DCC

CALIFORNIA INSTITUTE OF TECHNOLOGY

Laser Interferometer Gravitational Wave Observatory (LIGO) Project

To/Mail Code: Larry Jones
From/Mail Code: Dennis Coyne D. Coyne
Refer to: LIGO-L960370-01-E
Date: 5 June 96

Subject: **Calculation/Design Check of the Alternative BT Guided Support Design**[1]

The CCB accepted CB&I's proposed alternate Beam Tube guided support design with the qualifier that a careful review of is structural adequacy be conducted. The purpose of this memorandum is to convey the results of this review. The CB&I calculations in support of the alternative design are documented in section 7 of CDRL 10 and 24 (LIGO document no. C960366-00-B). Attached is a marked-up copy of CB&I's calculations and additional calculations performed in the course of the review which augment CB&I's calculations.

In summary I find that the design meets the requirements and is adequate structurally; I see no reason not to proceed with the CCB's recommendation to adopt the alternative design. In addition, I offer the following comments:
1) It is stated in CB&I's document that only main members of the guided support have been analyzed and that at a later date other details will be designed (e.g. bolts, welds, etc.); To date no further information has been submitted by CB&I. I have addressed (attachment 1) the weld stresses for the cable attachment fittings to the BT stiffener ring and the clamp plate used to transfer load from the horizontal cable to the vertical columns and find these elements to be structurally adequate; No further analysis seems warranted.

2) I do have a couple of concerns regarding the design:
a) The clamping plates used to transfer load from the horizontal cable to the vertical columns are not fixed in place, but "float" presumably to better align to the BT as it is adjusted vertically. However, this would seem to be prone to lateral mis-alignment. I suggest that the clamp plates be fillet welded to the vertical columns at their nominal height (i.e. corresponding to the middle of the range of vertical adjustment).

b) Rather than using a torque wrench to calibrate the anchor bolt pre-load, CB&I proposes to use spring washers. The embedded bolt bond strength is only 20% higher than the pre-load (2210# vs. 2000#) and the pre-load is only 25% higher than required to prevent slippage/re-alignment under the seismic load[2]. It seems unlikely that the accuracy with which the bolt pre-load can be

1. This version has minor changes from the original version (L960370-00-E) issued with limited distribution on 16 May 96:
   a) Item (3) was reworded for clarity
   b) Extraneous calculations on one page of Attachment #2 were deleted.
2. Contrary to CB&I's supposition, their calculated value of required friction force is not conservative, but realistic given the reduction in coefficient of friction which can be expected with an oxide film.

set with a spring washer is well within +/- 20%. CB&I may want to revisit this approach.

c) On sheet 4 of section 7, it is stated that there will be no bending of anchor bolts because there will be a base plate under the horizontal beam where it is clamped. However, this base plate does not appear in the drawing (#19). In addition, the analysis on the following pages appear to explicitly exclude such a plate. Furthermore, it is difficult to see how such a plate will help mitigate/preclude anchor bolt bending. CB&I should clarify.

d) While thermally and electrically insulating grommets are used in three of the four cable end connections, they are not used at the horizontal cable to clamping plate connection at the vertical columns; these grommets should be added to the design.

3) The compression buckling of the web of the lower structural tube was calculated incorrectly. A correct calculation in accordance with the AISC's "Manual of Steel Construction: Allowable Stress Design (ASD)[1]", then it appears to be in adequate. However, further analysis indicates that the web will not buckle, as shown in the attachment.

4) The drawing does not contain all of the necessary dimensional details and should be revised.

DCC:dcc

Attachments:
1) D. Coyne, Structural calculations of CB&I's Alternate Guided Support for the Beam Tube (augments CB&I's calculations, i.e. attachment #2)
2) CB&I, Structural Calculations of the Alternate Guided Support, Section 7, CDRLs 10 and 24, LIGO Beam Tube Contract, CB&I reference no. 953571, dated 3/12/96.

cc with attachments:
Chronological File
Document Control Center

cc without attachments:
W. Althouse
M. Coles
G. Stapfer
A. Lazzarini
R. Weiss
S. Whitcomb

1. Manual of Steel Construction: Allowable Stress Design, ninth ed., American Institute of Steel Construction Inc., 1989.

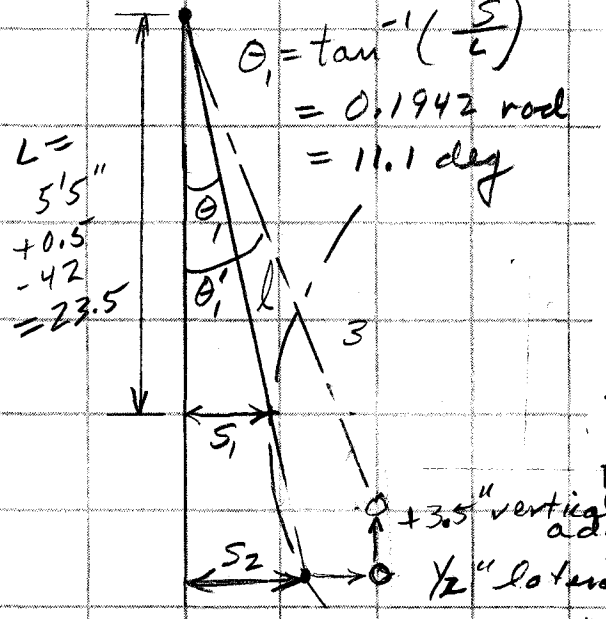
L960370-00-E
Attachment #1

MADE BY D. Coyne DATE 5/16/96 CHKD BY DATE	SUBJECT: LATERAL ANGLE OF THE VERTICAL CABLE Alternate Guided Support	PAGE 1 OF 9 DOC. NO. L960370 REV. 0

$$R = \frac{48.75}{2} + 0.127 + 2$$
$$= 26.502$$

l = (Length of Part #19-15)
$-\frac{1}{2}$(Threaded Length)
− Straight Plug Length

$$l = 40.5 - 5.25 - (\approx 1.5)$$
$$l \approx 33.75''$$



$$\theta_1 = \tan^{-1}\left(\frac{S}{L}\right)$$
$$= 0.1942 \text{ rad}$$
$$= 11.1 \text{ deg}$$

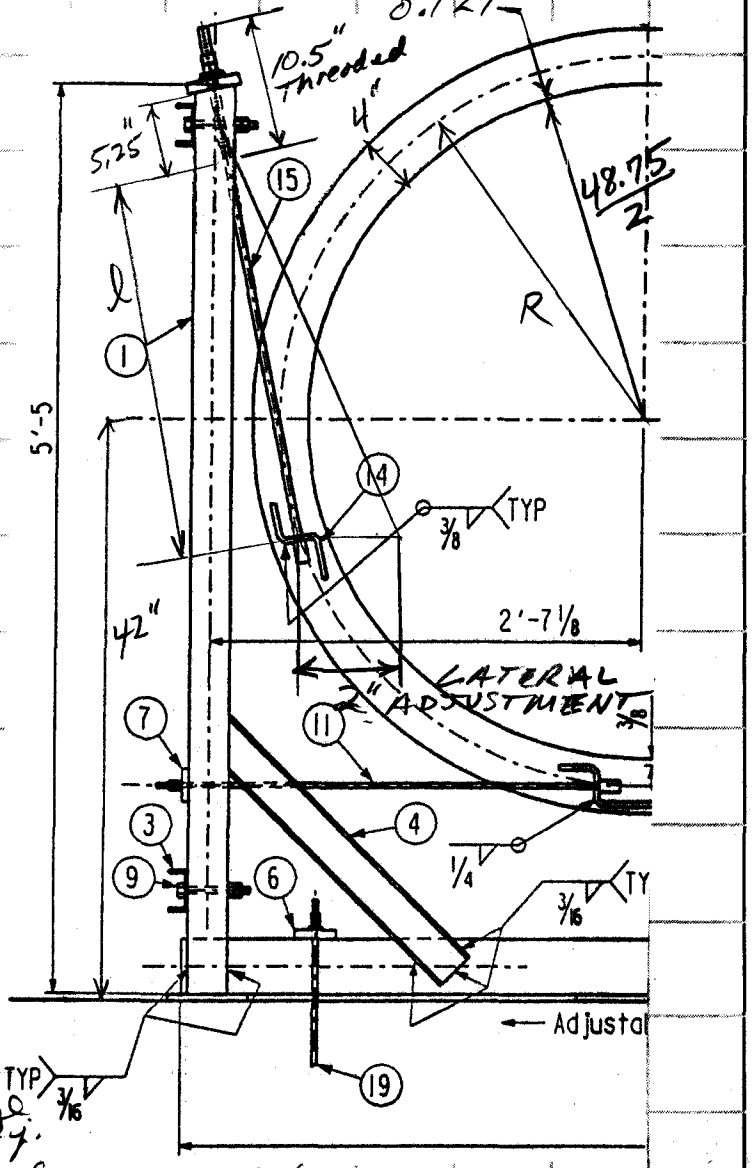
$$S_1 = 2'7\tfrac{1}{8} - R = 4.623''$$

$$S_2 = l \sin\theta_1 = 6.515''$$

$$S_2' = S_2 + 0.5$$

$$\theta_1' \approx \sin^{-1}\left(\frac{S_2'}{l - 3.5}\right) = 0.234 \text{ rad}$$
$$= 13.4 \text{ deg}$$

