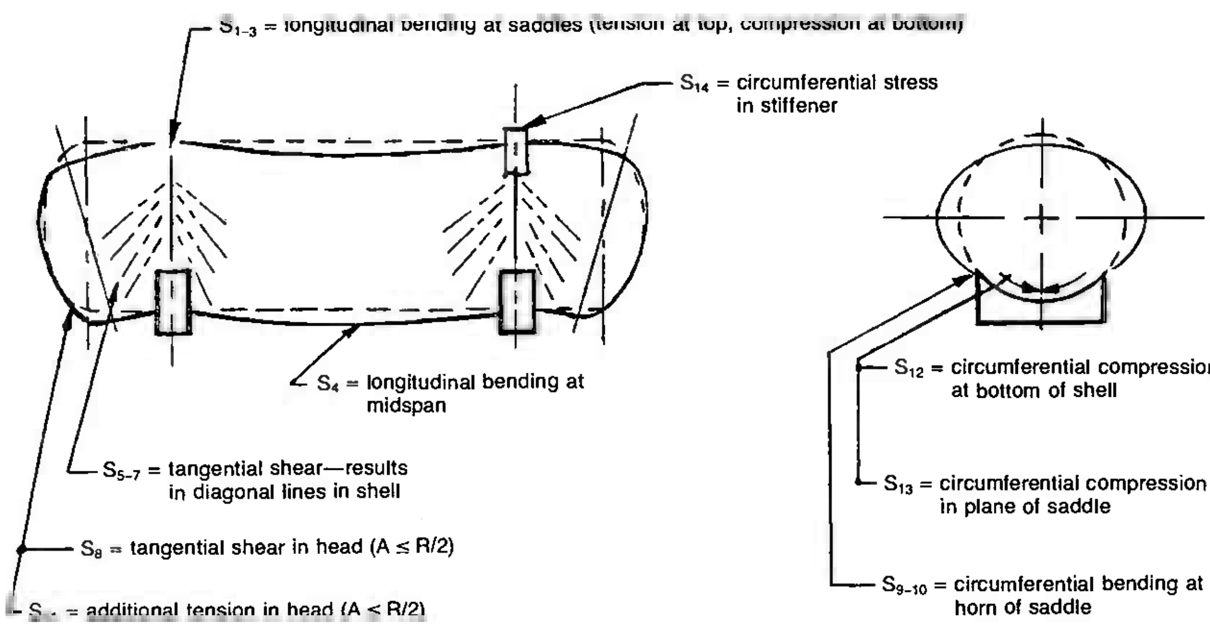
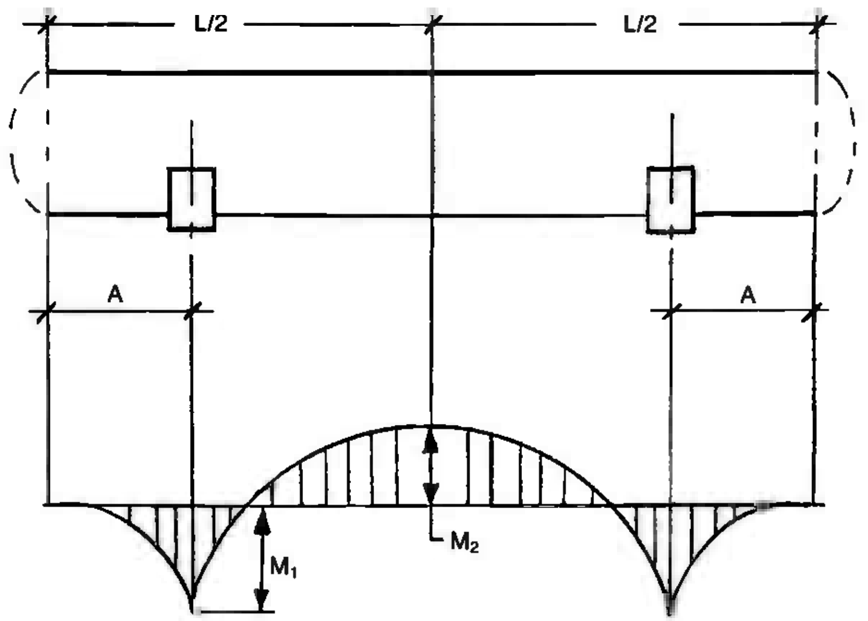


Figure 4-41. Stress diagram.



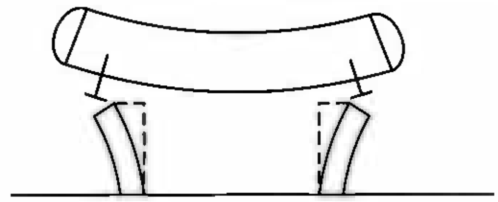
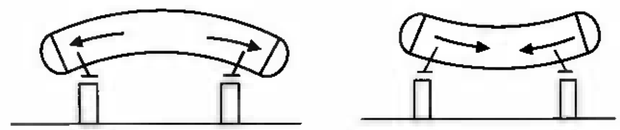
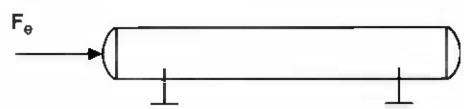
M_2 is negative for

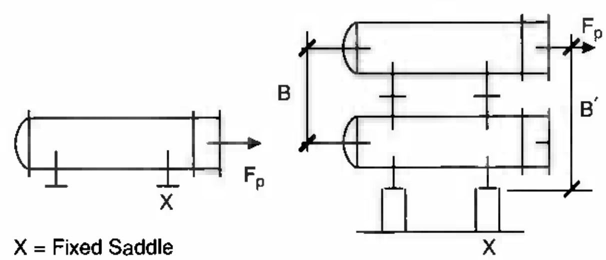
- Hemi-heads.
- If any of the below conditions are exceeded.

M_2 is positive for

- Flat heads where A/R < 0.707.
- 100%–6% F&D heads where A/R < 0.44
- 2:1 S.E. heads where A/R < 0.363

Figure 4-42. Moment diagram.

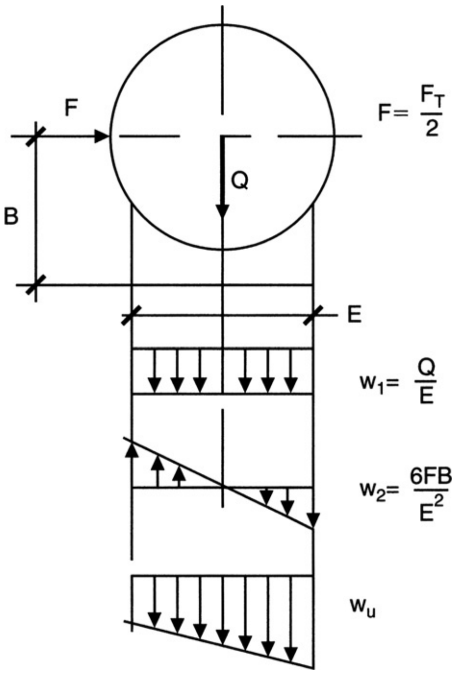
<table>
<tr><th>Longitudinal Forces, F_L</th><th></th></tr>
<tr><td>Case 1: Pier Deflection
$F_{L1} = \frac{K_s y}{2}$
$S_a = S$</td><td></td></tr>
<tr><td>Case 2: Expansion/Contraction
$F_{L2} = \mu Q_0$
$S_a = S$</td><td></td></tr>
<tr><td>Case 3: Wind
$F_{L3} = F_{wL} = A_f C_f G q_z$
$S_a = 1.33S$</td><td></td></tr>
<tr><td>Case 4: Seismic
$F_{L4} = F_e = C_h W_o$
$S_a = 1.33S$</td><td></td></tr>
<tr><td>Case 5: Shipping/Transportation
F_{L5} (See Chapter 10.)
$S_a = 0.9F_y$</td><td></td></tr>
<tr><td>Case 6: Bundle Pulling
$F_{L6} = F_p$
$S_a = 0.9F_y$

Full load applies to fixed saddle only!</td><td>
X = Fixed Saddle</td></tr>
</table>

Note: For Cases 5 and 6, assume the vessel is cold and not pressurized.

Transverse Load: Basis for Equations

Method 1



- *Unit load at edge of base plate, w_u.*

  $$W_u = W_1 + W_2$$

- *Derivation of equation for w_2.*

  $$\sigma = \frac{M}{Z} \qquad M = FB \qquad Z = \frac{E^2}{6}$$

  Therefore

  $$\frac{M}{Z} = \frac{6FB}{E^2}$$

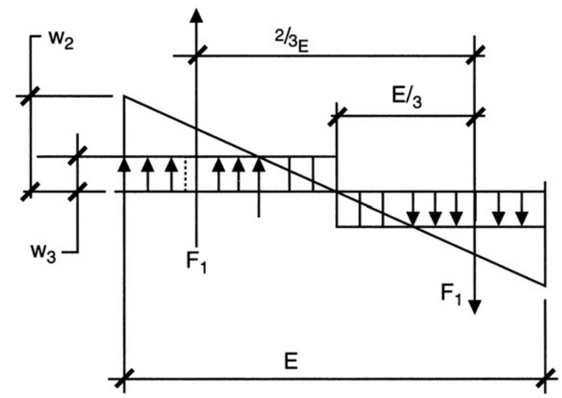
- *Equivalent total load Q_2.*

  $$Q_2 = w_u E$$

This assumes that the maximum load at the edge of the baseplate is uniform across the entire baseplate. This is very conservative, so the equation is modified as follows:

- *Using a triangular loading and 2/3 rule to develop a more realistic "uniform load"*

  $$F_1 = \frac{FB}{(2/3)E} = \frac{3FB}{2E}$$

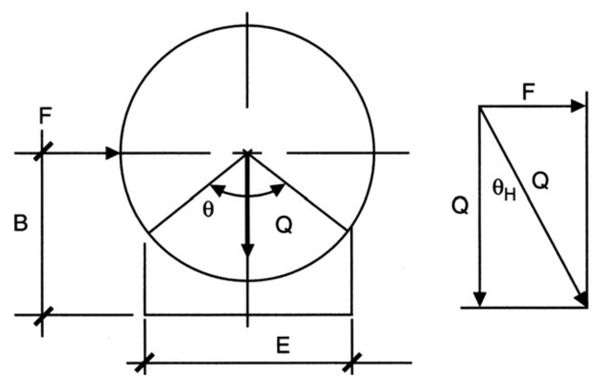


$$w_3 = \frac{3FB}{2E} \div \frac{E}{2} = \frac{6FB}{2E^2} = \frac{3FB}{E^2}$$

Therefore the total load, Q_F, due to force F is

$$Q_F = w_3 E = \frac{3FB}{E^2} E = \frac{3FB}{E}$$

Method 2



This method is based on the rationale that the load is no longer spread over the entire saddle but is shifted to one side.

- *Combined force, Q_2.*

  $$Q_2 = \sqrt{F^2 + Q^2}$$

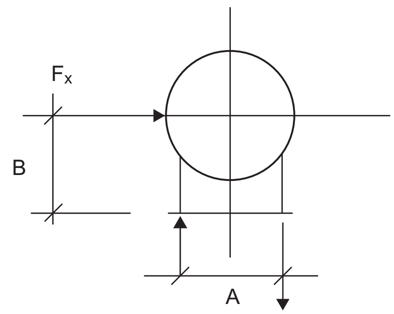
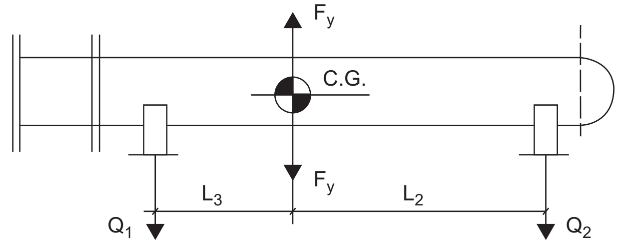
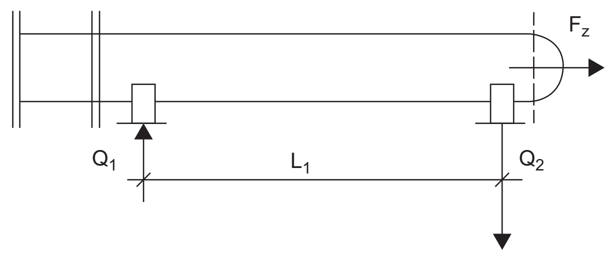
- *Angle, θ_H.*

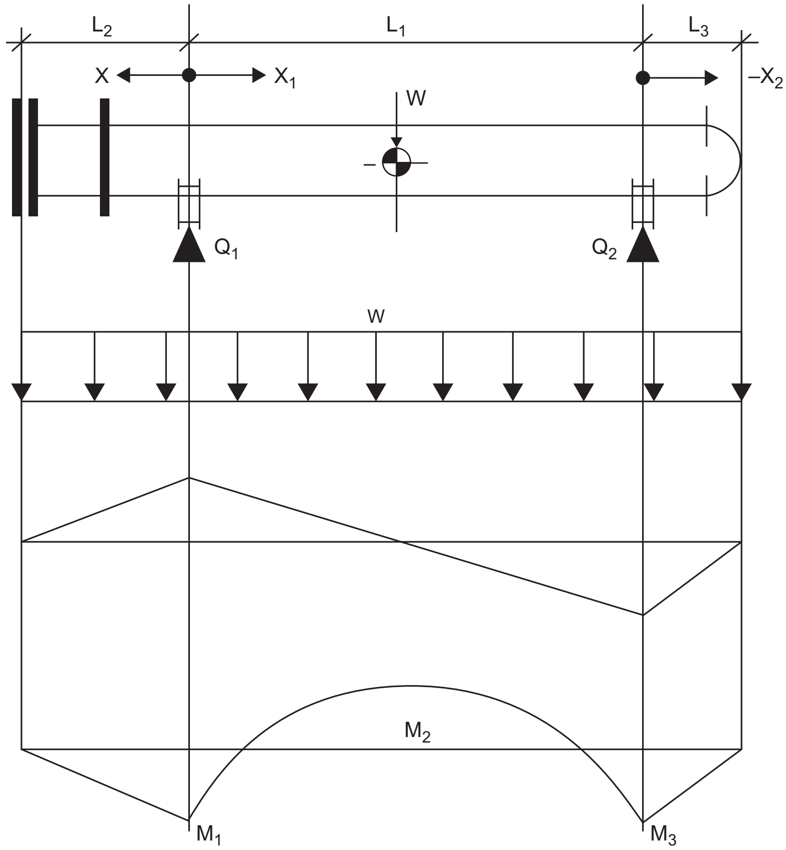
  $$\theta_H = \left(\arctan\right)\frac{F}{Q}$$

- *Modified saddle angle, θ_1.*

  $$\theta_1 = 2\left[\frac{\theta}{2}\right] - \theta_H$$

Saddle Reactions and Moments for Exchangers or Vessels with Offset Saddles

Due to…	Load per Saddle	Diagram
F_x	$Q_1 = \frac{W_s L_2}{L_1} + \frac{F_x B}{2A}$ $Q_2 = \frac{W_s L_3}{L_1} + \frac{F_x B}{2A}$	
F_y	$Q_1 = \frac{(W_s + F_y)L_2}{L_1}$ $Q_2 = \frac{(W_s + F_y)L_3}{L_1}$	
F_z	$Q_1 = \frac{W_S L_2}{L_1} + \frac{F_z B}{L_1}$ $Q_2 = \frac{W_S L_3}{L_1} + \frac{F_z B}{L_1}$	



Note: W = weight of vessel plus any impact factors

$$OAL = L_1 + L_2 + L_3 \quad w = \frac{W}{OAL}$$

$$Q_1 = \frac{w\left[(L_1 + L_2)^2 - L_3^2\right]}{2L_1}$$

$$Q_2 = W - Q_1$$

$$M_1 = \frac{wL_2^2}{2}$$

$$M_2 = Q_1\left(\frac{Q_1}{2w} - L_2\right)$$

$$M_3 = \frac{wL_3^2}{2}$$

$$M_x = \frac{w(L_2 - X)^2}{2}$$

$$M_{x1} = \frac{w(L_2 + X_1)^2}{2} - Q_1X_1$$

$$M_{x2} = \frac{w(L_3 - X_2)^2}{2}$$

Types of Stresses and Allowables

- *S_1 to S_4: longitudinal bending.*

  Tension: $S_1,\ S_3,\ \text{or}\ S_4 + \sigma_x < SE$

  Compression: $S_2,\ S_3,\ \text{or}\ S_4 - \sigma_e < S_c$

  where S_c = factor “B” or S or $t_sE_1/16r$ whichever is less.

1. Compressive stress is not significant where R_m/t <200 and the vessel is designed for internal pressure only.
2. When longitudinal bending at midspan is excessive, move saddles away from heads; however, do not exceed $A \geq 0.2$ L.
3. When longitudinal bending at saddles is excessive, move saddles toward heads.

4. If longitudinal bending is excessive at both saddles and midspan, add stiffening rings. If stresses are still excessive, increase shell thickness.

- *S_5 to $S_8 < 0.8S$: tangential shear.*
  1. Tangential shear is not combined with other stresses.
  2. If a wear plate is used, t_s may be taken as $t_s + t_w$, providing the wear plate extends R/10 above the horn of the saddle.
  3. If the shell is unstiffened, the maximum tangential shear stress occurs at the horn of the saddle.
  4. If the shell is stiffened, the maximum tangential shear occurs at the equator.
  5. When tangential shear stress is excessive, move saddles toward heads, $A \leq 0.5$ R, add rings, or increase shell thickness.
  6. When stiffening rings are used, the shell-to-ring weld must be designed to be adequate to resist the tangential shear as follows:

$$S_t = \frac{Q}{\pi r} : \frac{\text{lb}}{\text{in. circumference}} < \frac{\text{allowable shear}}{\text{in. of weld}}$$

- *$S_{11} + \sigma_h < 1.25$ SE: additional stress in head.*
  1. S_{11} is a shear stress that is additive to the hoop stress in the head and occurs whenever the saddles are located close to the heads, $A \leq 0.5$ R. Due to their close proximity the shear of the saddle extends into the head.
  2. If stress in the head is excessive, move saddles away from heads, increase head thickness, or add stiffening rings.
- *S_9 and $S_{10} < 1.5$ S and $0.9F_y$: circumferential bending at horn of saddle.*
  1. If a wear plate is used, t_s may be taken as $t_s + t_w$ providing the wear plate extends R/10 above the horn of the saddle. Stresses must also be checked at the top of the wear plate.
  2. If stresses at the horn of the saddle are excessive:
     a. Add a wear plate.
     b. Increase contact angle θ.
     c. Move saddles toward heads, $A < R$.
     d. Add stiffening rings.
- *$S_{12} < 0.5F_y$ or 1.5 S: circumferential compressive stress.*
  1. If a wear plate is used, t_s may be taken as $t_s + t_w$, providing the width of the wear plate is at least $b + 1.56\sqrt{rt_s}$.
  2. If the shell is unstiffened the maximum stress occurs at the horn of the saddle.
  3. If the shell is stiffened the maximum hoop compression occurs at the bottom of the shell.
  4. If stresses are excessive add stiffening rings.
- *$(+)S_{13} + \sigma_\phi < 1.5$ S: circumferential tension stress—shell stiffened.*
- *$(-)S_{13} - \sigma_s < 0.5F_y$: circumferential compression stress—shell stiffened.*
- *$(-)S_{14} - \sigma_s < 0.9F_y$: circumferential compression stress in stiffening ring.*

Procedure for Locating Saddles

Trial 1: Set A = 0.2 L and $\theta = 120°$ and check stress at the horn of the saddle, S_9 or S_{10}. This stress will govern for most vessels except for those with large L/R ratios.

