LIGO BEAM TUBE MODULES
TABLE OF CONTENTS FOR DETAILED DESIGN CALCULATIONS

SUBJECT	CBI	OFFICE LIGO	REVISION	2	REFERENCE NO. 953571
LIGO Beam Tube Modules **Detailed Design Calculations** **Table Of Contents**	MADE BY ARL	CHKD BY MLT	MADE BY DTR	CHKD BY MLT	SHT OF
	DATE 3/12/96	DATE 3/12/96	DATE 3/10/97	DATE 5-22-97	

FOUNDATION LOAD SUMMARY FOR ICD-BTSLAB

BEAM TUBE FIXED AND GUIDED SUPPORT LOADS WERE ORIGINALLY PRESENTED IN SECTION 9 OF DESIGN CALCULATIONS FOR CONTRACT 930212, DESIGN & QUALIFICATION TEST. IN RESPONSE TO CHANGES IN SCOPE AND CHANGES IN THE CONFIGURATION, CBI PROVIDED UPDATED FOUNDATION LOADS ON DECEMBER 12, 1995 IN LETTER CBI-CT-2.2/0019.

FIXED SUPPORT - AXIAL BAKE OUT LOAD

ORIGINAL DESIGN

THIS DESIGN DID NOT CONSIDER THE FIXED SUPPORT NEXT TO THE TERMINATION. THE AXIAL LOAD WAS BASED ON A MAXIMUM SPRING RATE RANGE OF 8,000 TO 9600, OR 1600 #/in. THE AXIAL COMPRESSION DUE TO BAKE OUT AND INSTALLATION VARIATION WAS 3.72" RESULTING IN AN AXIAL LOAD OF 5959 #. SEE SHEET 9.1. OPERATING AXIAL LOAD (771 #) AND AXIAL SEISMIC (2169 #) WERE ADDED TO THIS LOAD RESULTING IN A MAXIMUM AXIAL LOAD FOR INTERMEDIATE FIXED SUPPORTS OF 8399 # REPORTED IN THE ORIGINAL DESIGN. THE EXPANSION JOINT INSTALLATION VARIATION WAS REDUCED RESULTING IN AN EXPANSION JOINT COMPRESSION OF 3.48". THE REDUCED COMPRESSION WITH THE MAXIMUM RANGE OF 1600 #/in RESULTED IN AN AXIAL BAKE LOAD OF 5566 # FOR A TOTAL AXIAL LOAD OF 8506 # AS REPORTED ON DEC. 12, 1995.

DECEMBER 12th UPDATE

THE DECEMBER 12, 1995 REPORT ALSO CONTAINED LOADS FOR THE FIXED SUPPORT NEXT TO THE TERMINATION. THIS LOAD WAS BASED ON EQUAL EXPANSION JOINT SPRING RATES OF 8,000 # ON EACH SIDE OF THE SUPPORT. THE EXACT POSITION OF THE TERMINATION WAS NOT KNOWN AT THE TIME. THE LENGTH TO THE FIRST SUPPORT FROM THE TERMINATION WAS ASSUMED TO BE 97'-8 RESULTING

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	CBI LIGO				953571
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	DATE 1-30-97	DATE 3-10-97	DATE	DATE	4.0a

IN A DIFFERENTIAL COMPRESSION OF

$$3.48\left(\frac{130 - 97.67}{130}\right) = .865"$$

AND AN AXIAL LOAD OF .865(8000) = 6922 #

THE TOTAL AXIAL REPORTED AXIAL LOAD WAS 9862 # =
6922# + 771#(OPERATING) + 2169#(SEISMIC).

ICD- BTSLAB

REVISION 0 WAS BASED ON A MAXIMUM SPRING RATE OF 8,000# AND A MAXIMUM SPRING RATE RANGE OF 1000 #/INCH. THE REVISED ICD FOUNDATION LOADS WILL BE BASED ON THE ACTUAL SPRING RATE RANGE AND MAXIMUM SPRING RATE MEASURED ON THE FIRST 111 EXPANSION JOINTS. THE HIGHEST AND LOWEST EXPANSION JOINT SPRING RATE IS 5301 #/in AND 4328 # FOR A RANGE OF 973 #/inch. TO DETERMINE THE LOADS, THE FOLLOWING CONDITIONS WILL BE USED:

MAXIMUM SPRING RATE AT ENDS	5425 #/in
MAXIMUM INTERMEDIATE SPRING RATE	5240 #/inch
MAXIMUM SPRING RATE RANGE	1000 #/inch

COMPRESSION DUE TO BAKE OUT:

INTERMEDIATE. $\Delta l = (130')(12)(232°F)(9.9 \times 10^{-6}\ in/in°F) = 3.583"$

NEXT TO TERMINATION $\Delta l = (93.25')(12)(232)(9.9 \times 10^{-6}) = 2.570"$

COMPRESSION VARIATION DUE TO INSTALLATION .25"

INTERMEDIATE SUPPORTS

AXIAL LOAD DUE TO BAKE = 1000(3.833) = 3833 #

TOTAL AXIAL LOAD = 3833 + 771 + 2169 = 6773 #

FIXED SUPPORT NEAR TERMINATION

AXIAL LOAD DUE TO BAKE = 5425 [(3.583 - 2.570)] = 5495

TOTAL AXIAL LOAD = $5495 + 771 + 2169\left(\frac{111.625}{130}\right) = 8125$ #

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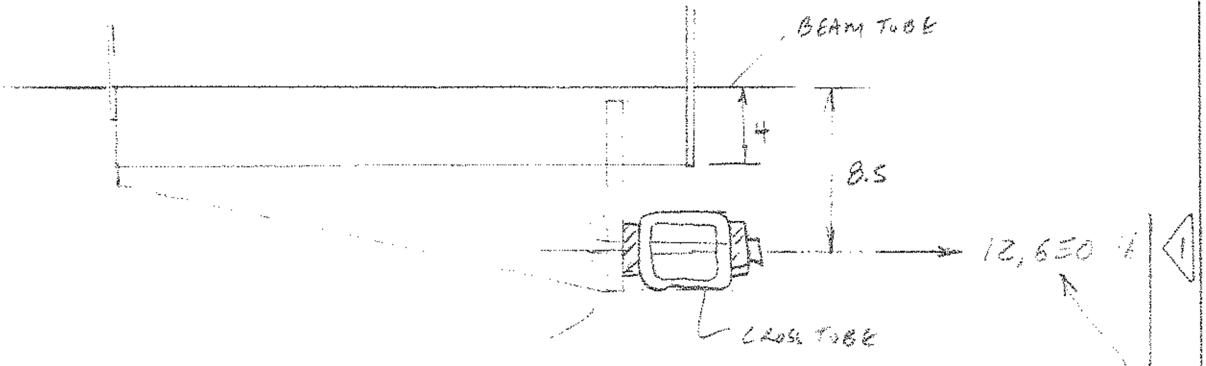
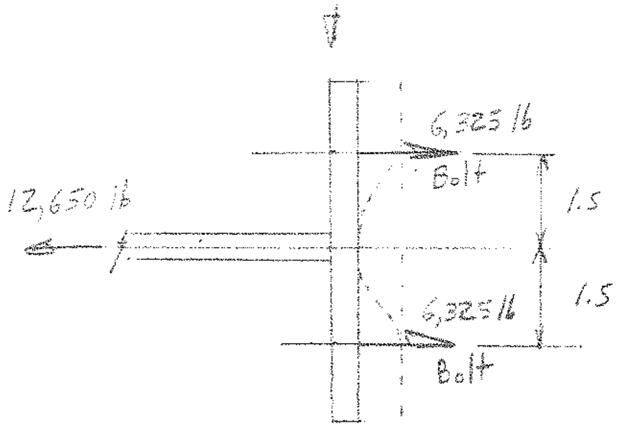
	DATE 1-30-97	DATE 3-10-97	DATE	DATE	4.06

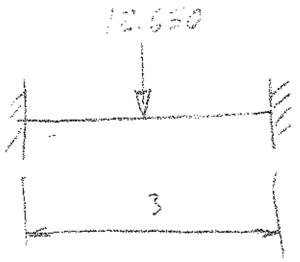
AXIAL FORCE TRANSFER LUG FOR FIXED SUPPORTS AWAY FROM TERMINATIONS –

These fixed supports are subjected to a maximum axial load of 6,773 lb. during operation (See sht. 4.0b)



Max. axial load during [illegible] [illegible] (See sht. 8.3)





ASSUME 75% FIXITY AT BOLTS – MICARTA PROVIDES SOME FLEXIBILITY

$$M_{FIXED} = \frac{Pl}{8} = \frac{(12,650)(3)}{8} = 4,744 \text{ in-lb}$$

$$M_{PINNED} = \frac{Pl}{4} = \frac{(12650)(3)}{4} = 9,488 \text{ in-lb}$$

$$M = 4,744 + (0.25)(9,488 - 4,744) = 5,930 \text{ in-lb}$$

SUBJECT	OFFICE 440		REVISION 1		REFERENCE NO. 953571
	MADE BY ARL	CHKD BY ETR	MADE BY ETR	CHKD BY MLT	SHT___ OF___
	DATE 3-6-96	DATE 3/6/96	DATE 9/21/96	DATE 3-14-97	4.1

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Total height = 9.5 in

ASSUME LOAD IS CARRIED BY 8^4 HEIGHT OF FLANGE

= 16(0.5) ← actual thickness

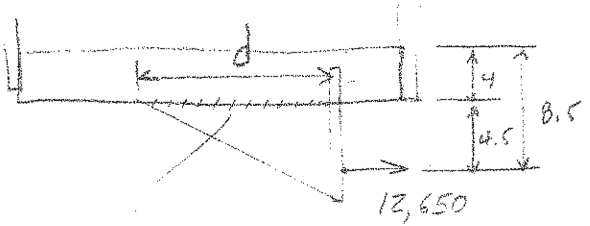
$$S = \frac{bd^2}{6} = \frac{(8)(d^2)}{6} = 1.33\ d^2$$

INCREASE ALLOWABLE FOR SEISMIC LOAD

$F_b = 0.75 \times 19100 \times 1.333 = 19095$ PSI

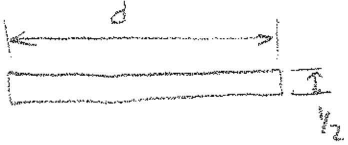
$$S = \frac{M}{F_b} = \frac{5,930}{19095} = 1.33\ d^2 \qquad d = 0.483$$

$\boxed{\text{USE } \frac{1}{2}''}$



FIND REQUIRED LENGTH HERE

$M = 12650\text{lb} \times 4.5\text{ in} = 56,925$ in-lb



$$S = \frac{M}{F_b} = \frac{56,925}{0.6 \times 19100 \times 1.333} = 3.73\ \text{in}^3$$

$$S = \frac{bd^2}{6} = \frac{(0.5)d^2}{6} = 3.73 \qquad d = 6.7\text{ IN}$$ (ASSUMES 100% PENETRATION WELD)

SUBJECT	OFFICE: CBI LIGO		REVISION 1		REFERENCE NO. 953571
	MADE BY ARL	CHKD BY DTR	MADE BY DTR	CHKD BY MLT	SHT___ OF___
	DATE 3-6-96	DATE 3/6/96	DATE 9/24/96	DATE 3-14-97	4.2

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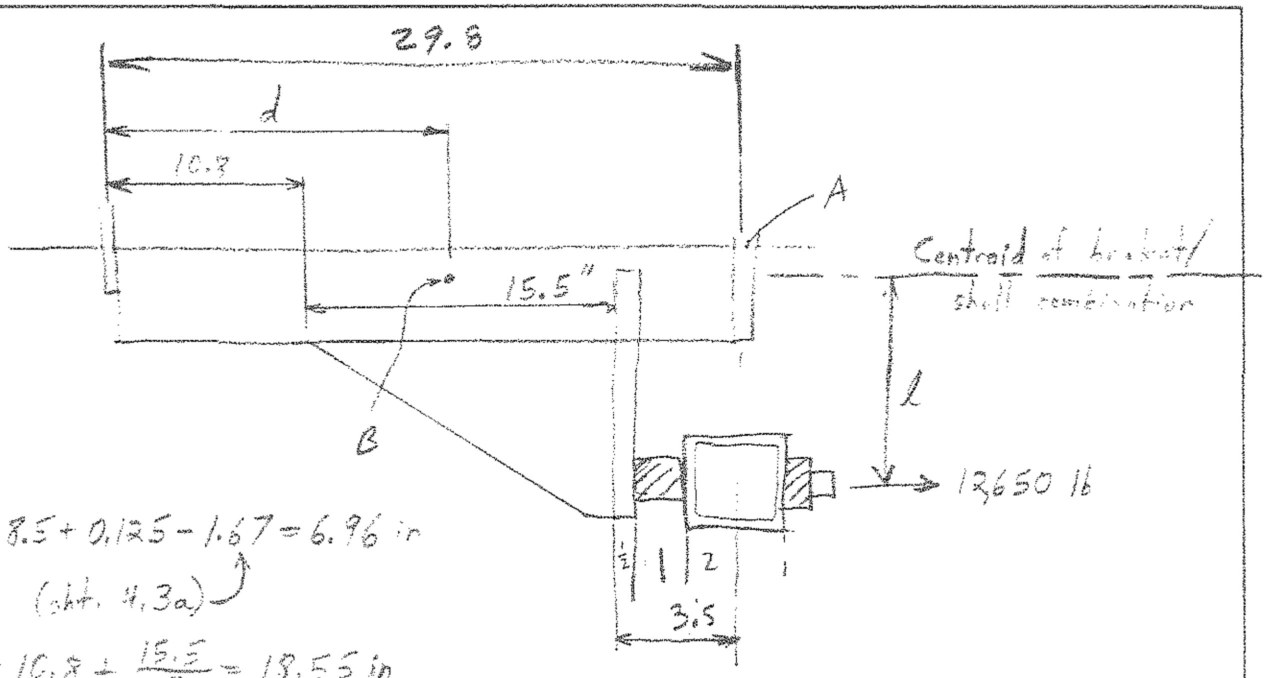

$\ell = 8.5 + 0.125 - 1.67 = 6.96$ in

(sht. 4.3a)

$d = 10.8 + \frac{15.5}{2} = 18.55$ in

$M_B = 12{,}650 \times \ell = 88{,}044$ in-lb

$\sigma = 11{,}931$ psi (sht. 4.4)

$F_b = 0.6 \times 19{,}100 \times 1.33 = 15{,}242$ psi

$\sigma < F_b$ ∴ a 15½" long bracket is adequate

$\triangleright$ 1 Entire page rev.