CB&I's assumption of 15 deg is OK



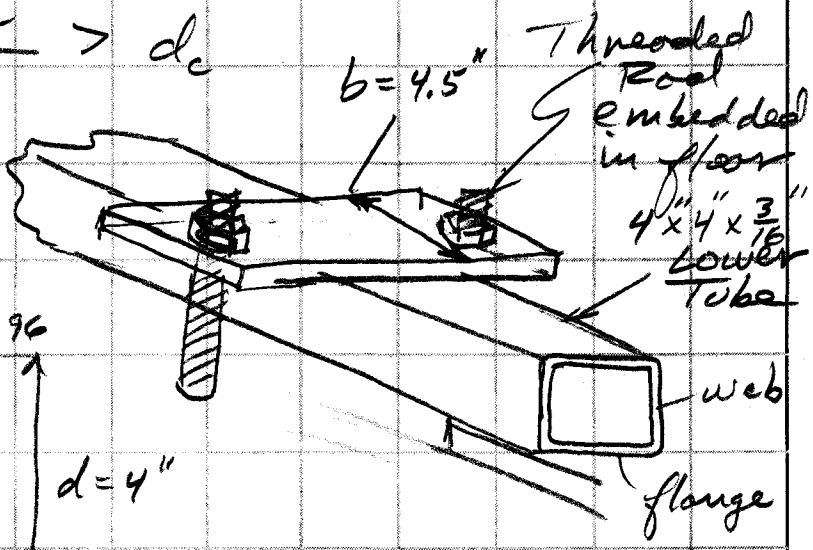
LIGO
CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

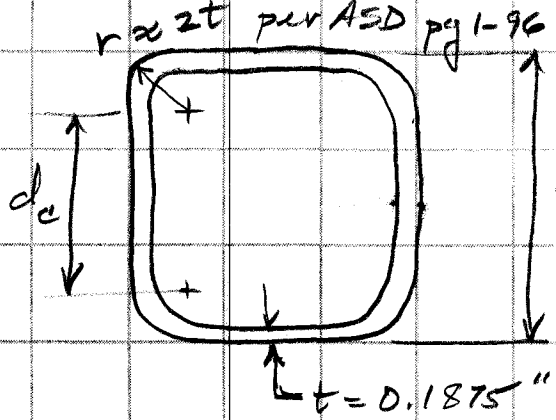
MADE BY D. Coyne DATE 5/15/96	SUBJECT: WEB BUCKLING LOWER TUBE ALTERNATE GUIDED SUPPORT	PAGE 2 OF 9
CHKD BY DATE		DOC. NO. L960370
		REV. 0

The limit for web clear depth d_c to prevent compressive buckling of the web under concentrated load is (ASD, section K1.6):

$$\frac{4100\, t_{wc}^3 \sqrt{F_{yc}}}{P_{bf}} > d_c$$

t_{wc} = column web thickness = $t = 3/16"$





$d_c = 4 - 2r = 3.25$

$P_{bf} = \frac{5}{3}$ Flange Load (ASD, section K1.2)

$= \frac{5}{3}$ (Bolt Load) $= \frac{5}{3}$ (2000 lb) per CB&I Contract #9535-71 CDRL's 10 and 24, section 7

$F_{yc} = 46$ ksi

$$\frac{4100\,(0.1875)^3\sqrt{46000}}{\frac{5}{3}(2000)} = 1.74 \text{ in} \not> d_c = 3.25$$

i.e. fails the ASD, Section K1.6 criteria

Note: CB&I use the total combined web thickness $t_{wc} = 2t$ and $P_{bf} = 5/3$ (2 Bolt Load). In this case the allowable length is 6.94 in. However the criteria is for local buckling of the web, so $t_{wc} \equiv t$, not $2t$.

LIGO CALIFORNIA INSTITUTE OF TECHNOLOGY MASSACHUSETTS INSTITUTE OF TECHNOLOGY

MADE BY D. Coyne	DATE 5/15/96	SUBJECT: WEB Buckling Lower Tube Alternate Guided Support	PAGE 3 OF 9
CHKD BY	DATE		DOC. NO. L960370
			REV. 0

Despite failing to meet the ASD criteria, web buckling is not likely as shown below.

(1) Reference: I. Lyse and H. Godfrey, "Investigation of Web Buckling in Steel Beams" Trans. Am. Soc. of Civil Eng., v100, 1935, p675-706.

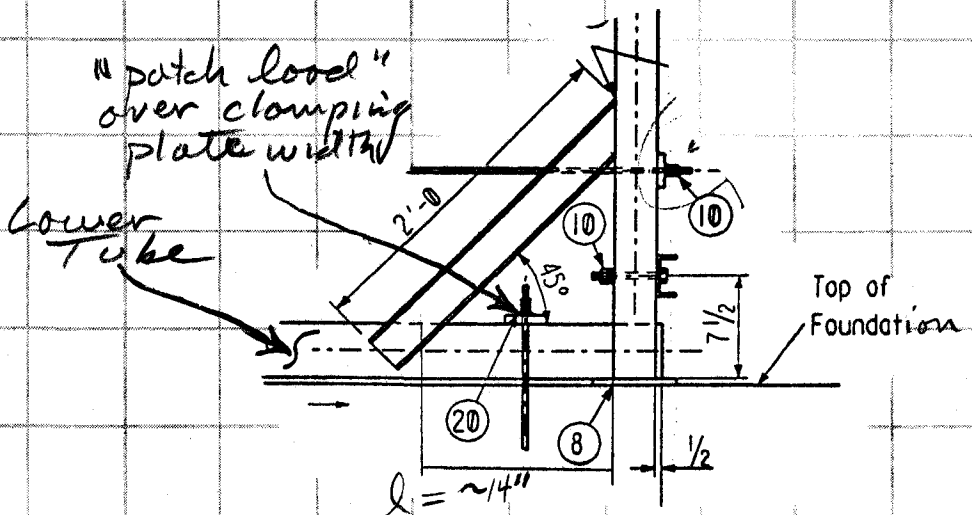
Yield dominates, not buckling if

$$\frac{h}{t} < 70$$

where h = distance between flanges = $d - 2t$

$$\frac{4 - 2\left(\frac{3}{16}\right)}{3/16} = 19 < 70 \quad \therefore \text{ No Web Buckling}$$

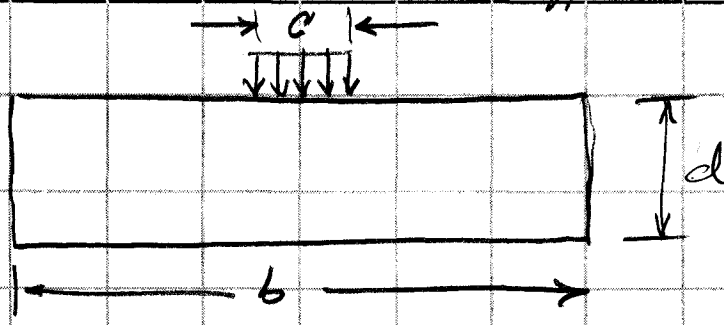
(2) Consider the Buckling of the web as a simply-supported plate (conservative, i.e. no rotational restraint offered by the flanges) with a "patch load":



laterally unsupported span

LIGO CALIFORNIA INSTITUTE OF TECHNOLOGY MASSACHUSETTS INSTITUTE OF TECHNOLOGY

MADE BY D. Coyne	DATE 5/15/96	SUBJECT: Web Buckling Lower Tube Alternate Guided Support	PAGE 4 OF 9
CHKD BY	DATE		DOC. NO. L960370
			REV. 0



$b = l \approx 14''$ (by scaling Dwg #19)

$t = 3/16 = 0.1875$ in

$c = 4.5$ in $\quad c/b = 0.32$

$b = 14$ in

$d = h = 3.625$ in $\quad d/t = 19$

Compare to the figure for $c/b = 2/9 = 0.22$ (conservative)

where σ_{yw} = web material yield stress = 46 ksi

Clearly at $d/t = 19$, The critical load, P_{cr} > yield load; ∴ Web will not buckle

REF: K. Rockey, "The Buckling of Longitudinally Reinforced Web Plates Loaded by a Central In-Plane Patch Load"

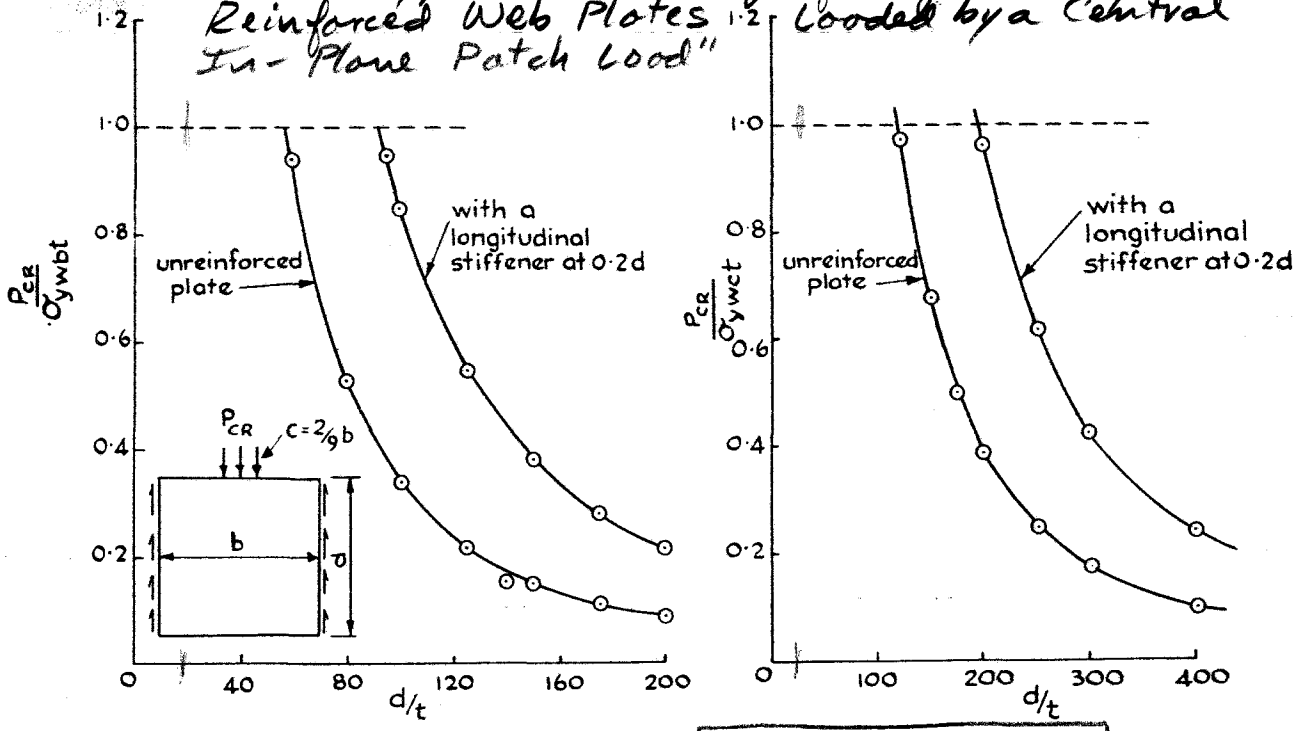


FIG. 11. Variation of critical load with d/t ratio. Simply supported square plate ($c/b = 2/9$).