Trial 2: Increase saddle angle θ to 150° and recheck stresses at horn or saddle, S_9 or S_{10}.

Trial 3: Move saddles near heads (A = R/2) and return θ to 120°. This will take advantage of stiffness provided by the heads and will also induce additional stresses in the heads. Compute stresses S_4, S_8, and S_9 or S_{10}. A wear plate may be used to reduce the stresses at the horn or saddle when the saddles are near the heads (A < R/2) and the wear plate extends R/10 above the horn of the saddle.

Trial 4: Increase the saddle angle to 150° and recheck stresses S_4, S_8, and S_9 or S_{10}. Increase the saddle angle progressively to a maximum of 168° to reduce stresses.

Trial 5: Move saddles to A = 0.2L and $\theta = 120°$ and design ring stiffeners in the plane of the saddles using the equations for S_{13} and S_{14} (see Note 7).

Total Saddle Reaction Forces, Q.

Q = greater of Q_1 or Q_2

Longitudinal, Q_1

$$Q_1 = \frac{W_o}{2} + \frac{F_L B}{L_s}$$

Transverse, Q_2

$$Q_2 = \frac{W_o}{2} + \frac{3F_t B}{E}$$

Shell Stresses

There are 14 main stresses to be considered in the design of a horizontal vessel on saddle supports:

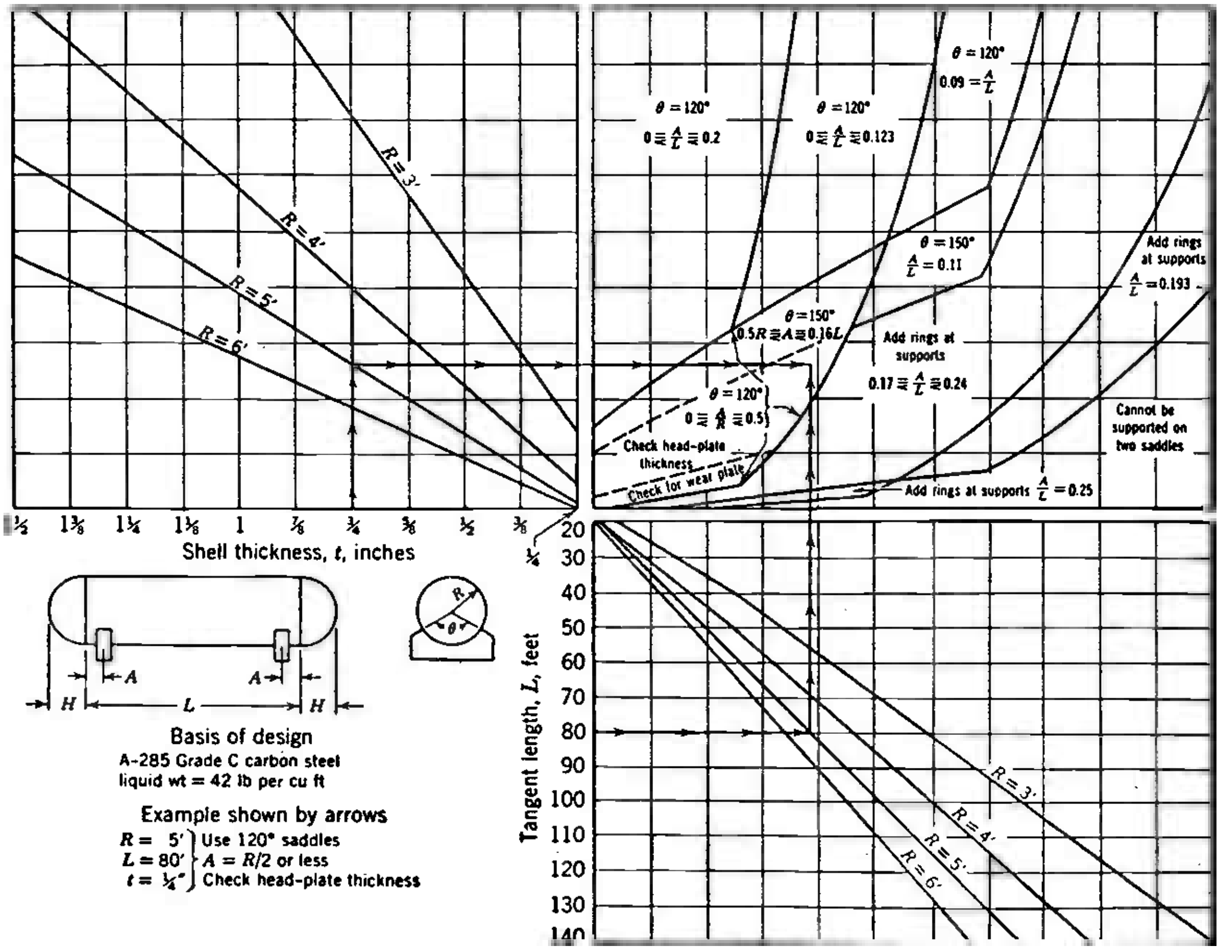


Figure 4-43. Chart for selection of saddles for horizontal vessels. *Reprinted by permission of the American Welding Society.*

S_1 = longitudinal bending at saddles without stiffeners, tension
S_2 = longitudinal bending at saddles without stiffeners, compression
S_3 = longitudinal bending at saddles with stiffeners
S_4 = longitudinal bending at midspan, tension at bottom, compression at top
S_5 = tangential shear—shell stiffened in plane of saddle
S_6 = tangential shear—shell not stiffened, $A > R/2$
S_7 = tangential shear—shell not stiffened except by heads, $A \leq R/2$
S_8 = tangential shear in head—shell not stiffened, $A \leq R/2$
S_9 = circumferential bending at horn of saddle—shell not stiffened, $L \geq 8R$
S_{10} = circumferential bending at horn of saddle—shell not stiffened, $L < 8R$
S_{11} = additional tension stress in head, shell not stiffened, $A \leq R/2$
S_{12} = circumferential compressive stress—stiffened or not stiffened, saddles attached or not
S_{13} = circumferential stress in shell with stiffener in plane of saddle
S_{14} = circumferential stress in ring stiffener

Longitudinal Bending

- *S_1, longitudinal bending at saddles—without stiffeners, tension.*

$$M_1 = 6Q\left[\frac{8AH + 6A^2 - 3R^2 + 3H^2}{3L + 4H}\right]$$

$$S_1 = (+)\frac{M_1}{K_1 r^2 t_s}$$

- *S_2, longitudinal bending at saddles—without stiffeners, compression.*

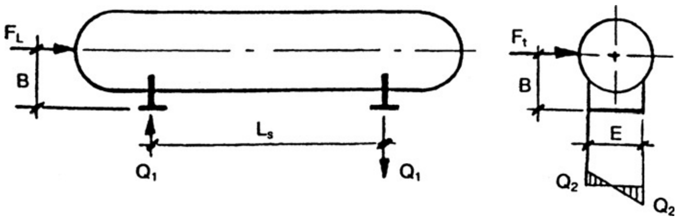


Figure 4-44. Saddle reaction forces.

$$S_2 = (-)\frac{M_1}{K_7 r^2 t_s}$$

- *S_3, longitudinal bending at saddles—with stiffeners.*

$$S_3 = (\pm)\frac{M_1}{\pi r^2 t_s}$$

- *S_4, longitudinal bending at midspan.*

$$M_2 = 3Q\left[\frac{3L^2 + 6R^2 - 6H^2 - 12AL - 16AH}{3L + 4H}\right]$$

$$S_4 = (\pm)\frac{M_2}{\pi r^2 t_s}$$

Tangential Shear

- *S_5, tangential shear—shell stiffened in the plane of the saddle.*

$$S_5 = \frac{Q}{\pi r t_s}\left[\frac{L - 2A}{L + \frac{4}{3}H}\right]$$

- *S_6, tangential shear—shell not stiffened, $A > 0.5R$.*

$$S_6 = \frac{K_2 Q}{r t_s}\left[\frac{L - 2A}{L + \frac{4}{3}H}\right]$$

- *S_7, tangential shear—shell not stiffened, $A \leq 0.5R$.*

$$S_7 = \frac{K_3 Q}{r t_s}$$

- S_8, *tangential shear in head—shell not stiffened, $A \leq 0.5R$.*

$$S_8 = \frac{K_3 Q}{r t_h}$$

Note: If shell is stiffened or $A > 0.5R$, $S_8 = 0$.

Circumferential Bending

- *S_9, circumferential bending at horn of saddle—shell not stiffened ($L \geq 8R$).*

$$S_9 = (-)\frac{Q}{4t_s(b + 1.56\sqrt{rt_s})} - \frac{3K_6 Q}{2t_s^2}$$

Note: $t_s = t_s + t_w$ and $t_s^2 = t_s^2 + t_w^2$ only if $A \leq 0.5R$ and wear plate extends R/10 above horn of saddle.

- *S_{10}, circumferential bending at horn of saddle—shell not stiffened ($L < 8R$).*

$$S_{10} = (-)\frac{Q}{4t_s(b + 1.56\sqrt{rt_s})} - \frac{12K_6 QR}{Lt_s^2}$$

Note: Requirements for t_s are same as for S_9.

Additional Tension Stress in Head

- *S_{11}, additional tension stress in head—shell not stiffened, $A \leq 0.5R$.*

$$S_{11} = \frac{K_4 Q}{r t_h}$$

Note: If shell is stiffened or $A > 0.5R$, $S_{11} = 0$.

Circumferential Tension/Compression

- *S_{12}, circumferential compression.*

$$S_{12} = (-)\frac{K_5 Q}{t_s(b + 1.56\sqrt{rt_s})}$$

Note: ts = ts + tw only if wear plate is attached to shell and width of wear plate is a minimum of $b + 1.56\sqrt{rt_s}$.

- *S_{13}, circumferential stress in shell with stiffener (see Note 8).*

$$S_{13} = (-)\frac{K_8 Q}{A_r} \pm \frac{K_9 QrC}{I_1}$$

Note: Add second expression if vessel has an internal stiffener, subtract if vessel has an external stiffener.

- *S_{14}, circumferential compressive stress in stiffener (see Note 8).*

$$S_{14} = (-)\frac{K_8 Q}{A_r} - \frac{K_9 Qrd}{I_1}$$

Pressure Stresses

$$\sigma_x = \frac{PR_m}{2t_s}$$

$$\sigma_\phi = \frac{PR_m}{t_s}$$

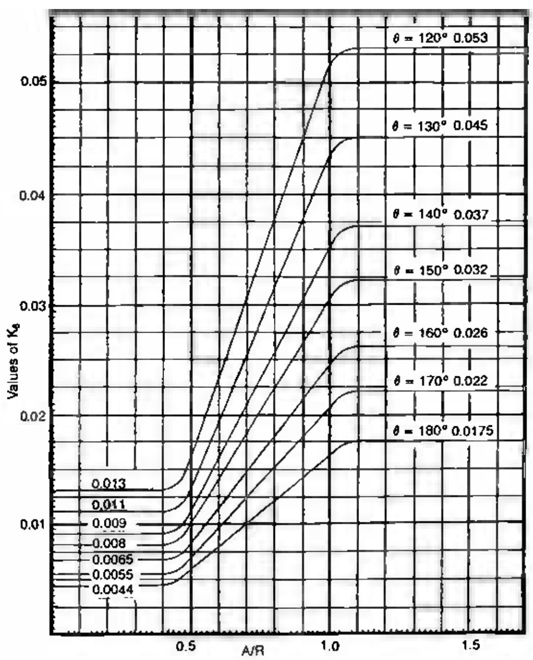
$$\sigma_e = \frac{P_e R_m}{2t_s}$$

$$\sigma_s = \frac{PIR_m}{A_r}$$

$\sigma_h = \sigma_\phi$, maximum circumferential stress in head is equal to hoop stress in shell

Combined Stresses

Tension		Compression	
Stress	**Allowable**	**Stress**	**Allowable**
$S_1 + \sigma_x$	SE =	$-S_2 - \sigma_e$	$S_c =$
$S_3 + \sigma_x$	SE =	$-S_3 - \sigma_e$	$S_c =$
$S_4 + \sigma_x$	SE =	$-S_4 - \sigma_e$	$S_c =$
$S_{11} + \sigma_h$	1.25SE =	$-S_{13} - \sigma_s$	$0.5F_y =$
$S_{13} + \sigma_\phi$	1.5SE =	$-S_{14} - \sigma_s$	$0.9F_y =$



Contact Angle θ	K_1*	K_2	K_3	K_4	K_5	K_7	K_8	K_9	Contact Angle θ	K_1*	K_2	K_3	K_4	K_5	K_7	K_8	K_9
120	0.335	1.171	0.880	0.401	0.760	0.603	0.340	0.053	152	0.518	0.781	0.466	0.289	0.669	0.894	0.298	0.03
122	0.345	1.139	0.846	0.393	0.753	0.618	0.338	0.051	154	0.531	0.763	0.448	0.283	0.665	0.913	0.296	0.030
124	0.355	1.108	0.813	0.385	0.746	0.634	0.336	0.050	156	0.544	0.746	0.430	0.278	0.661	0.933	0.294	0.028
126	0.366	1.078	0.781	0.377	0.739	0.651	0.334	0.048	158	0.557	0.729	0.413	0.272	0.657	0.954	0.292	0.027
128	0.376	1.050	0.751	0.369	0.732	0.669	0.332	0.047	160	0.571	0.713	0.396	0.266	0.654	0.976	0.290	0.026
130	0.387	1.022	0.722	0.362	0.726	0.689	0.330	0.045	162	0.585	0.698	0.380	0.261	0.650	0.994	0.286	0.025
132	0.398	0.996	0.694	0.355	0.720	0.705	0.328	0.043	164	0.599	0.683	0.365	0.256	0.647	1.013	0.282	0.024
134	0.409	0.971	0.667	0.347	0.714	0.722	0.326	0.042	166	0.613	0.668	0.350	0.250	0.643	1.033	0.278	0.024
136	0.420	0.946	0.641	0.340	0.708	0.740	0.324	0.040	168	0.627	0.654	0.336	0.245	0.640	1.054	0.274	0.023
138	0.432	0.923	0.616	0.334	0.702	0.759	0.322	0.039	170	0.642	0.640	0.322	0.240	0.637	1.079	0.270	0.022
140	0.443	0.900	0.592	0.327	0.697	0.780	0.320	0.037	172	0.657	0.627	0.309	0.235	0.635	1.097	0.266	0.02
142	0.455	0.879	0.569	0.320	0.692	0.796	0.316	0.036	174	0.672	0.614	0.296	0.230	0.632	1.116	0.262	0.020
144	0.467	0.858	0.547	0.314	0.687	0.813	0.312	0.035	176	0.0687	0.601	0.283	0.225	0.629	1.137	0.258	0.019
146	0.480	0.837	0.526	0.308	0.682	0.831	0.308	0.034	178	0.702	0.589	0.271	0.220	0.627	1.158	0.254	0.018
148	0.492	0.818	0.505	0.301	0.678	0.853	0.304	0.033	180	0.718	0.577	0.260	0.216	0.624	1.183	0.250	0.017
150	0.505	0.799	0.485	0.295	0.673	0.876	0.300	0.032									

K_1 = 3.14 if the shell is stiffened by ring or head (A < R/2).

Figure 4-45. Coefficients.

