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Assessment of CISF TSAR
Doug Gute 210.522.2307

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Contents

	Page
Title Page / Initial Entries	1
Clevis Bolt Spring Constant Approximation	2
Clevis Bolt Block Bearing Pressure Assessment	7
Clevis Bolt Engagement Length Evaluation	9
Clevis Pin Spring Constant Assessment	15
Approximation of the HI-STAR & HI-STORM Overpack Natural Frequencies (provided by Dan Pomerening)	23

Safety Evaluation of HI-STAR/HI-STORM Casks for High Seismic Sites

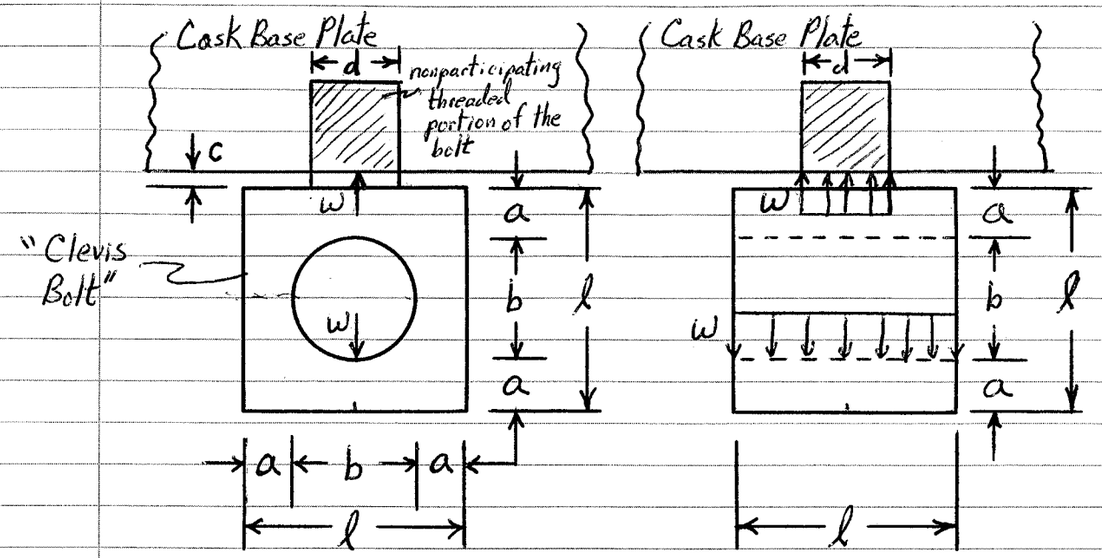
Asadul Chowdhury
Dan Pomerening
Rui Chen
Doug Gute
Ted Krauthammer

The objectives of this task are to support the NRC in reviewing the DOE centralized interim storage facility (CISF) topical safety analysis report (TSAR), developing an assessment report (AR) for the CISF, and reviewing a Holtec International Topical Report (TR) covering the use of the HI-STAR and HI-STORM spent fuel storage casks and anchorage systems in unspecified areas of the country that are considered to be "High Seismic Activity Areas." See the Operations Manual for more detailed information regarding the proposed approach and procedures for achieving these objectives.

Personnel qualifications and skills are environmental engineering/health physics (specifically accident analysis), mechanical engineering (specifically transportation cask design, storage cask design, and fuel handling equipment design), civil/structural engineering (specifically seismology), nuclear engineering (specifically criticality and shielding), nuclear plant operations (specifically fuel handling experience), and material engineering (specifically nuclear plant operations/environment).

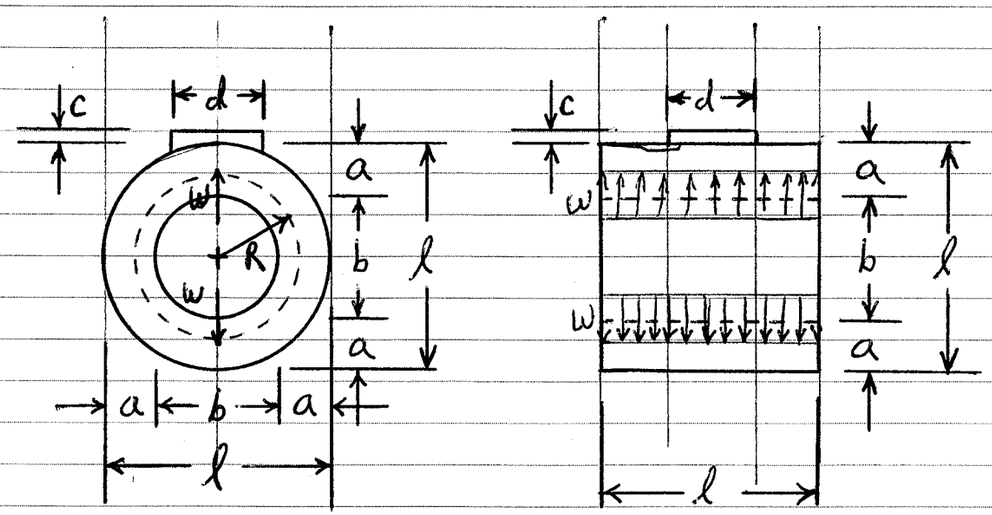
Doug Gute, 6/10/99

Clevis Bolt Spring Constant Approximation



$a = 1.4375$ in $\quad d = 2.5$ in.
$b = 3.00$ in
$c = 0.1250$ in
$l = 5.875$ in

Assume the geometry and loading can be approximated as follows:



From "Roark's Formulas for Stress & Strain, 6th Edition," Table 17, Case 1:

The change in vertical diameter, Δ_V, can be approximated as

$$\Delta_V = 0.1488 \frac{WR^3}{EI} \qquad (1)$$

where

W = load (force)
R = radius to the centroid of the cross section (length)
E = modulus of elasticity (force per unit area)
I = area moment of inertia of ring cross section about the principal axis perpindicular to the plane of the ring (length^4)