K. C. Rockey, A. Samuelsson and H. Wennerström

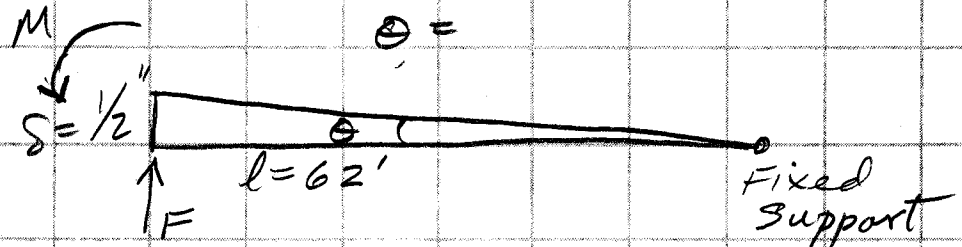
86

in Stability Problems in Engineering Structures and Components, T. Richards (ed.), Applied Science Pub LTD, 1978.

MADE BY D. Coyne	DATE 5/16/96	SUBJECT: Horizontal Cable Force Due to Lateral Alignment (Alternate Guided Support)	PAGE 5 OF 9
CHKD BY	DATE		DOC. NO. L960370
			REV. 0

Lateral alignment of 1/2" causes an increase in the horizontal cable force:

(1) Due to rotational spring rate of the bellow



$$Fl = M = k_r\theta = k_r \tan^{-1}\left(\frac{\delta}{l}\right) \approx \frac{k_r\delta}{l}$$

$$F = \frac{k_r\delta}{l^2}$$

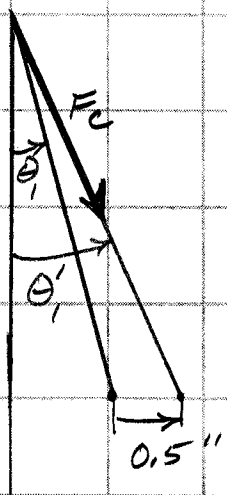
$k_r \approx 56000 \frac{in-lb}{deg}$

$= 3.2\times10^6 \frac{in\text{-}\#}{rad}\ deg$

(Hyspan design calculation for BT bellows, dated 7/3/95)

$F = 2.9$ lb. i.e. negligible

(2) Due to an increased component of the upper cables in the horizontal direction



$$\Delta F_L = F_c(\sin\theta_1' - \sin\theta_1)$$

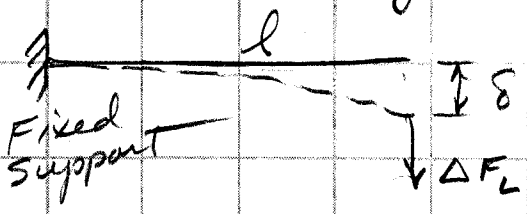
$= 3700^{\#}(\sin 13.4^\circ - \sin 11.1^\circ)$

$= 145^{\#}$

If $\theta_1' = 15$ deg, $\Delta F_L = 245^{\#}$

LIGO CALIFORNIA INSTITUTE OF TECHNOLOGY MASSACHUSETTS INSTITUTE OF TECHNOLOGY

(3) Due to bending stiffness of the TST



$$\delta = \frac{\Delta F_L \, l^3}{3EI}$$

$$I = \pi R^3 t = \pi \left(\frac{48.75}{2}\right)^3 (0.127) = 5778 \text{ in}^4$$

$E = 29 \times 10^6$ psi

$l = 60'$

$\delta = 0.5''$

$\Delta F_L = 673$

∴ Total horizontal cable force increase due to 1/2" lateral alignment is:

$$\Delta F_L = 3 + 145 + 673$$

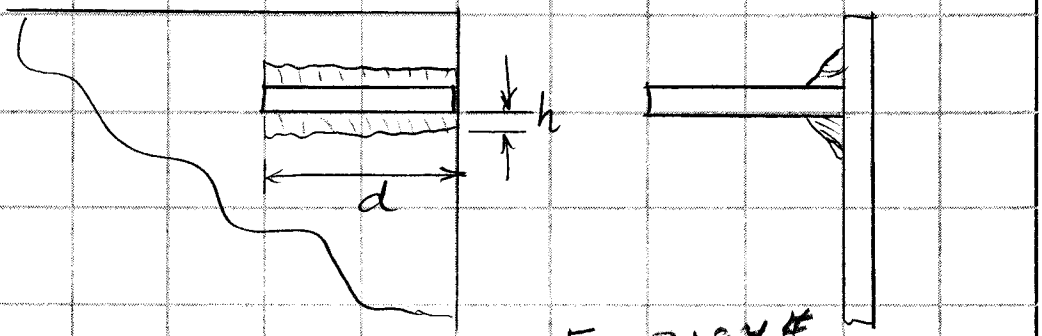
$$\boxed{\Delta F_L = 821\ \#}$$

(NOT 570 # AS INDICATED ON CB&I'S SHT 12, Section 7 of CDRL'S 10 & 24 for Contract # 953571 Dated 3/12/96)

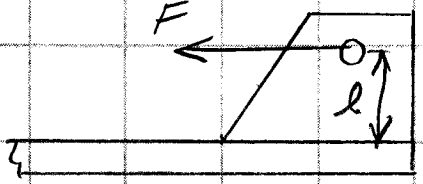
MADE BY D. Coyne	DATE 5/16/96	SUBJECT: Weld Stress Guided Support Alignment Component	PAGE 7 OF 9
CHKD BY	DATE		DOC. NO. L960370
			REV. 0

Correction to CB&I Calc. for Weld Stress — see Sht 14, Section 7, CDRL's 10 and 24, Contract # 953571

Ref: A. Blake, Practical Stress Analysis in Engineering Design, pg. 465, Marcel Dekker, 1982.



$F = 3084\ \#$
$h = 0.25\ in$
$d = 3.0\ in$
$M = Fl = 4241\ in\#$ (from CB&I Sht 14)



Weld section modulus, $S = \frac{hd^2}{6\sqrt{2}}$

and $\sigma = \frac{3\sqrt{2}M}{hd^2} = 7997\ psi$

$\tau = \frac{\sqrt{2}F}{2hd} = 2908\ psi$

$\tau_{max} = \sqrt{\left(\frac{\sigma}{2}\right)^2 + \tau^2} = 4944\ psi$

ASD Table J2.5 Requirement:
$< 0.3 F_{ty} = 0.3(36ksi)$
$< 10800\ psi$

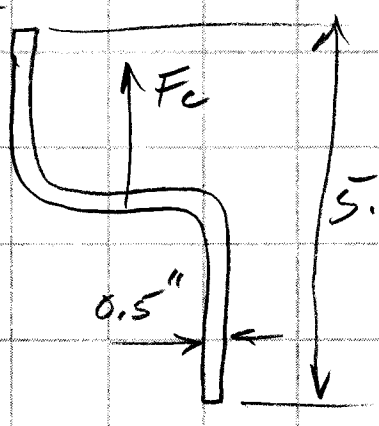
OK ✓

LIGO CALIFORNIA INSTITUTE OF TECHNOLOGY MASSACHUSETTS INSTITUTE OF TECHNOLOGY

MADE BY D. Coyne	DATE 5/16/96	SUBJECT: Weld Stress Cable Attachment Fittings (Alternate Guided Support)	PAGE 8 OF 9
CHKD BY	DATE		DOC. NO. L960370
			REV. 0.

CTS+I did not check the weld stress for the cable attachment fittings welded to the BT stiffener ring.

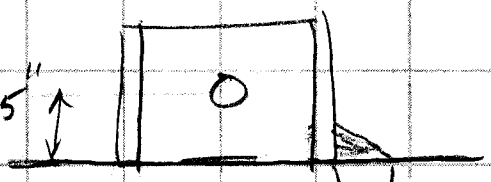
Worst case load and minimum fillet weld length is for the "Z" shaped fittings used to attach the vertical cable



$M = F_c (1.5)$

$= 3700 (1.5)$

$= 5550$ in#



h = 3/8 fillet weld single side

$$\sigma = \frac{6\sqrt{2}M}{h d^2}$$

$\sigma = 4151$ psi

$$\tau = \frac{\sqrt{2}F}{hd} = 2537 \text{ psi}$$

ASD Table J2.5 Requirmt:

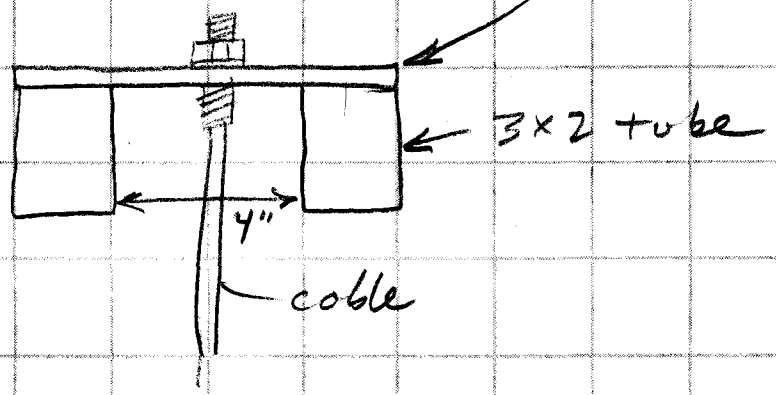
$$\tau_{max} = \sqrt{\left(\frac{\sigma}{2}\right)^2 + \tau^2} = 3278 \text{ psi} < 0.3 F_{ty} = 10500 \text{ psi}$$