Table 4-22
Coefficients for Zick's analysis (angles 80° to 120°)

						A/R ≤ 0.5	A/R ≥ 1.0			
SADDLE ANGLE θ	**K_1**	**K_2**	**K_3**	**K_4**	**K_5**	**K_6**	**K_6**	**K_7**	**K_8**	**K_9**
80	0.1711	2.2747	2.0419	0.6238	0.9890	0.0237	0.0947	0.3212	0.3592	−0.0947
81	0.1744	2.2302	1.9956	0.6163	0.9807	0.0234	0.0934	0.3271	0.3592	0.0934
82	0.1777	2.1070	1.9506	0.6090	0.9726	0.0230	0.0922	0.3331	0.3593	0.0922
83	0.1811	2.1451	1.9070	0.6018	0.9646	0.0227	0.0910	0.3391	0.3593	0.0910
84	0.1845	2.1044	1.8645	0.5947	0.9568	0.0224	0.0897	0.3451	0.3593	0.0897
85	0.1879	2.0648	1.8233	0.5877	0.9492	0.0221	0.0885	0.3513	0.3593	0.0885
86	0.1914	2.0264	1.7831	0.5808	0.9417	0.0218	0.0873	0.3575	0.3592	0.0873
87	0.1949	1.9891	1.7441	0.5741	0.9344	0.0215	0.0861	0.3637	0.3591	0.0861
88	0.1985	1.9528	1.7061	0.5675	0.9273	0.0212	0.0849	0.3700	0.3590	0.0849
89	0.2021	1.9175	1.6692	0.5610	0.9203	0.0209	0.0838	0.3764	0.3588	0.0830
90	0.2057	1.8832	1.6332	0.5546	0.9134	0.0207	0.0826	0.3828	0.3586	0.0826
91	0.2094	1.8497	1.5981	0.5483	0.9067	0.0204	0.0815	0.3893	0.3584	0.0815
92	0.2132	1.8172	1.5640	0.5421	0.9001	0.0201	0.0803	0.3959	0.3582	0.0803
93	0.2169	1.7856	1.5308	0.5360	0.8937	0.0198	0.0792	0.4025	0.3579	0.0792
94	0.2207	1.7548	1.4984	0.5300	0.8874	0.0195	0.0781	0.4092	0.3576	0.0781
95	0.2246	1.7247	1.4668	0.5241	0.8812	0.0192	0.0770	0.4160	0.3573	0.0770
96	0.2285	1.6955	1.4360	0.5183	0.8751	0.0190	0.0759	0.4228	0.3569	0.0759
97	0.2324	1.6670	1.4060	0.5125	0.8692	0.0187	0.0748	0.4296	0.3565	0.0748
98	0.2364	1.6392	1.3767	0.5069	0.8634	0.0184	0.0737	0.4366	0.3561	0.0737
99	0.2404	1.6122	1.3482	0.5013	0.8577	0.0182	0.0727	0.4436	0.3557	0.0727
100	0.2445	1.5858	1.3203	0.4959	0.8521	0.0179	0.0716	0.4506	0.3552	0.0716
101	0.2486	1.5600	1.2931	0.4905	0.8466	0.0176	0.0706	0.4577	0.3547	0.0706
102	0.2528	1.5349	1.2666	0.4852	0.8412	0.0174	0.0696	0.4649	0.3542	0.0696
103	0.2570	1.5104	1.2407	0.4799	0.8359	0.0171	0.0686	0.4721	0.3536	0.0686
104	0.2612	1.4865	1.2154	0.4748	0.8308	0.0169	0.0675	0.4794	0.3531	0.0675
105	0.2655	1.4631	1.1907	0.4697	0.8257	0.0166	0.0666	0.4868	0.3525	0.0666
106	0.2698	1.4404	1.1665	0.4647	0.8207	0.0164	0.0656	0.4942	0.3518	0.0656
107	0.2742	1.4181	1.1429	0.4597	0.8159	0.0161	0.0646	0.5017	0.3512	0.0646
108	0.2786	1.3964	1.1199	0.4549	0.8111	0.0159	0.0636	0.5092	0.3505	0.0636
109	0.2830	1.3751	1.0974	0.4500	0.8064	0.0157	0.0627	0.5168	0.3498	0.0627
110	0.2875	1.3544	1.0753	0.4453	0.8018	0.0154	0.0617	0.5245	0.3491	0.0617
111	0.2921	1.3341	1.0538	0.4406	0.7973	0.0152	0.0608	0.5322	0.3483	0.0608
112	0.2966	1.3143	1.0327	0.4360	0.7928	0.0150	0.0599	0.5400	0.3475	0.0599
113	0.3013	1.2949	1.0121	0.4314	0.7885	0.0147	0.0590	0.5478	0.3467	0.0590
114	0.3059	1.2760	0.9920	0.4269	0.7842	0.0145	0.0581	0.5557	0.3459	0.0581
115	0.3107	1.2575	0.9723	0.4225	0.7800	0.0143	0.0572	0.5636	0.3451	0.0572
116	0.3154	1.2394	0.9530	0.4181	0.7759	0.0141	0.0563	0.5717	0.3442	0.0563
117	0.3202	1.2216	0.9341	0.4137	0.7719	0.0139	0.0554	0.5797	0.3433	0.0554
118	0.3251	1.2043	0.9157	0.4095	0.7680	0.0136	0.0546	0.5878	0.3424	0.0546
119	0.3300	1.1873	0.8976	0.4052	0.7641	0.0134	0.0537	0.5960	0.3414	0.0537
120	0.3349	1.1707	0.8799	0.4011	0.7603	0.0132	0.0529	0.6043	0.3405	0.0529
θ	K_1	K_2	K_3	K_4	K_5	K_6	K_6	K_7	K_8	K_9
SADDLE ANGLE						A/R ≤ 0.5	A/R ≥ 1.0			

Notes:

1. These coefficients are derived from Zick's equations.
2. The ASME Code does not recommend the use of saddles with an included angle, θ, less than 120°. Therefore the values in this table should be used for very small-diameter vessels or to evaluate existing vessels built prior to this ASME recommendation.
3. Values of K_6 for A/R ratios between 0.5 and 1 can be interpolated.

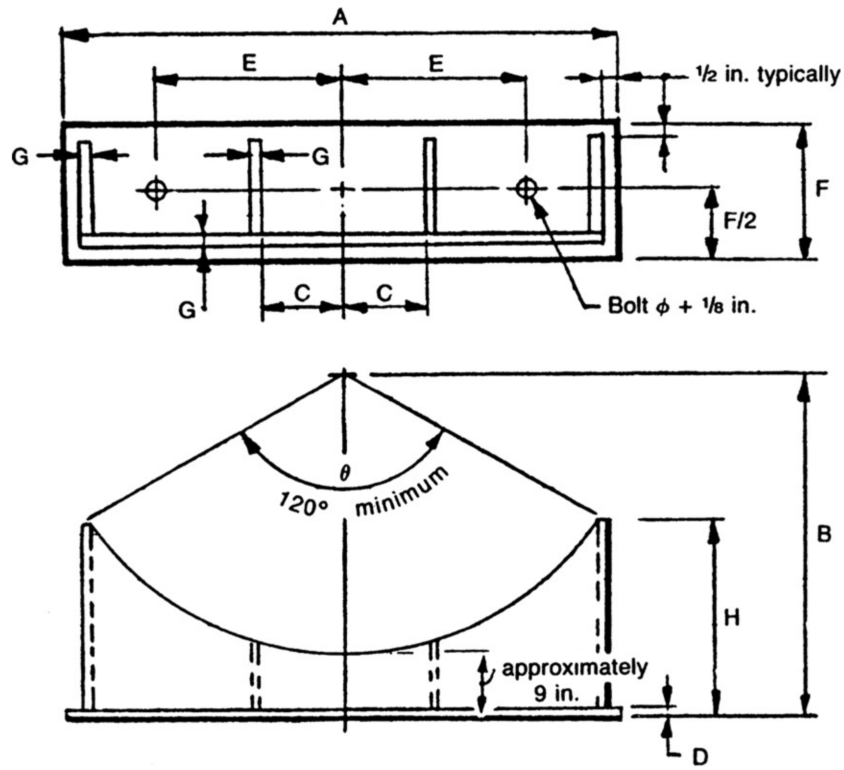


Figure 4-46. Saddle dimensions.

Table 4-23
Slot dimensions

Temperature °F	Distance Between Saddles				
	10ft	20ft	30ft	40ft	50ft
−50	0	0	0.25	0.25	0.375
100	0	0	0.125	0.125	0.250
200	0	0.250	0.375	0.375	0.500
300	0.250	0.375	0.625	0.750	1.00
400	0.375	0.625	0.875	1.125	1.375
500	0.375	0.750	1.125	1.500	1.625
600	0.500	1.00	1.375	1.875	2.250
700	0.625	1.125	1.625	2.125	2.625
800	0.750	1.250	1.625	2.375	3.000
900	0.750	1.375	2.000	2.500	3.375

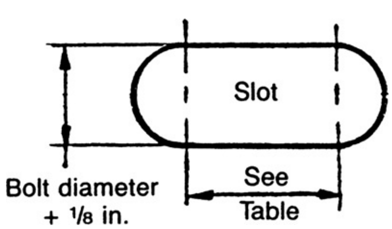


Table 4-24
Typical saddle dimensions*

Vessel O.D.	Maximum Operating Weight	A	B	C	D	E	F	G	H	Bolt Diameter	θ	Approximate Weight/Set
24	15,400	22	21	N.A.	0.5	7	4	0.25	15.2	1	122°	80
30	16,700	27	24			9	4		16.5		120°	100
36	15,700	33	27			12	6		18.8		125°	170
42	15,100	38	30			15			20.0		123°	200
48	25,330	44	33			18			22.3		127°	230
54	26,730	48	36			20			22.7		121°	270
60	38,000	54	39			23			25.0		124°	310
66	38,950	60	42			26			27.2		127°	35D
72	50,700	64	45	10		28		0.375	27.6		122°	420
78	56,500	70	48	11	0.75	31	8		29.8		124°	710
84	57,525	74	51	12		33			30.2		121°	810
90	64,200	80	54	13		36			32.5		123°	880
96	65,400	86	57	14		39			34.7		125°	940
102	94,500	92	60	15		42	10	0.500	37.0	1¼	126°	1,350
108	85,000	96	63	16		44			37.3		123°	1,430
114	164,000	102	66	17		47		0.625	39.6		125°	1,760
120	150,000	106	69	18		49			40.0		122°	1,800
132	127,500	118	75	20		55			44.5		125°	2,180
144	280,000	128	81	22		60			47.0		124°	2,500
156	266,000	140	87	24		66			51.6		126°	2,730

** Table is in inches and pounds and degrees.*

Notes

1. Horizontal vessels act as beams with the following exceptions:
   a. Loading conditions vary for full or partially full vessels.
   b. Stresses vary according to angle θ and distance "A."
   c. Load due to weight is combined with other loads.
2. Large-diameter, thin-walled vessels are best supported near the heads, provided the shell can take the load between the saddles. The resulting stresses in the heads must be checked to ensure the heads are stiff enough to transfer the load back to the saddles.
3. Thick-walled vessels are best supported where the longitudinal bending stresses at the saddles are about equal to the longitudinal bending at midspan. However, "A" should not exceed 0.2 L.
4. Minimum saddle angle $\theta = 120°$, except for small vessels. For vessels designed for external pressure only θ should always = 120°. The maximum angle is 168° if a wear plate is used.
5. Except for large L/R ratios or $A > R/2$, the governing stress is circumferential bending at the horn of the saddle. Weld seams should be avoided at the horn of the saddle.
6. A wear plate may be used to reduce stresses at the horn of the saddle *only* if saddles are near heads ($A \leq R/2$), and the wear plate extends R/10 (5.73 deg.) above the horn of the saddle.
7. If it is determined that stiffening rings will be required to reduce shell stresses, move saddles away from the heads (preferable to $A = 0.2$ L). This will prevent designing a vessel with a flexible center and rigid ends. Stiffening ring sizes may be reduced by using a saddle angle of 150°.
8. An internal stiffening ring is the most desirable from a strength standpoint because the maximum stress in the shell is compressive, which is reduced by internal pressure. An internal ring may not be practical from a process or corrosion standpoint, however.
9. Friction factors:

Surfaces	*Friction Factor, μ*
Lubricated steel-to-concrete	0.45
Steel-to-steel	0.4
Lubrite-to-steel	
• Temperature over 500°F	0.15
• Temperature 500°F or less	0.10
• Bearing pressure less than 500 psi	0.15
Teflon-to-Teflon	
• Bearing 800 psi or more	0.06
• Bearing 300 psi or less	0.1

Procedure 4-11: Design of Saddle Supports for Large Vessels [4,15–17,20]

Notation

A_s = cross-sectional area of saddle, in.^{2}
A_b = area of base plate, in.^{2}
A_p = pressure area on ribs, in.^{2}
A_r = cross-sectional area, rib, in.^{2}
Q = maximum load per saddle, lb
$Q_1 = Q_o + Q_R$, lb
$Q_2 = Q_o + Q_L$, lb
Q_o = load per saddle, operating, lb
Q_T = load per saddle, test, lb
Q_L = vertical load per saddle due to longitudinal loads, lb
Q_R = vertical load per saddle due to transverse loads, lb
F_L = maximum longitudinal force due to wind, seismic, pier deflection, etc. (see Procedure 4-10 for detailed description)
F_a = allowable axial stress, psi
F_b = allowable bending stress, psi
F_T = transverse wind or seismic load, lb
N = number of anchor bolts in the fixed saddle
a_t = cross-sectional area of bolts in tension, in.^{2}
Y = effective bearing length, in.
T = tension load in outer bolt, lb
n_1 = modular ratio, steel to concrete, use 10
F_b = allowable bending stress, psi
F_y = yield stress, psi
f_h = saddle splitting force, lb
f_a = axial stress, psi
f_b = bending stress, psi
f_u = unit force, lb/in.
B_p = bearing pressure, psi
M = bending moment, or overturning moment, in.-lb
I = moment of inertia, in.^{4}
Z = section modulus, in.^{3}
r = radius of gyration, in.
K_1 = saddle splitting coefficient
n = number of ribs, including outer ribs, in one saddle
P = equivalent column load, lb
d = distance from base to centroid of saddle arc, in.
W_o = operating weight of vessel plus contents, lb
W_T = vessel weight full of water, lb
σ_T = tension stress, psi
w = uniform load, lb

Forces and Loads

Vertical Load per Saddle

For loads due to the following causes, use the given formulas.

- *Operating weight.*

$$Q_o = \frac{W_o}{2}$$

- *Test weight.*

$$Q_T = \frac{W_T}{2}$$

- *Longitudinal wind or seismic.*

$$Q_L = \frac{F_L B}{L_s}$$

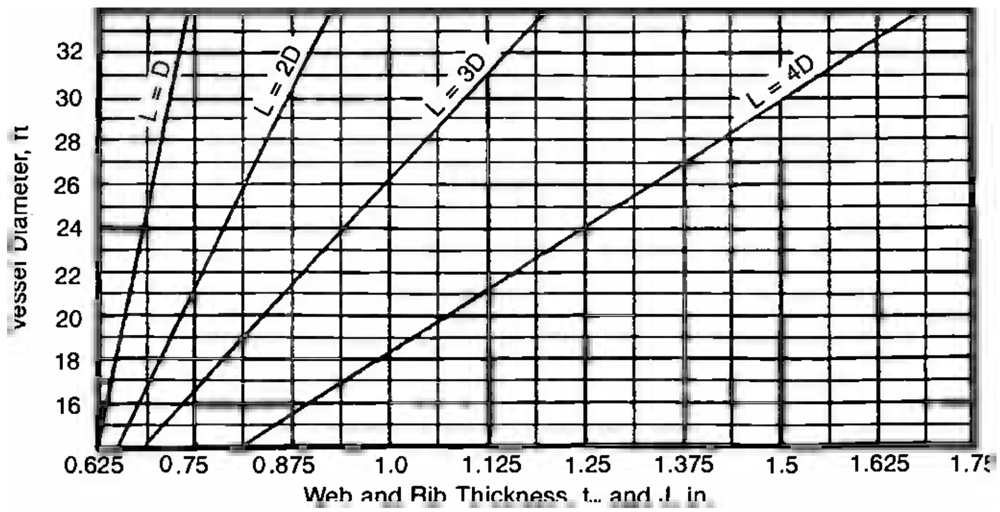


Figure 4-47. Graph for determining web and rib thicknesses.

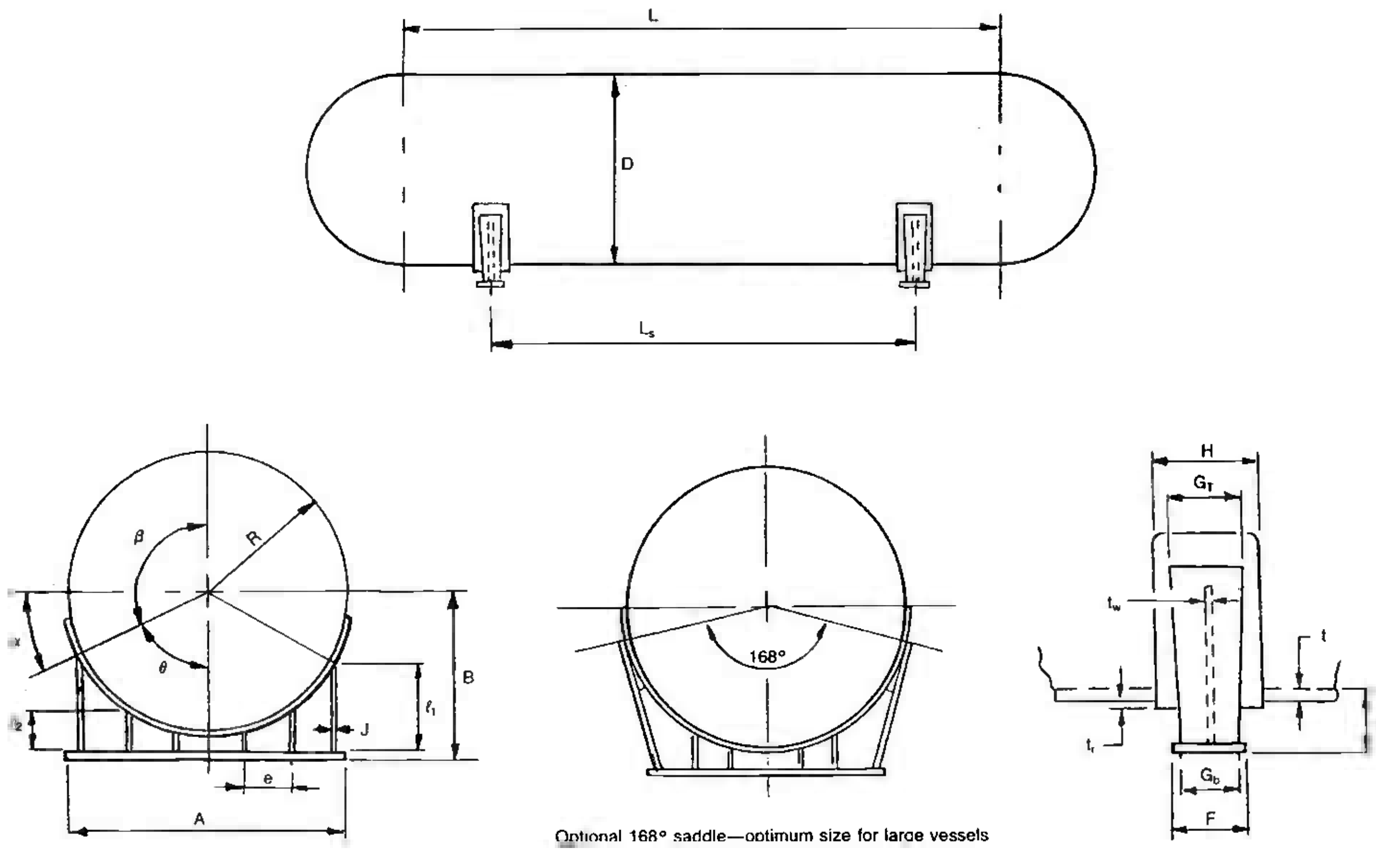


Figure 4-48. Dimensions of horizontal vessels and saddles.