Recasting eqn (1) in the following form,

$$W = \frac{EI}{0.1488 R^3} \Delta_V \qquad (2)$$

we see that the spring constant for the clevis block can be approximated as

$$K_{block} = \frac{EI}{0.1488 R^3} \qquad (3)$$

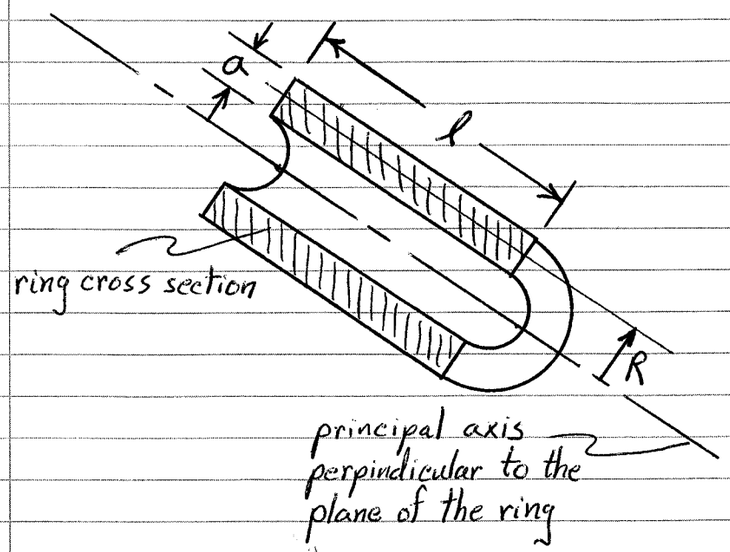
From the TSAR,

$$E = 29.0 (10^6) \text{ lb/in}^2$$

For the radius to the centroid of the cross section,

$$R = \frac{a}{2} + \frac{b}{2} \qquad (4)$$
$$= 2.2188 \text{ in}$$

The area moment of inertia is calculated as follows:



Employing the parallel axis theorem,

$$I = \frac{1}{12} a \ell^3 + (a\ell)(R^2) \quad ; \quad (5)$$

$$= 43.0293 \text{ in}^4$$

; Formulation for I is in error! See correction on p.6. Doug Tate, 12/27/99

Substituting E, R, and I into (3) yields,

$$\therefore K_{block} = \frac{[29.0(10^6) \text{ lb/in}^2](43.0293 \text{ in}^4)}{(0.1488)(2.2188 \text{ in})^3}$$

$$= 7.68(10^8) \text{ lb/in}$$

To include the 0.125 in nonthreaded portion of the bolt,

$$\frac{1}{K_{TOTAL}} = \frac{1}{K_{block}} + \frac{1}{K_{bolt}} \quad (7)$$

where

$$K_{bolt} = \frac{EA}{L} \quad ; \quad E = 29.0(10^6) \text{ lb/in}^2 \quad (8)$$

$$A = \pi/4 (d^2) = 4.909 \text{ in}^2$$

$$L = c = 0.125 \text{ in}$$

$$\therefore K_{bolt} = 1.139(10^9) \text{ lb/in}$$

Substituting the results from eqns (6) and (8) into (7) and solving for K_{TOTAL} gives

$$K_{TOTAL} = 4.586(10^8) \text{ lb/in}$$

Note that this spring constant is 18 times larger than the "Bolt Spring Constant" calculated in the TSAR (i.e., $K_{bolt} = 2.56(10^7)$).

Doug Tate 12/21/99

Upon review of the I formulation given on p. 4, eq'n (5), it was found that a mistake was made. The correct form is given below:

$$I = \frac{1}{12} l a^3$$
$$= 1.4543 \text{ in}^4$$

As a result of this error, K_{block} becomes

$$K_{block} = 2.5947(10^7) \text{ lb/in}$$

And, subsequently,

$$K_{TOTAL} = 2.5369(10^7) \text{ lb/in.}$$

Doug Lute 12/22/99

Clevis Bolt Block Bearing Pressure Assessment

Even though ASME B&PV Code, Section III, Appendix F, Paragraph F-1334.10 states that "Except for pinned and bolted joints, bearing stresses need not be evaluated for loads for which Level D Service Limits are specified," the TR attempted to do so anyway for the Clevis Bolt Block.

From ASME B&PV Code, Section III, Appendix F, Paragraph F-1341.1, the primary stress limits when using elastic analysis are:

(a) The general primary membrane stress intensity P_m shall not exceed the lesser of 2.4 Sm and 0.7 Su for materials included in Section II, Part D, Subpart 1, Tables 2A and 2B, or 0.7 Su for materials included in Section II, Part D, Subpart 1, Table 2A.

(b) The local primary membrane stress intensity P_L shall not exceed 150% of the limit for general primary membrane stress intensity P_m.

(c) The primary membrane (general or local) plus primary bending stress intensity, $P_L + P_B$, shall not exceed 150% of the limit for general primary membrane stress intensity P_m.

(d) The average primary shear across a section loaded in pure shear shall not exceed 0.42 Su.

The definitions for P_m, P_L, and P_B are provided in ASME B&PV Code, Section III, Division 1 - Subsection NB, NB-3221.1 through NB-3221.3.

For SA564-630 H1075 (from ASME B&PV Code, Section II, Part D, Subpart 1, Table 2A)

$S_u = 145$ ksi
$S_y = 125$ ksi
$S_m = 48.3$ ksi @ 200°F

Notes:
- This material has reduced toughness at room temperature after exposure for about 5000 hr at 600°F and after shorter exposure above 650°F.
- Not for welded construction
- This material is not included in ASME B&PV Code, Section II, Part D, Subpart 1, Table 2B.

For SB637-N07718

Notes:
- This material was not included in either Table 2A or 2B of the ASME B&PV Code, Section II, Part D, Subpart 1.