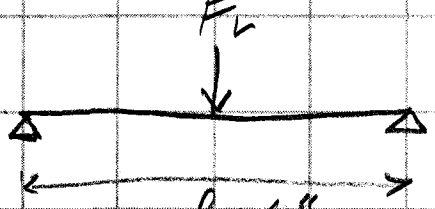
Ok ✓

LIGO CALIFORNIA INSTITUTE OF TECHNOLOGY MASSACHUSETTS INSTITUTE OF TECHNOLOGY

MADE BY B. Coyne	DATE 5/16/96	SUBJECT: CLAMP PLATE — Horizontal Cable to Column (Alternate Guided Support)	PAGE 9 OF 9
CHKD BY	DATE		DOC. NO. L960370
			REV. 0

4" × 8" × 5/8" Part #19-7





F_L = 1730 # per CB&E sht 1a, Sect 7 CDRLs 10 & 24 Contract #953571

$$M_{max} = \frac{Fl}{4}$$

$$\sigma = \frac{Mc}{I} \qquad I = \frac{bh^3}{12} \qquad c = \frac{h}{2}$$

$$\sigma = \frac{6M}{bh^2} = \frac{3Fl}{2bh^2} = 9965 \text{ psi}$$

$\sigma < 0.75 F_y$ ASD Sect F2.1 Requirement

$< 0.75 (36 \text{ ksi})$

$< 27 \text{ ksi}$

OK ✓

LIGO
CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

L960370-00-E
Attachment #2

The following calcs. were developed to size the main members of the guided support. At a later date, other details will be designed (i.e. bolts, welds, etc.) (i.e. not a complete FDR!)

Design Code: AISC 1989 Edition "Allowable Stress Design" (ASD)

Reference Drawings: CBI Contract #930212 Dwg. #19
CBI Contract #953571 Dwg. #19

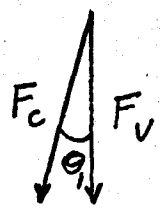
SUBJECT	OFFICE		REVISION		REFERENCE NO.
Guided Support LIGO	CBI LIGO				953571
	MADE BY DJR	CHKD BY MRS	MADE BY	CHKD BY	SHT 1 OF ___
	DATE 3/11/96	DATE 3/12/96	DATE	DATE	

oads on Guided Supports

L760-D950029-C
Max F_L = 1625 lb.

Total Lateral = 1,730 lb = F_L (cons.) — conservative
Largest Vertical Load per "Arm" = 3,563 lb = F_V } From Caltech dwg # D950029
Expansion Joint Contraction = 3.25 in
Each Support Movement = 1.63 in
Reference CBI Contract # 953571 Dwg. 19 for dimensions

able Design

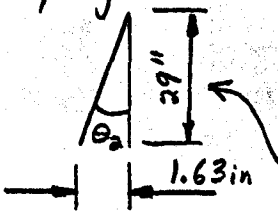


F_V = 3,563 lb
θ_1 = 15° (Assumed max.) — see attached
$F_c = \frac{F_V}{\cos\theta_1}$ = 3,689 lb

Don't have this catalog to check

From SAVA Industries Catalog # 11, use 3/8" ∅ cable Galv. C.S.
Min. breaking strength = 14,400 lb
Gives a F.S. = $\frac{14,400}{F_c}$ = 3.9 > 3.5 per SAVA Catalog # 11, p 7

Also from same catalog, for a 3/8" ∅ cable, we will use a 3/4" ∅ threaded plug on one end and a straight plug on the other end.



$\theta_2 = \tan^{-1}\left(\frac{1.63}{29}\right) = 3.2°$

Assumed min. vertical height of cables

ECT: Guided Support Design LIGO	CBI OFFICE LIGO	REVISION		REFERENCE NO. 953571
	MADE BY DTR / CHKD BY MRS	MADE BY	CHKD BY	SHT 1a OF
	DATE 3/5/96 / DATE 3/12/96	DATE	DATE	

n USA

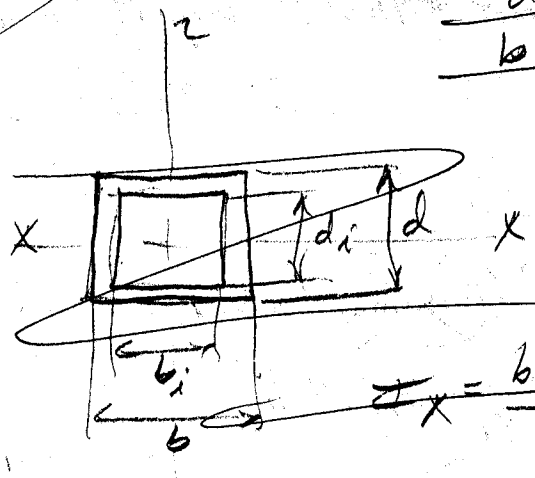
GO 64 REV SEP 84

L960370-1/8-E

Strike-outs for version 01

$d = 3$ $\quad d_i = 3 - \frac{3}{8}$

$b = 2$ $\quad b_i = 2 - \frac{3}{8}$



$$I_x = \frac{bd^3 - b_i d_i^3}{12}$$

2

~~$I_x = 2.05 \text{ in}^4$~~

$$r_x = \sqrt{\frac{I_x}{A}} =$$

$$S_x = \frac{I_x}{c}$$

$c = d/2$

~~$S_x = 2(1.367) = 2.73$~~ ~~$S_x = 0.977 \text{ in}^3$~~

ASD 9th ed., pg 1-103

$I_x = 1.86 \text{ in}^4$

$S_x = 1.24 \text{ in}^3$

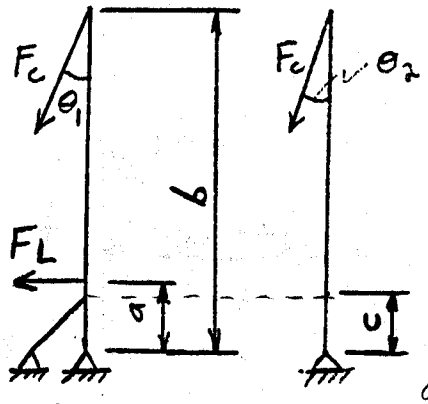
$A = 1.64 \text{ in}^2$

$r_x = 1.06 \text{ in.}$

$r_y = 0.771 \text{ in}$

Can't find A500, Gr.B properties, but ASD uses $F_y = 46$ ksi for rectangular structural tubing

Size Column



Adjustability — Adjustment is actually ±
Fnd. to ℄ lug

$a = 27'' \pm 3.5'' - 10.25'' - 1.5'' = 18.75$ in ✓

$b = 65.5'' \pm 3.5'' = 69$ in Conservative — The column height Adjustability is not increased by adjustment

$c = 20$ in

→ Also ref. CBI contract #930212, dwg. 19

actually c > a so sketch is mis-leading

$$f_a = \frac{P}{A} = 1{,}128 \text{ psi} \checkmark$$

where $P = F_c = 3{,}700$ lb ✓ (cons., sht. 1)

$A = 2(1.64 \text{ in}^2) = 3.28 \text{ in}^2$ (for Tube 3×2×3/16) ✓ part #19-1

$$f_{bx} = \frac{M}{S} = 19{,}793 \text{ psi}$$

where $M = F_c(b-c)\sin\theta_1 + |F_L(a-c)| = 49{,}086$ in·lb ✓ should be a signed quantity — + this is a conservative approach.

$S = 2(1.24 \text{ in}^3) = 2.48 \text{ in}^3$ (for Tube 3×2×3/16)

$$\left(\frac{Kl}{r}\right)_x = \frac{2.1(69-20)}{1.06} = 97 \leftarrow \text{Governs} \rightarrow \frac{Kl}{r} = 97$$

$$\left(\frac{Kl}{r}\right)_y = \frac{1.0(69)}{0.77} = 90$$

Agrees w/ Parts list & mat'l spec

$F_y = 46$ ksi (A500 Gr. B) → $C_c = 111.6$ (ASD, 9th Ed., Table 4)

$\frac{Kl}{r}/C_c = 0.87 \rightarrow C_a = 0.325$ (ASD, 9th Ed., Table 3)

$\sigma_a = C_a F_y = 14{,}950$ psi ✓

SUBJECT	CBI OFFICE LIGO	REVISION		REFERENCE NO. 95357
	MADE BY DTR / CHKD BY MRS	MADE BY	CHKD BY	SHT 2 OF ___
	DATE 3/5/96 / DATE 3/12/96	DATE	DATE	

$f_{by} = \frac{M}{S} = 5{,}163$ psi ✓ (sht. 2) used $F_c = 3700$ lb not $F_c = 3689$ lb

where $M = F_c(b-c)\sin\theta_2 = 10{,}120$ in·lb

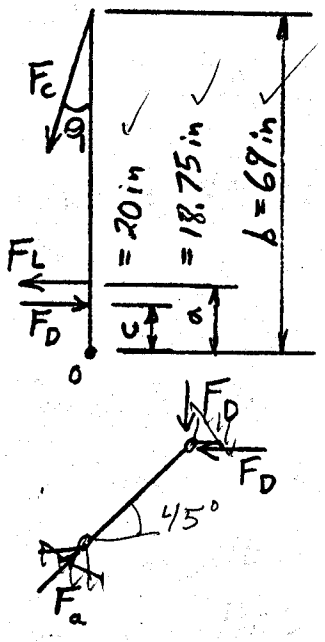
$S = 2(0.98\ in^3) = 1.96\ in^3$ (for 3×2×3/16 Tube)

$\sigma_b = 0.66 F_y = 30{,}360$ psi ✓

Since $\frac{f_a}{\sigma_a} = 0.075 < 0.15$, can use ASD eqn. H1-3

$\frac{f_a}{\sigma_a} + \frac{f_{bx} + f_{by}}{\sigma_b} = 0.90 < 1.0$ ✓ ∴ OK

Size Diagonal Braces (Try C3×4.1)



Sht 2 → $\theta_1 = 15°$

$F_c = 3{,}700$ lb, $F_L = 1{,}730$ lb (sht. 1)

$\Sigma M_o = 0$ conservative -- assumes no floor moment reaction

$F_c\, b \sin\theta_1 + F_L a = F_D c$ ✓

$F_D = \frac{F_c b \sin\theta_1 + F_L a}{c} = 4{,}926$ lb ✓

Assume only axial load on diagonal brace

$F_a = \sqrt{F_D^2 + F_D^2} = 6{,}966$ lb ✓

$f_a = \frac{F_a}{A} = \frac{2879}{5{,}757}$ psi ✓

where $A = 2(1.21)\ in^2 = 2.42\ in^2$ ✓ There are 2 diagonal brace C channels per column.