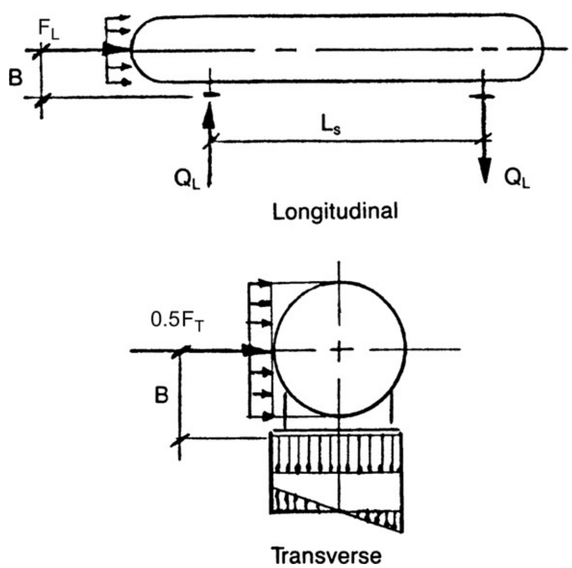


Figure 4-49. Saddle loadings.

- *Transverse wind or seismic.*

$$Q_R = \frac{3F_TB}{A}$$

Maximum Loads

- *Vertical.*
  greater of Q_1, Q_2, or Q_T

$$Q_1 = Q_o + Q_R$$
$$Q_2 = Q_o + Q_L$$

- *Longitudinal.*
  F_L = greater of F_{L1} through F_{L6}

Saddle Properties

- *Preliminary web and rib thicknesses, t_w and J.* From Figure 4-47:

$$J = t_w$$

- *Number of ribs required, n.*

$$n = \frac{A}{24} + 1$$

Round up to the nearest even number.

- *Minimum width of saddle at top, G_T, in.*

$$G_T = \sqrt{\frac{5.012F_L}{J(n-1)F_b}\left[h + \frac{A}{1.96}(1 - \sin\ \alpha)\right]}$$

where F_L and F_b are in kips and ksi or lb and psi, and J, h, A are in inches.

- *Minimum wear plate dimensions.*

Width:

$$H = G_T + 1.56\sqrt{Rt_s}$$

Thickness:

$$t_r = \frac{(H - G_T)^2}{2.43R}$$

- *Moment of inertia of saddle, I.* See Figure 4-50

$$C_1 = \frac{\sum AY}{\sum A}$$
$$C_2 = h - C_1$$
$$I = \sum AY^2 + \sum I_o - C_1 \sum AY$$

- *Cross-sectional area of saddle (excluding shell).*

$$A_s = \sum A - A_1$$

Design of Saddle Parts

Web

Web is in tension and bending as a result of saddle splitting forces. The saddle splitting forces, f_h, are the sum of all the horizontal reactions on the saddle.

- *Saddle coefficient.* See Table 4-25

$$K_1 = \frac{1 + \cos\beta - 0.5\sin^2\beta}{\pi - \beta + \sin\beta\cos\beta}$$

Note: β is in radians.

- *Saddle splitting force.* See Figure 4-51 and 4-52

$$f_h = K_1(Q \text{ or } Q_T)$$

- *Tension stress.*

$$\sigma_T = \frac{f_h}{A_s} < 0.6F_y$$

Note: For tension assume saddle depth "h" as R/3 maximum.

- *Bending moment.*

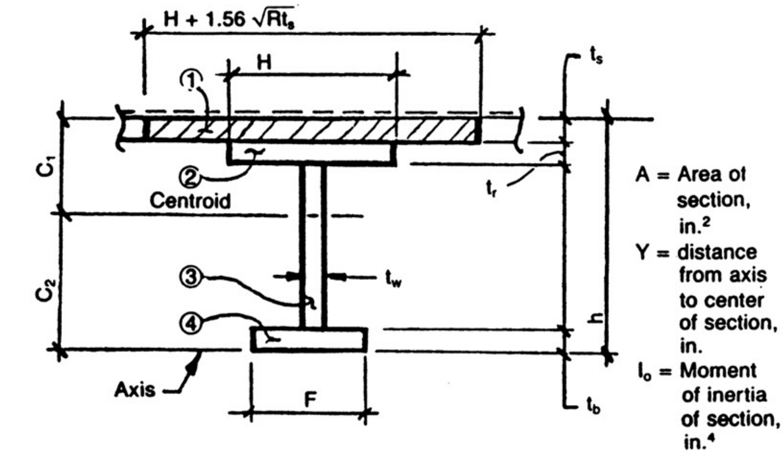
$$d = B - \frac{R\sin\theta}{\theta}$$

θ is in radians.

$$M = f_hd$$

- *Bending stress.*

$$f_b = \frac{MC_1}{I} < 0.66\,F_y$$



	A	Y	AY	AY^2	I_o
①					
②					
③					
④					
Σ					

Note: I_o for rectangles $= \frac{bh^3}{12}$

Figure 4-50. Cross-sectional properties of saddles.

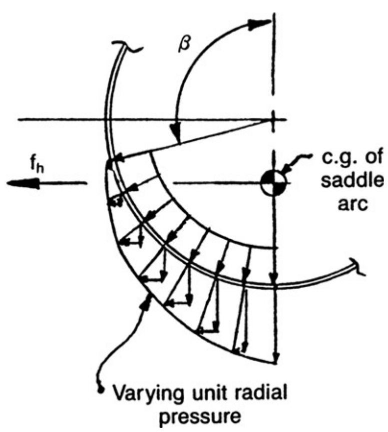
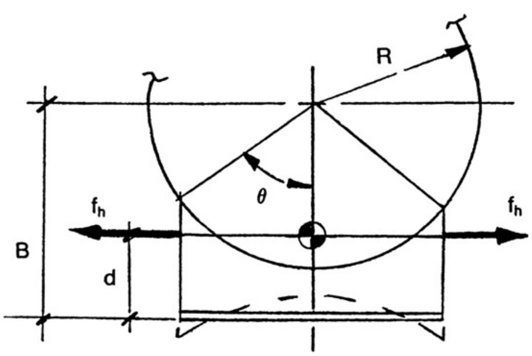


Figure 4-51. Saddle splitting forces.



Note: Circumferential bending at horn is neglected for this calculation.

Figure 4-52. Bending in saddle due to splitting forces.

Base plate with center web see Figure 4-53

- *Area.*

$$A_b = AF$$

- *Bearing pressure.*

$$B_p = \frac{Q}{A_b}$$

- *Base plate thickness.*

$$\text{Now } M = \frac{QF}{8}$$

$$Z = \frac{At_b^2}{6}$$

$$\text{and } f_b = \frac{M}{Z} = \frac{3QF}{4At_b^2}$$

Therefore

Table 4-25
Values of K_1

k_1	2θ
0.204	120°
0.214	126°
0.226	132°
0.237	138°
0.248	144°
0.260	150°
0.271	156°
0.278	162°
0.294	168°

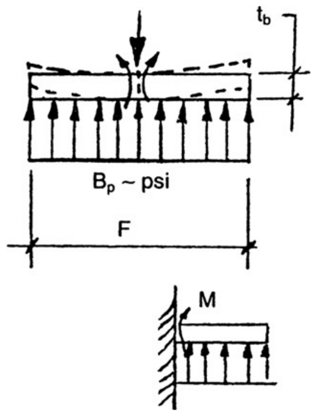


Figure 4-53. Loading diagram of base plate.

$$t_b = \sqrt{\frac{3QF}{4AF_b}}$$

Assumes uniform load fixed in center.

Base plate analysis for offset web (see Figure 4-54)

- *Overall length,* $\sum L$.
  Web $L_w = A - 2d_1 - 2J$
  ribs $L_r = n(G - t_w)$
  $$\sum L = L_w + L_r$$
- *Unit linear load, fu.*
  $$fu = \frac{Q}{\sum L} \text{Ib/linear in.}$$
- *Distances* ℓ_1 *and* ℓ_2.
  $$\ell_1 = d_2 + t_w + W_w + t_b$$
  $$\ell_2 = F - \ell_1$$
- *Loads / moment.*

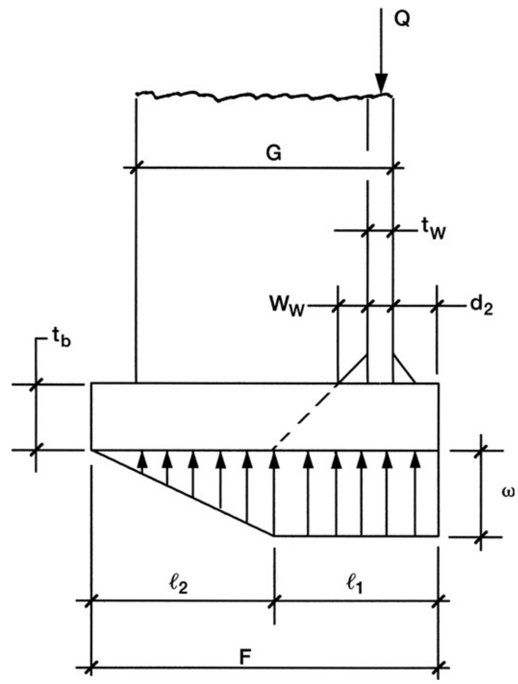


Figure 4-54. Load diagram and dimensions for base plate with an offset web.

$$\omega = \frac{fu}{\ell_1 + 0.5\ell_2}$$

$$M = \frac{\omega \ell_2^2}{6}$$

- *Bending stress,* f_b.

$$f_b = \frac{6M}{t_b^2}$$

Anchor Bolts

Anchor bolts are governed by one of the three following load cases:

1. *Longitudinal load*: If $Q_o > Q_L$, then no uplift occurs, and the minimum number and size of anchor bolts should be used.
   If $Q_o < Q_L$, then uplift does occur:
   $$\frac{Q_L - Q_o}{N} = \text{load per bolt}$$
2. *Shear*: Assume the fixed saddle takes the entire shear load.
   $$\frac{F_L}{N} = \text{shear per bolt}$$

3. *Transverse load*: This method of determining uplift and overturning is determined from Ref. [20] (see Figure 4-56).

$$M = 0.5\, F_T\, B$$

$$e = \frac{M}{Q_o}$$

If $e < A/6$, then there is no uplift.

If $e \geq A/6$, then proceed with the following steps. This is an iterative procedure for finding the tension force, T, in the outermost bolt.

Step 1: Find the effective bearing length, Y. Start by calculating factors $K_{1\text{-}3}$.

$$K_1 = 3(e - 0.5A)$$

$$K_2 = \frac{6 n_1 a_t}{F}(f + e)$$

$$K_3 = (-)K_2\left[\frac{A}{2} + f\right]$$

Step 2: Substitute values of K_{1-3} into the following equation and assume a value of $Y = \tfrac{2}{3} A$ as a first trial.

$$Y^3 + K_1 Y^2 + K_2 Y + K_3 = 0$$

If not equal to 0, then proceed with Step 3.

Step 3: Assume a new value of Y and recalculate the equation in Step 2 until the equation balances out to approximately 0. Once Y is determined, proceed to Step 4.

Step 4: Calculate the tension force, T, in the outermost bolt or bolts.

$$T = (-)Q_o\left[\frac{\frac{A}{2} - \frac{Y}{3} - e}{\frac{A}{2} - \frac{Y}{3} + f}\right]$$

Step 5: Select an appropriate bolt material and size corresponding to tension force, T.

Step 6: Analyze the bending in the base plate.

Distance, $x = 0.5A + f - Y$

Moment, $M = Tx$

Bending stress, $f_b = \frac{6M}{t_b^2}$

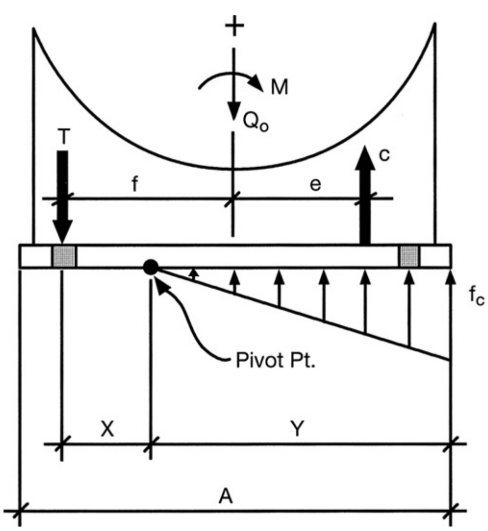


Figure 4-55. Dimensions and loading for base plate and anchor bolt analysis.

Ribs

Outside Ribs

- *Axial load, P.*

$$P = B_p A_p$$

- *Compressive stress, f_a.*

$$f_a = \frac{P}{A_r}$$

- *Radius of gyration, r.*

$$r = \sqrt{\frac{I_1}{A_r}}$$

- *Slenderness ratio, ℓ_1/r.*

$l_1/r =$

$F_a =$

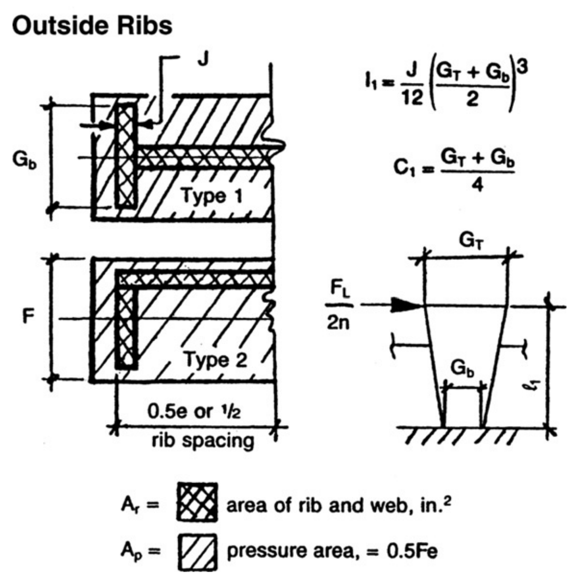


Figure 4-56. Dimensions of outside saddle ribs and webs.

- *Unit force, f_u.*

$$f_u = \frac{F_L}{2A}$$

- *Bending moment, M.*

$$M = 0.5 f_u e l_1$$

- *Bending stress, $F_b = 0.66\ F_y$.*

$$f_b = \frac{MC_1}{I} < F_b$$

- *Combined stress.*

$$\frac{f_a}{F_a} + \frac{f_b}{F_b} < 1$$

Inside Ribs

- *Axial load, P.*

$$P = B_p A_p$$

- *Compressive stress, f_a.*

$$f_a = \frac{P}{A_r}$$

- *Radius of gyration, r.*

$$r = \sqrt{\frac{I_2}{A_r}}$$

- *Slenderness ratio, ℓ_2/r.*

$l_2/r =$

$F_a =$

- *Unit force, f_u.*

$$f_u = \frac{F_L}{2A}$$

- *Bending moment, M.*

$$M = f_u l_2 e$$

- *Bending stress, f_b.*

$$f_b = \frac{MC_2}{I}$$

- *Combined stress.*

$$\frac{f_a}{F_a} + \frac{f_b}{F_b} < 1$$

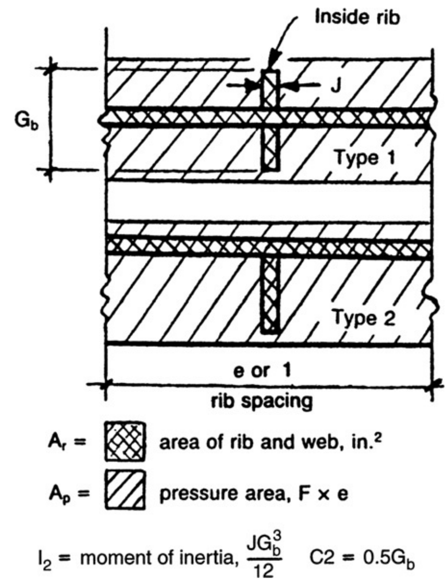


Figure 4-57. Dimensions of inside saddle ribs and webs.

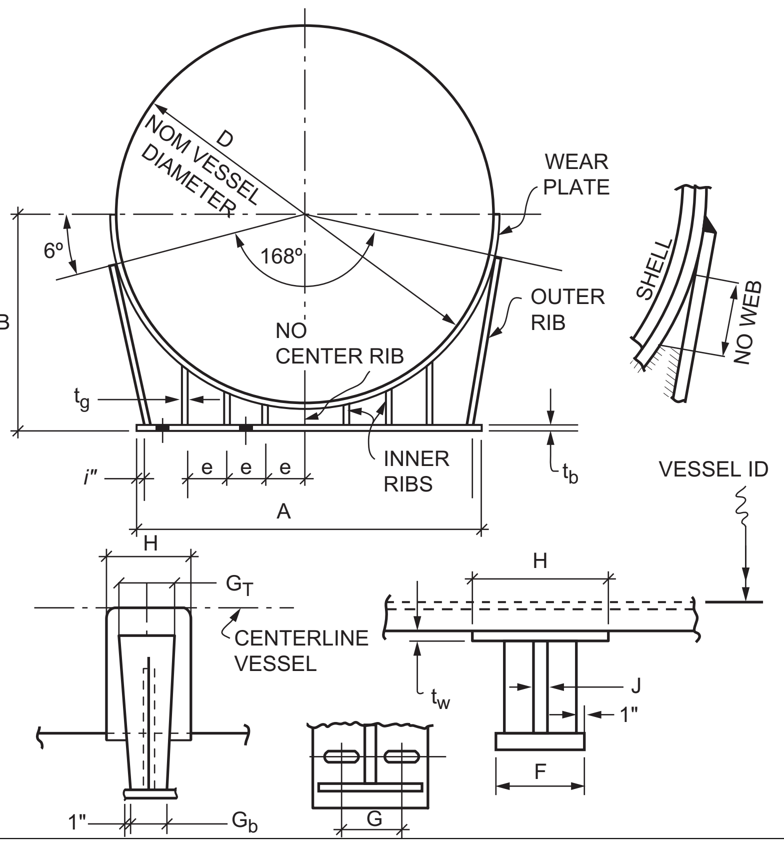
Notes

1. The depth of web is important in developing stiffness to prevent bending about the cross-sectional axis of the saddle. For larger vessels, assume 6 in. as the minimum depth from the bottom of the wear plate to the top of the base plate.
2. The full length of the web may be assumed effective in carrying compressive stresses along with ribs. Ribs are not effective at carrying compressive load if they are spaced greater than 25 times the web thickness apart.
3. Concrete compressive stresses are usually considered to be uniform. This assumes the saddle is rigid enough to distribute the load uniformly.
4. Large-diameter horizontal vessels are best supported with 168° saddles. Larger saddle angles do not effectively contribute to lower shell stresses and are more difficult to fabricate. The wear plate need not extend beyond center lines of vessel in any case or 6° beyond saddles.
5. Assume fixed saddle takes all of the longitudinal loading.