SUBJECT	CBI OFFICE L160		REVISION 1		REFERENCE NO. 953571
	MADE BY ARL	CHKD BY DTR	MADE BY DTR	CHKD BY MLT	SHT___ OF___
	DATE 3-6-96	DATE 3/6/96	DATE 9/24/96	DATE 3-14-97	4.3

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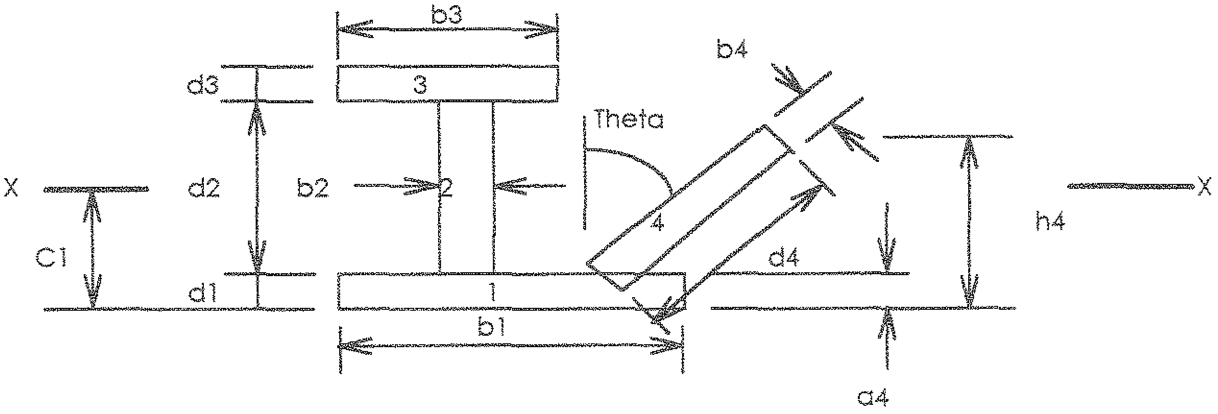
MOMENT OF INERTIA CALCULATION

INERTIA4.XLS, Rev 4
Pg 1 of 1



	Previous Area	b	d	Theta	a	h	AREA	Y	AY	AY^2	Io
1	-	0	0	0	0.000	0.000	0.000	0.000	0.00	0.0	0.00
2	1	4.5	0.125	0	0.000	0.125	0.563	0.063	0.04	0.0	0.00
3	2	0.5	4	0	0.125	4.125	2.000	2.125	4.25	9.0	2.67
4	3	0	0	0	4.125	4.125	0.000	4.125	0.00	0.0	0.00
5	4	0	0	0	4.125	4.125	0.000	4.125	0.00	0.0	0.00
6	5	0	0	0	4.125	4.125	0.000	4.125	0.00	0.0	0.00
7	6	0	0	0	4.125	4.125	0.000	4.125	0.00	0.0	0.00
8	7	0	0	0	4.125	4.125	0.000	4.125	0.00	0.0	0.00
9	8	0	0	0	4.125	4.125	0.000	4.125	0.00	0.0	0.00
10	9	0	0	0	4.125	4.125	0.000	4.125	0.00	0.0	0.00
						TOTAL AREA=	2.563 in^2		4.29		11.7

TOTAL DEPTH = 4.125 in
CENTROID (Y) = SUM(AY)/SUM(AREA) = 1.672 in
C1 = Y = 1.672 in
C2 = DEPTH - Ybar = 2.453 in.

I(total)= [SUM(AY^2)+SUM(Io)]-(AREA)(Y)^2 = 4.5 in^4
Sx1 = I/C1 = 2.71 in.^3
Sx2 = I/C2 = 1.85 in.^3
Radius of gyration (r) = (I/A)^1/2= 1.330 in.

SUBJECT Fixed Support Axial Bracket w/ Shell LIGO	OFFICE: PVE		REVISION:		REFERENCE NO. 953571
	MADE BY DTR	CHKD BY MLT	MADE BY	CHKD BY	SHT OF
	DATE 9/20/96	DATE 3-14-97	DATE	DATE	4.3a

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=========================== VARIABLE SHEET ==================================================
St Input---- Name---- Output---- Unit------ Comment-----------------------------------------
                                            Both simple support
                                            Table 10 Case 3-Roark & Young Handbook
                                            Axial Compressive Load and
                                            Concentrated Intermediate Moment p.167
             case     'CASE_3e              End Restraints Reference Number
             matnum                         Material Number (See Material Table)
             matl
             plot     'y                    Generate plots ? 'n=no (Default=yes)
   29.8      L                   in         Length of beam
   18.55     a                   in         Moment distance from left end
   88044     MO                  lbf-in     Moment
   12650     P                   lbf        Axial Compressive Load
             Pcr      1450366.4  lbf        CRITICAL Compressive Load
             err      '_                    Caution Message
             k        .00984555
   2.9E7     E                   psi        Young's Modulus
   4.5       I                   in^4       Area moment of inertia
   1.672     z                   in         Neutral axis to stress point
                                            AT SECTION:
   10.8      x                   in          Distance from left end
             V        -2962.122  lbf         Transverse shear
             M        -32112.04  lbf-in      Bending moment
             theta    .0006028   rad         Slope
             y        .0160849   in          Deflection
                                             Stress:(Axial Load Comp NOT Included)
             st       -11931.41  psi          Fiber stress at stress point z
             sty      '_         psi          Max Fiber stress at extremity y
                                            AT LEFT END:
             RA       -2954.497  lbf         Vertical reaction
             MA       0          lbf-in      Bending moment
             thetaA   .0019329   rad         Slope
             yA       0          in          Deflection
                                            AT RIGHT END:
             RB       2954.497   lbf         Vertical reaction
             MB       0          lbf-in      Bending moment
             thetaB   -.0005559  rad         Slope
             yB       0          in          Deflection
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1 Entire page rev.

SUBJECT

CBI OFFICE Ligo		REVISION 1		REFERENCE NO. 953571
MADE BY ARL	CHKD BY DTR	MADE BY DTR	CHKD BY MLT	SHT___ OF___
DATE 3-6-96	DATE 3/6/96	DATE [illegible]	DATE 3-14-97	4.4

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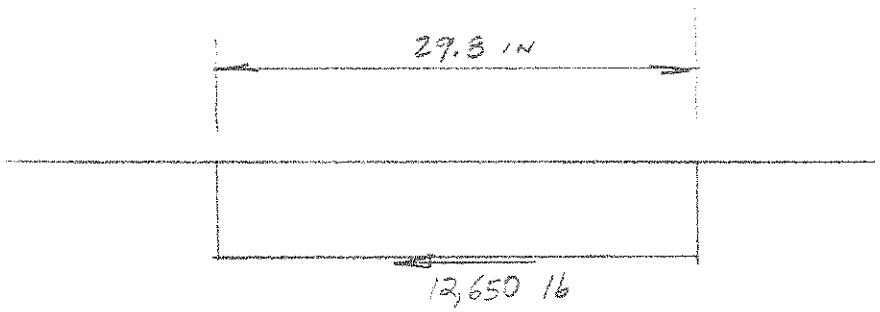
DESIGN SHEAR CONNECTION WELD TO TUBE —



$$f = \frac{12650 \text{ lb}}{29.8 \text{ in}} = 424 \frac{\text{lb}}{\text{in}}$$

19110 @ 300°F

LIMIT STRESS IN WELD TO $0.3 \times F_y = 5730$ PSI

Seismic allowable increase for short duration load

$f = 0.707 \omega \tau = 0.707 \times \omega \times 5730 \times 1.33 = 424$

$\omega = 0.079$ USE $\frac{1}{8}$" ON ONE OR
STITCH WELD BOTH SIDES ($\frac{0.079}{0.125} = 63\%$ or greater,
A 34 @ 150mm weld length is
is adequate.

1 Entire page rev

SUBJECT	CBI OFFICE LIGO		REVISION 1		REFERENCE NO. 953571
	MADE BY ARL	CHKD BY RTR	MADE BY RTR	CHKD BY MLT	SHT___ OF___
	DATE 3-7-96	DATE 3/8/96	DATE 9/24/96	DATE 3-14-97	4.5

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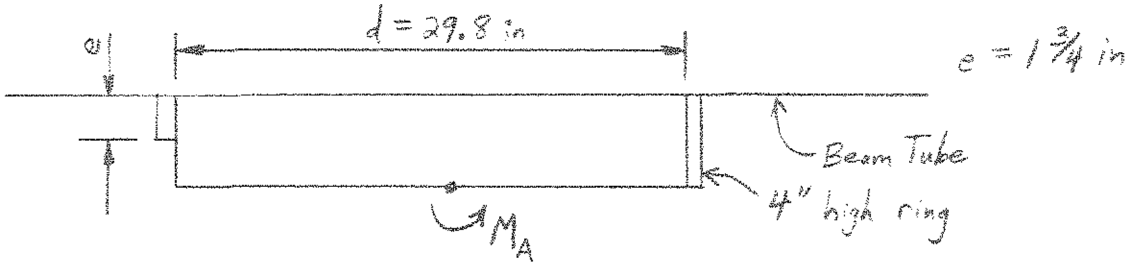
Design Moment Connection Weld to Rings



M_A = 12,650 lb (8.5 in) = 107,525 in·lb

R = reaction at end of bracket = $\frac{M_A}{d}$ = 3,608 lb

$W = \frac{R}{A} = 2{,}062$ lb/in
where A = e = 1.75 in

$w = \frac{W}{5{,}358} = 0.38$ in → **Use a 5 mm weld on both sides of bracket to small ring and a 5 mm weld on one side of bracket to large ring (min.)**

From previous page = 0.707 × 5730 × 1.33

SUBJECT	CBI OFFICE LIGO	REVISION 1		REFERENCE NO. 953571
	MADE BY DTR	CHKD BY ARL	MADE BY DTR	CHKD BY MLT	SHT ___ OF ___
	DATE 3/8/96	DATE 3-8-96	DATE 9/24/96	DATE 3-14-97	4.6

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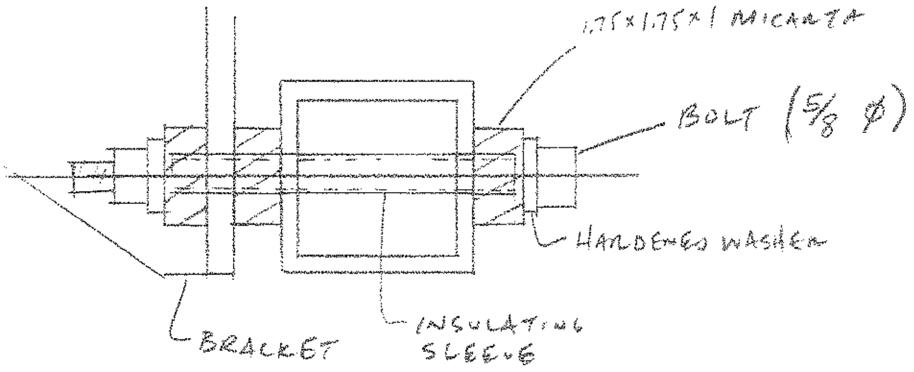
A325 BOLTING. - Type 3 (Weathering Steel)

BOLT TENSION = $\frac{12650 \text{ lb}}{2 \text{ BOLTS}}$ = 6,325 lb = 6.3 kips

Per ASD, 9th Ed., Part 4, p. 4-3 Allowable tension = 13.5 kips
(A325, 5/8" ⌀)

Allowable = 13.5 kips > 6.3 kips = Actual

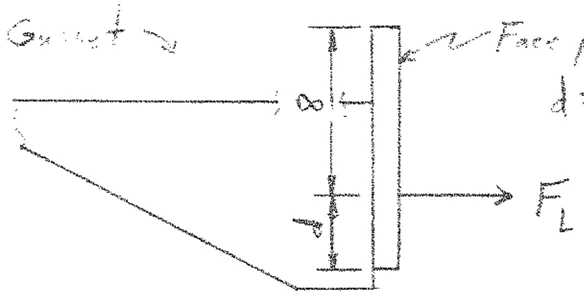
5/8 ⌀ BOLT HAS TENSILE STRESS AREA = 0.226 in²



②▷ Entire page rev.