Since the clevis bolt block is, in essence, carrying/supporting the clevis bolt bearing loads, they need to be evaluated in accordance with F-1334.10. Moreover, it appears that SA564-630 and SB637-N07718 are materials used predominantly for bolting applications.

Doug Gute 1/14/00

Clevis Bolt Engagement Length ~~Formulation~~ Evaluation

This evaluation is based on the "Screw-Thread Standards for Federal Services." Refer to this document for the definition of the variables and equations.

For the 2.5" UNC 3A External Thread of the Clevis Bolt:

$d_{bsc} = d_{max} = 2.5$ in ; maximum major diameter; basic major diam.

$d_{min} = 2.4762$ in ; minimum major diameter

$d_{2bsc} = d_{2max} = 2.3376$ in ; maximum pitch diameter; basic pitch diam.

$d_{2min} = 2.3298$ in ; minimum pitch diameter

$T_{d2} = 0.0078$ in ; pitch diameter tolerance

$es = 0.0000$ in ; allowance

$n = 4$; threads/in

$UTS_s = 130{,}000$ psi ; From ASME B&PV Code, Section II, Part D, Table 4, "Design Stress Intensity Values for Bolting Materials." SA 564-630

External Nominal Minor Diameter = 2.1933 in.

$T_d = 0.0238$ in

$T_{d2} = 0.00780$ in

For the 2.5" UNC 3B Internal Thread of the Cask Base Plate.

$D_{1min} = 2.2290$ in ; minimum minor diameter

$D_{1max} = 2.2594$ in ; maximum minor diameter

$d_{2bsc} = d_{2max} = D_{2min} = 2.3376$ in ; minimum pitch diameter

$D_{2max} = 2.3477\,in$; maximum pitch diameter

$TD_2 = 0.0101\,in$; pitch diameter tolerance

Internal Major Diameter (min) = 2.5 in

$UTS_n = 70{,}000\,psi$; From ASME B&PV Code, Section II, Part D, Table U, "Tensile Strength Values for Ferrous and Nonferrous Materials." SA-350 LF3

$\frac{3H}{16} = 0.04059\,in$; half external thread addendum

Nominal Internal Minor Diameter, $D_{1bsc} = 2.2294\,in$

Note: Equation numbers referenced below correspond to those equations provided in Table II. B. 1 "Formulas for Screw-Thread Strength Factors." from the "Screw-Threads Standard for Federal Services," (FED-STD-H28/2A)

(1a) $A_s = \pi\left(\frac{d_{2bsc}}{2} - \frac{3H}{16}\right)^2$

$= \pi\left[\frac{(2.3376\,in)}{2} - 0.04059\,in\right]^2$

$= 3.9988\,in^2$

(1b) $A_s = 0.7854\left(d_{bsc} - \frac{0.9743}{n}\right)^2$

$= (0.7854)\left[(2.5) - \frac{(0.9743)}{(4)}\right]^2$

$= 3.9988\,in^2$

(2a) $\frac{AS_{n\,min}}{LE} = 3.1416\,n\,d_{min}\left[\frac{1}{2n} + 0.57735\left(d_{min} - D_{2max}\right)\right]$

$= (3.1416)(4)(2.4762)\left[\frac{1}{(2)(4)} + (0.57735)(2.4762 - 2.3477)\right]$

$= 6.1981$

(2b) $\frac{AS_{n\,min}}{LE} = 3.1416\,d_{min}\left[0.875 - 0.57735\,n\,(T_d + TD_2 + es)\right]$

$= (3.1416)(2.4762)\{(0.875) - (0.57735)(4)[(0.0238) + (0.0101) + (0)]\}$

$= 6.1978$

(3) $\frac{AS_n}{L_E} = 3.1416\,D_{2bsc}\,\frac{3}{4}$

$= (3.1416)(2.3376)\frac{(3)}{(4)}$; Not sure if the value for D_{2bsc} is correct!!!

$= 5.5078$

(4a) $\frac{AS_{s\,min}}{LE} = 3.1416\,n\,D_{1max}\left[\frac{1}{2n} + 0.57735\left(d_{2min} - D_{1max}\right)\right]$

$= (3.1416)(4)(2.2594)\left[\frac{1}{(2)(4)} + 0.57735\left[(2.3298) - (2.2594)\right]\right]$

$= 4.7031$

(4b) $\frac{AS_{s\,min}}{LE} = 3.1416\,D_{1max}\left[0.75 - 0.57735\,n\,(TD_1 + Td_2 + es)\right]$; TD_1 unspecified

$= (3.1416)(2.2594)\{(0.75) - (0.57735)(4)[(TD_1) + (0.00780) + (0)]$

$=$

(5) $\frac{AS_s}{LE} = 3.1416\,d_{2bsc}\,\frac{5}{8}$

$= (3.1416)(2.3376)\frac{(5)}{(8)}$

$= 4.5899$

(6a) $\dfrac{AS_{s\,max}}{\left(\dfrac{LE}{d_{bsc}}\text{ from Fig. 2.B.2}\right)d_{bsc}} = 3.1416\, D_{1bsc}\, \dfrac{3}{4}$

$= (3.1416)(2.2294)\dfrac{(3)}{(4)}$

$= 5.2529$

(6b) $\dfrac{AS_{s\,max}}{LE} = 3.1416\, D_{1bsc}\, \dfrac{3}{4}$

$= 5.2529$

(7) $\dfrac{AS}{LE} = \dfrac{3.1416}{2} D_{2bsc}$

$= \dfrac{(3.1416)}{(2)}(2.3376)$

$= 3.6719$

(8) $R_1 = \dfrac{\text{Formula (6a) or (6b)}}{\text{Formula (2a) or (2b)}}$

$= \dfrac{5.2529}{6.1981}$

$= 0.8475$

(9) $R_2 = \dfrac{UTS_n}{UTS_s}$

$= \dfrac{70,000}{140,000}$

$= 0.5$

(10) No eqn (10) exists in Table II. B. 2.