Table 4-26
Allowable tension load on bolts, kips, per AISC

Nominal Bolt Diameter, in		0.625	0.750	0.875	1.000	1.125	1.250	1.375	1.500
Cross-sectional Area, a_b, in^2		0.3068	0.4418	0.6013	0.7854	0.9940	1.2272	1.4849	1.7671
A-307 F_t	22.5	6.9	9.9	13.5	17.7	22.4	27.6	33.4	39.8
A-325 F_t	45.0	13.8	19.9	27.1	35.3	44.7	55.2	66.8	79.5

Table 4-27
Large diameter saddle supports



DIA (Ft)	A	B	D (Note 3)	E	F	G	G_B	G_T	H	J	N	n	t_b	t_g	t_w	Approx wt for 2 Saddles (Kips)
14	155	92	1.375	19	18	9	16	28	34	0.75	8	8	1	0.75	0.75	7
15	171	100	1.375	21	18	9	16	28	34	0.75	8	8	1	0.75	0.75	8
16	183	108	1.375	18	18	9.25	16	28	34	1	10	8	1.125	0.875	0.875	10
17	193	114	1.625	19	21	10.75	19	31	37	1	10	8	1.25	1	1	11
18	207	122	1.625	17	21	11	19	31	37	1.125	12	12	1.375	1.125	1	12
20	207	132	1.625	17	21	11	19	31	37	1.125	12	12	1.375	1.125	1.125	15.5
22	219	144	1.875	18	24	12.5	22	34	40	1.25	12	12	1.5	1.25	1.25	19
24	241	156	1.875	17	24	12.5	22	34	40	1.25	14	12	1.5	1.25	1.25	22
26	255	172	1.875	18	24	12.5	22	34	40	1.375	14	12	1.625	1.25	1.25	26
28	275	184	2.125	17	27	14	25	37	43	1.375	16	16	1.625	1.375	1.25	31
30	308	196	2.125	19	27	14.25	25	37	43	1.5	16	16	1.75	1.5	1.375	37
32	328	208	2.125	18	27	14.25	25	37	43	1.5	18	16	1.75	1.5	1.375	44
34	346	220	2.375	19	31	16	29	41	47	1.75	18	16	2	1.75	1.375	54
36	364	230	2.375	18	31	16	29	41	47	1.75	20	16	2	1.75	1.375	66
38	384	244	2.375	19	32	16.25	30	42	48	2	20	16	2.25	2	1.5	80
40	404	256	2.625	20	34	17.75	32	44	50	2	20	20	2.5	2	1.5	100

Notes:

1. All dimensions are in inches unless noted otherwise
2. All saddles in this size range must be fully designed. The dimensions shown are a starting place or to be used for estimating only!
3. Assume that anchor bolts diameter is d − .125", where d is the diameter of the hole. Assume that slots for sliding saddle are 6 d long.
4. N = Number of ribs
5. n = Number of anchor bolts

Procedure 4-12: Design of Base Plates for Legs [20,21]

Notation

- Y = effective bearing length, in.
- M = overturning moment, in.-lb
- M_b = bending moment, in.-lb
- P = axial load, lb
- f_t = tension stress in anchor bolt, psi
- A = actual area of base plate, in.^{2}
- A_r = area required, base plate, in.^{2}
- f'_c = ultimate 28-day strength, psi
- f_c = bearing pressure, psi
- f_1 = equivalent bearing pressure, psi
- F_b = allowable bending stress, psi
- F_t = allowable tension stress, psi
- F_c = allowable compression stress, psi
- E_s = modulus of elasticity, steel, psi
- E_c = modulus of elasticity, concrete, psi
- n = modular ratio, steel-concrete
- n' = equivalent cantilever dimension of base plate, in.
- B_p = allowable bearing pressure, psi
- $K_{1,2,3}$ = factor
- T = tension force in outermost bolt, lb
- C = compressive load in concrete, lb
- V = base shear, lb
- N = total number of anchor bolts
- N_t = number of anchor bolts in tension
- A_b = cross-sectional area of one bolt, in.^{2}
- A_s = total cross-sectional area of bolts in tension, in.^{2}
- α = coefficient
- T_s = shear stress

Calculations

- *Axial loading only, no moment.*

Angle legs:

$$f_c = \frac{P}{BD}$$

L = greater of m, n, or n′

$$t = \sqrt{\frac{3f_c L^2}{F_b}}$$

Beam legs:

$$A_r = \frac{P}{0.7f'_c}$$

$$m = \frac{D - 0.95d}{2}$$

$$n = \frac{B - 0.8d}{2}$$

$$\alpha = \frac{b - t_w}{2(d - 2t_f)}$$

$$n' = \frac{b - t_w}{2}\sqrt{\frac{1}{1 + 3.2\alpha^3}} \text{ (See Table 4-27)}$$

Pipe legs:

$$m = \frac{B - 0.707W}{2}$$

$$f_c = \frac{P}{A}$$

$$t = \sqrt{\frac{3f_c m^2}{F_b}}$$

- *Axial load plus bending, load condition #1, full compression, uplift, $e \le D/6$.* (See Figure 4-59)

Eccentricity:

$$e = \frac{M}{P} \le \frac{D}{6}$$

Loadings:

$$f_c = \frac{P}{A}\left[1 + \frac{6e}{D}\right]$$

$$f_1 = \frac{P}{A}\left[1 + \frac{6e(D - 2a)}{D^2}\right]$$

Moment:

$$M_b = \frac{a^2 B}{6}(f_1 + 2f_c)$$

Thickness:

$$t = \sqrt{\frac{6M_b}{BF_b}}$$

- *Axial load plus bending, load condition #2, partial compression, uplift, $e > D/6$.* (See Figure 4-59)

Eccentricity:

$$e = \frac{M}{P} > \frac{D}{6}$$

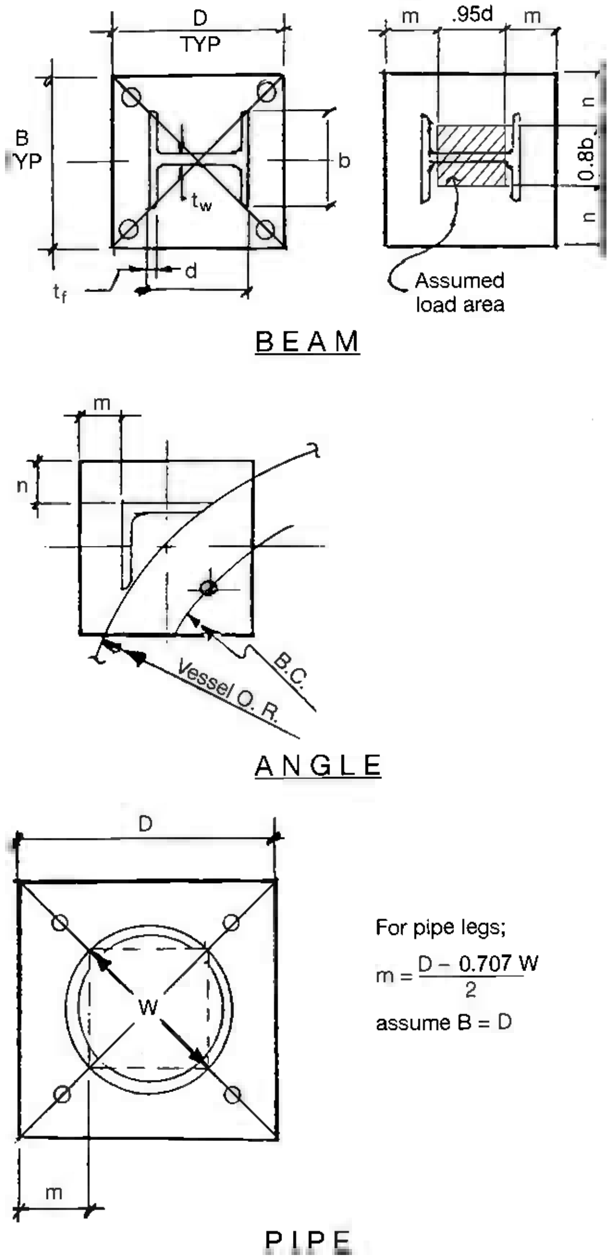


Figure 4-58. Dimensions and loadings of base plates.

Coefficient: (See Table 4-29)

$$n_r = \frac{E_s}{E_c}$$

Dimension:

$$f = 0.5d + z$$

By trial and error, determine Y, effective bearing length, utilizing factors K_{1-3}.

Factors:

$$K_1 = 3\left(e + \frac{D}{2}\right)$$

$$K_2 = \frac{6n_r A_s}{B}(f + e)$$

$$K_3 = (-)K_2(0.5D + f)$$

By successive approximations, determine distance Y. Substitute $K_{1\text{-}3}$ into the following equation and assume an initial value of Y = ⅔ A as a first trial.

$$Y^3 + K_1Y^2 + K_2Y + K_3 = 0$$

Tension force:

$$T = (-)P\left[\frac{\frac{D}{2} - \frac{Y}{3} - e}{\frac{D}{2} - \frac{Y}{3} + f}\right]$$

Bearing pressure:

$$f_c = \frac{2(P + T)}{YB} < f'_c$$

Moment:

$$x = 0.5D + f - Y$$

$$M_t = Tx$$

$$f_1 = f_c\left(\frac{Y - a}{Y}\right)$$

$$M_c = \frac{a^2B}{6}(f_1 + 2f_c)$$

Thickness:

$$t = \sqrt{\frac{6M_b}{BF_b}}$$

where M_b is greater of M_T or M_c.

- *Anchor bolts.*
  Without uplift: design anchor bolts for shear only.

$$T_s = \frac{V}{NA_b}$$

With uplift: design anchor bolts for full shear and tension force, T.

$$f_t = \frac{T}{N_TA_b}$$

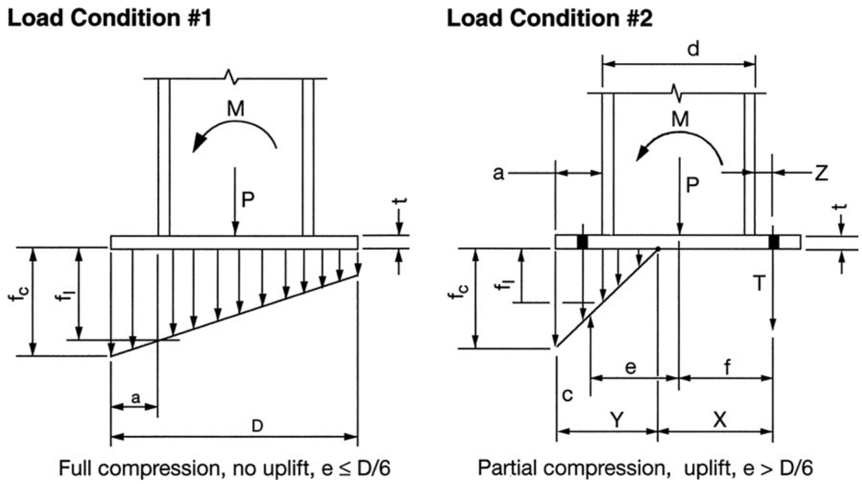


Figure 4-59. Load conditions on base plates.

Table 4-28
Values of n′ for beams

Column Section	n′	Column Section	n′
W14 × 730 – W14 × 145	5.77	W10 × 45 – W10 × 33	3.42
W14 × 132 – W14 × 90	5.64	W8 × 67 – W8 × 31	3.14
W14 × 82 – W14 × 61	4.43	W8 × 28 – W8 × 24	2.77
W14 × 53 – W14 × 43	3.68	W6 × 25 – W6 × 15	2.38
W12 × 336 – W12 × 65	4.77	W6 × 16 – W6 × 9	1.77
W12 × 58 – W12 × 53	4.27	W5 × 19 – W5 × 16	1.91
W12 × 50 – W12 × 40	3.61	W4 × 13	1.53
W10 × 112 – W10 × 49	3.92		

Table 4-29
Average properties of concrete

Water Content/Bag	Ult f'_c 28 -Day Str (psi)	Allowable Compression, F_c (psi)	Allowable B_p (psi)	Coefficient, n_r
7.5	2000	800	500	15
6.75	2500	1000	625	12
6	3000	1200	750	10
5	3750	1400	938	8

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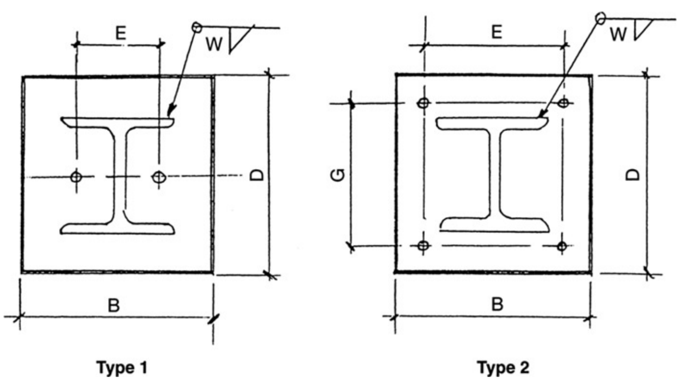

Figure 4-60. Dimensions for base plates-beams.

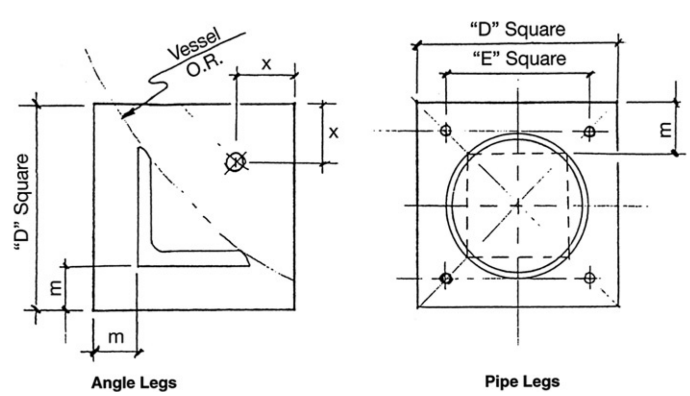

Figure 4-61. Dimensions for base plates—angle/pipe.

Dimensions for Type 1—(2) Bolt Base Plate

Column Size	D, in.	B, in.	E, in.	W, in.	Min Plate Thk, in.	Max Bolt ϕ, in.
W4	8	8	4	¼	⅝	¾
W6	8	8	4	¼	¾	¾
W8	10	10	6	¼	¾	¾
W10–33 thru 45	12	12	6	5/16	¾	1
W10–49 thru 112	13	13	6	5/16	¾	1
W12–40 thru 50	14	10	6	5/16	⅞	1
W12–53 thru 58	14	12	6	5/16	⅞	1
W12–65 thru 152	15	15	8	5/16	⅞	1¼

Dimensions for Type 2—(4) Bolt Base Plate

Column Size	D, in.	B, in.	G, in.	E, in.	W, in.	Min Plate Thk, in.	Max Bolt ϕ, in.
W4	10	10	7	7	¼	⅝	1
W6	12	12	9	9	5/16	¾	1
W8	15	15	11	11	⅜	⅞	1
W10–33 thru 45	17	15	13	11	⅜	⅜	1¼
W10–49 thru 112	17	17	13	13	⅜	⅜	1¼
W12–40 thru 50	19	15	15	11	⅜	1	1½
W12–53 thru 58	19	17	15	13	⅜	1	1½
W12–65 thru 152	19	19	15	15	⅜	1	1½

Dimensions for Angle Legs

Leg Size	D	X	m	Min. Plate Thk
L2 in. × 2 in.	4 in.	1.5	1	½ in.
L2½in. × 2½in.	5 in.	1.5	1.25	½ in.
L3 in. × 3 in.	6 in.	1.75	1.5	½ in.
L4 in. × 4 in.	8 in.	2	2	⅝ in.
L5 in. × 5 in.	9 in.	2.75	2	⅝ in.
L6 in. × 6 in.	10 in.	3.5	2	¾ in.

Dimensions for Pipe Legs

Leg Size	D	E	m	Min. Plate Thk
3 in. NPS	7 ½in.	4 ½ in.	2.5 in.	½ in.
4 in. NPS	8 ½in.	5 ½ in.	2.7 in.	½ in.
6 in. NPS	10 in.	7 in.	2.7 in.	⅝ in.
8 in. NPS	11 ½in.	8 ½ in.	2.7 in.	¾ in.
10 in. NPS	14 in.	10 in.	3.2 in.	⅞ in.
12 in. NPS	16 in.	12 in.	3.5in.	1 in.

