10110TA

BELOW-THE-HOOK LIFTING DEVICE
Engineering Note Cover Page

Lifting Device Numbers:

FNAL Site No. ______________ (If applicable) Div. Specific No. EN02070 (If applicable) Asset No. ______________ (If applicable)

ASME B30.20 Group: (check one)

[x] Chapter 20-1 Structural and Mechanical Lifting Devices
[ ] Chapter 20-2 Vacuum Lifting Devices
[ ] Chapter 20-3 Close Proximity Operated Lifting Magnets
[ ] Chapter 20-4 Remotely Operated Lifting Magnets
[ ] Chapter 20-5 Scrap and Material Handling Grapples

Device Name or Description: 1.3 GHz LCLS-II Transport System

Device was (check all applicable)

[ ] Purchased from a Commercial Lifting Device Manufacturer. Mfg Name ______________
[x] Designed and Built at Fermilab. Assy drawing number ______________
[ ] Designed by Fermilab and Built by a Vendor. Assy drawing number ______________
[ ] Provided by a User or other Laboratory
[ ] Other: Describe ______________

Engineering Note Prepared by: Michael McGee Date: 19 Nov 2015

Engineering Note Reviewed by: ______________ Date: ______________

Lifting Device Data:

Capacity: 36,000 lbs.

Fixture Weight: 9,500 lbs.

ASME BTH -1 Design Category: (See ASME BTH-1 Section 2-2) [X] Category A [ ] Category B

ASME BTH -1 Service Class: (See ASME BTH-1 Section 2-3) [x] 0 [ ] 1 [ ] 2 [ ] 3 [ ] 4

Duty Cycle ______ 8, 16 or 24 hour rating (applicable to groups III, and IV)

Inspections Frequency ______________

Service (refer to B30.20 for definitions) [x] normal [ ] heavy [ ] severe

Rated Load Test by FNAL (if applicable) Date ______________ Load ______________

[ ] Check if Load Test was by Vendor and attach the certificate

Satisfactory Load Test Witnessed by: ______________

Signature (of Load Test Witness) ______________

Notes or Special Information:

1.3 GHz LCLS-II Cryomodule Transport Base Frame and Lifting Lug Analysis

M.W. McGee
EN02070 - March 30, 2015, Updated November 19, 2015
(-Load Test)

This device is used to lift and transport a 1.3 GHz LCLS-II Cryomodule.

The lifting device is rated in accordance with ANSI/ASME Standards B30.20 2011, Below-the-Hook Lifting Devices, Section 20-1, Structural and Mechanical Lifting Devices, and also the Fermilab ES&H Manual Section 10110-Cranes, Hoists and Rigging, and the Below-the-Hook Lifting Devices Safety Standard draft revision dated November 5, 2012.

ANSI/ASME B30.20-2011 requires the following:

1. A rated load marking is to be visible on the device.
2. An identification name plate or other permanent marking shall display:
   a. manufacturer's name, in this case Fermilab
   b. a serial number, in this case the Engineering Note No. EN02070, and the drawing number F10038883.
   c. the tare weight of the lifting device, in this case 9,500 lbs.
   d. the **rated load**, in this case 21,781 lbs. (cryomodule and isolation fixture weight) plus 9,500 lbs. (tare weight of the base frame) plus 457 lbs. (upper truss) and 4,262 lbs. (any additional loading) or **36,000 lbs.** total.
   e. ASME BTH-1 Design Category, in this case Design Category A since use of this fixture is limited in scope and the loads are well understood.
   f. ASME BTH-1 Service Class, in this case Service Class "0" applies since the number of cycles will be less than 20,000.
   g. Attach product safety labels to fixture denoting cautions during use.
3. The design shall be able to withstand stress applied by the rated load based on the allowable stress, given minimum values of the nominal design factor N_d , where N_d = 2.0.
4. The device must be load tested at 125% of the rated load.
5. Welding shall be in accordance with ANSI/AWS D14.1-2005.

Summary of load rating:

The highest stress with a simulated load of 1.3 GHz cryomodule attached to the isolation fixture 21,781 lbs. plus 457 lbs. (upper truss) plus 9,500 lbs. (tare weight of base frame) plus 4,262 lbs. (any additional loading) the in the lifting lug was 5,485 psi, due to longitudinal bending stress (in weak axis). The allowable stress is 22,500 psi.