SUBJECT	CBI OFFICE LIGO		REVISION 2		REFERENCE NO. 953571
	MADE BY ARL	CHKD BY DJR	MADE BY DJR	CHKD BY MLT	SHT___OF___
	DATE 3-6-96	DATE 3/6/96	DATE 9/24/96	DATE 3-14-97	4.7

Size Weld Between Face Plate and Gusset



Due to misfabrication at Hanford.
d = 2 in for Lousiana site.

d = 1½ in (CBI dwg. 7, sht. 1, Sect. B-B)

Greatest moment on weld occurs when d = 1½ in.

Effective weld height = 7.5 + d = 9.5 in $F_L = 12,650$ lb (Sht. 4.1)

$A_w = 2(9.5\text{ in}) = 19\text{ in}$
← Weld both sides of gusset

$W_t = \frac{F_L}{A_w} = 666$ lb/in

$W_b = \frac{M}{S_w} = 1,366$ lb/in

where $M = F_L(\frac{7.5}{2} - d) = 41,113$ in·lb

$S_w = \frac{(9.5)^2}{3} = 30.1\text{ in}^2$

$W = W_t + W_b = 2,032$ lb/in

$w = \frac{W}{7,070(1.33)}$

← $(0.707)(0.4)F_y = 0.4\,(25,000\text{ psi})(.707) = 7,070$ lb/in

$w = 0.216$ in = 5.5 mm

This 5.5 mm fillet size slightly exceeds the existing 5 mm weld size, therefore increase the minimum installation T to 0°F. Use a 5 mm weld both sides (min. installation T = 0°F)

▷1 Rev. entire sheet

SUBJECT

CBI OFFICE LIGO		REVISION 1		REFERENCE NO. 953571
MADE BY RTR	CHKD BY ARL	MADE BY RTR	CHKD BY MLT	SHT___ OF___
DATE 4/17/96	DATE 5-9-96	DATE [illegible]	DATE 3-14-97	4.7a

ASME SECTION VIII DIV 1 ALLOWABLE STRESSES

FROM TABLE 1A FOR 304L @ 300°F —

MAX TENSILE STRESS (MEMBRANE STRESS)
S = 12.8 KSI

UG23 (d) ALLOWS 20% INCREASE IN STRESSES
FOR EARTHQUAKE LOADS

1.2 x 12.8 KSI = 15.4 KSI

FROM ANSYS OUTPUT — MAX MEMBRANE STRESS IN REINFORCED VACUUM RING = 11582 PSI (COMPRESSION) IN OUTER FIBERS OF RING WITH FULL AXIAL LOAD OF 6419 lb PLUS EXTERNAL PRESSURE OF 14.7 PSI APPLIED SIMULTANEOUSLY. THIS LOAD CASE WILL GENERATE MAX. RADIAL LOAD IN VACUUM STIFFENER RING. MAX. TENSILE STRESS = 4635 PSI IN 4" x 3/8" RING.

11582 PSI < 15400 PSI OK

▷1 By inspection, this arrangement is adequate for a 12,650 # axial load (no ext. pressure)

ASME TENSILE ALLOWABLE DOES NOT STRICTLY APPLY TO IN-PLANE BENDING OF STIFFENER RING. ALSO CHECK STRESS AGAINST AISC BENDING ALLOWABLE.

SEISMIC STRESS INCREASE PER AISC

$F_b = 0.6 \times F_y \times 1.333 = (0.6)(19100)(1.333) = 15276$ PSI

F_y OF 304L @ 300°F

11582 < 15276 OK

SUBJECT	OFFICE	REVISION		REFERENCE NO.
	CBI LIGO			953571
	MADE BY ARL	CHKD BY RTC	MADE BY STR	CHKD BY MLT	SHT ___ OF ___
	DATE 3-11-96	DATE 3-12-96	DATE 3/13/96	DATE 3-14-97	4.9

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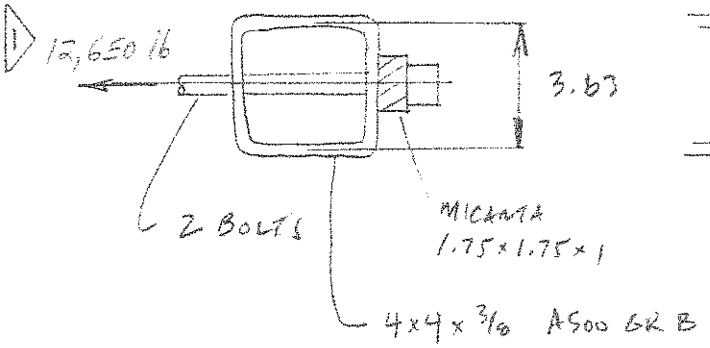
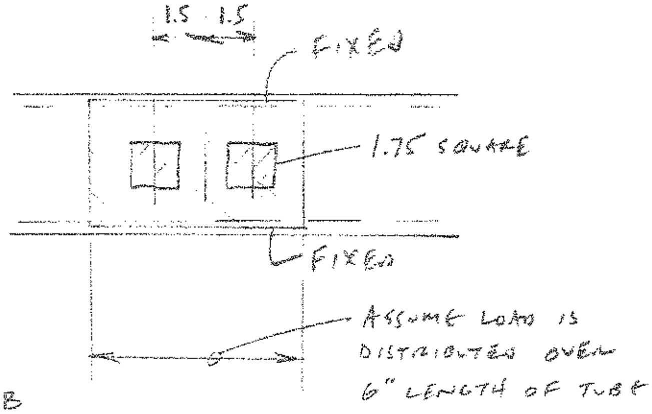
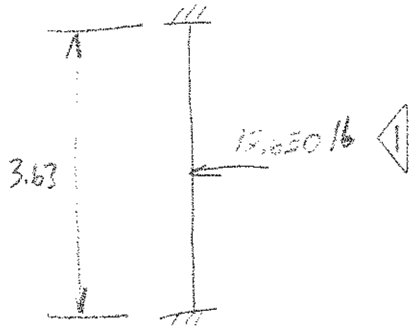
CHECK STRENGTH OF TUBE WALL —







$$M = \frac{Pl}{8} = \frac{(12{,}650)(3.63)}{8} = 5740 \text{ in-lb}$$ ◁1

$$F_b = \underbrace{0.75}_{\text{PLATE BENT ABOUT WEAK AXIS}} \times \underbrace{46000}_{F_y \text{ A500 GR B}} \times \underbrace{1.333}_{\text{SEISMIC LOAD}} = 45989 \text{ PSI}$$

$$S = \frac{bd^2}{6} = \frac{(6)(0.375)^2}{6} = 0.141$$

$$\sigma = \frac{M}{S} = \frac{5{,}740}{0.141} = 40{,}709 \text{ PSI}$$

$40{,}709 < 45989$ OK

◁1

SUBJECT	CBI OFFICE LICO	REVISION 1		REFERENCE NO. 953571
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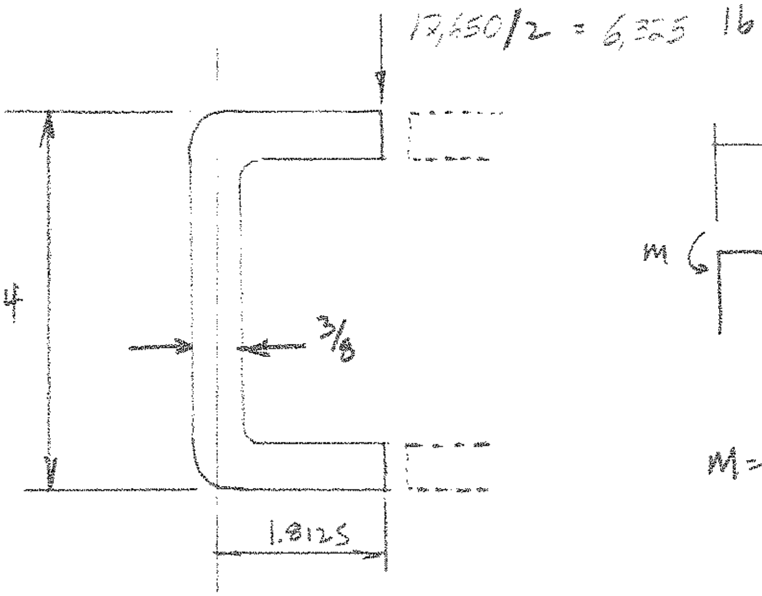
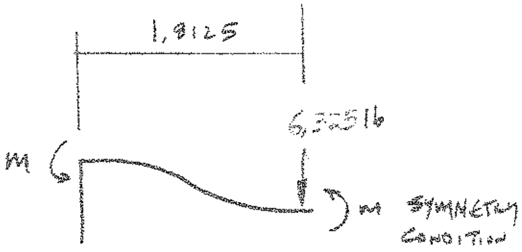
DATE 3-6-96	DATE 3/6/96	DATE 9/11/96	DATE 3-14-97	4.13

CHECK BUCKLING OF TUBE WALLS —





$$M = \frac{PL}{2} = \frac{(6325)(1.8125)}{2}$$

$$= 5{,}732 \text{ in-lb}$$

$$f_a = \frac{6{,}325 \text{ lb}}{(6 \text{ in})(0.375 \text{ in})} = 2{,}811 \text{ PSI}$$

$$\frac{kl}{r} = \frac{(1.0)(4)}{(0.375/\sqrt{12})} = 37$$

$$C_c = 111.6 \quad (F_y = 46 \text{ KSI})$$

FROM TABLE 3
ASD, 9TH ED

$$\frac{Kl/r}{C_c} = 0.33 \rightarrow C_a = 0.529$$

$$F_a = C_a F_y \underbrace{(1.333)}_{\text{SEISMIC INCREASE}} = 32437 \text{ PSI}$$

$$f_b = \frac{M}{S} = \frac{5{,}732 \text{ in-lb}}{\left(\frac{(6)(0.375)^2}{6}\right)} = 40{,}761 \text{ PSI}$$

$$F_b = (0.75)(46000)(1.333) = 45989 \text{ PSI}$$

1▷ Entire page rev.

$$\frac{2811}{32437} + \frac{40{,}761}{45989} = 0.97 < 1 \quad \text{OK}$$

SUBJECT	CBI OFFICE L160		REVISION 1		REFERENCE NO. 953571
	MADE BY AWL	CHKD BY DTR	MADE BY DTR	CHKD BY MLT	SHT___ OF___
	DATE 3-6-96	DATE 3/8/96	DATE 9/24/96	DATE 3-14-97	4.14

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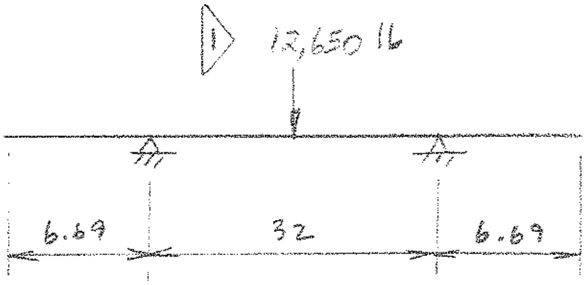
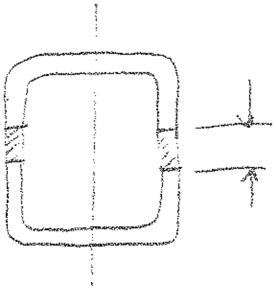
GO 64 REV SEP 84

CHECK BENDING STRENGTH OF CROSS-BEAM AT HOLES –



LONGITUDINAL LOAD

1 $M = \frac{Pl}{4} = \frac{(12,650)(32)}{4} = 101,200$ IN-lb



ASSUME 13/16 DIA HOLE 1

INERTIA OF 4 x 4 x 3/8 TUBE = 10.7 IN^4

1

INERTIA OF REMOVED MATERIAL $= (2)\left(\frac{(13/16)(0.375)^3}{12} + (13/16)(0.375)(2-0.1875)^2\right)$

$= 2.01$ IN^4

$I = 10.7 - 2.01 = 8.69$ IN^4 $\quad S = \frac{I}{c} = \frac{8.69}{2} = 4.35$ IN^3

$f = \frac{M}{S} = \frac{101,200}{4.35} = 23,264$ PSI

SUBJECT	CBI OFFICE LIGO		REVISION 1		REFERENCE NO. 953 571
	MADE BY ARL	CHKD BY DTR	MADE BY DTR	CHKD BY MLT	SHT___ OF___
	DATE 3-6-96	DATE 3/6/96	DATE 9/28/96	DATE 3-14-97	4.15