Procedure 4-13: Design of Lug Supports

Notation

Q = vertical load per lug, lb
Q_a = axial load on gusset, lb
Q_b = bending load on gusset, lb
n = number of gussets per lug
F_a = allowable axial stress, psi
F_b = allowable bending stress, psi
f_a = axial stress, psi
f_b = bending stress, psi
A = cross-sectional area of assumed column, in.^{2}
Z = section modulus, in.^{3}
w = uniform load on base plate, lb/in.
I = moment of inertia of compression plate, in.^{4}
E_v = modulus of elasticity of vessel shell at design temperature, psi
E_s = modulus of elasticity of compression plate at design temperature, psi
e = log base 2.71
M_b = bending moment, in.-lb
M_x = internal bending moment in compression plate, in.-lb
K = spring constant or foundation modulus
β = damping factor

Design of Gussets

Assume gusset thickness from Table 4-30.

$$Q_a = Q \sin\theta$$

$$Q_b = Q \cos\theta$$

$$C = \frac{b \sin\theta}{2}$$

$$A = t_g C$$

$$F_a = 0.4F_y$$

$$F_b = 0.6F_y$$

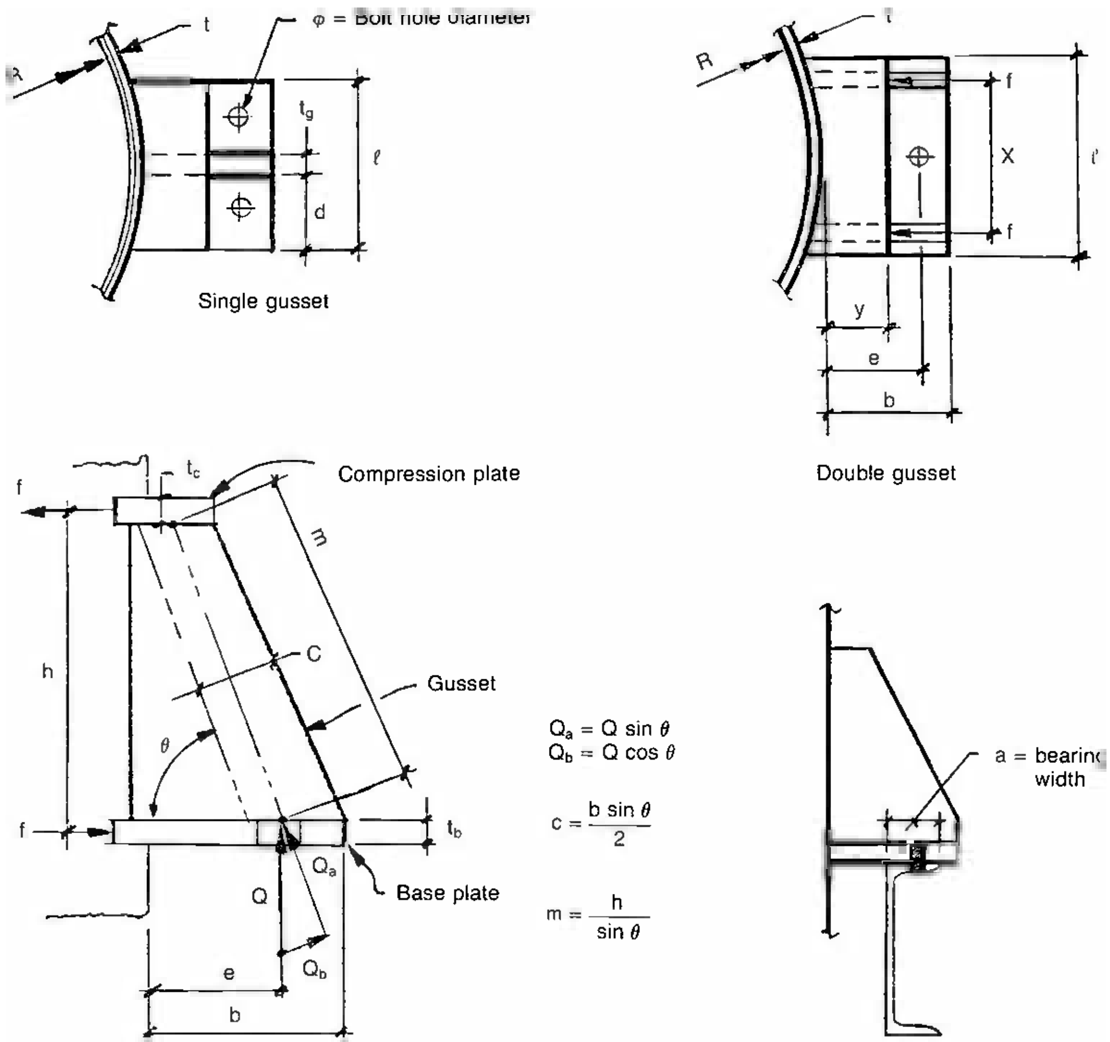

Figure 4-62. Dimensions and forces on a lug support.

$$Z = \frac{t_g C^2}{6}$$

$$M_b = \frac{Q_b m}{n}$$

$$f_a = \frac{Q_a}{nA}$$

$$f_b = \frac{M_b}{Z}$$

Design of Base Plate

Single Gusset

- *Bending.* Assume to be a simply supported beam.

$$M_b = \frac{Ql}{4}$$

- *Bearing.*

$$w = \frac{Q}{al}$$

$$M_b = \frac{wd^2}{2}$$

- *Thickness required base plate.*

$$t_b = \sqrt{\frac{6M_b}{(b - \phi)F_b}}$$

where M_b is greater moment from bending or bearing.

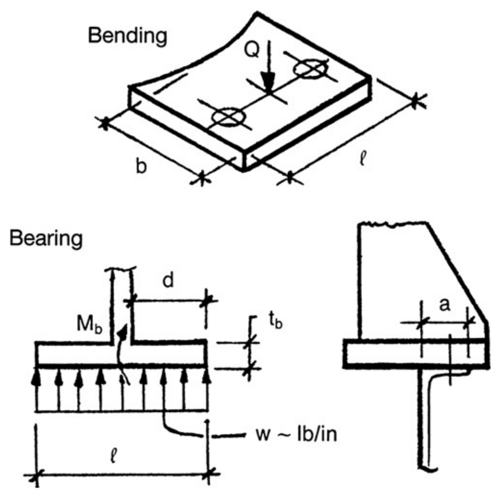

Figure 4-63. Loading diagram of base plate with one gusset.

Double Gusset

- *Bending*. Assume to be between simply supported and fixed.

$$M_b = \frac{Ql}{6}$$

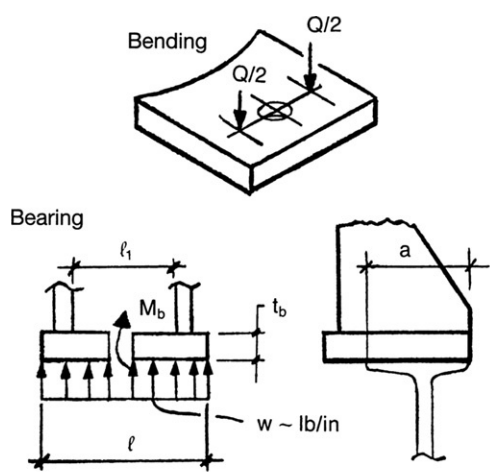

Figure 4-64. Loading diagram of base plate with two gussets.

- *Bearing*.

$$w = \frac{Q}{al}$$

$$M_b = \frac{wl_1^2}{10}$$

- *Thickness required base plate*.

$$t_b = \sqrt{\frac{6M_b}{(b-\phi)F_b}}$$

where M_b is greater moment from bending or bearing.

Compression Plate

Single Gusset

$$f = \frac{Qe}{h}$$

$$K = \frac{E_v t}{R^2}$$

Assume thickness t_c and calculate **I** and **Z**:

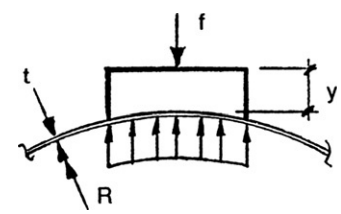

Figure 4-65. Loading diagram of compression plate with one gusset.

$$I = \frac{t_c y^3}{12}$$

$$Z = \frac{t_c y^2}{6}$$

$$\beta = \sqrt[4]{\frac{K}{4E_s I}}$$

$$M_x = \frac{f}{4\beta}$$

$$f_b = \frac{M_x}{Z} \quad < 0.6F_y$$

Note: These calculations are based on a beam on elastic foundation methods.

Double Gusset

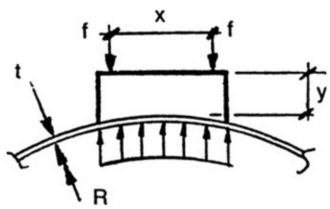

Figure 4-66. Loading diagram of compression plate with two gussets.

$$f = \frac{Qe}{2h}$$

$$K = \frac{E_v t}{R^2}$$

$$I = \frac{t_c y^3}{12}$$

$$Z = \frac{t_c y^2}{6}$$

$$\beta = \sqrt[4]{\frac{K}{4E_s I}}$$

Table 4-30
Standard lug dimensions

Type	e	b	y	x	h	$t_g = t_b$	Capacity (lb)
1	4	6	2	6	6	3/8	23,500
2	4	6	2	6	9	7/16	45,000
3	4	6	2	6	12	½	45,000
4	5	7	2.5	7	15	9/16	70,000
5	5	7	2.5	7	18	5/8	70,000
6	5	7	2.5	7	21	11/16	70,000
7	6	8	3	8	24	3/4	100,000

$$M_x = \frac{f}{4\beta}\left[1 + \left(e^{-\beta x}(\cos \beta x - \sin \beta x)\right)\right]$$

β x is in radians.

$$f_b = \frac{M_x}{Z} < 0.6F_y$$

Procedure 4-14: Design of Base Details for Vertical Vessels – Shifted Neutral Axis Method [4,9,13,17,18]

Notation

A_b = required area of anchor bolts, in.^{2}
B_d = anchor bolt diameter, in.
B_p = allowable bearing pressure, psi
b_p = bearing stress, psi
C = compressive load on concrete, lb
d = diameter of bolt circle, in.
d_b = diameter of hole in base plate of compression plate or ring, in.
F_{LT} = longitudinal tension load, lb/in.
F_{LC} = longitudinal compression load, lb/in.
F_b = allowable bending stress, psi
F_c = allowable compressive stress, concrete, psi
F_s = allowable tension stress, anchor bolts, psi
F_y = minimum specified yield strength, psi
f_b = bending stress, psi
f_c = compressive stress, concrete, psi
f_s = equivalent tension stress in anchor bolts, psi
M_b = overturning moment at base, in.-lb
M_t = overturning moment at tangent line, in.-lb
M_x = unit bending moment in base plate, circumferential, in.-lb/in.
M_y = unit bending moment in base plate, radial, in.-lb/in.
H = overall vessel height, ft
δ = vessel deflection, in.
M_o = bending moment per unit length in.-lb/in.
N = number of anchor bolts
n = ratio of modulus of elasticity of steel to concrete
P = maximum anchor bolt force, lb
P_1 = maximum axial force in gusset, lb

E = joint efficiency of skirt-head attachment weld
R_a = root area of anchor bolt, $in.^2$
r = radius of bolt circle, in.
W_b = weight of vessel at base, lb
W_t = weight of vessel at tangent line, lb
w = width of base plate, in.
Z_1 = section modulus of skirt, $in.^3$
S_t = allowable stress (tension) of skirt, psi
S_c = allowable stress (compression) of skirt, psi
G = width of unreinforced opening in skirt, in.
C_c,C_T,J,Z,K = coefficients
γ_1,γ_2 = coefficients for moment calculation in compression ring
S = code allowable stress, tension, psi
E_1 = modulus of elasticity, psi
t_s = equivalent thickness of steel shell which represents the anchor bolts in tension, in.
T = tensile load in steel, lb
ν = Poisson's ratio, 0.3 for steel
B = code allowable longitudinal compressive stress, psi

Equivalent Area Method

The "Equivalent Area Method" is also known as the "Shifted Neutral Axis Method". This procedure is in contrast with the "Centered Neutral Axis Method" which assumes that the neutral axis is on the centerline. The Centered Neutral Axis Method is easier to apply but also results in a conservative anchorage design. The Equivalent Area method is more accurate and will result in reduced anchorage requirements. Both methods are used to determine the anchorage requirements and the base plate details of a vertical vessel supported on a skirt.

The Equivalent Area Method is based on reinforced concrete beam design that utilizes a balance between the steel in tension and the concrete in compression. Because of the different properties the neutral axis is shifted from the centerline. This procedure enables the designer to find the exact position of the neutral axis and compute the properties required based on this location.

In order to find the minimum anchor bolt area required that is consistent with a given base ring area and a given working stress in the anchor bolts, it is necessary to resort to a trial and error basis, an iterative procedure. To start, the variables are either given or assumed. The variables in this process are as follows;

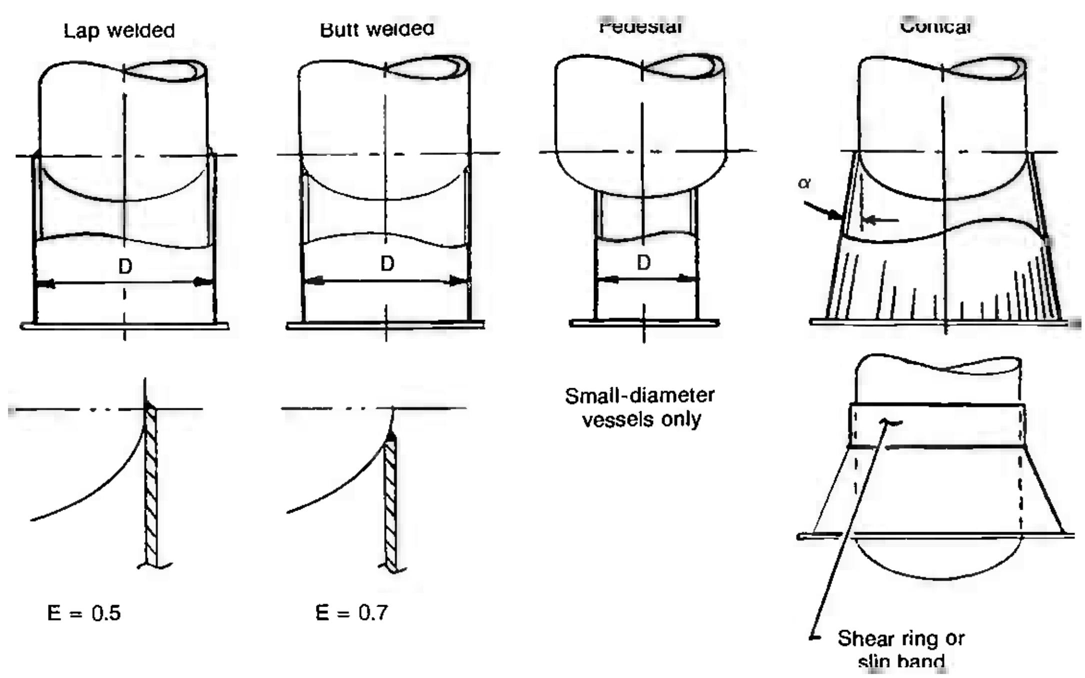

Figure 4-67. Skirt types.

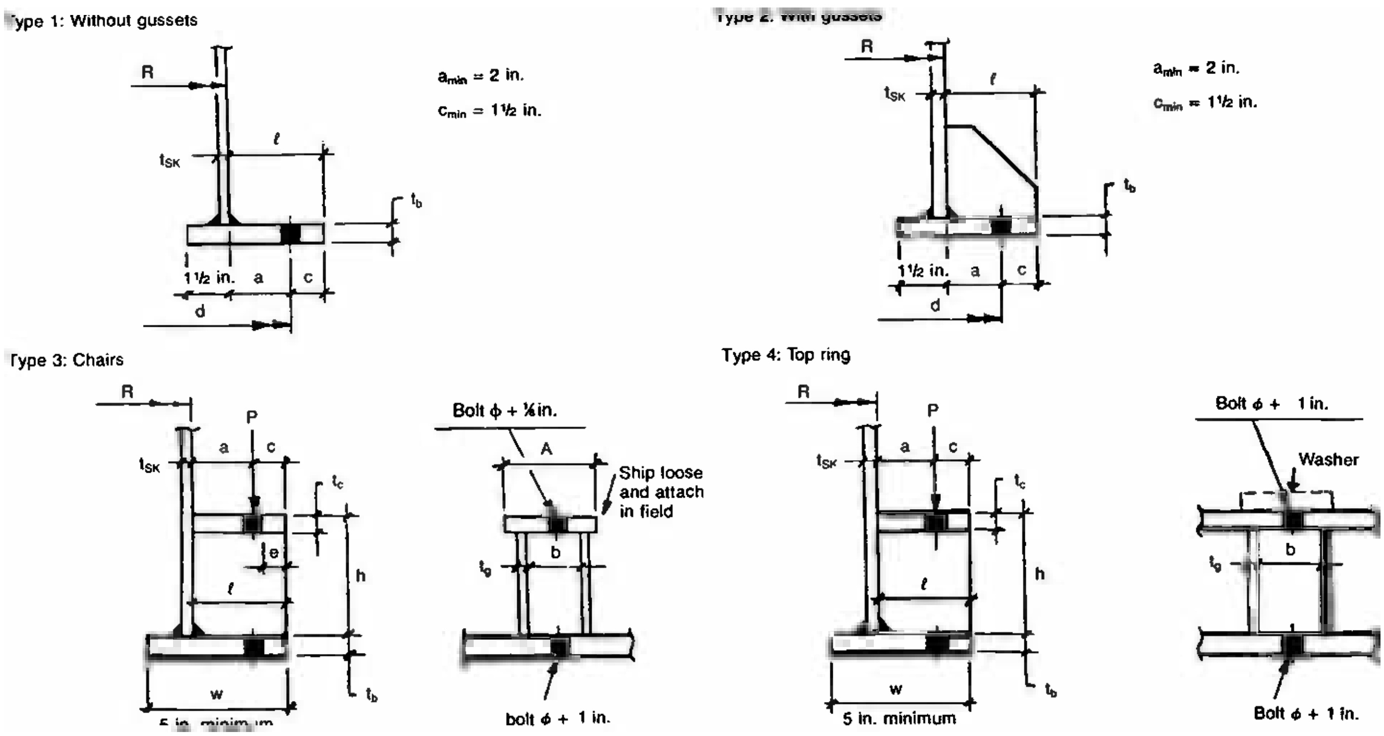

Figure 4-68. Base details of various types of skirt-supported vessels.