Therefore, using conservative design factors higher than the minimum of 3, the load rating is set at 36,000 lbs. The test load is 45,000 lbs.

LCLS-II 1.3 GHz Cryomodule Transport Frame and Lifting Lug Analysis

Michael McGee (AD/MSD)
Eng. Note EN02070 March 30, 2015
Updated: November 19, 2015

INTRODUCTION

The safe transport of a LCLS-II 1.3 GHz Cryomodule from either Fermilab or Jefferson Lab to SLAC requires a base frame and isolation fixture (shown in Figure 1). Four lifting lugs exist on this frame for use during overhead crane operation. These four lugs, welded to the base frame are rated for a total weight of 36,000 lbs (estimated assembly load of 31,500 lbs.). This report summaries the analysis performed on the base frame, isolation fixture and lifting lugs to ensure that the stresses are within the allowable levels according to the American Institue of Steel Construction (AISC) Standards[1] and ASME Design of Below-the-Hook Lifting Devices [2]. The base frame and isolation fixture's design details are given in drawing F10039188. Note that the lifting lugs are roughly positioned at the vertical, longitudinal and transverse center of gravity for lifting stability. Three seperate components are considered in this report; the base frame, the isolation fixture and upper truss.

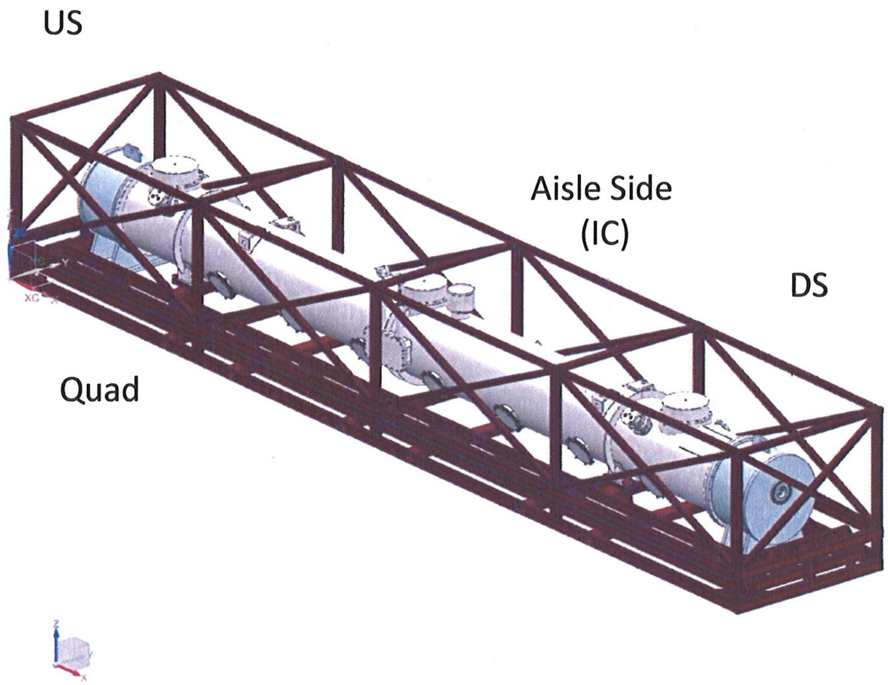

Figure 1: Layout of LCLS-II Transport (FNAL drawing # F10039188).

Weights and parameters were taken from the document; "LCLS-II 1.3 GHz Cryomodule Transport System," Fermilab TeamCenter # ED0002675 [3].

Isolation System Assembly $W_{iso} := 21105 \cdot lb$

Number of Isolation (note that (38) possible locations exist) $N_{iso} := 32$

Weight Per Isolator	$W_{per} := W_{iso} \cdot N_{iso}^{-1}$	$W_{per} = 660 \cdot lb$
Total Weight (Cryomodule and Transport System)		$W_{TS} := 31500 \cdot lb$
Rated Weight		$W_{rated} := 36000 \cdot lb$

Multiframe Model

The base frame was considered in this 3D Multiframe model with pinned constrainats at each of (4) lug position. The weight of the isolation fixture and assemblied cryomodule was divided into (32) equal points and appied as 660 lbs. Also, the isolation fixture was considered in the same manner (pinned at points of connection with base frame). Multiframe also considers the self weight of the base frame and isolation fixture. Beyond the expected weight of the cryomodule and the transport components, an extra 4,500 lbs. was added to the model in order to consider the transport system for a rating of 36,000 lbs. This added weight for rating purposes is described in Section "Lifting Configuration." Given this rating, the moment and shear diagrams from Multiframe is provided in Figures 2 and 3, respectively. Also, shown in Figures 4 and 5, examples of the lower load carrying 6" x 3" x 1/4" members along their lengths.