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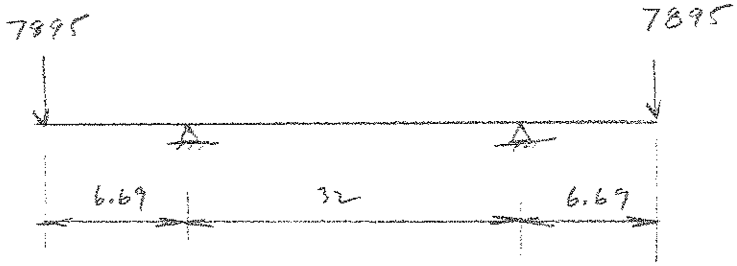
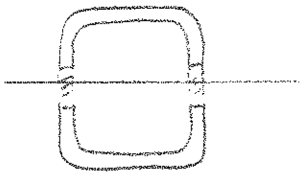
GO 64 REV SEP 84



VERTICAL LOAD

$M = Pa = (7895)(6.69) = 52818$ in-lb

← Max. load per side of fixed support (ref. Caltech dwg. D950029, Rev. C) | 1



TUBE INERTIA = 10.7 in^4

1 | INERTIA OF REMOVED MATERIAL $= (2)\left(\frac{(0.375)(13/16)^3}{12}\right) = 0.034$ in^4

$I = 10.7 - 0.034 = 10.67$ in^4 $\quad S = \frac{10.67}{2} = 5.34$ in^3

$\sigma = \frac{52818}{5.34} = 9891$ PSI

SEISMIC FACTOR

$F_b = 0.6 \times 46000 \times 1.333 = 36791$ PSI

1 $\underbrace{\frac{23,264}{36791}}_{\text{LONGITUDINAL}} + \underbrace{\frac{9891}{36791}}_{\text{VERTICAL}} = 0.90 < 1$ OK

SUBJECT	OFFICE		REVISION		REFERENCE NO.
	CBI LIGO				953571
	MADE BY ARL	CHKD BY STR	MADE BY STR	CHKD BY MLT	SHT ___ OF ___
	DATE 3-6-96	DATE 3/8/96	DATE 7/24/96	DATE 3-14-97	4.16

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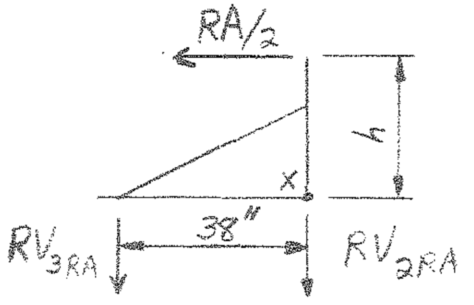
GO 64 REV SEP 84

Force on Bolts Due to Axial Load



$RA = 12,650$ lb △2

$h = 42.13 + 3.5 - 24.5 - 8.5 = 12.63$ in

Lug height

Adjustability

Tube radius

Nominal height of Tube ℄ off floor

$\Sigma M_x = 0 \qquad 12.63\left(\frac{RA}{2}\right) + 38(RV_{3RA}) = 0$

$$RV_{3RA} = \frac{-12.63(RA)}{38(2)} = -2,102 \text{ lb}$$

$\Sigma F_v = 0 \qquad RV_{2RA} = -RV_{3RA} = 2,102$ lb

△2

Max. Tension of Anchor Bolts

from drawing D950029

$$T_{total} = \frac{-RV2_{min} + RV_{2RA}}{2} = \frac{377 + 2,102}{2} = 1,240 \text{ lb/bolt}$$ △2

Compression on Base Plate

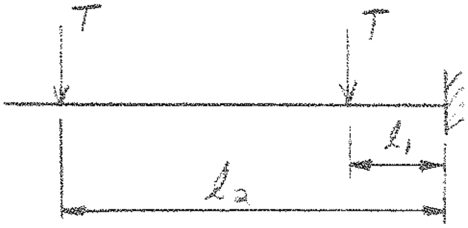
from drawing D950029

$C_{total} = RV_{2RA} + RV1_{max} = 9,997$ lb △2

where $RV1_{max} = 7,895$ lb

SUBJECT Fixed Support	CBI OFFICE LIGO		REVISION 2	REFERENCE NO. 153571
	MADE BY DTK	CHKD BY AKL	MADE BY ETR	CHKD BY MLT	SHT___ OF___
	DATE 12-19-95	DATE 12-20-95	DATE 9/24/96	DATE 3-14-97	4.21

Size Gusset for Anchor Bolts



$M = T(l_1 + l_2) = 22,320$ in·lb

where $T = 1,240$ lb

$l_1 = 5$ in

$l_2 = 13$ in

△2

$S = \frac{M}{\sigma} = 1.03\,in^3$ △2

where $\sigma = 0.6F_y = 0.6\,(36\,ksi) = 21.6\,ksi$

$S = \frac{bd^2}{6} \rightarrow d = \sqrt{\frac{6S}{b}} = 3.5$ in $\rightarrow$ Use $d = 4$ in △2

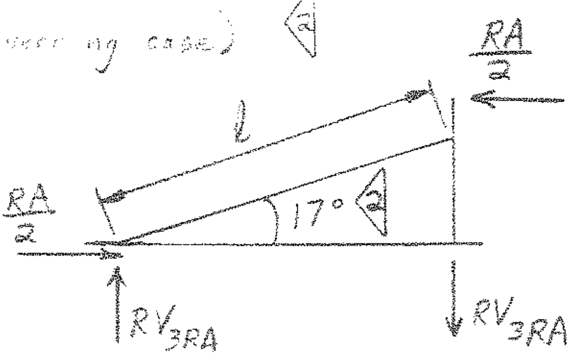
where $b = 0.5$ in

Use a $4 \times \frac{1}{2}$ Gusset

SUBJECT	OFFICE CBI PVE-A		REVISION 2		REFERENCE NO. 953571
	MADE BY KTR	CHKD BY ARL	MADE BY KTR	CHKD BY MLT	SHT___ OF___
	DATE 12/20/95	DATE 12-20-95	DATE 9/24/96	DATE 3-14-97	4.22

Check Angle Brace (Compression is governing case) ◁2

$l = 4$ ft (slightly conservative)



▷2 | $RA = 6,419$ lb
$RV_{3RA} = 1,067$ lb } Compression case

Axial load on angle $= P = \sqrt{\left(\frac{RA}{2}\right)^2 + \left(RV_{3RA}\right)^2} = 3.4$ kips (conservative)

From AISC Engr. Journal for L 3×3×3/16 and
$KL = 1(4) = 4$ ft $\longrightarrow P_{all} = 5.1$ kips ∴ OK

▷2 By inspection angle is adequate for RA = [illegible] lb (tension)

Check Anchor Bolts

▷2 | Tension = $T_{total} = 1,240$ lb (sht. 4.21)
Shear $= v = 1,899$ lb (greatest of sht. 4.24 and 4.24a)

Using Hilti KB-II Carbon Steel Anchor Bolts w/ ICBO allowables (5/8" ø w/ 4" Embed.)

▷2 | $\frac{T_{total}}{T_{all}} + \frac{V}{V_{all}} = 1.34 \approx 1.33$ ∴ Anchors are adequate
↳ increase for upset condition

where AS = 6 in, $T_{all} = 2,670$ lb $(0.80) = 2,136$ lb
$V_{all} = 3,125$ lb $(0.80) = 2,500$ lb

Spacing = 6 in → ∴ Use the above reduced allow. $\left(\frac{9.6\ \text{dia.}}{12\ \text{dia.}}\right) 100\% = 80$

Min. base material thk. $= 1.3(4\text{ in}) = 5.2$ in < 6" slab thk.
∴ OK

SUBJECT	OFFICE		REVISION 2		REFERENCE NO.
Fixed Support	CBI PYE-A				
	MADE BY DTR	CHKD BY ARL	MADE BY DTR	CHKD BY MLT	SHT ___ OF ___
	DATE 12/19/95	DATE 12-20-95	DATE 9/24/96	DATE 3-14-97	4.23

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This spreadsheet calculates the load carried by the individual bolts in a group. The bolt locations are described using x and y coordinates relative to the point of load application, i.e. loads Px and Py are applied at coordinate (0,0).

Px	0	Nbolts	4
Py	-6325	xbar	-7.125
M	-45066	ybar	-20.5

Px, Py = x & y load components
M=resultant moment at bolt pattern centroid
xbar, ybar = centroid coordinates
x, y = bolt location coordinates
r=radius to bolt from centroid
Rm=shear at bolt due to moment M
rxm,rym = x & y components of Rm
rx,ry = x & y components of Rm + Px + Py
v=shear resultant at bolt due to rx & ry

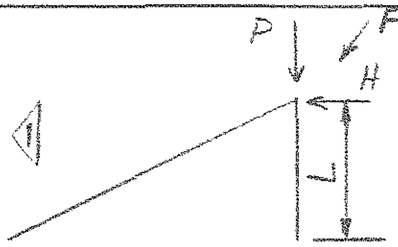
Bolt Diameter	0.625
No. of Shear Planes	1
Max Bolt Shear Stress	6188

x	y	r	r^2	Rm	rxm	rym	rx	ry	v
1.281	-39.5	20.776	431.661	-590	-540	-239	-540	-1820	1899
-6.719	-39.5	19.004	361.165	-540	-540	-12	-540	-1593	1682
-7.531	-1.5	19.004	361.165	-540	540	12	540	-1570	1660
-15.531	-1.5	20.776	431.661	-590	540	239	540	-1342	1447

SUBJECT Anchor Bolt Shears at Fixed Support (Installation Load) LIGO Hanford, WA and Livingston, LA	OFFICE: PVE		REVISION:		REFERENCE NO. 953571
	MADE BY DTR	CHKD MLT	MADE BY	CHKD BY	SHT OF
	DATE 9/24/96	DATE 3-14-97	DATE	DATE	4.24a

Design Vertical Members

(conservatively assume all loads simultaneously) ◁1



$P = 7{,}895$ lb $\qquad F = 1{,}304$ lb

▷1 $H = \frac{12{,}650}{2} = 6{,}325$ lb

$L = 42.13 + 3.5 - 24.5 - 8.5 = 12.63$ in

$f_a = \frac{P}{2A} = 2{,}407$ psi

where $A = 1.64\ in^2$ (for Tube $3 \times 2 \times 3/16$)

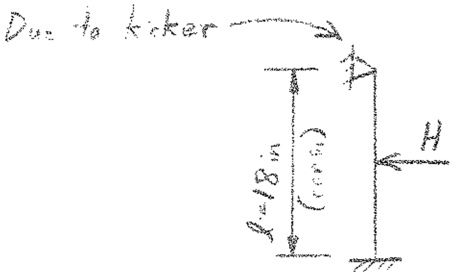
$\frac{KL}{r} = \frac{1.0\,(12.63)}{0.771} = 16.4$

$C_c = 111.6$ $(F_y = 46\,ksi)$

$\Big\rangle \rightarrow \frac{KL/r}{C_c} = 0.15 \rightarrow C_a = 0.574$

(AISC, Table 3)

$F_a = C_a F_y = 26{,}404$ psi



▷1 $f_{bx1} = \frac{M_{x1}}{S_x} = 17{,}215$ psi

where $M_{x1} = \frac{3H\ell}{16} = 21{,}347$ in·lb

$S_x = 1.24\ in^3$ (only (1) Tube $3 \times 2 \times 3/16$ is braced)

$F_b = 0.66\,F_y = 30{,}360$ psi

$f_{by} = \frac{M_y}{2S_y} = 8{,}429$ psi (both tubes resist bending)

where $M_y = FL = 16{,}470$ in·lb

$S_y = 0.977\ in^3$ (for Tube $3 \times 2 \times 3/16$)

$f_{bx2} = \frac{M_{x2}}{2S_x} = 11{,}142$ psi (both tubes resist bending due to eccentricity of vertical load)

where $M_{x2} = P\left(\frac{3}{2} + \frac{4}{2}\right) = 27{,}633$ in·lb

SUBJECT	OFFICE		REVISION		REFERENCE NO.
	CBI LIGO		REVISION 1		953571
	MADE BY RTP	CHKD BY ARL	MADE BY RTP	CHKD BY MLT	SHT____ OF____
	DATE 3/4/96	DATE 3-8-96	DATE 9/24/96	DATE 3-14-97	4.30

$$\frac{f_a}{F_a} + \frac{f_{bx1} + f_{bx2} + f_{by}}{F_b} = 1.30 < \underset{\text{Incr. due to seismic}}{1.33} \quad \therefore OK$$ ◁1

SUBJECT	CBI OFFICE LIGO		REVISION 1		REFERENCE NO. 953571
	MADE BY DTR	CHKD BY ARL	MADE BY DTR	CHKD BY MLT	SHT___ OF___
	DATE 3/4/96	DATE 3-8-96	DATE 9/24/96	DATE 3-14-97	4.31