Table 4-31
Bolt chair data

Size (in.)	A_{min}	R_a	a_{min}	b	c_{min}
¾–10	5.50	0.302	2	3.50	1.5
⅞–9	5.50	0.419	2	3.50	1.5
1–8	5.50	0.551	2	3.50	1.5
1 ⅛–7	5.50	0.693	2	3.50	1.5
1 ¼–7	5.50	0.890	2	3.50	1.5
1 ⅜–6	5.50	1.054	2.13	3.50	1.75
1 ½–6	5.75	1.294	2.25	3.50	2
1 ⅝–5 ½	5.75	1.515	2.38	4.00	2
1 ¾–5	6.00	1.744	2.5	4.00	2.25
1 7/8–5	6.25	2.049	2.63	4.00	2.5
2–4 ½	6.50	2.300	2.75	4.00	2.5
2¼–4 ½	7.00	3.020	3	4.50	2.75
2½–4	7.25	3.715	3.25	4.50	3
2 ¾–4	7.50	4.618	3.50	4.75	3.25
3–4	8.00	5.621	3.75	5.00	3.50

Table 4-32
Number of anchor bolts, N

Skirt Diameter (in.)	Minimum	Maximum
24–36	4	4
42–54	4	8
60–78	8	12
84–102	12	16
108–126	16	20
132–144	20	24

See also Table 4-40

Table 4-33
Allowable stress for bolts, F_s

Spec	Diameter (in.)	Allowable Stress (KSI)
A-307	All	20.0
A-36	All	19.0
A-325	<1-1/2”	44.0
A-449	<1”	39.6
	1-1/8” to 1-1/2”	34.7
	1-5/8” to 3”	29.7

Table 4-34
Average properties of concrete

Water Content/ Bag	Ult 28–Day Str (psi)	Allowable Compression, F_c (psi)	Allowable B_p (psi)	Coefficient, n
7.5	2000	800	500	15
6.75	2500	1000	625	12
6	3000	1200	750	10
5	3750	1400	938	8

**See also Table 4-43*
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Table 4-35
Bending moment unit length

ℓ/b	$M_x\left(\begin{matrix} x = 0.5b \\ y = \ell \end{matrix}\right)$	$M_y\left(\begin{matrix} x = .5b \\ y = 0 \end{matrix}\right)$
0	0	$-0.5f_c\,\ell^2$
0.333	$0.0078f_cb^2$	$-0.428f_c\,\ell^2$
0.5	$0.0293f_cb^2$	$-0.319f_c\,\ell^2$
0.667	$0.0558f_cb^2$	$-0.227f_c\,\ell^2$
1.0	$0.0972f_cb^2$	$-0.119f_c\,\ell^2$
1.5	$0.123f_cb^2$	$-0.124f_c\,\ell^2$
2.0	$0.131f_cb^2$	$-0.125f_c\,\ell^2$
3.0	$0.133f_cb^2$	$-0.125f_c\,\ell^2$
∞	$0.133f_cb^2$	$-0.125f_c\,\ell^2$

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Table 4-36
Constant for moment calculation, γ_1, and γ_2

b/ℓ	γ_1	γ_2
1.0	0.565	0.135
1.2	0.350	0.115
1.4	0.211	0.085
1.6	0.125	0.057
1.8	0.073	0.037
2.0	0.042	0.023
∞	0	0

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Table 4-37
Values of constants as a function of K

K	C_c	C_t	J	Z	K	C_c	C_t	J	Z
0.1	0.852	2.887	0.766	0.480	0.55	2.113	1.884	0.785	0.381
0.15	1.049	2.772	0.771	0.469	0.6	2.224	1.765	0.784	0.369
0.2	1.218	2.661	0.776	0.459	0.65	2.333	1.640	0.783	0.357
0.25	1.370	2.551	0.779	0.448	0.7	2.442	1.510	0.781	0.344
0.3	1.510	2.442	0.781	0.438	0.75	2.551	1.370	0.779	0.331
0.35	1.640	2.333	0.783	0.427	0.8	2.661	1.218	0.776	0.316
0.4	1.765	2.224	0.784	0.416	0.85	2.772	1.049	0.771	0.302
0.45	1.884	2.113	0.785	0.404	0.9	2.887	0.852	0.766	0.286
0.5	2.000	2.000	0.785	0.393	0.95	3.008	0.600	0.760	0.270

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1. Width of base ring
2. Quantity of anchor bolts
3. Sizes of anchor bolts
4. Strength of anchor bolts
5. Strength of concrete

If the width of the base plate is increased, the neutral axis will be displaced toward the compression side and the stresses in the concrete and steel will be reduced. The maximum compressive stress between base plate and the concrete occurs at the outer periphery of the base plate. When uplift occurs, part of the base plate lifts up, resulting in a shift of the neutral axis toward the compression side.

The value of K represents the location of the neutral axis between the anchor bolts in tension and the concrete in compression. A preliminary value of K is estimated based on a ratio of the "allowable" stresses of the anchor bolts and concrete and a ratio of the modulus of elasticity of the two materials. From this preliminary value, anchor bolt sizes and numbers are determined and actual stresses computed. Using these actual stresses, the location of the neutral axis is found and thus an actual corresponding K value. A comparison of these K values tells the designer whether the location of the neutral axis that was assumed for selection of anchor bolts was accurate. In successive trials, the anchor bolt sizes and quantity and width of base plate can be varied to obtain an optimum design. At each trial a new K is estimated and calculations repeated until the estimated K and actual K are approximately equal. This indicates both a balanced design and accurate calculations.

Rather than apportioning a load to each anchor bolt, the anchor bolt area is assumed as a continuous uniform cylinder whose thickness corresponds to the area of the bolts.

The equations can be manipulated to find the exact width of base plate required, w_r, for the parameters of each case. The equation is;

$$w_r = [W_b + (C_t\, f_S - C_C\, f_C\, n) r\, t_S]/(C_C\, f_C\, r)$$

Example is based on the illustrated case in this procedure;

Trial 1:

$W_b = 194,000$ Lbs

$C_t = 2.113$

$C_C = 1.884$

$n = 10$

$r = 52.5$ in

$t_S = 0.225$ in

$f_S = 13,660$ PSI

$f_C = 449$ PSI

$$w_r = [194,000 + (2.113\ (13,660) - 1.884(449)\ 10) \times 52.5(225)/[1.884(449)52.5] = 9.79 \text{ in}$$

Trial 2:

$C_t = 2.355$

$C_C = 1.610$

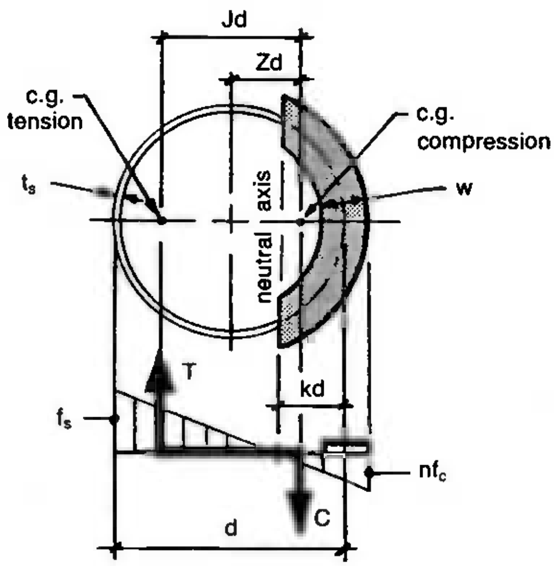
$t_S = 0.225$ in

$f_S = 12,100$ PSI

$f_C = 611$ PSI

$$w_r = [194,000 + (2.355(12,100) - 1.61(611)10) \times 52.5(.225)/[1.610(611)52.5] = 8.02 \text{ in}$$

ANCHOR BOLTS: EQUIVALENT AREA METHOD



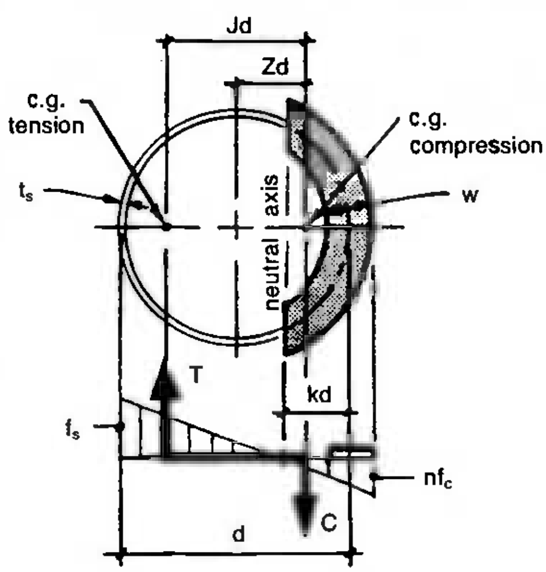
PROCEDURE

1. **Calculate preliminary K value based on allowables.**
2. **Make preliminary selection of anchor bolts and width of base plate.**
3. **Calculate loads and stresses.**
4. **Calculate K based on actual stresses and compare with value computed in Step 2.**
5. **If difference exceeds .01, select a new K between both values and repeat Steps 2–8.**

TRIAL 1				TRIAL 2	
1		**Data**		**1 Data**	
F_s (Table 4-33)		M_b			
F_c (Table 4-34)		d			
n (Table 4-34)		r			
W_b					
2 Approximate K Using Allowables		**Coefficients**		**2 Approximate K Using Allowables**	
$K = \frac{1}{1 + \frac{F_s}{nF_c}}$		C_c			
		C_t			
		J			
		Z			
3 Tensile Load in Steel				**3 Tensile Load in Steel**	
$T = \frac{M_b - W_b(Zd)}{Jd}$					
4 Number of Anchor Bolts Required				**4 Number of Anchor Bolts Required**	
$A_b = \frac{T\pi d}{F_s r C_t}$		R_a (Table 4-31)	in.^{2}		
A_b/N		Use ( )	bolts		
5 Stress in Equivalent Steel Band				**5 Stress in Equivalent Steel Band**	
$t_s = \frac{NR_a}{\pi d}$		$f_s = \frac{T}{t_s r C_t}$			
6 Compressive Load in Concrete				**6 Compressive Load in Concrete**	
$C = T + W_b$					
7 Stress in Concrete				**7 Stress in Concrete**	
$f_c = \frac{C}{[(w - t_s) + nt_s]rC_c}$					
8 Recheck K Using Actual f_s and f_c				**8 Recheck K Using Actual f_s and f_c**	
$K = \frac{1}{1 + \frac{f_s}{nf_c}}$					

See example of completed form on next page.

ANCHOR BOLTS: EQUIVALENT AREA METHOD EXAMPLE



PROCEDURE

1. Calculate preliminary K value based on allowables.
2. Make preliminary selection of anchor bolts and width of base plate.
3. Calculate loads and stresses.
4. Calculate K based on actual stresses and compare with value computed in Step 2.
5. If difference exceeds .01, select a new K between both values and repeat Steps 2–8.

TRIAL 1

1 Data

F_s (Table 4-33)	= 15 KSI	M_b = 3034 FT-KIPS	
F_c (Table 4-34)	= 1.2 KSI	d = 8.75' or 105"	
n (Table 4-34)	= 10	r = 4.38' or 52.5"	
W_b	= 194 KIPS		

2 Approximate K Using Allowables

$K = \frac{1}{1 + \frac{F_s}{nF_c}}$ = .444

Coefficients

C_c	= 1.884
C_t	= 2.113
J	= .785
Z	= .404

3 Tensile Load in Steel

$T = \frac{M_b - W_b(Zd)}{Jd} = \frac{3034 - 194(.404)\,8.75}{.785\,(8.75)} = 341^K$

4 Number of Anchor Bolts Required

$A_b = \frac{T\pi d}{F_s r C_t} = \frac{341\ \pi\ 8.75}{15\,(4.38)\,2.113} = 67.5\ in^2$ | R_a (Table 4-31) = 3.715 in.²

$A_b/N = 67.5/20 = 3.37$ | Use (20) $2\frac{1}{2}$" φ bolts

5 Stress in Equivalent Steel Band

$t_s = \frac{NR_a}{\pi d} = \frac{20(3.715)}{\pi\ 105} = .225$

$f_s = \frac{T}{t_s r C_t} = \frac{341}{.225(52.5)2.113} = 13.66$ KSI < 15 KSI OK

6 Compressive Load in Concrete

$C = T + W_b = 341 + 194 = 535^K$

7 Stress in Concrete

$f_c = \frac{C}{[(w - t_s) + nt_s]rC_c} = \frac{535}{[(10 - .225) + 2.25]\,52.5\,(1.884)} = .449$ KSI

8 Recheck K Using Actual f_s and f_c

$K = \frac{1}{1 + \frac{f_s}{nf_c}} = \frac{1}{1 + \frac{13.66}{10(.449)}} = .247 \neq .444$ NO GOOD!

TRIAL 2

1 Data

USE W = 8.25"
and K = .34

2 Approximate K Using Allowables

K = .34
C_c = 1.610 J = .7826
C_t = 2.355 Z = .429

3 Tensile Load in Steel

336.7^K

4 Number of Anchor Bolts Required

$\frac{336.7\ \pi\ 8.75}{15\,(4.38)\,2.355} : \frac{59.82}{20} = 2.99\ in^2$

59.82 USE (20) $2\frac{1}{2}$" φ BOLTS

5 Stress in Equivalent Steel Band

$t_s = .225$

$f_s = \frac{336.7}{.225(52.5)2.355} = 12.10$ OK

6 Compressive Load in Concrete

$C = 336.7 + 194 = 530.7^K$

7 Stress in Concrete

$f_c = \frac{530.7}{10.225(52.5)1.61} = .611$ KSI

8 Recheck K Using Actual f_s and f_c

$K = \frac{1}{1 + \frac{12.10}{10(.611)}} = .336$ OK ≈ .34

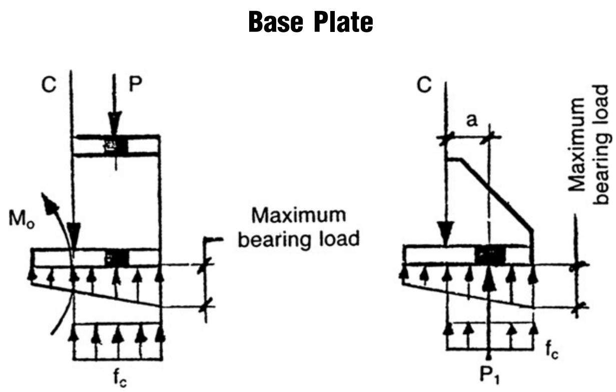


Figure 4-69. Loading diagram of base plate with gussets and chairs.

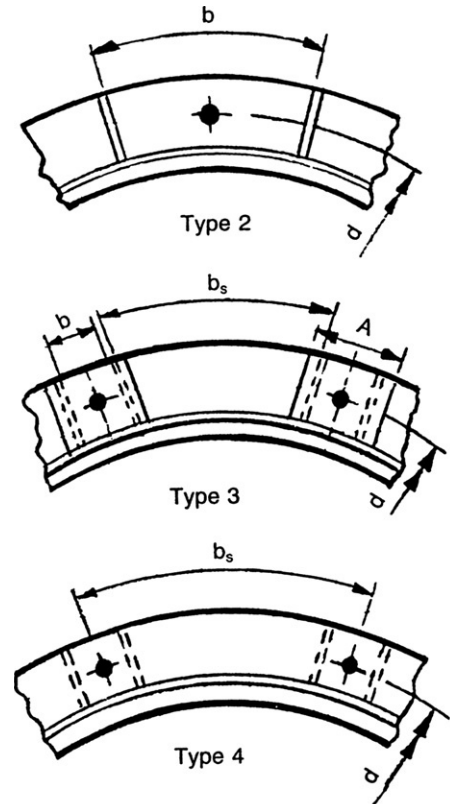


Figure 4-70. Dimensions of various base plate configurations.

Type 1: Without Chairs or Gussets

K = from "Anchor Bolts."

l =

f_c = from "Anchor Bolts."

d =

- *Bending moment per unit length.*

$$M_o = 0.5 f_c l^2$$

- *Maximum bearing load.*

$$b_p = f_c\left(\frac{2Kd + w}{2Kd}\right) < B_p \text{ (see Table 4-34)}$$

- *Thickness required.*

$$t_b = \sqrt{\frac{6M_o}{F_b}}$$

Type 2: With Gussets Equally Spaced, Straddling Anchor Bolts

- *With same number as anchor bolts.*

$$b = \frac{\pi d}{N}$$

$$\frac{l}{b}$$

M_o = greater of M_x or M_y from Table 4-35

$$t_b = \sqrt{\frac{6M_o}{F_b}}$$

- *With twice as many gussets as anchor bolts.*

$$b = \frac{\pi d}{2N}$$

$$\frac{l}{b}$$

M_o = greater of M_x or M_y from Table 4-35

$$t_b = \sqrt{\frac{6M_o}{F_b}}$$

Type 3 or 4: With Anchor Chairs or Full Ring

- *Between gussets.*

$$P = F_s R_a$$

$$M_o = \frac{Pb}{8}$$

$$t_b = \sqrt{\frac{6M_o}{(w - d_b)F_b}}$$

• *Between chairs.*

$\frac{\ell}{b_s}$

M_o = greater of M_x or M_y from Table 4-35

$$t_b = \sqrt{\frac{6M_o}{F_b}}$$

Top Plate or Ring (Type 3 or 4)

• *Minimum required height of anchor chair (Type 3 or 4).*

$$h_{min} = \frac{7.29\delta d}{H} < 18 \text{ in.}$$

• *Minimum required thickness of top plate of anchor chair.*

$$t_c = \sqrt{\frac{P}{F_b e}(0.375b - 0.22d_b)}$$

Top plate is assumed as a beam, e x A with partially fixed ends and a portion of the total anchor bolt force P/3, distributed along part of the span. (See Figure 4-71.)

• *Bending moment, M_o, in top ring (Type 4).*

$\frac{b}{\ell}$

γ_1 = (see Table 4-36)
γ_2 = (see Table 4-36)

1. If $a = \ell/2$ and $b/\ell > 1$, M_y governs

$$M_o = \frac{P}{4\pi}\left[(1+\nu)\log\left(\frac{2\ell}{\pi g}\right) + (1-\gamma_1)\right]$$

2. If $a \neq \ell/2$ but $b/\ell > 1$, M_y governs

$$M_o = \frac{P}{4\pi}\left[(1+\nu)\log\left(\frac{2\ell \sin\frac{\pi a}{\ell}}{\pi g}\right) + 1\right] - \frac{\gamma_1 P}{4\pi}$$

3. If $b/\ell < 1$, invert b/ℓ and rotate axis X-X and Y-Y 90°

$$M_o = \frac{P}{4\pi}\left[(1+\nu)\log\left(\frac{2\ell \sin\frac{\pi a}{\ell}}{\pi g}\right) + 1\right] - \left[(1-\nu-\gamma_2)\frac{P}{4\pi}\right]$$

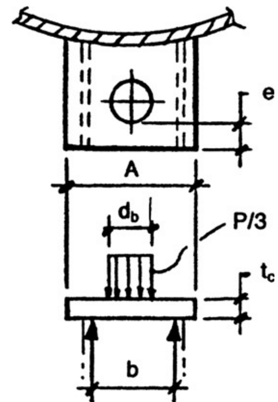


Figure 4-71. Top plate dimensions and loadings.