Multiframe 15 V8i Model Moments, Shear Forces and Displacements:

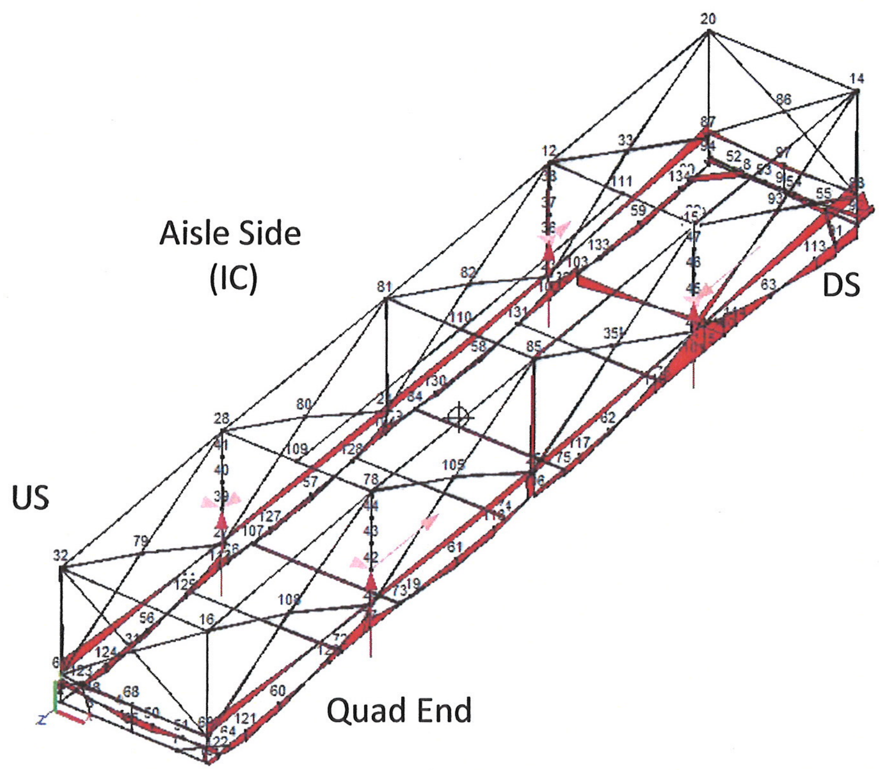

Figure 2: Moment diagram for base frame based on Multiframe analysis.

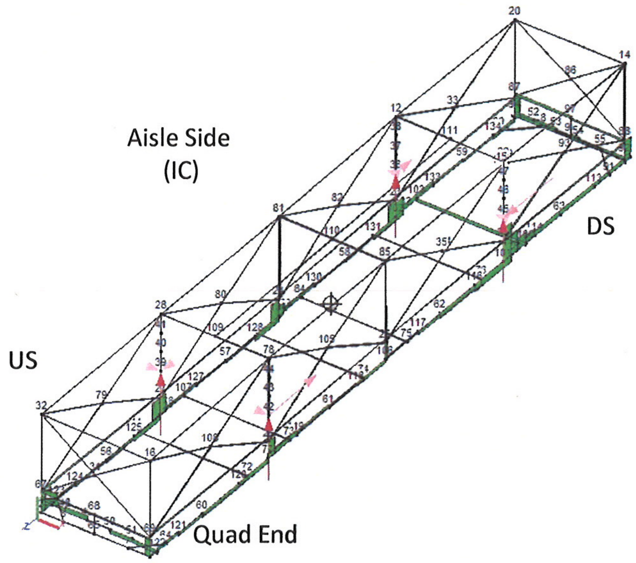

Figure 3: Shear diagram for base frame based on Multiframe analysis.