$\ell = \sqrt{c^2 + c^2} = 28.3$ in ✓ (cons.)

$\frac{K\ell}{r} = \frac{1.0(28.3)}{0.404} = 70$ ✓ (pinned)

$C_c = 126.1$ ✓ ($F_y = 36$ ksi, A36) (ASD, 9th Ed, Table 4)

Agrees w/ Parts list & Detail sheet

SUBJECT	CBI OFFICE LIGO	REVISION		REFERENCE NO. 953571
	MADE BY DTR / CHKD BY MRS	MADE BY	CHKD BY	SHT 3 OF ___
	DATE 3/5/96 / DATE 3/12/96	DATE	DATE	

L960370-0-E

Mark's Hdbk, 8th ed., pg. 3-25, 3-26

	Dry	Oxide film
Hard steel on hard steel	0.78	0.27
Mild steel on mild steel	0.74	—

Effective F.S. for seismic load:

$$\frac{F_{friction}}{F_L} = \frac{4(2000)(0.27)}{1730} = 1.25$$

don't have catalog to check

If the bolt bond strength is only 20% higher than the pre-load (2210 vs 2000) and the pre-load is only 25% higher than reqd to prevent slippage/re-alignment under the seismic load, then is setting the pre-load with a spring washer accurate enough?

$\frac{Kl/r}{C_c} = 0.56 \rightarrow C_a = 0.455$ (ASD Table 3)

$\sigma_a = C_a F_y = 16{,}380$ psi $> f_a = \cancel{5{,}757}\ 2879$ psi $\therefore$ OK

Anchorage (Size anchor bolts)

Not conservative -- realistic

$F_{friction} = N(F_{pre})(0.25) \rightarrow F_{pre} = \frac{F_{friction}}{N(0.25)} = 2{,}000$ lb/bolt

F_{pre}: Anchor bolt preload reqd. to resist lateral seismic

0.25: Coef. of friction for steel on steel is 0.5 (cons., per Marks Std. Handbook for Mech. Engr., 9th Ed., Table 3.2.1, Mild Steel on Mild Steel, Dry = 0.74)

where $N = 4$ bolts

$F_{friction} = F_L = 2{,}000$ lb (cons.)

There are no other loads on anchor bolts (see sht 9+10), therefore

→ from Hilti Product Technical Guide 1/95, use 3/8" ø HAS Super Anchors w/ min. Emed. Depth = 3½"

→ HEA Bond Strength = 2210 lb

HAS Super Strength = 3,250 lb

allowable w/ Margin?

Both > 2,000 lb

$\therefore$ OK

→ Notes: 1) Spring washers will be used to determine load on anchors.

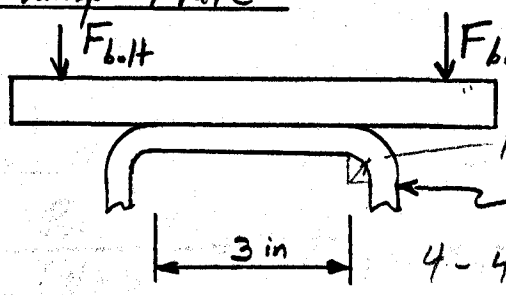
Not in Dwg 19 — don't understand how this helps anyway

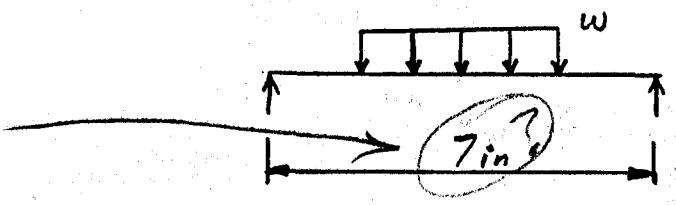
2) There will be no bending of anchor bolts because there will be a base plate under the horizontal beam where it is clamped.

3) Anchors are zinc-plated for corrosion protection.

SUBJECT	CBI OFFICE LIGO	REVISION		REFERENCE NO. 95357I
	MADE BY DTR / CHKD BY MRS	MADE BY	CHKD BY	SHT 4 OF ___
	DATE 3/5/96 / DATE 3/12/96	DATE	DATE	

Size Clamp Plate





$$w = \frac{2F_{bolt}}{3\text{ in}} = \frac{1,333}{3.25} \frac{\text{lb}}{\text{in}} \quad \frac{}{1230}$$

$$M = F_{bolt}\left(\frac{7-3}{2} + \frac{F_{bolt}}{2w}\right) = 5,500 \text{ in}\cdot\text{lb} \quad (5626)$$

(from ASD, 9th Ed., Beam Form. Case 4, p. 2-297)

$$S = \frac{M}{\sigma} = 0.20 \text{ in}^3 \quad (0.208)$$

ASD Eqn. F2-1

where $\sigma = 0.75 F_y = 0.75(36 \text{ ksi}) = 27,000$ psi

$$S = \frac{bd^2}{6} \rightarrow d = \sqrt{\frac{6S}{b}} = 0.52 \text{ in} \quad (0.527) \rightarrow \text{Use } d = 5/8\text{" thk.}$$

agrees w/ BOM part # A-6

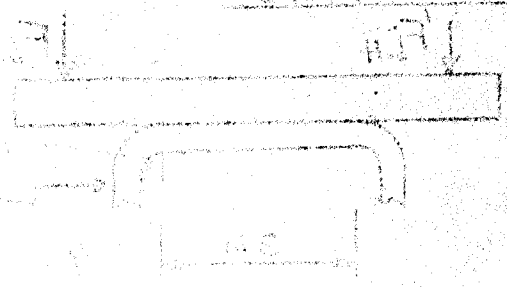
where $b = 4.5$ in (assumed) $b = 4.5$" per the BOM for part # 19-6

∴ Use a 4½ wide, 5/8" thk. clamp plate

Note: Because spring washers will be used, the actual bolt load can be used.

SUBJECT	OFFICE		REVISION		REFERENCE NO.
	CBI LIGO				953571
	MADE BY	CHKD BY	MADE BY	CHKD BY	SHT 5 OF ___
	DATE 3/5/96	DATE 3/12/96	DATE	DATE	

L960370-0-E



Even if $k = 0$, then

$$\frac{R}{t_w(N+5k)} = 2370 \text{ psi} \ll 0.66F_y$$

$\therefore$ not an issue

If $t_w = t = 0.1875$,

$$R_2 = \underbrace{67.5(.1875)^2}_{2.373}\underbrace{\left[1+3\left(\frac{4.5}{4}\right)\right]}_{4.375}\underbrace{\sqrt{46000}}_{214.5}$$

$2227 \text{ lb.} > F_{pre} = 2000$ just!

If $t_w \equiv 2t = 0.375$

$$R_2 = \underbrace{67.5(.375)^2}_{9.49}\underbrace{\left[1+3\left(\frac{4.5}{4}\right)(2)^{1.5}\right]}_{10.55}\underbrace{\sqrt{\frac{46000}{2}}}_{151.7}$$

$15192 \text{ lb.} > 2F_{pre} = 4000$

Check Bottom Tube for Anchor Loads (Using a Tube 4×4×3/16)
(Ref. AISC, Sect. K1.3, K1.4 and K1.6)

Local Web Yeilding (Load away from ends)

$$\frac{R_1}{t_w(N+5k)} = 1673 \text{ psi} \le 0.66F_y = 0.66(46 \text{ ksi}) = 30{,}360 \quad \therefore \text{OK} \checkmark$$

where $R_1 = 2F_{pre} = 2(2{,}000 \text{ lb}) = 4{,}000 \text{ lb}$ ✓ (Sht. 4)

$t_w = 2(3/16 \text{ in}) = 0.375 \text{ in}$ ✓

$N = 6 - 4\frac{1}{2} \text{ in}$ ✓ (Sht. 5)

$k = 2t_w = 0.375 \text{ in}$ ✓

→ Add Sect K1.3 pg. 5-81

k = "distance from outer face of flange to web toe of fillet"