(11) $S_t \equiv$ tensile stress, externally threaded part - pure tension

(12) $S'_t \equiv$ combined tensile stress, externally threade part.

(13) $LE = \dfrac{4\,A_s \text{ from (1a) or (1b)}}{3.1416\, d_{2bsc}}$

$= \dfrac{(4)(3.9988)}{(3.1416)(2.3376)}$

$= 2.1781$ in ; based on combined shear failure of external and internal threads

(14) $LE = \dfrac{2\,A_s \text{ from (1a) or (1b)}}{\dfrac{AS_s \text{ from (4a) or (4b)}}{LE}}$

$= \dfrac{(2)(3.9988)}{(4.7031)}$

$= 1.7005$ in ; based on shear of external thread.

(15) $LE = \dfrac{2\,A_s \text{ from (1a) or (1b)}}{\dfrac{AS_s \text{ from (6b)}}{LE}}$

$= \dfrac{(2)(3.9988)}{(5.2529)}$

$= 1.5225$; based on developing full tensile strength of external thread with threads at basic size.

(16) $LE = LE \text{ from (15)} \times \dfrac{R_1 \text{ from (8)}}{R_2 \text{ from (9)}}$; only if $R_1 > R_2$

$= (1.5225)\dfrac{(0.8475)}{(0.5)}$

$\therefore$ $LE = 2.5807$ in ; based on shear of internal thread

From Machinery's Handbook, 25'th Edition, page 1415 + 1416

$$L_e = \frac{2\,A_t}{3.1416\, K_{n\,max}\left[\tfrac{1}{2} + 0.57735\, n\,(E_{s\,min} - K_{n\,max})\right]}$$

where

A_t = tensile stress area of screw thread

L_e = engagement length

n = number of threads per inch

$K_{n\,max}$ = max. minor diam. of int. thrd.

$E_{s\,min}$ = min. pitch diam. of ext. thrd.

$K_{n\,max} = 2.2594\ in$ $\qquad D_{s\,min} = 2.4762\ in$; min. major diam. ext. thrd.

$E_{s\,min} = 2.3298\ in$ $\qquad E_{n\,max} = 2.3477\ in$; max. pitch diam. int. thrd.

$n = 4$

$$A_t = 3.1416\left(\frac{E_{s\,min}}{2} - \frac{0.16238}{n}\right)^2$$; for steels of over 100ksi ultimate tensile strength

$$= (3.1416)\left[\frac{(2.3298)}{(2)} - \frac{(0.16238)}{(4)}\right]^2$$

$$= 3.9712\ in^2$$

$$L_e = \frac{(2)(3.9712)}{(3.1416)(2.2594)\{(0.5) + (0.57735)(4)[(2.3298) - (2.2594)]\}}$$

$= 1.6888\ in$; based on stripping of the external thread.

$$J = \frac{A_s\ UTS_s}{A_n\ UTS_n}$$

$$\frac{A_s}{L_e} = 3.1416\, n\, K_{n\,max}\left[\frac{1}{2n} + 0.57735\,(E_{s\,min} - K_{n\,max})\right]$$

$$= (3.1416)(4)(2.2594)\left\{\frac{1}{(2)(4)} + (0.57735)[(2.3298) - (2.2594)]\right\}$$

$$= 4.7031$$

$$\frac{A_n}{L_e} = 3.1416\, n\, D_{s\,min}\left[\frac{1}{2n} + (0.57735)(D_{s\,min} - E_{n\,max})\right]$$

$$= (3.1416)(4)(2.4762)\left\{\frac{1}{(2)(4)} + (0.57735)[(2.4762) - (2.3477)]\right\}$$

$$= 6.1981$$

$$\therefore\ J = \frac{(4.7031)}{(6.1981)}\frac{(140{,}000)}{(70{,}000)}$$

$$= 1.5176$$

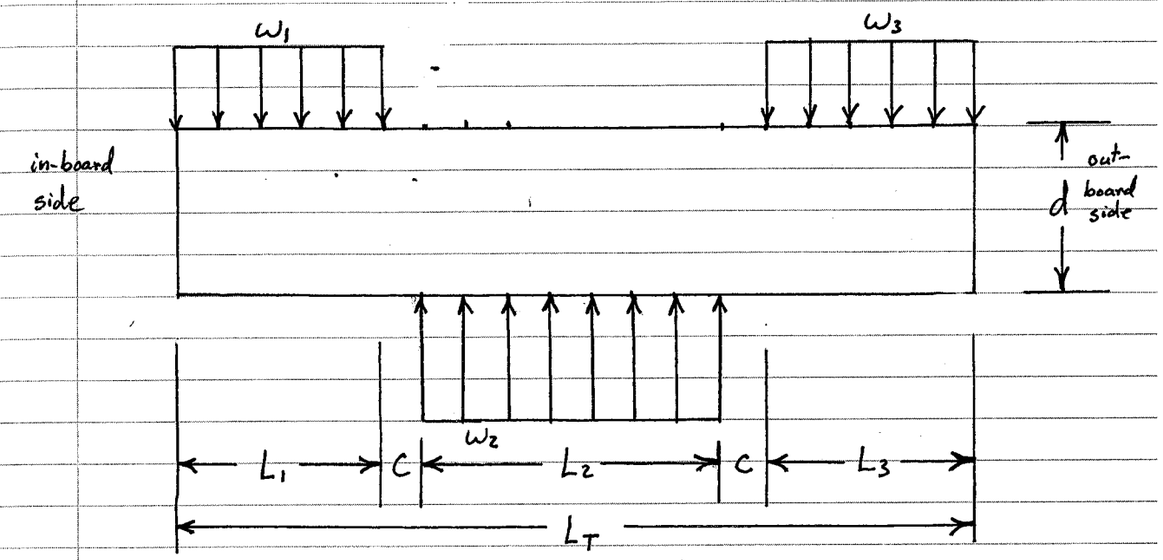
$Q = J L_e$; required length of engagement to prevent stripping of the internal thread.