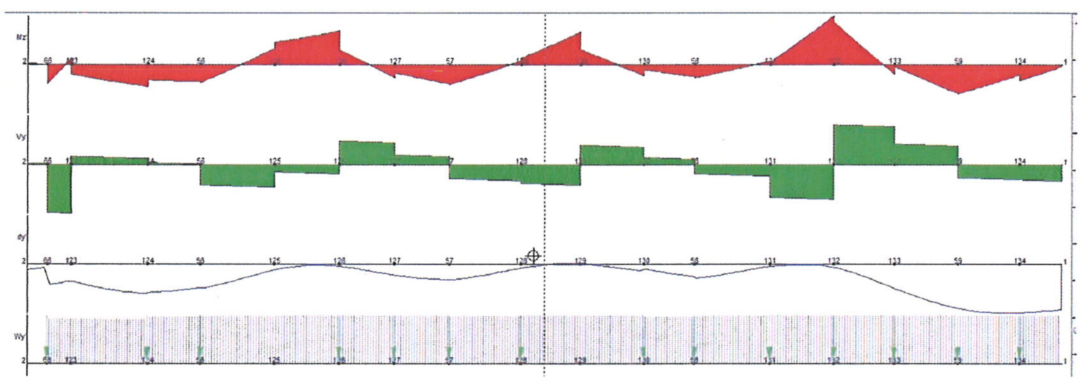

Figure 4: Multiframe results for lower 6" x 3" x 1/4" member (aisle-side).

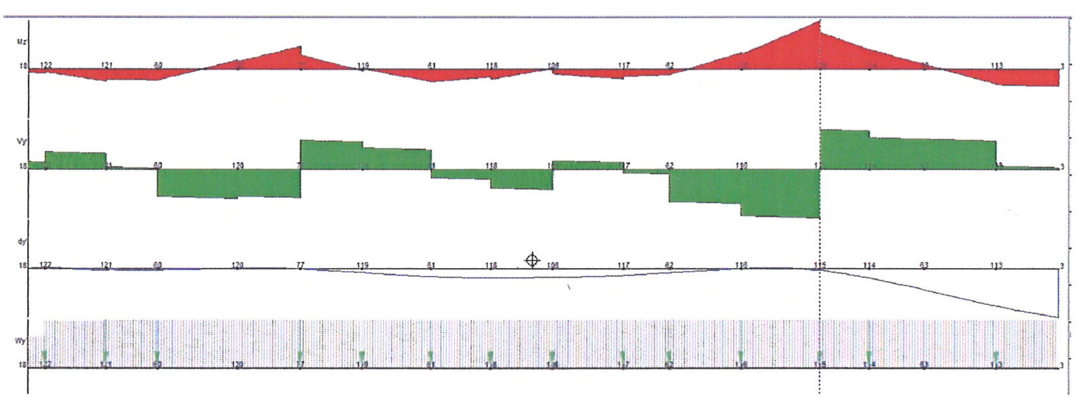

Figure 5: Multiframe results for lower 6" x 3" x 1/4" member (back-side).

Multiframe Base Frame Results

Table 1 provides the summary of lifting lug reactions taken from the MultiFrame results. The worst case vertical loading from Table 1, Ry' = 9716 lbs. is used to evaluate the lifting lugs and slings. Note if the loading were symmetric, then the value used would be 36,000 lbs./(4 lugs) or 9,000 lbs. Table 2 gives a summary of the maximum loads reported by MultiFrame given the princple members under stress.

Table 1: Summary of Lifting Lug Multiframe reactions.

Lug Location	R_x' (lbs)	R_y' (lbs)	R_z' (lbs)
US Aisle	-117	9,716	220
US Back	-15	8,759	240
DS Aisle	32	8,079	303
DS Back	101	9,455	206

Table 2: Summary of maximum loads of Multiframe structual member type and sizes.

Location	Member	M_z' (lbs-in)	V_y' (lbs)	d_y' (in)
Lower Back	TS 6" x 3" x ¼"	67,718	1,149	0.062
Lower Aisle	TS 6" x 3" x ¼"	25,615	1,014	0.042
Cross Member	TS 8" x 3" x ¼"	22,140	565	0.026
Upper Frame	TS 3" x 3" x ¼"	17,844	365	0.036

Table 3: Summary of maximum loads of Multiframe structual member type and sizes.