Can't find a better description ⇒ see note on next page

Web Crippling (Load away from ends)

$$R_2 = 67.5\,t_w^2\left[1 + 3\left(\frac{N}{d}\right)\left(\frac{t_w}{t_f}\right)^{1.5}\right]\sqrt{F_{yw}\,t_f/t_w} = 2227 \text{ lbs} = 480 \text{ kips}$$

where $t_w = 0.375 \text{ in}$ ~~3/16~~ $= 0.1875 \text{ in}$

$N = 4.5 \text{ in}$ ✓

$d = 4 \text{ in}$ ✓

$t_f = 3/16 \text{ in}$ ✓

$F_{yw} = F_y = 46 \text{ ksi}$ ✓

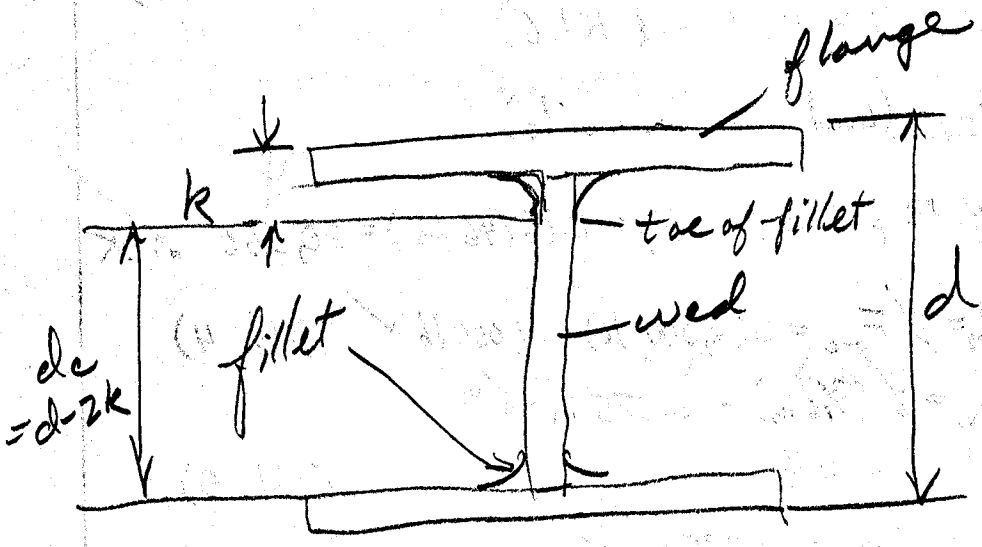
Incorrect calculation; given chosen parameters, $R_2 = 15.2$ kips

$R_2 > R_1 = 4 \text{ kips}$ ∴ OK ✓

see opposite page

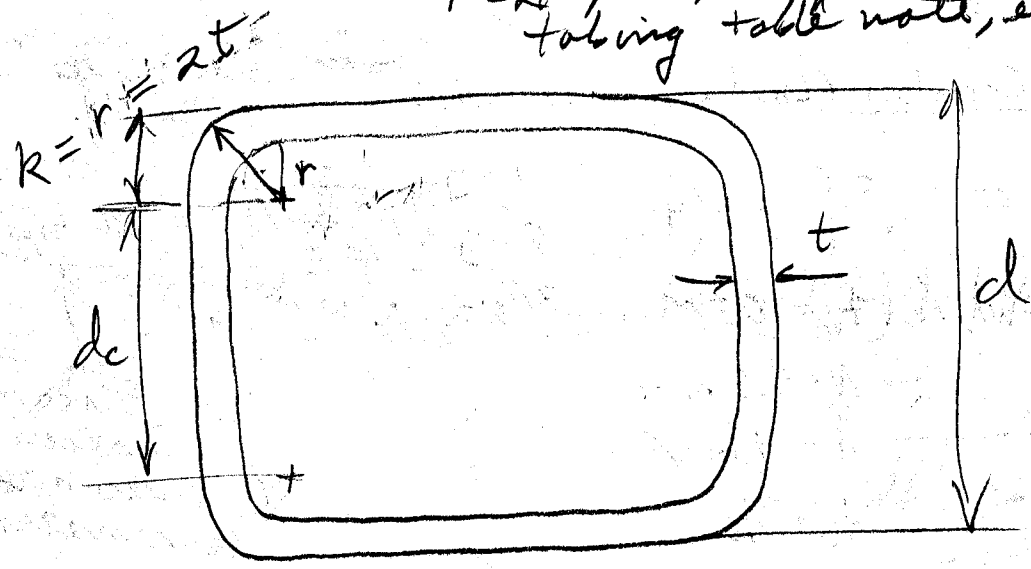
ECT	CBI OFFICE LIGO		REVISION		REFERENCE NO. 953571
	MADE BY DTR	CHKD BY MRS	MADE BY	CHKD BY	SHT 6 OF ___
	DATE 3/11/96	DATE 3/12/96	DATE	DATE	

USA GO 64 REV SEP 84



Interpretation per ASD, sect. K1.5, pg. 5-82

r = 2t per ASD rectangular structural tubing table note, eg. pg. 1-97



$d_c = d - 2k = 4 - 4\left(\frac{3}{16}\right) = 3.25$ in

$t_w = 0.1875$ in

$b_f = 4$ flange width

$l \approx 14$ in laterally unbraced length

$\frac{(d_c/t_w)}{(l/b_f)} = 4.95 > 2.3$ OK ✓

→ Sidesway Web Buckling ASD, Sect. K1.5

(This wasn't checked by CB&I)

L960370-0-E

Incorrect calculation:

① Used $F_{yc} = 46$ ksi instead of 46 ksi

② Used $P_{bf} = 5/3$ instead of $5/3 (F_{pre})$

ASD, Section K1.6

Compression Buckling of the Web

$$\frac{4100\, t_{wc}^3 \sqrt{F_{yc}}}{P_{bf}} = \frac{880 \text{ in}}{1.74} > d_c = \frac{4 \text{ in (cons.)}}{3.25} \quad \therefore \text{OK}$$

where $t_{wc} = t_w = 0.375$ in $\rightarrow 0.1875$

$F_{yc} = F_y = 46$ ksi

$P_{bf} = \frac{5}{3} F_{pre} = 3333$ lb.

Because all of the above checks

If $t_w \equiv 2t = 0.375$

and $P_{bf} = \frac{5}{3}(2 F_{pre}) = 6667$ lb.

Then $\frac{4100\, t_{wc}^3 \sqrt{F_{yc}}}{P_{bf}} = 6.96 \text{ in} > d_c = 3.25$"

Young, Roark's Formulas for Stress & Strain, 6th ed., Web buckling; local failure pg. 218-19. cites the following criteria for crippling of the web at the toe of the fillet:

$$\frac{R}{t(N+2k)} \leq 24000 \quad \text{(presumably for steel)}$$

$$\frac{2000}{0.1875[4.5+2(.375)]} = 2032 \leq 24000 \quad \text{OK} \checkmark$$

According to Lyse & Godfrey, "Investigation of Web Buckling in Steel Beams," Trans. Am Soc Civil Eng. V100, 1935, p 675, No need to design for buckling if $\frac{h}{t} < 70$ $\quad h = d - 2t = 4 - 2(\frac{3}{16}) = 3.625$

$\frac{h}{t} = 19 < 70$ OK ✓

Will yield before buckling

SUBJECT	OFFICE		REVISION		REFERENCE NO.
	CBI LIGO				953571
	MADE BY DTR	CHKD BY MRS	MADE BY	CHKD BY	SHT 6a OF ___
	DATE 3/11/96	DATE 3/12/96	DATE	DATE	

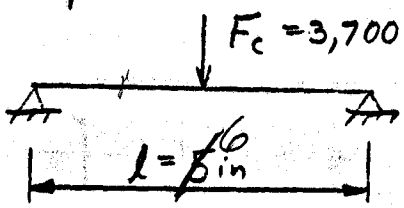
Printed in USA

GO 84 REV SEP 84

L960370-0-E

Part #19-5

Size Top Plate



Assume S.S. Ends and width = ~~3~~ 4 in = b

$M = \frac{F_c l}{4} = \frac{5550}{4} = \cancel{4,625}$ in·lb

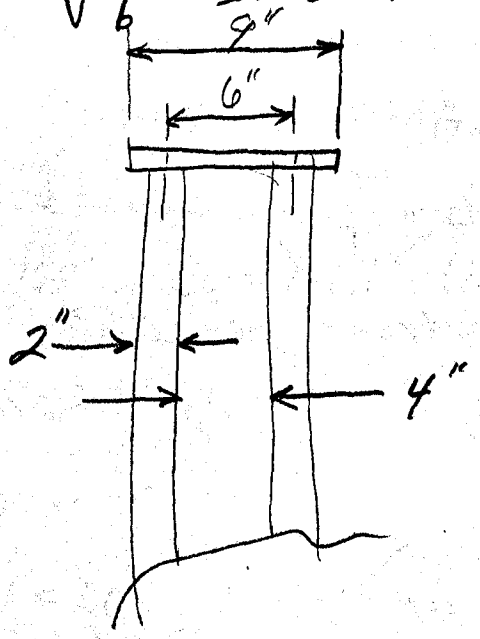
$S = \frac{M}{\sigma} = \frac{0.21}{} = \cancel{0.17}$ in³

where $\sigma = 0.75 F_y = 0.75 (36 ksi) = 27,000$ psi

A36

$S = \frac{bd^2}{6} \rightarrow d = \sqrt{\frac{6S}{b}} = \cancel{0.58}\ 0.56$ in → Use $d = \frac{5}{8}$ in

Agrees with BOM for part #19-5



SUBJECT	OFFICE LIGO	REVISION		REFERENCE NO. 953571
	MADE BY ATR / CHKD BY mrs	MADE BY	CHKD BY	SHT 1 OF
	DATE 3/5/96 / DATE 3/12/96	DATE	DATE	

Printed in USA

GO 84 REV SEP 84

L960370-0-E

ASD Section F1.1

$$L_c = \text{Min}\left\{ \frac{766 b_f}{\sqrt{F_y}} , \frac{20000}{(d/A_f) F_y} \right\}$$