$= (1.5176)(1.6888)$

$\therefore\ = 2.5629\ in.$; Doug [illegible] 1/15/2000

Clevis Pin Spring Constant Assessment

Assess the influence of a uniformly distributed load as opposed to the concentrated couplesassumed in the Holtec Topical Report.



$C = 0.25\ in$

$d = 2.875\ in$

$L_2 = 5.75\ in$

$E = 29.0\,(10^6)\ psi$; $\nu = 0.3$

$$I = \frac{\pi}{64} d^4 = 3.3537\ in^4$$

$L_T = 16.625\ in$

$L_1 = 5\ in$

$L_3 = 5.375\ in$

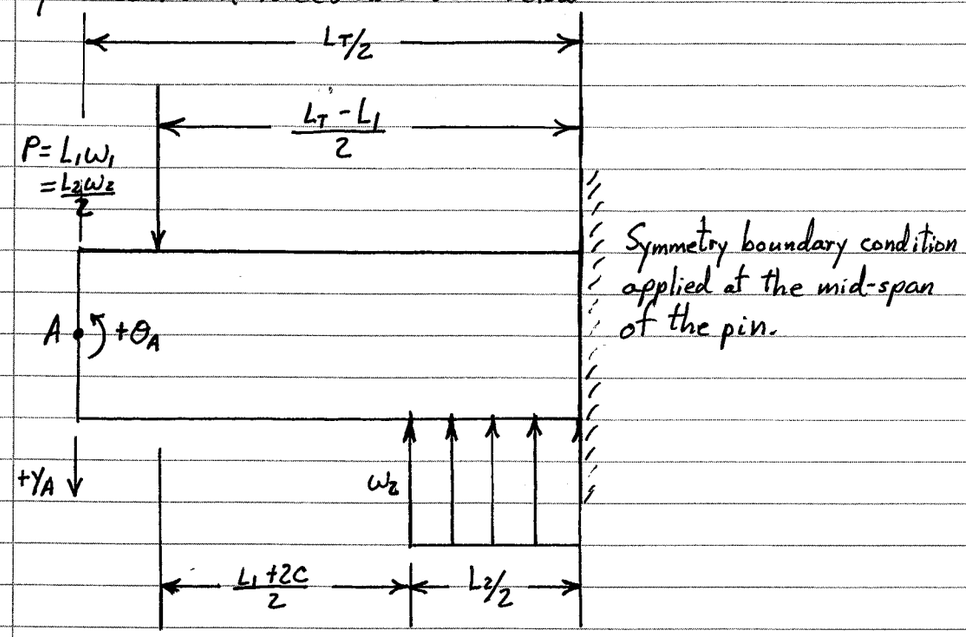
Note: L_1 and L_3 are nearly equal. As a result, it will be assumed that $L_1 = L_3 = (L_1 + L_3)/2 = 5.1875\ in$

$$L_2 w_2 = L_1 w_1 + L_3 w_3$$
$$= 1$$

$$A = \frac{\pi}{4} d^2 = 6.4918\ in^2$$

$$G = \frac{E}{2(1+\nu)} = \frac{29\,(10^6)}{2(1+0.3)} = 11.1538\,(10^6)\ psi$$

Now, assume the distributed loads ω_1 and ω_2 can be approximated by concentrated forces as shown below:



From "Roark's Formulas for Stress & Strain, 6'th Edition," Table 3, Cases 1a and 2a (linear superposition is used to combine the two solutions).

For Case 1a, using the notation defined above,

$$\theta_A = \frac{P\left[(L_T/2) - (L_1/2)\right]^2}{2EI}$$

$$Y_A = \frac{P}{6EI}\left[2(L_T/2)^3 - 3(L_T/2)^2(L_1/2) + (L_1/2)^3\right]$$

For Case 2a,

$$\theta_A = \frac{-\omega_2}{6EI}\left[(L_T/2) - (L_T/2 - L_2/2)\right]^3$$

$$Y_A = \frac{-\omega_2}{24EI}\left[(L_T/2) - (L_T/2 - L_2/2)\right]^3\left[3(L_T/2) + (L_T/2 - L_2/2)\right]$$

Adding the two solutions together yields

$$\theta_A = \frac{P}{2EI}\left[(L_T/2) - (L_1/2)\right]^2 - \frac{\omega_2}{6EI}\left[(L_T/2) - (L_T/2 - L_2/2)\right]^3$$

and

$$Y_A = \frac{P}{6EI}\left[2(L_T/2)^3 - 3(L_T/2)^2(L_1/2) + (L_1/2)^3\right] - \frac{\omega_2}{24EI}\left[(L_T/2) - (L_T/2 - L_2/2)\right]^3\left[3(L_T/2) + (L_T/2 - L_2/2)\right]$$

Check the span/depth ratio to assess whether the shear deflection is negligible.