Location	Member	Detail(s)	M_z' (lbs-in)	P_x' (lbs)	V_y' (lbs)
Upper US Middle	TS 6" x 3" x ¼"	B & C	2,125.5	4,252	130
Upper US End	TS 6" x 3" x ¼"	D, G, L & P	737.7	4,252	73
Lower US End	TS 6" x 3" x ¼"	M, R & T	8,177	1,518	1,001
Mid US	TS 3" x 3" x ¼"	N, V & W	4,608	5,122	340
Lower US End	TS 6" x 3" x ¼"	U & Y	5,630	1,830	1,110

Lifting Configuration

Lifting slings (Mfgr, type, length and capacity of slings) are derated given the worst case angle of 30 degrees. This derating considers the recommended minimum capacity of 10 ton per connection by the angle factor (0.86) or 10 ton (0.86) = 8.6 ton.

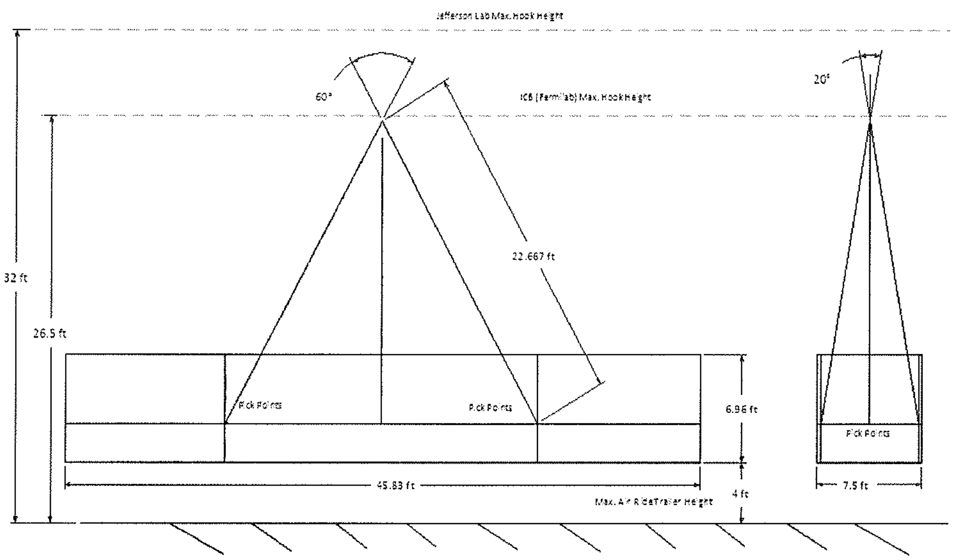

Figure 6: Lifting configuration for normal crane transport.

In the Multiframe model, the reactions given in Table 1 were found by applying self-weight of the base frame and defining loads at the (32) isolators. The lugs were constrained. To consider reactions at lugs given the lifting configuration shown in Figure 6, we must apply the estimated vertical reaction from the Multiframe model to actual geometry (given the worst-case loading, corresponding to a total system load rating of 36,000 lbs).

Maximum Vertical Reaction per Lug (from Multiframe) $R_y := 9716 \cdot lb$

Maximum Transverse Reaction $R_x := R_y \cdot \sin(20 \cdot deg)$ $R_x = 3323.0677 \cdot lb$

Maximum Longitudinal Reaction $R_z := R_y \cdot \sin(60 \cdot deg)$ $R_z = 8.414 \times 10^3 \cdot lb$

Component Stress Analysis for Base Frame

Section 1: Vertical Bending Stress in Lug (strong axis) Dwg # F10044101 (TeamCenter)

Material: ASTM A-36 Steel

Minimum Yield Stress $F_{y1} := 36000 \cdot lb \cdot in^{-2}$

Design Factor (Design Category A) $N_d := 2$

Modulus of Elasticity $E_1 := 29 \cdot 10^6 \cdot lb \cdot in^{-2}$

Lug (plate) Thickness $t_1 := 1.5 \cdot in$

Depth of Lug (plate shown in Figure 7)		$d_1 := 10 \cdot in$
Distance Between Cross Sections Braced		$L_{b1} := 2 \cdot in$
Maximum Vertical Reaction (from Multiframe, Table 1)		$R_y = 9.716 \times 10^3 \cdot lb$
Maximum Vertical Moment	$M_y := R_y \cdot L_{b1}$	$M_y = 1.943 \times 10^4 \cdot lb \cdot in$