C3x4.1 : $b_f = 1.410$ in

$F_y = 36000$ psi

$$L_c \leq \frac{766 b_f}{\sqrt{F_y}} = 0.56$$

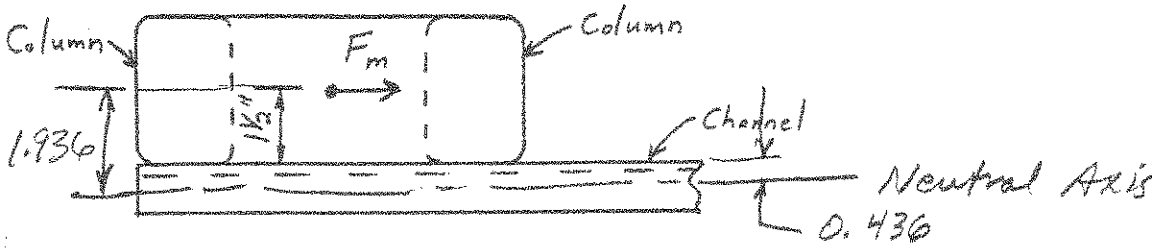
Allowable stress per ASD section F1.3

$$F_b = 0.60 F_y = 21600 \text{ psi}$$

per ASD, Section H1, $\frac{f_a}{F_a} = 0.03 \leq 0.15$

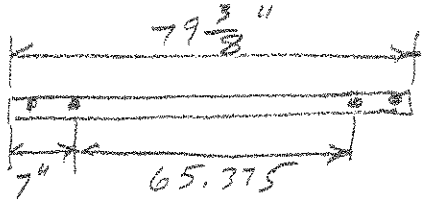
therefore $\frac{f_a}{F_a} + \frac{f_b}{F_b} \leq 1.0$ is the criteria for combined axial & bending loads

ads on Horizontal Channels Part #19-3



F_m = Load from cable due to contraction of bellows

$F_m = F_c \sin\theta_2 = 3{,}700 \sin 3.2 = 207$ lb ✓



$f_a = \frac{F_m}{A} = 171$ psi ✓

where $A = 1.21$ in^2 (for C3×4.1) ✓

$f_b = \frac{M}{S} = \frac{1985}{2{,}050}$ psi

where $M = F_m \frac{(1.936\ \text{in})}{401} = 414$ in·lb (cons.)

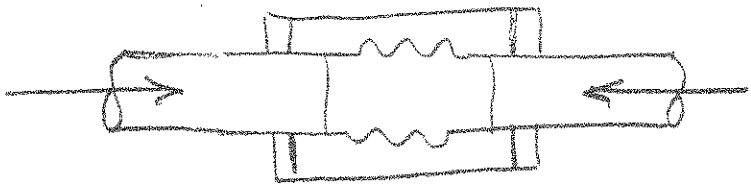
$S = 0.202$ in^3 (for C3×4.1, weak axis) ✓

$\frac{Kl}{r} = \frac{1.0(80\ \text{in})}{0.404} = \frac{65.375}{162} = 198 > C_c = 126.1$ (A36, $F_y = 36$ ksi) Table 4, ASD

$\therefore F_a = \frac{12\pi^2 E}{23(Kl/r)^2} = \frac{5690}{3{,}209}$ psi

$F_b = 0.6 F_y = 21{,}600$ psi ✓

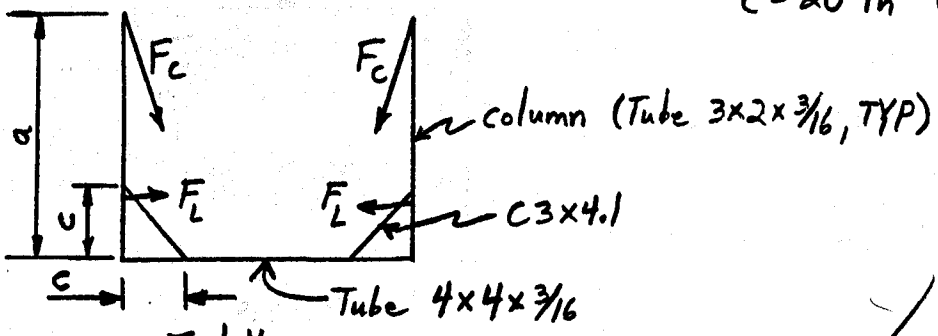
$\frac{f_a}{F_a} + \frac{f_b}{F_b} = \frac{0.12}{0.14} < 1.0$ ∴ OK ✓



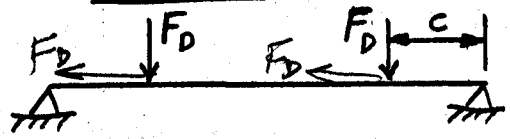
CT	OFFICE	REVISION		REFERENCE NO.
	LIGO			95357I
MADE BY / CHKD BY	STR / MKS	MADE BY	CHKD BY	SHT 8 OF ___
DATE	3/5/96 / 3/12/96	DATE	DATE	

Check for Bending in Horizontal Beam (and compression)

$c = 20$ in (Sht. 2)



End View



$F_D = 4{,}926$ lb (Sht. 3)
↑ Caused by F_c and F_L

$f_b = \frac{M}{S} = 23{,}884$ psi

where $M = F_D(c - 4\text{in}) = 78{,}816$ in·lb ← min. distance of anchor bolt to column ℄

$S = 3.3$ in^3 (Tube 4x4x3/16)

$F_b = 0.66 F_y = 0.66(46\text{ ksi}) = 30{,}360$ psi

$\frac{Kl}{r} = \frac{(1.0)(66.25\text{ in})}{1.54\text{ in}} = 43$ (l = length of horiz. beam)

$C_c = 111.6$ (ASD, 9th Ed., Table 4)

$\frac{Kl/r}{C_c} = 0.39 \longrightarrow C_a = 0.512$ (ASD, 9th Ed., Table 3)

$F_a = C_a F_y = 23{,}552$ psi

$f_a = \frac{F_D}{A} = \frac{4{,}926\text{ lb}}{2.77\text{ in}^2} = 1{,}778$ psi

$\frac{f_a}{F_a} + \frac{f_b}{F_b} = 0.86 \leq 1.0$ ∴ Use a Tube 4x4x3/16

SUBJECT	OFFICE LIGO		REVISION		REFERENCE NO. 95357
	MADE BY DTR	CHKD BY MRS	MADE BY	CHKD BY	SHT 9 OF ___
	DATE 3/11/96	DATE 3/12/96	DATE	DATE	

L960370-0-E

GUIDED SUPPORT ADJUSTMENT PROVISIONS

VERTICAL ALIGNMENT AT THE GUIDED SUPPORT IS ACCOMPLISHED THROUGH JACKING OF THE BEAM TUBE UNDER THE TUBE AND TIGHTENING THE VERTICAL CABLES, ACCORDINGLY. NO ATTACHMENTS ARE REQUIRED FOR VERTICAL ADJUSTMENT.

HORIZONTAL ADJUSTMENT AT THE GUIDED SUPPORT REQUIRES THAT A FORCE BE DEVELOPED BETWEEN THE SLAB AND THE SUPPORT OR TUBE. DIFFERENTIAL SPRING RATES WILL IMPOSE AXIAL FORCES ON THE TUBE WHICH COULD CAUSE THE TUBE TO MOVE TRANSVERSE TO THE TUBE AXIS. AS SUCH, THE TUBE SHOULD BE RESTRAINED LATERALLY AT ALL TIMES DURING GUIDED SUPPORT ADJUSTMENT.

THE ONLY FIXED COMPONENT AT THE GUIDED SUPPORT ARE THE EPOXIED ANCHORS USED TO HOLD THE SUPPORT IN PLACE. A BASE PLATE WILL BE PLACED OVER THE ANCHORS FOR PLACEMENT OF A TURNBUCKLE BETWEEN THE BASE PLATE AND GUIDED SUPPORT FRAME.

LATERAL RESTRAINT CAPACITY

THE LATERAL LOAD REQUIRED TO MOVE THE TUBE AND SUPPORT WILL BE COMPOSED OF THE FOLLOWING COMPONENTS:

1) SLIDING FORCE FOR BEAM TUBE ON SLIDE BEARINGS
2) SLIDING FORCE FOR GUIDED SUPPORT WEIGHT ON CONCRETE
3) NET HORIZONTAL CABLE FORCE DUE TO INITIAL TUBE MIS-ALIGNMENT, DL, VACUUM & THERMAL
4) SLIDING FORCE FOR (2) FIXED SUPPORTS ON SLIDE BEARINGS.

Dead Load

SUBJECT	OFFICE		REVISION		REFERENCE NO.
	CBI LIGO				953571
	MADE BY MLT	CHKD BY DTR	MADE BY	CHKD BY	SHT 11 OF ___
	DATE 3/8/96	DATE 3/12/96	DATE	DATE	

L960370-0-E

1) SLIDING FORCE FOR B.T. WEIGHT @ GUIDED
RV MAX PER CALTECH DWG 950029, SHT 2 = 7,824 # ✓
SLIDE BEARING COEFFICIENT OF FRICTION .05 SAY 10%
HORIZONTAL FORCE .1 (7,824#) = 782# ✓

2) SLIDING FORCE FOR GUIDED SUPPORT WT ON CONCRETE
~~FRAME~~ GUIDED SUPPORT WT = ~~500~~ 665 # (See Weight Tally on BOM)
COEFFICIENT OF FRICTION ON CONCRETE .75 seems OK
HORIZONTAL FORCE = .75 (~~500~~ 665) = ~~375~~ 499 # w/o reference

3) NET HORIZONTAL CABLE FORCES: ½ ALIGNMENT = ~~821~~ 576 #
CALTECH DWG 950029, Sht 2 Thermal = 657 # ✓ DL+VAC = 86 # ✓ Σ = ~~1,315~~ 1564 #

4) SLIDING FORCE FOR BOT FIXED SUPPORT
WEIGHT @ EACH FIXED SUPPORT = 8,948 # ✓
SLIDE BEARING COEFFICIENT OF FRICTION .05 SAY 10%
2 SUPPORTS x (8,948) x .10 = 1,790 #

CONSERVATIVELY THE ~~TOTAL~~ LATERAL FORCE REQUIRED:
F_L = 782 + 375 + ~~1315~~ 1564 + 1,790 #
= ~~4,260~~ 4511 # OR ~~2,130~~ 2256 @ EACH SIDE OF SUPPORT OK
USE F_L = 3,084 IN CALCS. (CONSERVATIVE)

SUPPORT CONFIGURATION

ATTACH A CLEVIS ENDED TURN BUCKLE TO A LUG ON A BASE PL AND TO THE SUPPORT FRAME COLUMN MEMBERS.