Doug Stutz Aug 23, 2000 →

$$\cancel{\frac{\text{span}}{\text{depth}} = \frac{(L_T/2)}{d} = \frac{L_T}{2d} = \frac{(16.625\,in)}{(2)(2.875\,in)} = 2.8913}$$

From "Roarks Formulas for Stress & Strain, 6'th Edition," Article 7.10, the span of the beam should be the entire length (see the table on page 203), relative to the supports.

$$\therefore \frac{\text{span}}{\text{depth}} = \frac{(L_T - L_1)}{d} = \frac{\left[(16.625\,in) - (5.1875\,in)\right]}{(2.875\,in)} = 3.9783$$

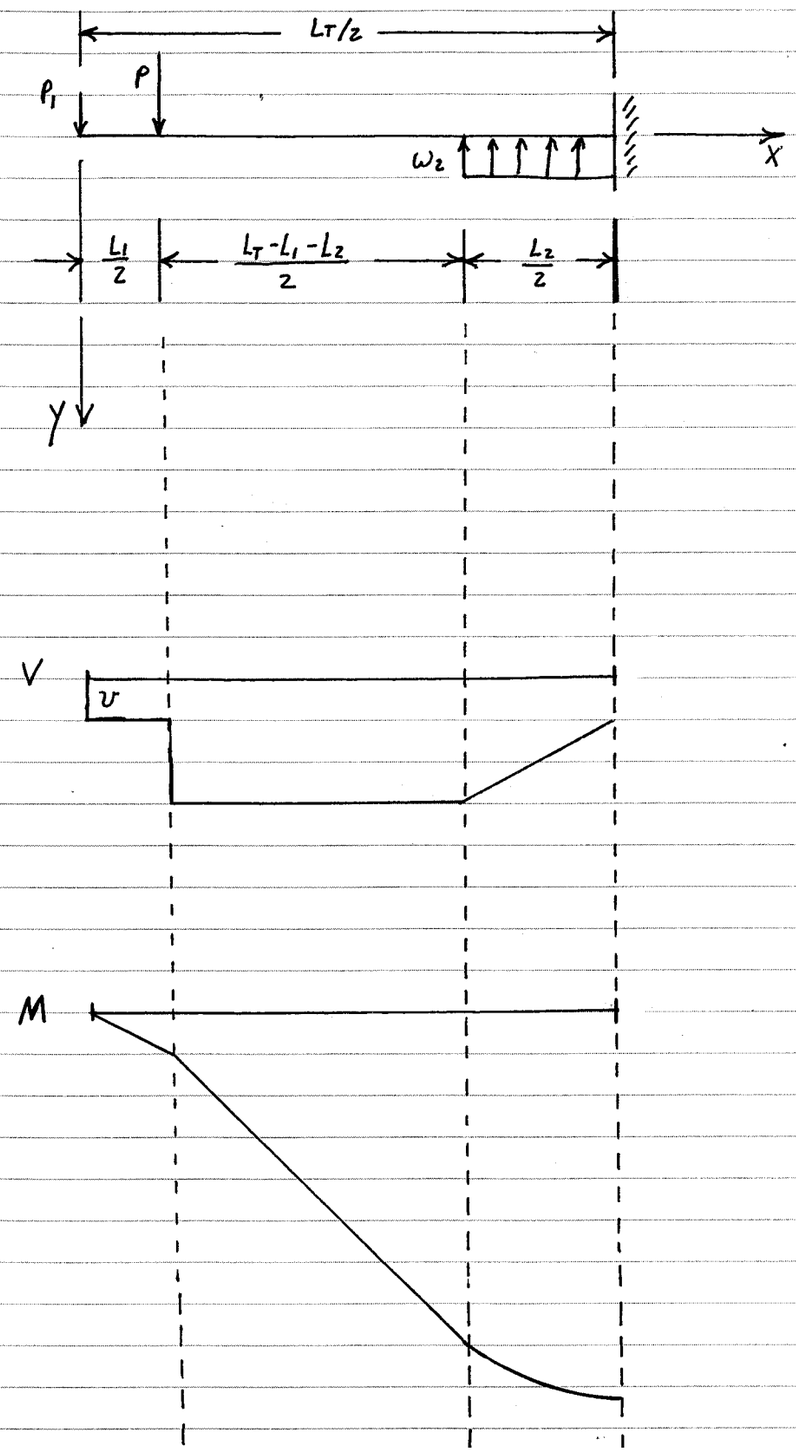
For $\frac{\text{span}}{\text{depth}}$ ratios of 3 or more, the deflection Y_s due to shear is found by the method of unit loads to be

$$Y_s = F\int \frac{Vv}{AG}\,dx$$

where

$Y_s \equiv$ deflection due to shear
$F \equiv$ cross section factor (10/9 for solid circular sections)
$V \equiv$ vertical shear due to actual loads
$v \equiv$ vertical shear due to a unit load acting at the section where the deflection is desired
$A \equiv$ cross section Area ; $G \equiv$ modulus of rigidity

Sketch a shear-moment diagram,



For $0 < x < (L_1/2)$,

$$V = -P_1$$

$$M = -P_1 x$$

For $L_1/2 < x < (L_T - L_2)/2$.

$$V = -(P_1 + P)$$

$$M = -P_1 x - P(x - L_1/2)$$

For $(L_T - L_2)/2 < x < (L_T/2)$

$$V = -P_1 - P + \omega_2 [x - (L_T - L_2)/2]$$

$$M = -P_1 x - P(x - L_1/2) + \frac{\omega_2}{2}[x - (L_T - L_2)/2]^2$$

Or,

$$V = -P_1 \langle x \rangle^0 - P \langle x - (L_1/2) \rangle^0 + \omega_2 \langle x - \tfrac{(L_T - L_2)}{2} \rangle^1$$

$$M = -P_1 \langle x \rangle^1 - P \langle x - (L_1/2) \rangle^1 + \frac{\omega_2}{2} \langle x - \tfrac{(L_T - L_2)}{2} \rangle^2$$

To use

$$y_s = F \int \frac{Vv}{AG}\, dx$$

and must be formulated separately, i.e.