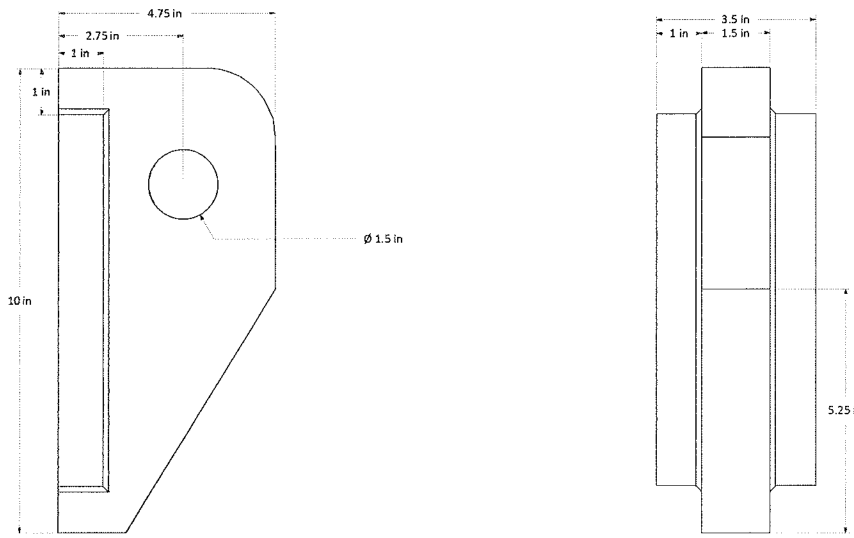

Figure 7: Lug dimensions.

Moment of Inertia (rectangular)	$I_{xx1} := 12^{-1} \cdot t_1 \cdot d_1^3$	$I_{xx1} = 125 \cdot in^4$
Distance to outermost fiber	$c_1 := (10 - 2.5) \cdot in$	$c_1 = 7.5 \cdot in$
Bending Stress	$f_{bx1} := M_y \cdot c_1 \cdot I_{xx1}^{-1}$	$f_{bx1} = 1.166 \times 10^3 \cdot lb \cdot in^{-2}$

when $\frac{L_{b1} \cdot d_1}{t_1^2} = 8.889 < \frac{1.9 \cdot E_1}{F_{y1}} = 1.531 \times 10^3$

Allowable Bending Stress (ASME BTH-1-2011, p. 20 [2])

$$F_{bx1} := \frac{1.25 \cdot F_{y1}}{N_d} \qquad F_{bx1} = 2.25 \times 10^4 \cdot \frac{lb}{in^2}$$

Factor of Safety	$FS_1 := F_{y1} \cdot f_{bx1}^{-1}$	$FS_1 = 30.877$

The bending stress is 1,166 psi and beneath the allowable of 22,500 psi with a safety factor of 30.9 based on the yield.

Section 2: Longitudinal Bending Stress in Lug (weak axis)

Material: ASTM A-36 Steel

Minimum Yield Stress		$F_{y2} := 36000 \cdot lb \cdot in^{-2}$
Design Factor (Design Category A)		$N_d = 2$
Modulus of Elasticity		$E_2 := 29 \cdot 10^6 \cdot lb \cdot in^{-2}$
Lug (plate) Thickness		$t_2 := 1.5 \cdot in$
Depth of Lug (plate)		$d_2 := 10 \cdot in$
Distance Between Cross Sections Braced		$L_{b2} := 2.75 \cdot in$
Maximum Longitudinal Reaction		$R_z = 8.414 \times 10^3 \cdot lb$
Maximum Vertical Moment	$M_z := R_z \cdot L_{b2}$	$M_z = 2.314 \times 10^4 \cdot lb \cdot in$
Moment of Inertia (rectangular)	$I_{yy2} := 12^{-1} \cdot d_2 \cdot t_2^{\ 3}$	$I_{yy2} = 2.812 \cdot in^4$
Distance to outermost fiber	$c_{z2} := .5 \cdot in$	$c_{z2} = 0.5 \cdot in$
Bending Stress	$f_{by2} := M_z \cdot c_{z2} \cdot I_{yy2}^{\ -1}$	$f_{by2} = 4.114 \times 10^3 \cdot lb \cdot in^{-2}$