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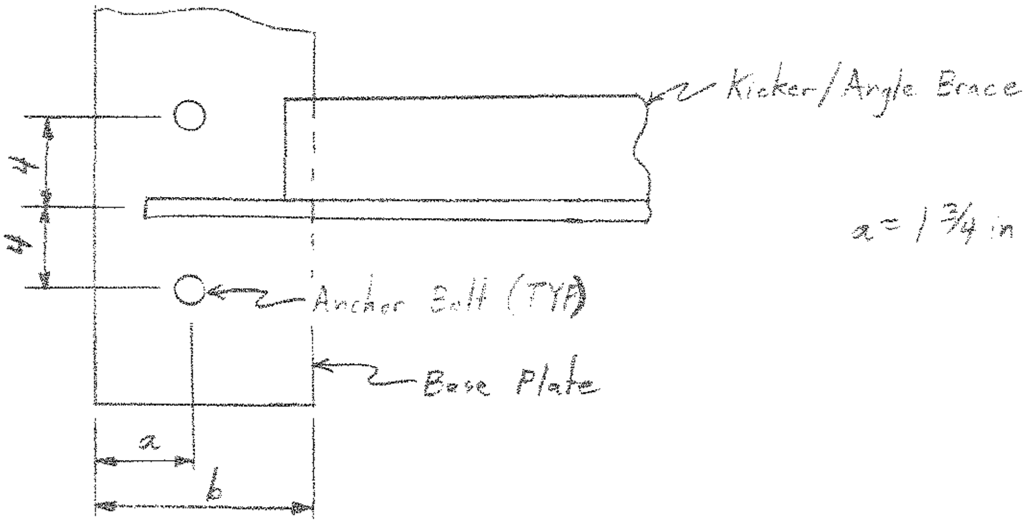
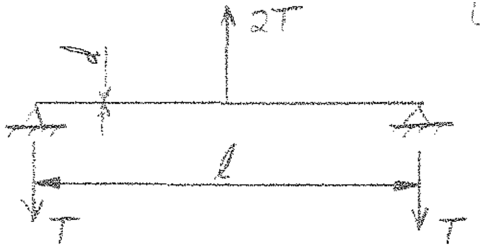
Determine Base Plate Thickness (Ref. Dwg. #8, Section M-M)



$a = 1\,3/4$ in

Uplift on anchors causes bending in base plate



Using highest load from support

$T = T_{total} = 1{,}240$ lb (sht. 4.21)

Contributory width = $b = 5$ in (assumed, min.)

$l = 4 + 4 = 8$ in

$$M = \frac{(2T)l}{4} = 4{,}960 \text{ in·lb}$$

$$S = \frac{M}{\sigma} = 0.18 \text{ in}^3$$

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

↖ A36

$$S = \frac{bd^2}{6} \rightarrow d = \sqrt{\frac{6S}{b}} = 0.46 \text{ in}$$ → Use a 1/2" thk. base plate

where $b = 5.0$ in

By inspection, the base plate [illegible] anchors

SUBJECT	OFFICE		REVISION		REFERENCE NO.
	CBI LIGO		REVISION 1		953571
	MADE BY RTR	CHKD BY ARL	MADE BY RTR	CHKD BY MLT	SHT ___ OF ___
	DATE 4/25/96	DATE 5-10-96	DATE 9/24/96	DATE 3-14-97	4.32

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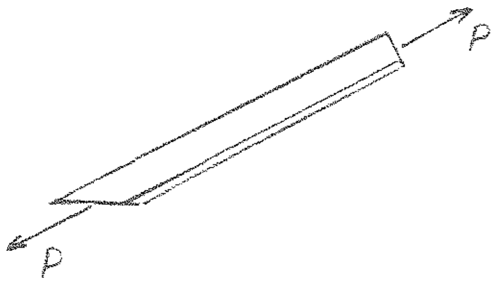
GO 64 REV SEP 84

Size Weld at Ends of Angle Brace



$$P = \sqrt{\left(\frac{RA}{2}\right)^2 + \left(RV_{3RA}\right)^2}$$

$$= \sqrt{\left(\frac{12{,}650}{2}\right)^2 + (2{,}102)^2}$$

$$P = 6{,}665 \text{ lb}$$

◁1

Try using a 3/16" fillet weld to find weld length required.

▷1 $W = \frac{P}{A} \longrightarrow A = \frac{P}{W} = 3.7 \text{ in}$

where $w = \frac{W}{9{,}600} \longrightarrow W = 9{,}600\,w = 9600\left(\frac{3}{16}\right) = 1{,}800 \text{ lb/in}$

By inspection, weld length is adequate.

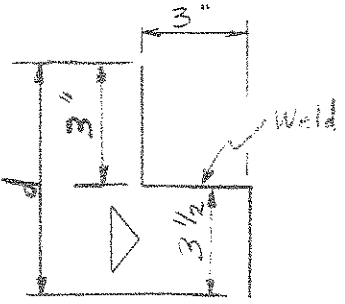
▷1 ∴ Use a 5mm fillet weld $3\frac{3}{4}$in long (min.)

SUBJECT	CBI OFFICE LIGO		REVISION 1		REFERENCE NO. 953571
	MADE BY BTR	CHKD BY ARL	MADE BY BTR	CHKD BY MLT	SHT__ OF__
	DATE 4/29/96	DATE 5-10-96	DATE 9/24/96	DATE 3-19-97	4.33

By inspection, the fixed support nearest to the termination is adequate to resist the installation loads (stretching of the expansion joint). Because the fixed support nearest to the termination is stronger than the fixed support away from the termination and the support away from the termination is adequate (with one weld size increased), the fixed support nearest to the termination is adequate without any changes. Refer to section 4 for the design of the fixed support away from the termination.

SUBJECT	CBI OFFICE 460		REVISION		REFERENCE NO. 953571
	MADE BY KTR	CHKD BY MLT	MADE BY	CHKD BY	SHT__ OF__
	DATE 7/24/96	DATE 3-14-97	DATE	DATE	5.0

Size Weld of Vertical Support Bracket to Support Ring

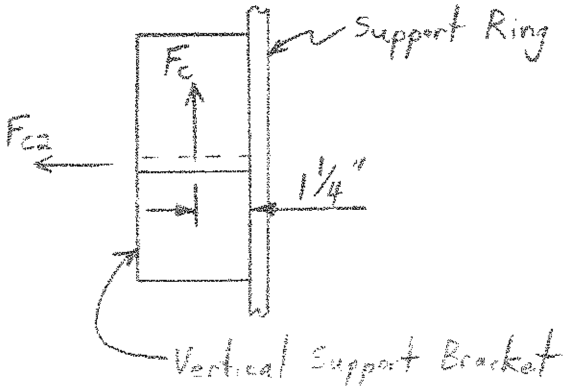


(see dwg #19)

▷ $A_w = d + 3" = 9.5 \text{ in}^2/\text{in}$

$S_w = \frac{d^2}{6} = \frac{6.5^2}{6} = 7.0 \text{ in}^3/\text{in}$

▷ Ignore twist on weld because load is close to centroid of **weld.** ∴ Torsion on weld is negligible.



$F_c = 3{,}700$ lb (sht. 7.3)

$M = F_c(1.25\text{in}) = 4{,}625$ in·lb

$F_{c2} = F_c \sin(3.2°) = 207$ lb

(sht. 7.2)

▷

$W_s = \frac{F_c}{A_w} = 389 \text{ lb/in}$ $W_{s2} = \frac{F_{c2}}{A_w} = 22 \text{ lb/in}$

$W_B = \frac{M}{S_w} = 661 \text{ lb/in}$

$W = \sqrt{W_B^2 + W_s^2 + W_{s2}^2} = 767 \text{ lb/in}$

$w = \frac{W}{4{,}051} = .19"$ ⟶ Use $w = 5$ mm

(sht. 3.75)

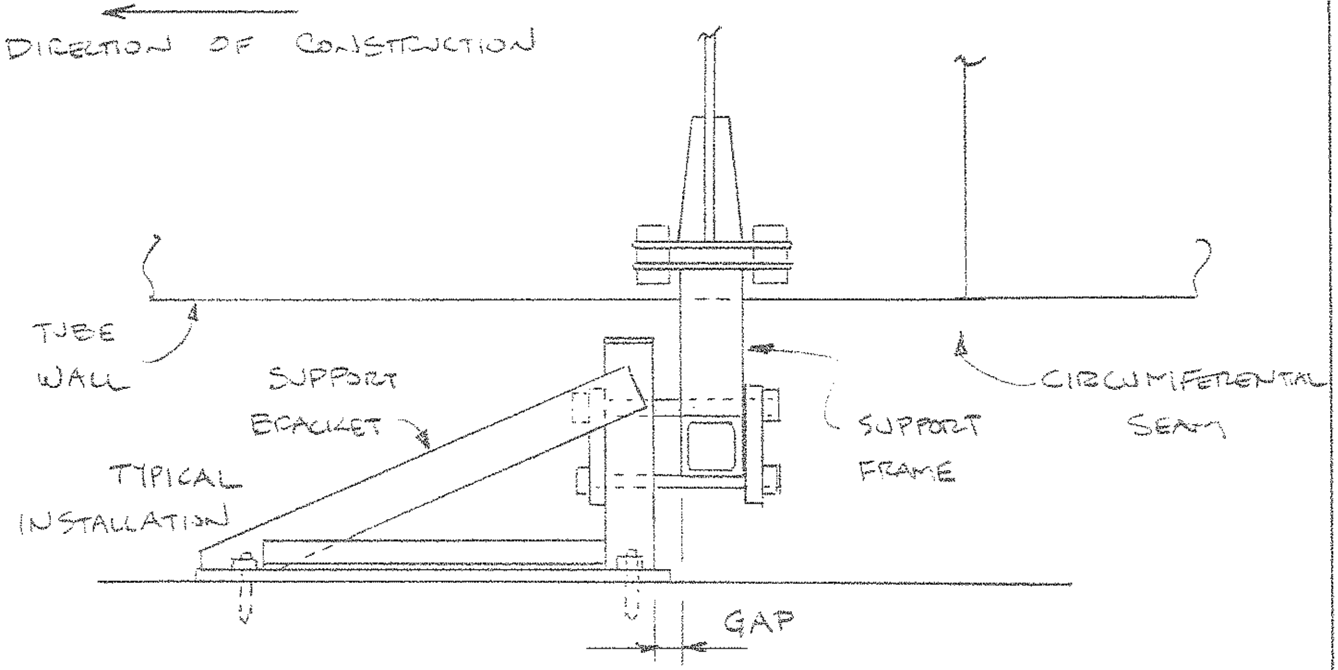
Size Vertical Support Bracket

Because $F_c = 3{,}700 \text{ lb} = F_L$ (lateral load on termination bracket, sht. 3.72)

use a ½" thk. bracket.

SUBJECT	CBI OFFICE LIGO	REVISION 1		REFERENCE NO. 953571
	MADE BY DTR	CHKD BY ARL	MADE BY MLT	CHKD BY DTR	SHT ___ OF ___
	DATE 4/8/96	DATE 4-29-96	DATE 4-1-97	DATE 4-1-97	7.24

SUPPORT INSTALLATION & EXPANSION JOINT STRETCHING TO RAISE BAKE TEMPERATURE 18°C – 1/2" STRETCH



THE ORIGINAL DESIGN WAS BASED ON A 70°F AMBIENT T. THE ALLOWABLE BAKE TEMPERATURE WILL BE INCREASED BY INSTALLING THE EXPANSION JOINTS IN THE TUBE SUCH THAT THEY ARE IN A RELAXED STATE AT A HIGHER TEMPERATURE.

LENGTH BETWEEN FIXED SUPPORTS = 130' = 1560"
COEFFICIENT OF THERMAL EXPANSION 9.9×10^{-6} in/in °F

∴ ALLOWABLE TEMPERATURE INCREASE FOR 1/2" STRETCH IN EXPANSION JOINT:

$$\Delta L = (\Delta T)(L)(\epsilon)$$

$$\Delta T_{\text{ALLOW INCREASE}} = \frac{\Delta L}{L\epsilon} = \frac{(1/2)}{1560\,(9.9\times10^{-6})}$$

$$\Delta T = 32.4\,°F$$
$$= 18.0\,°C$$

∴ EXP. JTS. WILL BE NUETRAL @ 102°F & ALLOWABLE BAKE TEMPERATURE IS NOW 102°F + 232°F = 334°F = 168°C

SUBJECT	CBI OFFICE LIGO		REVISION	REFERENCE NO. 953571
	MADE BY MJT	CHKD BY DTR	MADE BY	CHKD BY	SHT ___ OF ___
	DATE 2/27/96	DATE 3/4/97	DATE	DATE	8.1

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GO 64 REV SEP 84

SUPPORT INSTALLATION SEQUENCE

THE EXPANSION JOINT IS TO BE NUETRAL AT A TEMPERATURE OF 102° F. IF THE BEAM TUBE IS LESS THAN 102°F AT INSTALLATION, THE THERMAL CONTRACTION OF THE BEAM TUBE WILL REQUIRE STRETCHING OF THE EXPANSION JOINT. THE EXPANSION JOINT MAY BE STRETCHED BY PULLING THE TUBE FORWARD IN THE DIRECTION OF CONSTRUCTION WITH THE SUPPORT FRAME AND SUPPORT BRACKET. THE STEPS FOR INSTALLATION OF THE FIXED SUPPORT AND EXPANSION JOINT STRETCHING ARE:

- ATTACH THE SUPPORT TUBULAR FRAME TO THE BEAM TUBE.
- DETERMINE THE REQUIRED SUPPORT BRACKET LOCATION ON THE BEAM TUBE SLAB BASED ON THE BEAM TUBE TEMPERATURE.
- ATTACH THE SUPPORT BRACKET TO THE FOUNDATION WITH THE HILTI ANCHORS. A GAP WILL EXIST BETWEEN THE SUPPORT FRAME AND SUPPORT BRACKET.
- PULL THE BEAM TUBE TO THE SUPPORT BRACKET WITH THE CLAMPING BOLTS TO CLOSE THE GAP.