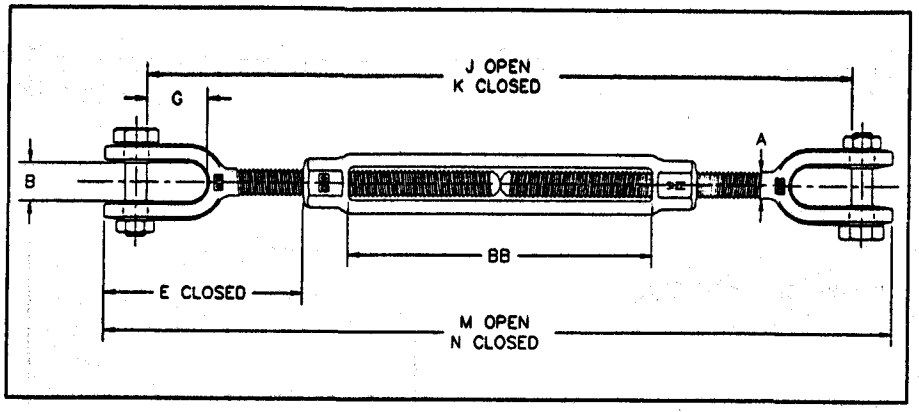
CROSBY JAW & JAW TURNBUCKLE
TAKE UP REQUIRED = 6"
CAPACITY REQUIRED = 3084 #

THE FOLLOWING INFORMATION IS FROM THE 1992 CROSBY CATALOG

1. deviation see attached

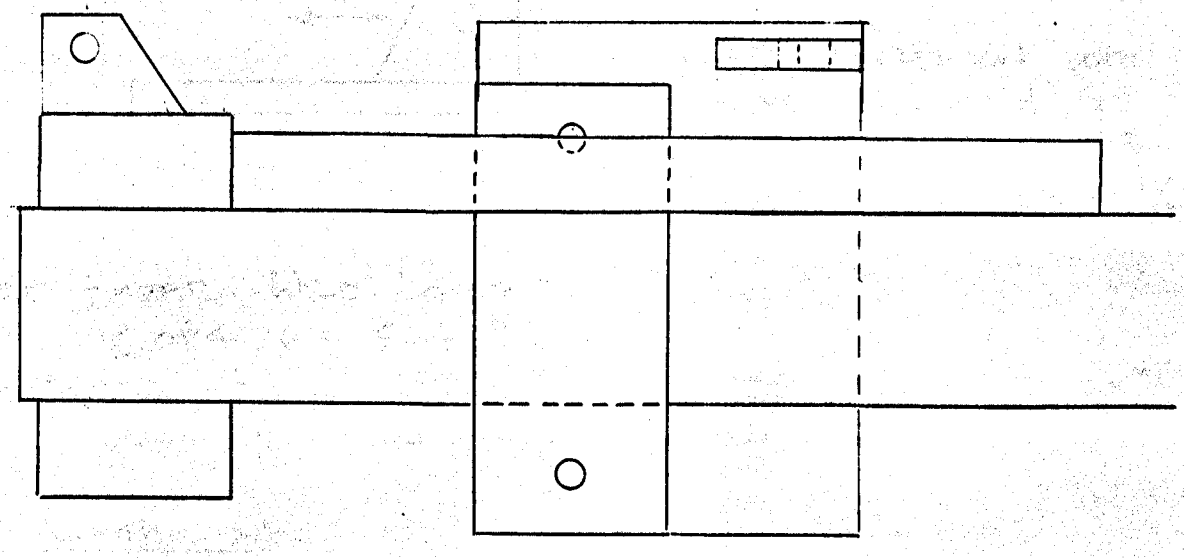
SUBJECT	OFFICE	REVISION		REFERENCE NO.
	CBI LIGO			953571
MADE BY MLT	CHKD BY BTR	MADE BY	CHKD BY	SHT 12 OF ___
DATE 3/12/96	DATE 3/12/96	DATE	DATE	

L960370-0-E



Thread Diameter & Take Up (in.)	Stock No. Galv.	Working Load Limit (lbs.)	Weight Each (lbs.)	Dimensions (in.) A	B	E Closed	G	J Open	K Closed	M Open	N Closed	BB
¼ x 4	1032493	500	.36	.25	.45	1.58	.62	10.90	6.90	11.90	7.90	4.00
5/16 x 4½	1032518	800	.52	.31	.50	1.98	.87	12.36	8.36	13.90	9.40	4.50
⅜ x 6	1032536	1200	.81	.38	.54	2.12	.87	16.14	10.14	17.38	11.38	6.00
½ x 6	1032554	2200	1.50	.50	.68	2.75	1.06	17.50	11.50	19.00	13.00	6.00
½ x 9	1032572	2200	1.74	.50	.68	2.75	1.06	23.50	14.50	25.00	16.00	9.00
½ x 12	1032590	2200	2.40	.50	.68	2.75	1.06	29.50	17.50	31.00	19.00	12.00
⅝ x 6	1032616	3500	2.72	.63	.82	3.50	1.31	18.80	12.80	20.88	14.88	6.00
⅝ x 9	1032634	3500	3.24	.63	.82	3.50	1.31	24.80	15.80	26.88	17.88	9.00

USE STOCK # 1032616 5/8" ϕ x 6" TAKE UP



SUBJECT	OFFICE	REVISION		REFERENCE NO.
	CBI LIGO			953571
MADE BY / CHKD BY	MLT / DTR	MADE BY	CHKD BY	SHT 13 OF ___
DATE / DATE	3/9/96 / 3/12/96	DATE	DATE	

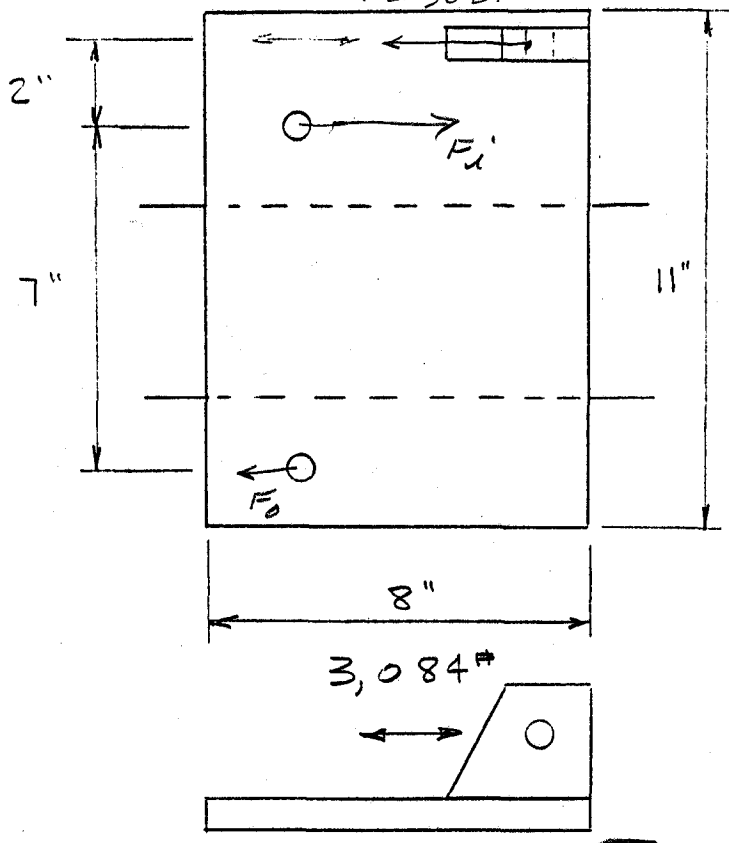
L960370-0-E

SHEAR LOAD ON ANCHOR BOLTS

$7F_i = 9F$

$F_i = \frac{9}{7}F \quad F_o = \frac{2}{7}F$

$F = 3084\#$



$2F_i = 9F_o$

$F_i - F_o = F$

$2F_i = 9(F_i - F)$

INSIDE BOLT SHEAR:

$3,084\left(\frac{2}{7}\right) = 881\#$ ✓

OUTSIDE BOLT SHEAR:

$3,084 + 881 = 3,965\#$ ✓

GUSSET WELD:

3" LONG TAB, $t = 5/8"$

℄ HOLE $1\frac{3}{8}"$ FROM BASE PL

No Dwg of part to check Dimensions

$M = 3,084(1.375)$

$= 4,241$ in-# ✓

FILLET WELD ON BOTH SIDES, $S_{WELD} = d^2/3 = 3 \text{ in}^3$?

$f_{WELD} = \frac{4,241}{3} = 1,414$ #/in ?

ASD Table J2.5:

$\tau_{allow} = 0.3 F_{ty} = 0.3(36000)$

$= 10800$ psi cans.

$.25(9600) = 2400$ #/in ✓

Meets min. fillet weld size per ASD J2.6

See alternate Calculation attached ⟹

DIRECT SHEAR, WELD LENGTH = 6"

$3,084/6 = 514$ #/in ✓

COMBINED SHEAR = 1928 #/in

USE 1/4" FILLET WELD AROUND

BASE PL THICKNESS

ANCHOR BOLTS ARE SNUG, ∴ PL IS SUBJECTED TO SHEAR, MOMENT, & TORSION ✓

SHEAR & MOMENT ARE INSIGNIFICANT, TORSION

$= 3,084 \times 1.375 = 4,241$ in-#

SUBJECT	OFFICE: CBI LIGO	REVISION		REFERENCE NO. 953571
	MADE BY: MLT	CHKD BY: DTR	MADE BY	CHKD BY
	DATE: 3/9/96	DATE: 3/12/96	DATE	DATE

SHT 14 OF ___

Printed In USA

GO 64 REV SEP 84