$v = -P_1 \langle x \rangle^0$; note that $P_1 = 1$

$V = -P \langle x - (L_1/2) \rangle^0 + \omega_2 \langle x - \tfrac{(L_T - L_2)}{2} \rangle^1$

$$\therefore\ y_s = F \int_0^{L_1/2} \frac{(0)(-1)}{AG}\, dx + F \int_{L_1/2}^{\frac{(L_T - L_2)}{2}} \frac{(-P)(-1)}{AG}\, dx + F \int_{\frac{(L_T - L_2)}{2}}^{L_T/2} \frac{(-1)\left\{-P + \omega_2 \left[x - \left(\frac{L_T - L_2}{2}\right)\right]\right\}}{AG}\, dx$$

$$y_s = \frac{FP}{AG}\left[X\right]_{L_1/2}^{\frac{(L_T-L_2)}{2}} - \frac{F}{AG}\left[-PX + \frac{\omega_2 X^2}{2} - \frac{\omega_2}{2}(L_T-L_2)X\right]_{\frac{(L_T-L_2)}{2}}^{L_T/2}$$

$$y_s = \frac{FP}{AG}\left[\frac{(L_T-L_2)}{2} - \frac{L_1}{2}\right]$$

$$-\frac{F}{AG}\left\{\left[-P\left(\frac{L_T}{2}\right) + \frac{\omega_2}{2}\left(\frac{L_T}{2}\right)^2 - \frac{\omega_2}{2}(L_T-L_2)\left(\frac{L_T}{2}\right)\right] - \left[-P\left(\frac{L_T-L_2}{2}\right) + \frac{\omega_2}{2}\left(\frac{L_T-L_2}{2}\right)^2 - \frac{\omega_2}{2}(L_T-L_2)\left(\frac{L_T-L_2}{2}\right)\right]\right\}$$

$$y_s = \frac{FP}{AG}\left(\frac{L_T-L_1-L_2}{2}\right) - \frac{F}{AG}\left\{\cancel{-\frac{PL_T}{2}} + \cancel{\frac{\omega_2}{8}L_T^2} - \cancel{\frac{\omega_2}{4}L_T^2} + \cancel{\frac{\omega_2}{4}L_TL_2} + \cancel{\frac{PL_T}{2}} - \cancel{\frac{PL_2}{2}} - \frac{\omega_2}{8}(L_T^2 - 2L_2L_T + L_2^2) + \frac{\omega_2}{4}(L_T^2 - 2L_2L_T + L_2^2)\right\}$$

$$= \frac{FP}{AG}\left(\frac{L_T-L_1-L_2}{2}\right) - \frac{F}{AG}\left[\cancel{-\frac{\omega_2}{8}L_T^2} + \cancel{\frac{\omega_2}{4}L_TL_2} - \cancel{\frac{PL_2}{2}} - \cancel{\frac{\omega_2}{8}L_T^2} + \cancel{\frac{\omega_2}{4}L_TL_2} - \frac{\omega_2}{8}L_2^2 + \cancel{\frac{\omega_2}{4}L_T^2} - \cancel{\frac{\omega_2}{2}L_TL_2} + \frac{\omega_2}{4}L_2^2\right]$$

$$= \frac{FP}{AG}\left(\frac{L_T-L_1-L_2}{2}\right) + \frac{F}{AG}\left[\frac{PL_2}{2} - \frac{\omega_2}{8}L_2^2\right]$$

$$\therefore\ y_s = \frac{F}{2AG}\left[P(L_T-L_1) - \frac{\omega_2 L_2^2}{4}\right]$$

Total displacement at the free end of the pin is

$$\delta_T = y_A + y_s$$

$$= \frac{P}{6EI}\left[\frac{L_T^3}{4} - \frac{3}{8}L_T^2L_1 + \frac{L_1^3}{8}\right] - \frac{\omega_2}{24EI}\left[\frac{L_2^3}{8}\right]\left[2L_T - \frac{L_2}{2}\right] + \frac{F}{2AG}\left[P(L_T-L_1) - \frac{\omega_2 L_2^2}{4}\right]$$

Recall that $P = \frac{L_2\omega_2}{2}$.

Then,

$$\delta_T = \frac{(\omega_2 L_2)}{12EI}\left(\frac{L_T^3}{4} - \frac{3}{8}L_T^2L_1 + \frac{L_1^3}{8}\right) - \frac{(\omega_2 L_2)}{192EI}L_2\left(2L_T - \frac{L_2}{2}\right) + \frac{F}{2AG}(\omega_2 L_2)\left[\frac{(L_T-L_1)}{2} - \frac{L_2}{4}\right]$$

$$\frac{1}{k_{pin}} = \frac{\delta_T}{(\omega_2 L_2)} = \frac{1}{12EI}\left(\frac{L_T^3}{4} - \frac{3}{8}L_T^2L_1 + \frac{L_1^3}{8}\right) - \frac{L_2}{192EI}\left(2L_T - \frac{L_2}{2}\right) + \frac{F}{2AG}\left(\frac{2L_T - 2L_1 - L_2}{4}\right)$$

$$= \frac{1}{96EI}\left(2L_T^3 - 3L_T^2L_1 + L_1^3\right) - \frac{L_2}{384EI}(4L_T - L_2) + \frac{F}{8AG}(2L_T - 2L_1 - L_2)$$

For $L_1 = 5.1875\ in$
$L_2 = 5.75\ in$
$L_T = 16.625\ in$
$E = 29(10^6)\ lb/in^2$
$I = 3.3537\ in^4$
$A = 6.4918\ in^2$
$G = 11.1538(10^6)\ lb/in^2$
$F = 10/9 = 1.1111$

$$\longrightarrow \frac{1}{k_{pin}} = 5.3855(10^{-7}) - 9.3532(10^{-9}) + 3.2848(10^{-8}) = 5.6204(10^{-7})$$

$$\therefore\ k_{pin} = 1.7792(10^6)\ lb/in$$

Note that this result is substantially smaller than that derived in the Holtec TR, i.e. $K_{pin} = 3.1(10^8)$ lb/in.