THIS PROCEDURE COULD PLACE LOADS ON THE SUPPORT FRAME AND SUPPORT BRACKET WHICH EXCEED DESIGN LOADS.
→ PER SECTION 2 OF CDRL #3, DESIGN CALCULATIONS:
AT TERM, AXIAL LOAD = 10993 # AXIAL LOAD + SEISMIC = 13162
AWAY FROM TERM, AXIAL = 4250 # AXIAL LOAD + SEISMIC = 6919
THESE LOADS WERE USED TO DESIGN THE SUPPORTS AND SHELL STIFFENING. THE ACTUAL LOADS HAVE BEEN REDUCED DUE TO THE ACTUAL EX. JT. SPRING RATE AND BY SELECTIVE PLACEMENT OF THE EX. JTs NEXT TO THE TERMINATIONS.

SUBJECT	CBI OFFICE LIGO		REVISION		REFERENCE NO. 953571
	MADE BY MLT	CHKD BY DTR	MADE BY	CHKD BY	SHT___ OF___
	DATE 1/31/97	DATE 2/4/97	DATE	DATE	8.2

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GO 64 REV SEP 84

AXIAL LOADS DURING INSTALLATION

THE FIXED SUPPORTS ARE SUBJECTED TO AXIAL LOADS DURING STRETCHING OF THE EXPANSION JOINT. THE AXIAL LOAD WILL BE COMPOSED OF THE EX. JT. SPRING FORCE PLUS THE RESISTANCE TO ROLLING OR SLIDING THE BEAM TUBE SECTIONS

$$F_{TOTAL} = F_{EX.JT.} + F_{SLIDE}$$

F_{SLIDE}: ASSUME UP TO 5 TUBE SECTIONS ARE INSTALLED IN FRONT OF THE LAST FIXED SUPPORT. BEAM TUBE SECTIONS WILL BE ON ROLLERS OR SLIDE PLATES. FROM THE ATTACHED SHEET, THE HIGHEST COEFFICIENT OF FRICTION WITH LOW SURFACE PRESSURES = .16

BEAM TUBE SECTION WT = 65' x 75#/FT = 4875 #

THE WEIGHT OF 4 1/2 TUBE WILL BE ON SLIDES OR ROLLERS

$\therefore F_{SLIDE} = 4.5[(.16)(4875\#)] = 3510\ \#$

$F_{EX.\ JOINT}$: THE MAXIMUM EXPANSION JOINT SPRING RATE USED IN THE DESIGN WAS 8,000 #/INCH. AFTER FABRICATION & TESTING OF ~ 100 EXPANSION JOINTS, THE MAXIMUM SPRING RATE IS CURRENTLY 5301 #/in

ASSUME THAT THE LOWEST BEAM TUBE INSTALLATION T = −10°F

$\therefore \Delta T = 112\ °F \qquad L = 130' = 1560'' \qquad \epsilon = 9.9 \times 10^{-6}\ in/in\,°F$

$$\therefore \Delta L = \Delta T(L)(\epsilon)$$
$$= 112°F(1560'')(99 \times 10^{-6}\ in/in\,°F) = 1.73\ inch$$

$$F_{EXP\ JT} = 1.73 \times 5300 = 9170\ \#$$

$$F_{TOTAL} = 3510 + 9170 = 12680\ \#$$

CHECK SUPPORT FOR 12650 #

SUBJECT	OFFICE CBI LIGO		REVISION		REFERENCE NO. 953571
	MADE BY MLT	CHKD BY BTR	MADE BY	CHKD BY	SHT ___ OF ___
	DATE 3/3/97	DATE 3/10/97	DATE	DATE	8.3

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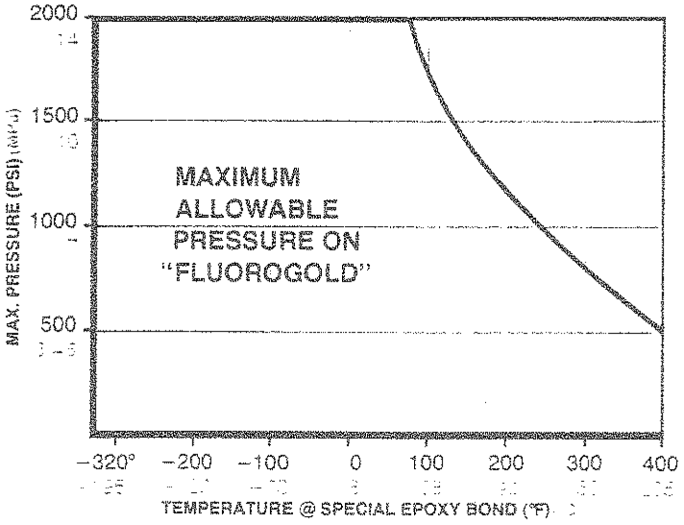
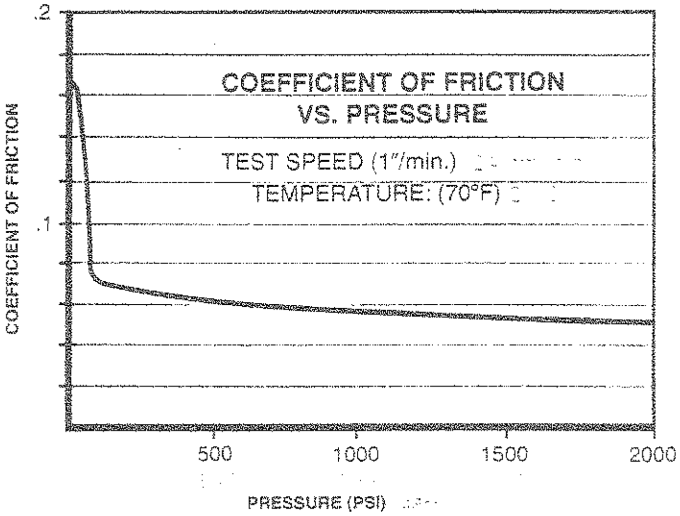
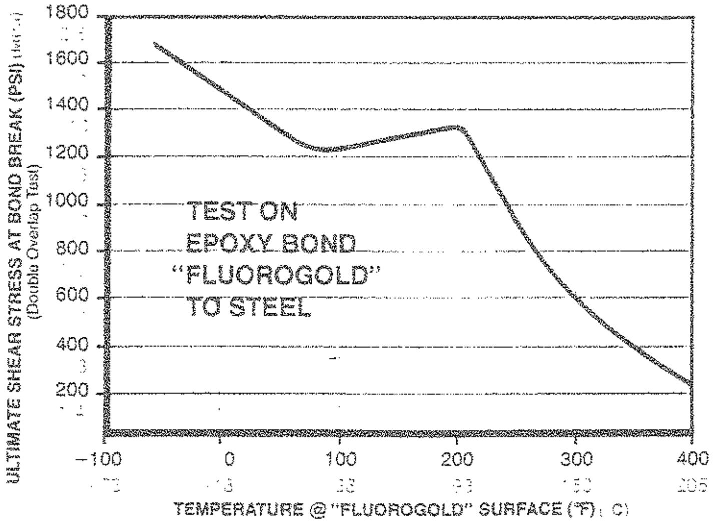
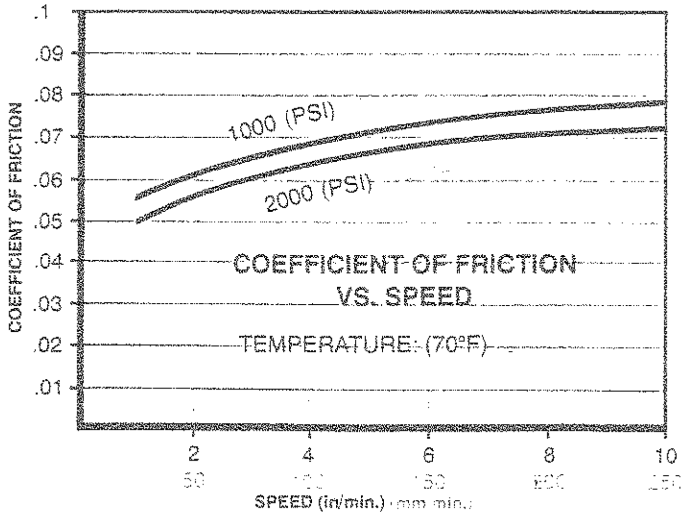
GO 64 REV SEP 84

The following information applies to "Fluorogold" epoxy bonded to a metal back-up plate:









8.4

BEAM TUBE MODULE
SPIRAL SEAM OFFSET TECHNICAL REVIEW
FEBRUARY 20, 1997
Revised April 14, 1997

Executive Summary

To date, CBI has fabricated over 223 spiral tube sections on the tube mill at CBI's fabrication facility. These 223 beam tube sections contain approximately 12 miles of spiral butt weld. The beam tube technical requirements were established in the original Design and Qualification Contract. The current technical requirements include a limit on the spiral seam offset of 1/4 times the thickness of .125" which is 1/32". The seam offset is the distance between the centerlines of two plates meeting at a butt welded joint. Out of the 223 tube sections produced, 12 tubes contain areas of the spiral weld where the mismatch exceeds 1/32". The areas of offset greater than 1/32" have been documented as they were discovered in Non Conformance Reports. This report describes the offset configuration, causes for the offset, the impact of the offset on the structural integrity of the modules, and proposed revised technical requirements for spiral seam offset. The proposed revised technical requirements are a limit of 3/32" for offsets at the locations of highest stress and a limit of 1/8" for offsets in all areas outside of the highest stressed areas.

Technical Requirements

CBI Specification C-BT-CO

The technical requirements for the beam tube sections are contained in CBI Specification C-BT-CO entitled "LIGO Beam Tube Sections - Construction Option". Although the specification was developed by CBI in the Design and Qualification Test contract for procurement of tube sections fabricated by an outside vendor, the scope of the specification is to provide technical requirements for the spiral welded tube sections. Based on the code guidelines specified by Caltech for the original design, the list of applicable codes in this specification includes:

> "ASME Unfired Pressure Vessel Code, Section VIII, Division 1, 1992 Edition, 1993 Addenda as applicable. (Code stamping is not required.)"

Section UW of ASME Section VIII, Division 1 is entitled "Requirements for Pressure Vessels Fabricated by Welding". Table UW-33 requires a maximum seam offset of t/4 for shell thicknesses less than 1/2".

Specification C-BT-CO, section 6 contains the requirements for fabrication of the spiral tube sections. Section 6.1 contains the requirements for welding. Paragraph 6.1.6 states:

> "Edge registry for spiral welds must be within 1/4 of the thickness which is 1/32 inch."

Basis of the ASME Seam Mismatch Requirements

The offset values in ASME table UW-33 are based on past experience of achievable fabrication for pressure vessels fabricated by conventional methods. These offset requirements are not directly tied to the design rules. During the initial design, CBI checked the interaction between longitudinal compressive stresses and circumferential compressive stresses per API Bulletin 2U entitled "Bulletin on Stability Design of Cylindrical Shells". This bulletin includes design rules for stiffened cylinders under external pressure and longitudinal stress. The rules are based on tolerances described in section 10 of API 2U. Although API 2U does not specifically address seam offset, the bulletin does provide recommendations for the local deviation from a straight line. The allowable deviation from a straight longitudinal line over 4 times $(Rt)^{1/2}$ is 1% of $4(Rt)^{1/2}$. This results in an allowable deviation of .07" over a length of 7". Based on API 2U, the allowable offset at any location in the beam tube is .07".

Development of the Welding Requirements

The specific requirement for weld registry of t/4 in the specification was based on extensive tests by CBI on the allowable edge mismatch using a standard Gas Tungsten Arc Weld (GTAW) process. The GTAW process is also know as the Tungsten Inert Gas (TIG) process. Weld tests with coupons performed by CBI and spiral welds made by tube fabricators demonstrated that offsets greater than approximately t/4 could not be successfully welded with the standard GTAW process. These offsets produced large holes and areas with a lack of fusion when a standard GTAW process was used. Tests conducted during the original design contract and qualification test also identified the fact that the standard GTAW process did not provide sufficient penetration into the material to ensure 100% fusion at all locations. To solve the problems associated with the lack of penetration, CBI investigated the use of high frequency pulsed GTAW process with tests performed in Plainfield prior to the Design Review for the current contract.. This weld process produces a deep and narrow weld penetration which not only provides 100% penetration and allows greater weld speeds, but also allows greater offset in the edge registry without producing the problems associated with the standard GTAW process. Caltech approved the change in the spiral weld procedure from the previously approved standard GTAW process to the new high frequency GTAW process.