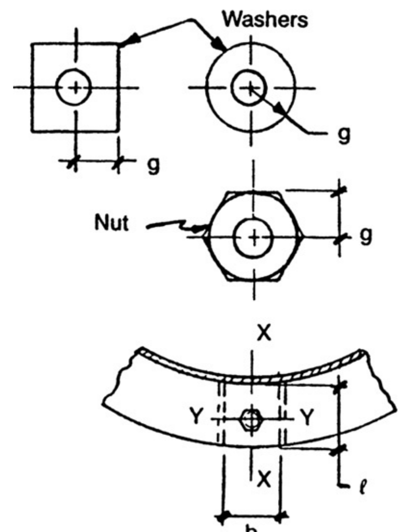


Figure 4-72. Compression plate dimensions.

• *Minimum required thickness of top ring (Type 4).*

$$t_c = \sqrt{\frac{6M_o}{F_b}}$$

Gussets

• *Type 2.* Assume each gusset shares load with each adjoining gusset. The uniform load on the base is f_c, and the area supported by each gusset is $\ell \times b$. Therefore the load on the gusset is

$$P_1 = f_c \ell b$$

Thickness required is

$$t_g = \frac{P_1(6a - 2\ell)}{F_b \ell^2}$$

- Type 3 or 4.

$$t_g = \frac{P}{18,000\,\ell} > \frac{3}{8} \text{ in.}$$

Skirt

- *Thickness required in skirt at compression plate or ring due to maximum bolt load reaction.*
  For Type 3:

$$Z = \frac{1.0}{\dfrac{1.77At_b}{\sqrt{Rt_{sk}}}\left[\dfrac{t_b}{t_{sk}}\right]^2 + 1}$$

$$S = \frac{Pa}{t_{sk}^2}\left[\frac{1.32Z}{\dfrac{1.43Ah^2}{Rt_{sk}} + \left[4Ah^2\right]^{0.333}} + \frac{0.031}{\sqrt{Rt_{sk}}}\right] < 25 \text{ ksi}$$

For Type 4:
Consider the top compression ring as a uniform ring with N number of equally spaced loads of magnitude.

$$\frac{Pa}{h}$$

See Procedure 7-1 for details.

The moment of inertia of the ring may include a portion of the skirt equal to 16 t_{sk} on either side of the ring (see Figure 4-74).

- *Thickness required at opening of skirt.*
  Note: If skirt is stiffened locally at the opening to compensate for lost moment of inertia of skirt cross section, this portion may be disregarded.
  G = width of opening, in.

$$f_b = \frac{1}{\pi D - 3G}\left[\frac{48\ M_b}{D} + W_b\right]$$

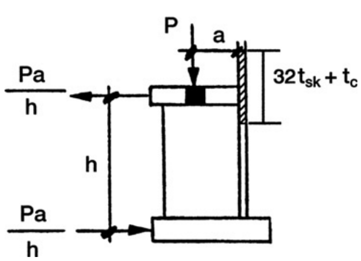


Figure 4-73. Dimensions and loadings on skirt due to load P.

Actual weights and moments at the elevation of the opening may be substituted in the foregoing equation if desired.

Skirt thickness required:

$$t_{sk} = \frac{f_b}{8F_y} \quad \text{or} \quad \sqrt{\frac{f_b}{4,640,000}}$$

whichever is greater

- *Determine allowable longitudinal stresses.*
  Tension

$$S_t = \text{lesser of } 0.6F_y \text{ or } 1.2\,S$$

Compression

$$S_c = 0.333\ F_y$$

$$= 1.2 \times \text{factor "B"}$$

$$= \frac{t_{sk}E_1}{16\ R}$$

$$= 1.2\,S$$

whichever is less.
Longitudinal forces

$$F_{LT} = \frac{48\ M_b}{\pi D^2} - \frac{W_b}{\pi D}$$

$$F_{LC} = (-)\frac{48\ M_b}{\pi D^2} - \frac{W_b}{\pi D}$$

Skirt thickness required

$$t_{sk} = \frac{F_{LT}}{S_t} \quad \text{or} \quad \frac{F_{LC}}{S_c}$$

whichever is greater.

- *Thickness required at skirt-head attachment due to M_t.*
  Longitudinal forces

$$F_{LT} = \frac{48\ M_t}{\pi D^2} - \frac{W_t}{\pi D}$$

$$F_{LC} = (-)\frac{48\ M_t}{\pi D^2} - \frac{W_t}{\pi D}$$

Skirt thickness required

$$t_{sk} = \frac{F_{LT}}{0.707\ S_tE} \quad \text{or} \quad \frac{F_{LC}}{0.707S_cE}$$

whichever is greater.

Notes

1. Base plate thickness:
   - If $t \leq ½$ in., use Type 1.
   - If ½ in. $< t \leq ¾$ in., use Type 2.
   - If $t > ¾$ in., use Type 3 or 4.
2. To reduce sizes of anchor bolts:
   - Increase number of anchor bolts.
   - Use higher-strength bolts.
   - Increase width of base plate.
3. Number of anchor bolts should always be a multiple of 4. If more anchor bolts are required than spacing allows, the skirt may be angled to provide a larger bolt circle or bolts may be used inside and outside of the skirt. Arc spacing should be kept to a minimum if possible.
4. The base plate is not made thinner by the addition of a compression ring, t_b would be the same as required for chair-type design. Use a compression ring to reduce induced stresses in the skirt or for ease of fabrication when chairs become too close.
5. Dimension "a" should be kept to a minimum to reduce induced stresses in the skirt. This will provide a more economical design for base plate, chairs, and anchor bolts.
6. For heavy-wall vessels, it is advantageous to have the center lines of the skirt and shell coincide if possible. For average applications, the O.D. of the vessel and O.D. of the skirt should be the same.
7. Skirt thickness should be a minimum of R/200.

Procedure 4-15: Design of Base Details for Vertical Vessels – Centered Neutral Axis Method

Notation

E = joint efficiency
E_1 = modulus of elasticity at design temperature, psi
A_b = cross-sectional area of bolts, in.^{2}
d = diameter of bolt circle, in.
W_b = weight of vessel at base, lb
W_T = weight of vessel at tangent line, lb
w = width of base plate, in.
S = code allowable stress, tension, psi
N = number of anchor bolts
F'_c = allowable bearing pressure, concrete, psi
F_y = minimum specified yield stress, skirt, psi
F_s = allowable stress, anchor bolts, psi
f_{LT} = axial load, tension, lb/in.-circumference
f_{LC} = axial load, compression, lb/in.-circumference
F_T = allowable stress, tension, skirt, psi
F_c = allowable stress, compression, skirt, psi
F_b = allowable stress, bending, psi
f_s = tension force per bolt, lb
f_c = bearing pressure on foundation, psi
M_b = overturning moment at base, ft-lb
M_T = overturning moment at tangent line, ft-lb

Allowable Stresses

$$F_T = \text{lesser of} \begin{cases} \bullet 0.6F_y = \\ \bullet 1.2\,S = \end{cases}$$

$$F_c = \text{lesser of} \begin{cases} \bullet 0.333F_y = \\ \bullet 1.2 \text{ Factor B} = \\ \bullet \dfrac{t_{sk}E_1}{16\ R} = \\ \bullet 1.2\,S = \end{cases}$$

$$F_b = 0.6\,F_y$$

$$F'_c = 500 \text{ psi for } 2000 \text{ lb concrete}$$
$$750 \text{ psi for } 3000 \text{ lb concrete}$$

$$\text{Factor A} = \frac{0.125t_{sk}}{R} =$$

Factor B = from applicable material chart of ASME Code, Section II, Part D, Subpart 3

Anchor Bolts

- *Force per bolt due to uplift.*

$$f_s = \frac{48M_b}{dN} - \frac{W_b}{N}$$

- *Required bolt area, A_b.*

$$A_b = \frac{f_s}{F_s} =$$

Use ( ) _____ diameter bolts

Note: Use four ¾-in.-diameter bolts as a minimum.

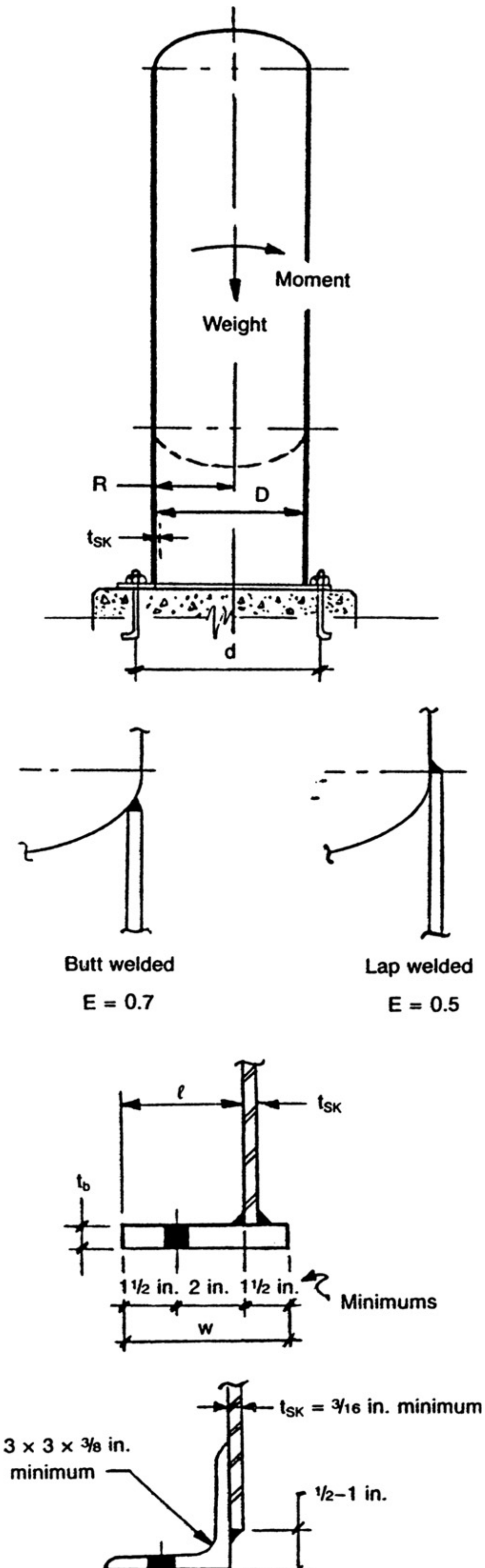


Figure 4-74. Typical dimensional data and forces for a vertical vessel supported on a skirt.

Base Plate

- *Bearing pressure, f_c (average at bolt circle).*

$$f_c = \frac{48M_b}{\pi d^2 w} + \frac{W_b}{\pi d w} =$$

- *Required thickness of base plate, t_b.*

$$t_b = 1\sqrt{\frac{3f_c}{20,000}}$$

Skirt

- *Longitudinal forces, f_{LT} and f_{LC}.*

$$f_{LT} = \frac{48M_b}{\pi D^2} - \frac{W_b}{\pi D}$$

$$f_{LC} = (-)\frac{48M_b}{\pi D^2} - \frac{W_b}{\pi D}$$

- Thickness required of skirt at base plate, t_{sk}.

$$t_{sk} = \text{greater of } \frac{f_{LT}}{F_T} =$$

$$\text{or } \frac{f_{LC}}{F_C} =$$

- Thickness required of skirt at skirt-head attachment.

Longitudinal forces:

$$f_{LT}, f_{LC} = \pm\frac{48M_T}{\pi D^2} - \frac{W_T}{\pi D} =$$

$$f_{LT} =$$

$$f_{LC} =$$

Thickness required:

$$t_{sk} = \text{greater of } \frac{f_{LT}}{0.707\ F_T E} =$$

$$\text{or } \frac{f_{LC}}{0.707\ F_C E} =$$

Notes

1. This procedure is based on the centered neutral axis method and should be used for relatively small or simple vertical vessels supported on skirts.
2. If moment M_b is from seismic, assume W_b as the operating weight at the base. If M_b is due to wind, assume empty weight for computing the maximum value of f_{LT} and operating weight for f_{LC}.

Procedure 4-16: Design of Anchor Bolts for Vertical Vessels

Notation

A_b = Cross sectional area of anchor bolt, in^2
A_r = Area of one anchor bolt required, In^2
D_b = Diameter of bolt circle, Ft
M = Overturning moment due to wind or seismic, Ft-lbs
N = Number of anchor bolts
S_b = Allowable tensile stress, PSI
W = Weight of vessel under consideration. Typically use empty for wind and full for seismic for worst case, Lbs

Formulas

$$N A_b = [(48 M/D_b) - W] [1/S_b]$$

- If N A_b is negative, no anchor bolts are required
- If N A_b is positive, than anchor bolts are required
- Size of anchor bolts required is as follows, A_r;

$$A_r = [(48 M/D_b) - W] [1/(N S_b)]$$

Notes

1. Values for S_b in table are based on .333 F_U
2. Assumes centered neutral axis method

Table 4-38
Area of anchor bolts, A_b

DIA	A_b	DIA	A_b
¾”–10	.302	1-3/4”–5	1.744
7/8”–9	.419	2”–4-1/2	2.3
1”–8	.551	2-1/2”–4	3.715
1-1/4”–7	.890	2-3/4”–4	4.618
1-1/2”–6	1.294	3”-4	5.621

Table 4-39
Allowable stress, KSI

MATL	DIA	F_y	F_U	S_b
A-36	<4”	36	58	19.14
A-307	<8”	36	60	20
A-193-B7	<2.5”	105	125	41.25
	2.5 –4”	95	115	38
A-449	<1”	92	120	39.6
	1–1.5”	81	105	34.65
	<3”	58	90	29.7

Table 4-40
Recommended quantity and spacing of anchor bolts

Diameter, D		Quantity, N		Spacing, b_S (Ft)	
Ft	In	MIN (1)	MAX (2)	MIN (3)	MAX (4)
2	24	4	4	1.75	6
3	36		4	2.35	
4	48		8	1.57	
5	60		12	1.31	
6	72		12	1.57	
7	84		16	1.37	
8	96		16	1.57	
9	108	8	20	1.41	6
10	120		20	1.57	
11	132		24	1.44	
12	144		24	1.57	
13	156		28	1.46	
14	168		28	1.57	
15	180		32	1.47	
16	192	12	32	1.57	6
17	204		36	1.48	
18	216		36	1.57	
19	228		40	1.49	
20	240		40	1.57	

(*Continued*)

Table 4-40
Recommended quantity and spacing of anchor bolts—cont'd

Diameter, D		Quantity, N		Spacing, b_S (Ft)	
Ft	In	MIN (1)	MAX (2)	MIN (3)	MAX (4)
21	252		44	1.5	
22	264		44	1.57	
23	276	16	48	1.51	6
24	288		48	1.57	
25	300		52	1.51	
26	312		52	1.57	
27	324		56	1.51	
28	336		56	1.57	
29	348		60	1.51	
30	360	20	60	1.57	6
31	372		64	1.52	
32	384		64	1.57	

Notes:

1. Minimum quantity is based on minimum arc spacing of 4' and maximum arc spacing of 6'.
2. Maximum quantity is based on 2D.
3. Minimum spacing of anchor bolts is based on the maximum quantity of anchor bolts, $\pi\ D_{b/N_{max}}$.
4. Maximum spacing is based on 6' max arc spacing as practical limit.
5. Minimum anchor bolt size is 3/4".

Table 4-41
Anchor bolt torque values

Bolt Dia (in)	Tensile Area, R_a	Design Bolt Tension (KIPS) (1) (2)	Torque Bolt Tension (KIPS) (4)	Torque (Ft-Lbs)
		CASE 2: A-449		
0.75 – 10 UNC	0.302	8.5	9.1	85
0.875 – 9 UNC	0.419	11.9	12.8	140
1-8 UNC	.551	15.1	16.8	210
1.25 – 7 UNC	0.89	23.9	27.5	430
1.5 – 6 UNC	1.294	33.8	40.5	760
1.75 – 5 UNC	1.744	42.5	54.9	1200
2 – 4.5 UNC	2.3	53.5	72	1800
2.25 – 4.5 UNC	3.02	69.2	93.5	2630
2.5 -4 UNC	3.715	85.2	115.2	3600
2.75 -4 UNC	4.618	99.3	142.3	4890
3-4 UNC	5.621	113.9	171.7	6440
		CASE 2: A-449		
0.75 – 10 UNC	0.302	22	23.5	220
0.875 – 9 UNC	0.419	29.6	32	350
1-8 UNC	.551	38.8	43.2	540
1.25 – 7 UNC	0.89	53.9	62.1	970
1.5 – 6 UNC	1.294	76	91.2	1710
1.75 – 5 UNC	1.744	68.5	88.2	1930

Table 4-41
Anchor bolt torque values—cont'd

Bolt Dia (in)	Tensile Area, R_a	Design Bolt Tension (KIPS) (1) (2)	Torque Bolt Tension (KIPS) (4)	Torque (Ft-Lbs)
		CASE 2: A-449		
2 – 4.5 UNC	2.3	86.3	116	2900
2.25 – 4.5 UNC	3.02	111.1	150.8	4230
2.5 -4 UNC	3.715	137.2	185.6	5800
2.75 -4 UNC	4.618	159.9	228.9	7870
3-4 UNC	5.621	183.7	276.8	10380

Notes:

1. Values in Table for A-36 and A-307 bolts are based on approximately 25 KSI tensile stress on the tensile area.
2. Values in Table for A-449 bolts are based on .7 F_y tensile stress on the tensile area.
3. The threads and underside of nuts should be waxed prior to installation to reduce friction.
4. Torque bolt tension allows a % increase over bolt tension to allow for loss of pretension due to creep of concrete and bolt material.
5. All torque values result in a tension stress less than .8 F_y.

Procedure 4-17: Properties of Concrete

Notation

f'_C = Ultimate 28 day Compressive Stress, PSI
F_C = Allowable Compressive Stress, PSI
B_P = Allowable Bearing pressure, PSI
E_S = Modulus of elasticity, steel, PSI
E_C = Modulus of elasticity, concrete, PSI
n = Ratio, E_S / E_C

Table 4-42
Soil bearing pressure

Type of Soil	Bearing Pressure, PSF
Rock	4000
Rocky	3000
Gravel	2000
Sandy	1500
Clay	1000

Table 4-43
Allowable stress, concrete

Ultimate 28 Day Compressive Stress, f'_C (PSI)	Allowable Compressive Stress, F_C (PSI) (1)	Allowable Bearing Pressure, B_P (PSI)(2)	Ratio, n
2000	800	500	15
2500	1000	625	12
3000	1200	750	10
3750	1500	938	8
4000	1600	1000	6

Notes:

1. F_C = 40% of f'_C
2. B_P = 25% of f'_C
3. See ACI 318 or AISC Steel construction Manual for F_c based on either ASD or LRFD methods.

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