Doug [illegible] 1/16/2000

Approximation of the HI-STAR & HI-STORM Overpack Natural Frequencies (provided by Dan Pomerening)

Rigid Body Response of Cask

Concrete Properties From Design of Concrete Structures by George Winter and Arthur H. Nislon

Density	150	lbs/ft3
Cylinder Strength	4000	psi
Split Cylinder Strength.	379	psi
Poisson's Ratio	0.17	
E	3.83E+06	psi
G	1.64E+06	psi

Metal Properties

Density	450	lbs/ft3
Poisson's Ratio	0.3	
E	2.90E+07	psi
G	1.12E+07	psi

from Formulas for Natural Frequncy and Mode Shape by Robert D. Blevins

Bending Modes

fi = (li^2/(2*pi*L^2))*sqrt(E*I/m)

for clamped-free	li	1.875
for free-sliding	li	2.365

m is mass per unit length
I is area moment of inertia
L is length

Shear Modes

fi = (li/(2*pi*L))*sqrt(K*G/mu)

for clamped-free	li	1.571

mu is mass density of material
K is shear coefficient from Table 8-14

Axial Modes

fi = (li/(2*pi*L))*sqrt(E/mu)

for clamped-free	li	1.571

mu is mass density of material

Torsional Modes

fi = (li/(2*pi*L))*sqrt(C*G/(mu*Ip))

for clamped-free	li	1.571

mu is mass density of material
Ip is polar area moment of inertia
C is torsional constant

Doug [illegible] Aug. 25, 2000

Rigid Body Response of Cask

HI-STORM Cask Geometry

Height	231.25 inches		
Diameter at Base	132.5 inches	0.554716981	
Diameter at Top	132.5 inches	0.554716981	
Inside Diameter	73.5 inches		
Overpack Weight	269003 lbs		
Full Weight	360000 lbs		
Area			
Base Diameter	9546 in^2		
Top Diameter	9546 in^2		
Area Moment of Inertia			
Bending		Torsion	
Base Diameter	13697227 in^4	Base Diameter	27394453 in^4
Top Diameter	13697227 in^4	Top Diameter	27394453 in^4
Mass			
Ovepack Weight	696.9 lbsec^2/in		
Full Weight	932.6 lbsec^2/in		
Mass per Unit Length			
Ovepack Weight	3.014 lbsec^2/in^2		
Full Weight	4.033 lbsec^2/in^2		
Mass Density			
Ovepack Weight			
Base Diameter	0.000316 lbsec^2/in^4		
Top Diameter	0.000316 lbsec^2/in^4		
Full Weight			
Base Diameter	0.000422 lbsec^2/in^4		
Top Diameter	0.000422 lbsec^2/in^4		
Shear Coefficient Table 8-14			
Base Diameter	0.5857		
Top Diameter	0.5857		

Doug Sente
Aug. 25, 2000

Bending Modes		Shear Modes	
Base Diameter		Base Diameter	
Overpack Weight	43.7 Hz	Overpack Weight	59.6 Hz
Full Weight	37.8 Hz	Full Weight	51.5 Hz
Top Diameter		Top Diameter	
Overpack Weight	43.7 Hz	Overpack Weight	59.6 Hz
Full Weight	37.8 Hz	Full Weight	51.5 Hz
Axial Modes		Torsion Modes	
Base Diameter		Base Diameter	
Overpack Weight	119.1 Hz	Overpack Weight	77.9 Hz
Full Weight	103.0 Hz	Full Weight	67.3 Hz
Top Diameter		Top Diameter	
Overpack Weight	119.1 Hz	Overpack Weight	77.9 Hz
Full Weight	103.0 Hz	Full Weight	67.3 Hz

Rigid Body Response of Cask

HI-STAR Cask Geometry

Height	203.125 inches		
Diameter at Base	83.25 inches	0.825825826	
Diameter at Top	96 inches	0.716145833	
Inside Diameter	68.75 inches		
Overpack Weight	153710 lbs		
Full Weight	250000 lbs		
Area			
Base Diameter	1731 in^2		
Top Diameter	3526 in^2		
Area Moment of Inertia			
Bending		Torsion	
Base Diameter	1261167.999 in^4	Base Diameter	2522336 in^4
Top Diameter	3072588.697 in^4	Top Diameter	6145177 in^4
Mass			
Ovepack Weight	398.2 lbsec^2/in		
Full Weight	647.7 lbsec^2/in		
Mass per Unit Length			
Ovepack Weight	1.960 lbsec^2/in^2		
Full Weight	3.189 lbsec^2/in^2		
Mass Density			
Ovepack Weight			
Base Diameter	0.001133 lbsec^2/in^4		
Top Diameter	0.000556 lbsec^2/in^4		
Full Weight			
Base Diameter	0.001842 lbsec^2/in^4		
Top Diameter	0.000904 lbsec^2/in^4		
Shear Coefficient Table 8-14			
Base Diameter	0.5265		
Top Diameter	0.5417		

Doug Sente
Aug. 25, 2000

Bending Modes		Shear Modes	
Base Diameter		Base Diameter	
Overpack Weight	58.6 Hz	Overpack Weight	88.6 Hz
Full Weight	45.9 Hz	Full Weight	69.5 Hz
Top Diameter		Top Diameter	
Overpack Weight	91.4 Hz	Overpack Weight	128.3 Hz
Full Weight	71.7 Hz	Full Weight	100.6 Hz
Axial Modes		Torsion Modes	
Base Diameter		Base Diameter	
Overpack Weight	196.9 Hz	Overpack Weight	122.1 Hz
Full Weight	154.4 Hz	Full Weight	95.8 Hz
Top Diameter		Top Diameter	
Overpack Weight	281.1 Hz	Overpack Weight	174.3 Hz
Full Weight	220.4 Hz	Full Weight	136.7 Hz

"I have reviewed this scientific notebook and find it in compliance with QAP-001. There is sufficient information regarding procedures used for conducting tests, acquiring and analyzing data so that another qualified individual could repeat the activity.

8-30-2000

MGFE

(Element Manager signature and date above line,
Name of Element beneath line)"