To date, approximately 200 tube section have been leak tested. In addition to a leak check, the test imposes significant circumferential and axial stress in the tube. The circumferential stress is 2.9 ksi and the axial stress is 1.5 ksi plus additional longitudinal stress due to dead load bending moments. All sections tested to date have been entirely leak free including those tube sections with spiral seam offsets greater than 1/32".

Description of Seam Offset

All beam tube sections are inspected after welding to ensure dimensional conformance to the technical requirements. Seam offsets greater than 1/32" have been measured and documented in Non Conformance Reports submitted to Caltech. The seam offset configurations and locations are presented in the attached "Summary of Tubes With Joint Offset". Twelve beam tube sections contain one or more areas of seam offset greater than 1/32". The total number of offset locations in all twelve tubes is 38. The total length of all offset locations is 741.5" for an average length of 19.5". The mean length is 11 inches. The longest continuous offset exceeding 1/32" is 180" and the shortest offset such is 4". All of the offset areas are 21" long or less except for 3 areas. The maximum offset at 28 locations is 1/16". The maximum offset at 9 locations is 3/32" and one location has an offset of 1/8".

Some tube sections which contain mismatches have been stiffened and leak tested. The severity of the discontinuity is reduced by adding weld metal to the seam mismatch to provide a 3 to 1 transition at the seam mismatch. A typical offset seam with a weld metal transition is shown in the attached Non Conformance Report.

Causes Leading To Weld Joint Offset

CBI has identified a number of items or conditions which are potentially responsible for spiral seam offsets greater than 1/32". These items are listed below.

1. Coil with deformed slit edge - Distorts area at weld joint marriage point making it very difficult to control alignment and tube diameter.
2. Coil with edge that is not straight - Causes gap control to make excessive and repeated movements distorting the weld joint marriage point.
3. Coil with excessive camber - Results in difficulty in controlling seaming rollers at weld joint marriage point.
4. Mill spider pressure - Can potentially distort shape of the tube in the weld joint marriage point.
5. Mill seaming roller adjustment - Improper adjustment can distort the area at the weld joint marriage point.
6. Mill operator error - Can directly cause excessive misalignment in the weld joint marriage point.
7. Welded Stop/Starts - Shrinkage distortion at an area of a mill stop/start results in a non-equilibrium condition when the mill is started. This has led to areas with weld joint offsets greater than 1/32".
8. Welded coil splices - Shrinkage distortion at an area of a coil splice may cause a variation in the fairing of the coil and tube edges at the weld joint marriage point. This has led to areas with weld joint offsets greater than 1/32".

Global Analysis of the Beam Tube

The stresses in the beam tube were determined by a global analysis of the beam tube module. The global analysis of the beam tube was performed in the original Design and Qualification Test contract. The beam tube analysis was presented in CDRL #15, DRD #9, Item IV entitled "Design Calculations and Analyses" dated April 11, 1994. After award of the construction option, the original analysis was reviewed to ensure that the design basis was consistent with the proposed final configuration. A review of the analysis was presented in DRD #3, CDRL #10 & 24 entitled "Design Document Revisions - Design Calculations" dated March 12, 1996 and June

28, 1996. The stresses in the current configuration are less than those predicted by the original design.

The governing load condition for the beam tube is the combination of the beam tube dead load, differential settlement of the fixed support, and vacuum during the beam tube bake out. The maximum allowable differential settlement is limited to keep the longitudinal beam tube stresses under the ASME allowable longitudinal stress of 5.9 ksi.

Stresses Due to Bake Out

Bake out of the beam tube causes compression of the expansion joints due to thermal expansion of the beam tube. This results in a direct compressive load on the beam tube accompanied by relatively small moments at the fixed support due to load eccentricity. The original axial load due to expansion joint compression was based on an estimated maximum expansion joint spring rate of 10,062 pounds per inch. The maximum actual spring rate measured to date is 5,301 pounds per inch. As such, axial load in the beam is approximately 15,000 pounds less than the value used for design. Based on the original design spring rate, the maximum longitudinal stress due to bake out was 1.7 ksi. Based on the current maximum spring rate, the maximum longitudinal stress due to bake out is 1.0 ksi.

Stresses Due to Beam Dead Load

The dead load of the stiffened beam tube is 75 pounds per foot. The design dead load is 91 pounds per foot to include the insulation dead load. The dead load results in normal beam bending stresses in the beam tube. The beam bending stresses were determined by finite element analysis in the original design. The finite element analysis modeled the continuous beam tube on fixed and guided supports with expansion joints at the guided supports. The shear, moments, and deflections of the beam tube due to the dead load are shown in sketch #1. As shown in the sketch, the maximum moment exists at the fixed support. The maximum longitudinal stress due to dead load bending is 2.2 ksi.

Stresses Due to Differential Settlement

Differential settlement also produces bending stresses in the beam tube. Although not shown on the sketch, the effects of differential settlement are limited to the sections immediately next to the settlement location due to the rotational flexibility of the expansion joints. Differential settlement of the fixed support produces the greatest bending moments in the beam tube. The shear loads, bending moments, and deflections of the beam tube due to differential settlement of the fixed support are shown in sketch #2. The shear loads, moments, and deflections associated with the combined dead load and differential settlement of the fixed support are shown in sketch #3. The dead load plus upward differential settlement of any fixed support between guided supports produces the greatest bending moments in the beam tube. Based on the original design, differential settlement of the fixed support of .56" produces a longitudinal bending stress of 2.0 ksi.

Stresses Due to Vacuum Conditions

Vacuum in the beam tube causes an external pressure on the beam tube resulting in compressive circumferential stresses. In addition, due to the expansion joint configuration, the external pressure at the expansion joint also produces slight longitudinal tensile stresses in the beam tube. The circumferential compressive stress in the beam tube due to vacuum is 2.9 ksi.

Finite Element Analysis of the Seam Offset

Analysis Description and Results

A finite element analysis of a beam tube section with a 3/32" offset has been performed and compared to the analysis of an idealized beam tube section. The offset model consists of a section of beam tube between stiffeners with a 3/32" offset around the full circumference at the midpoint between the stiffeners. The idealized model consists of half of a section of beam tube between stiffeners which is perfectly cylindrical. The analysis includes elastic-plastic material behavior and geometric non-linearity. Both models use a non linear approximate stress strain curve for A240 type 304L stainless steel at 300 °F. Both models are subjected to a constant external pressure of 14.7 psi while the axial load is increased from zero to the maximum capacity. The axial load is uniform around the circumference. The analysis report is provided in appendix A.

As noted earlier, the ASME allowable longitudinal stress is 5.9 ksi. An axial load of 113.8 kips is required to induce this stress around the entire circumference. The maximum load capacity of the idealized model and the offset model with a 14.7 psi external pressure are given below. The axial displacement over the 30" stiffener spacing and the maximum radial displacement due to the maximum axial load are also provided below.

	Max Axial Load	Axial Displacement	Radial Displacement
Idealized Model:	374.0 kips	.0548"	.0173"
Offset Model:	230.4 kips	.0170"	.0165"

These maximum loads are factors of 3.286 and 2.024 over the equivalent allowable design load for the idealized model and offset model, respectively.

Discussion of Analysis Results

In general, the design of shell structures involves the determination of predicted buckling stresses in the structure and the application of safety factors to the predicted buckling stresses to ensure stability. The predicted buckling stresses are based on classical linear theory for idealized shapes reduced by capacity reduction factors and plasticity reduction factors. Capacity reduction factors account for the effects of imperfections. Plasticity reduction factors account for non linearity in material properties. The analysis contains non linear material properties for both the idealized model and the offset model. The idealized model does not contain any imperfections and as such, the predicted buckling stress of an actual tube section is less than the maximum stress in the idealized model. The analysis of the offset model determines the axial load capacity reduction associated with the seam offset of 3/32" over the entire circumference. The analysis predicts that the seam offset will cause a 38.4% reduction in the maximum axial stress of an idealized cylinder.

As stated above, the finite element analysis determined the reduction factor associated with a 3/32" offset compared to an idealized perfect cylinder. For analysis, the 3/32" offset exists around the full circumference of a tube section at the mid point between circumferential vacuum stiffeners. The maximum axial compressive stress was 61.6% of the maximum axial compressive stress of the idealized perfect cylinder.

Fabricated structures can not reach the stress levels of idealized shapes due to geometric imperfections and non linear material behavior. API Bulletin 2U contains formulas for the predicted buckling stresses of cylindrical shells including the capacity reduction factors for geometric imperfections and plasticity reduction factors for non linear material properties. The predicted inelastic longitudinal buckling stress for the beam tube modules per API 2U, formula 4-7 is 12.3 ksi without superimposing the external pressure. The finite element analysis of the 3/32" offset predicted a longitudinal buckling stress of 2.024 times 5.9 ksi times or 11.9 ksi with the presence of an external pressure. This indicates that an offset of 3/32" around the entire circumference causes less of a reduction in the predicted longitudinal buckling stress that of the general shell imperfections allowed by bulletin 2U.

Implementation of Analysis Results

The spiral seam offset will be limited to 3/32" in all areas. The longitudinal distance from any offset greater than 1/32" to a circumferential stiffener will not be greater than 7.5". When offset areas exist at a distance greater than 7.5" from a circumferential stiffener, an additional circumferential stiffener will be attached at the midpoint between normal circumferential stiffeners.~~the areas of highest longitudinal compressive stress. Based on the global analysis, the highest longitudinal compressive stress exists in the immediate vicinity of the fixed support at the bottom of the beam tube. As shown in the global analysis, the longitudinal stress decreases rapidly going away from the fixed support. The maximum bending moment in the beam tube is approximately 51.5 foot kips for all locations at least 8' away from the fixed support. This moment produces a longitudinal compressive stress in the shell of 2.6 ksi, which when combined with the direct compressive stress of 1.0 ksi, results in a maximum compressive stress of 3.6 ksi. The maximum offset will be limited to 1/8" in all areas at least 8' away from the fixed support and in the bottom quadrant of the circumference. The bottom quadrant is between 135° and 225°.~~

Factors of Safety

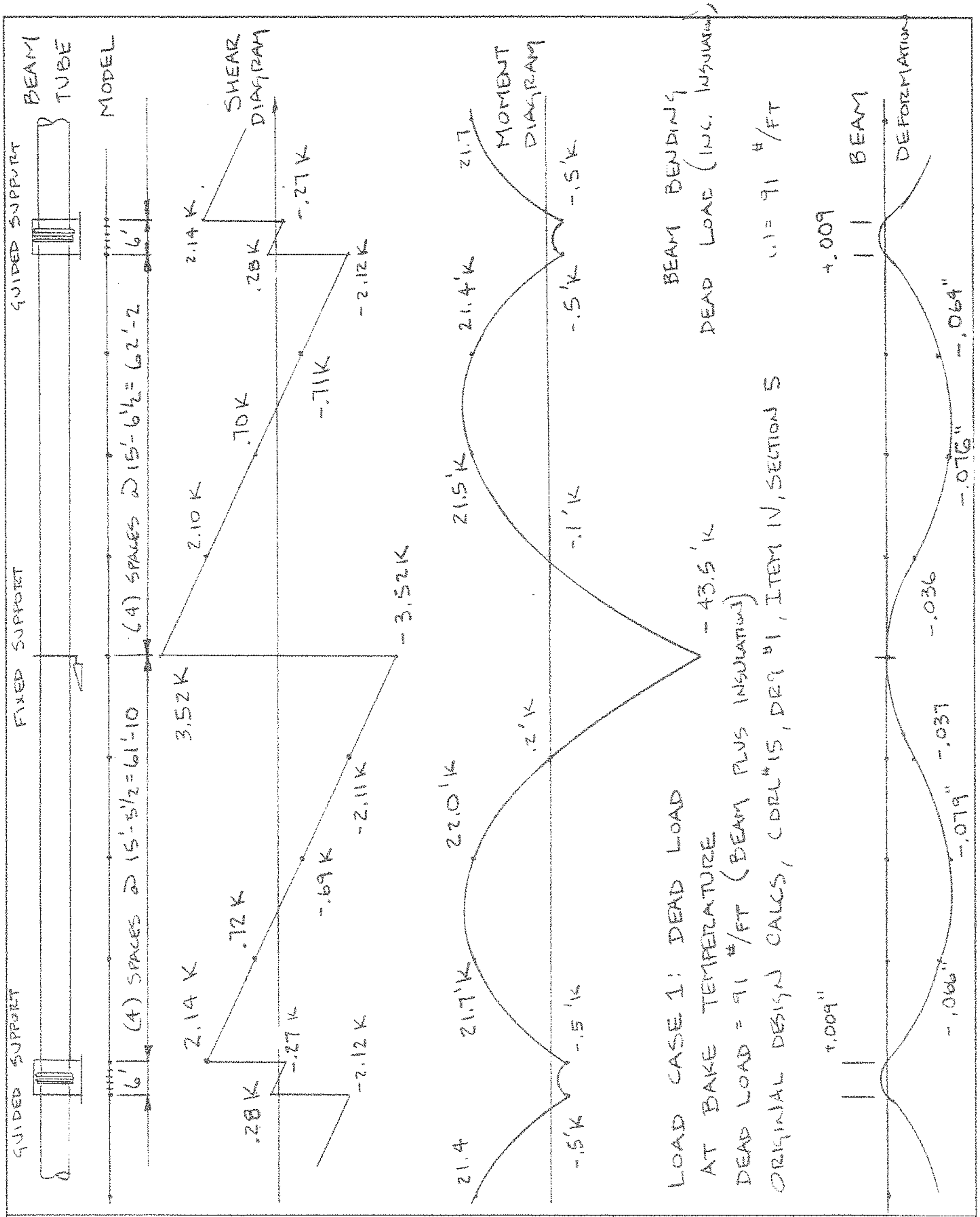
As noted earlier, the design of shell structures involves the determination of predicted buckling stresses in the structure and the application of safety factors to the predicted buckling stresses to ensure stability. The original design determined the predicted longitudinal and circumferential compressive stresses and checked the interaction of the stresses per API 2U. API 2U recommends a factor of safety of 1.5 for the combined stresses. The factor of safety on the original design per API 2U was 1.55. However, the actual factors of safety of the beam tube modules is in fact much greater due to the nature of the beam tube loading and the offset configuration as described below.

Nature of Beam Tube Loading

The circumferential compressive stresses in the beam tube are due to vacuum conditions and can not exceed the current design values. The longitudinal stresses are due primarily to beam bending moments. Beam bending stresses could exceed the current design values if differential settlements exceed the current limits. However, the predicted bending stresses were determined based on linear elastic behavior. In the beam tube module, the bending stresses will be less than the predicted stresses due to the non linear properties of the material. Greater differential settlements will be accompanied by proportionally lower bending stresses. Differential settlements of over 2" would be required to reach the maximum compressive stress in the shell along the bottom of the shell. In addition, the bending capacity of the beam tube would continue to increase long after the maximum compressive stress was reached a the bottom of the tube.

Offset Configuration

The offsets in the beam tubes are along the spiral seam. The spiral seam makes an angle with the circumference of 9^0 and 13.5^0 for 24" wide and 36" wide coil material, respectively. The maximum axial compressive stress capability of a section containing a spiral offset is significantly higher than that of a section with a full circumferential offset.



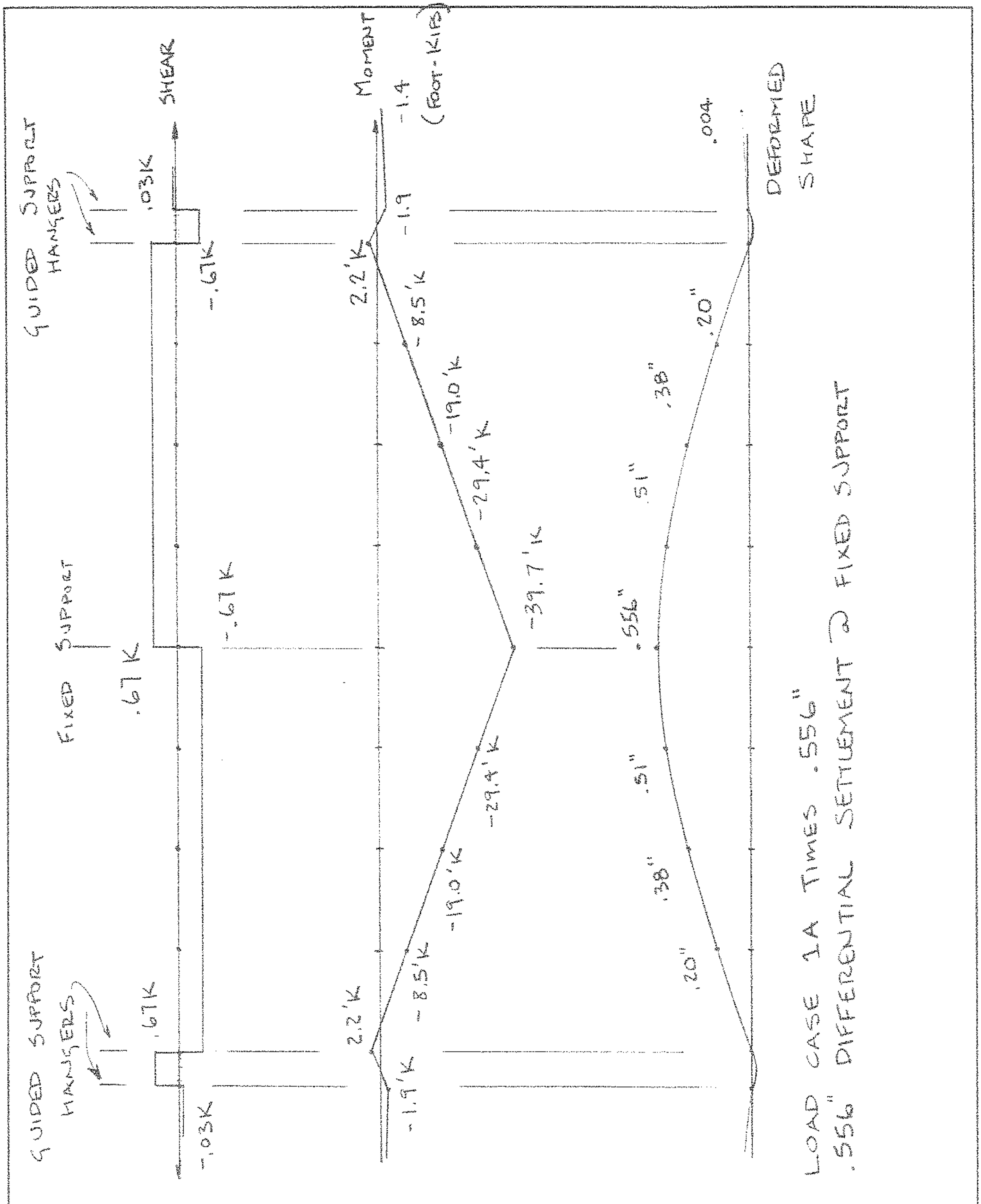
LOAD CASE 1: DEAD LOAD
AT BAKE TEMPERATURE
DEAD LOAD = 91 #/FT (BEAM PLUS INSULATION)
ORIGINAL DESIGN CALCS, CDRL #15, DRG #1, ITEM IV, SECTION 5

BEAM BENDING
DEAD LOAD (INC. INSULATION)
w = 91 #/FT

SUBJECT
DEAD LOAD ONLY - 91 #/FT
BEAM BENDING

CBI OFFICE LIGO
REVISION
REFERENCE NO. 958571
MADE BY MLT
CHKD BY RJR
MADE BY
CHKD BY
SHT 9-11 OF
DATE 2-11-97
DATE 5-22-97
DATE
DATE
SKETCH #1

Printed In USA
GO 64 REV SEP 84



LOAD CASE 1A TIMES .556"
.556" DIFFERENTIAL SETTLEMENT @ FIXED SUPPORT

SUBJECT
.556 DIFFERENTIAL
SETTLEMENT ONLY
BEAM BENDING

CBI OFFICE LIGO

REVISION

REFERENCE NO. 953571

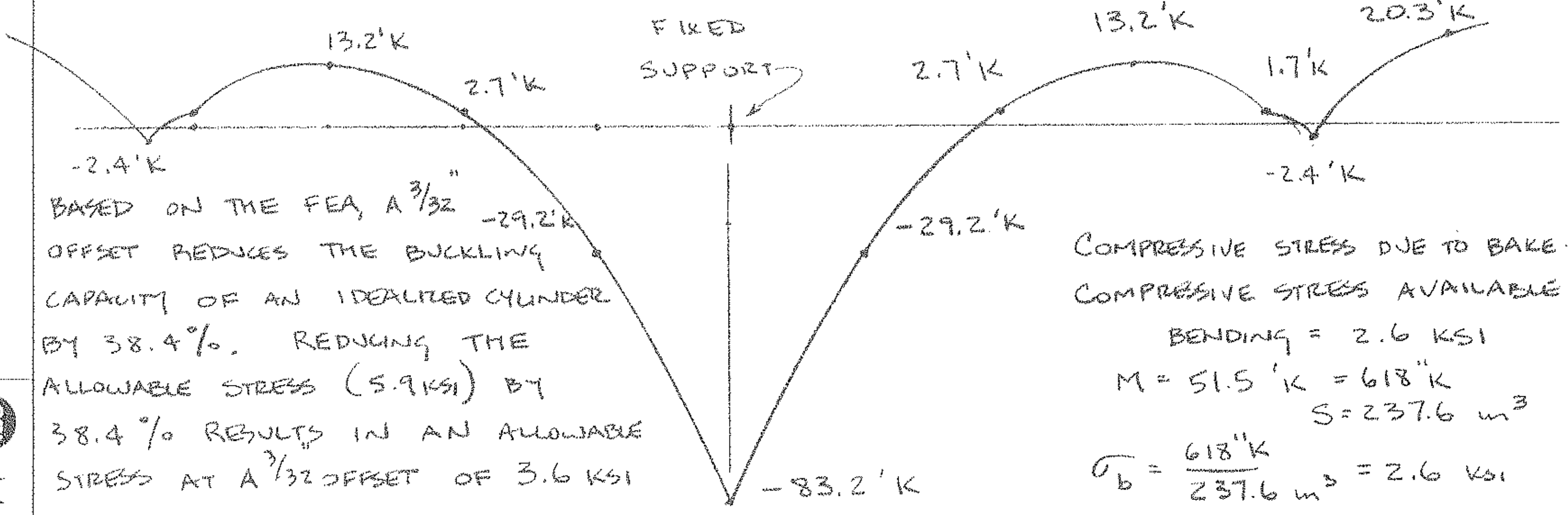
MADE BY	CHKD BY	MADE BY	CHKD BY	SHT 9 OF 12
MLT	DTR			
DATE 2-11-97	DATE 5-22-97	DATE	DATE	SKETCH #2

Printed In USA

GO 64 REV SEP 84

Combined Beam Bending Due to Dead Load Plus .556" Differential Settlement

Dead Load Plus .556" Upward Movement @ Fixed Support



BASED ON THE FEA, A $3/32$" OFFSET REDUCES THE BUCKLING CAPACITY OF AN IDEALIZED CYLINDER BY 38.4%. REDUCING THE ALLOWABLE STRESS (5.9 KSI) BY 38.4% RESULTS IN AN ALLOWABLE STRESS AT A $3/32$ OFFSET OF 3.6 KSI

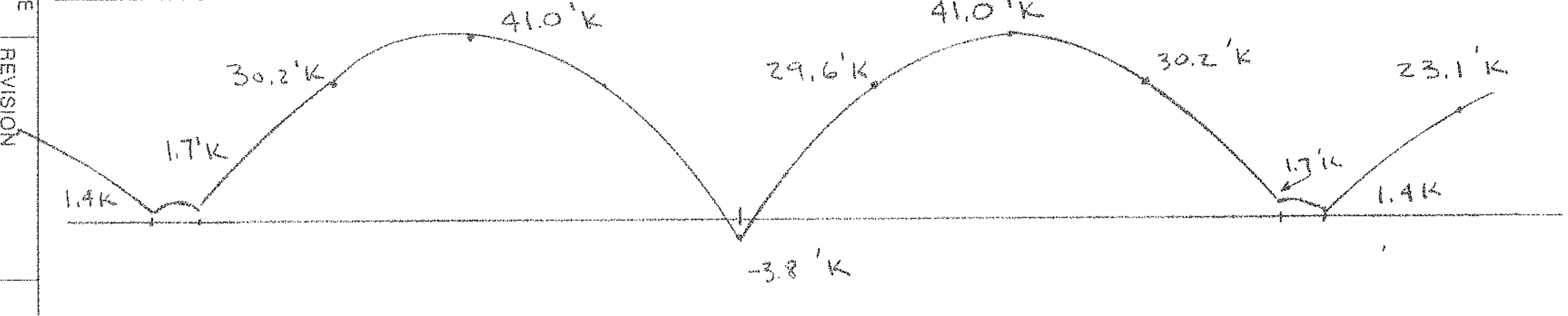
COMPRESSIVE STRESS DUE TO BAKE = 1.0
COMPRESSIVE STRESS AVAILABLE FOR BENDING = 2.6 KSI

$M = 51.5\,'K = 618\,''K$

$S = 237.6\ \text{in}^3$

$$\sigma_b = \frac{618\,''K}{237.6\ \text{in}^3} = 2.6\ \text{ksi}$$

Dead Load Plus .556" Downward Movement @ Fixed Support



DATA TAKEN FROM ORIGINAL DESIGN CALCULATIONS CDRL#15, DRD#9, ITEM IV, SECTION 5

SUBJECT
BENDING MOMENT DIAGRAMS
DEAD LOAD PLUS .556"
DIFFERENTIAL SETTLEMENT

CBI OFFICE LIGO	REVISION			REFERENCE NO. 953571
MADE BY MLT	CHKD BY ETR	MADE BY	CHKD BY	SHT 9-13 OF
DATE 2-11-97	DATE 5-22-97	DATE	DATE	SKETCH #3