Allowable Bending Stress (ASME BTH-1-2011, p. 20 [2])

$$F_{by2} := \frac{1.25 \cdot F_{y2}}{N_d} \qquad F_{by2} = 2.25 \times 10^4 \cdot \frac{lb}{in^2}$$

Factor of Safety $\quad FS_2 := F_{y2} \cdot f_{by2}^{\ -1} \qquad FS_2 = 8.751$

Bi-axial Bending Stress

Satisfied $$\frac{f_{bx1}}{F_{bx1}} + \frac{f_{by2}}{F_{by2}} = 0.235 < 1$$

The bending stress is 4,144 psi and beneath the allowable of 22,500 psi with a safety factor of 8.8 based on the yield.

Section 3: Shear Stress in Lug

Minimum Yield Stress	$F_{y3} := 36000 \cdot lb \cdot in^{-2}$
Modulus of Elasticity	$E_3 := 29 \cdot 10^6 \cdot lb \cdot in^{-2}$
Design Factor (Design Category A)	$N_d = 2$
Maximum Vertical Reaction (from Multiframe, Table 1)	$R_y = 9.716 \times 10^3 \cdot lb$

Lug (plate) Thickness $t_3 := 1.5 \cdot in$

Depth of Lug (plate) $h_3 := 10 \cdot in$

Area $A_{c3} := t_3 \cdot h_3$ $A_{c3} = 15 \cdot in^2$

Shear Stress $S_{v3} := R_y \cdot A_{c3}^{-1}$ $S_{v3} = 647.733 \cdot lb \cdot in^{-2}$

when $\frac{h_3}{t_3} = 6.667 < 2.45 \cdot \sqrt{E_3 \cdot F_{y3}^{-1}} = 69.537$

Allowable Shear Stress (ASME BTH-1-2011, p. 20 [2])

$$F_{v3} := \frac{F_{y3}}{N_d \cdot \sqrt{3}} \qquad F_{v3} = 1.039 \times 10^4 \cdot \frac{lb}{in^2}$$

Factor of Safety $FS_3 := F_{y3} \cdot S_{v3}^{-1}$ $FS_3 = 55.578$

The shear stress in lugs is 648 psi and beneath the allowable of 10,390 psi with a safety factor of 55.6 based on the yield.

Section 4: Bearing Stress at Lug Hole (AISC Ninth Edition, p. 5-74 [1])

Ultimate Strength $F_{u4} := 49500 \cdot lb \cdot in^{-2}$

Minimum Yield Stress $F_{y4} := 36000 \cdot lb \cdot in^{-2}$

Design Factor (Design Category A) $N_d = 2$

Plate Thickness $t_4 := 1.5 \cdot in$

Hole Diameter $D_{p4} := 1.5 \cdot in$

Bearing Area $A_{b4} := D_{p4} \cdot t_4$ $A_{b4} = 2.25 \cdot in^2$

Bearing Stress $S_{b4} := R_y \cdot A_{b4}^{-1}$ $S_{b4} = 4.318 \times 10^3 \cdot lb \cdot in^{-2}$

Allowable Bearing Stress (ASME BTH-1-2011, p. 26 [2])

$$F_{p4} := \frac{1.25 \cdot F_{y4}}{N_d} \qquad F_{p4} = 2.25 \times 10^4 \cdot \frac{lb}{in^2}$$

Factor of Safety (based on Ultimate) $FS_4 := F_{u4} \cdot S_{b4}^{-1}$ $FS_4 = 11.463$

The bearing stress on lugs is 4,318 psi and beneath the allowable of 22,500 psi with a safety factor of 11.5 based on the ultimate.

Section 5: Minimum Distance to Nearest Edge of Material
AISC J3.9 (Safety factor of 2) p. 5-169 to 5-170 [1].

Tensile strength of the connected material (ASTM-A36 [4])		$F_{u5} := 58000 \cdot lb \cdot in^{-2}$
Maximum Vertical Reaction (from Multiframe, Table 1)		$R_y = 9.716 \times 10^3 \cdot lb$
Hole Diameter		$d_{p5} := 1.5 \cdot in$
Lug Thickness		$t_{p5} := 1.5 \cdot in$
Bearing Area	$A_{b5} := d_{p5} \cdot t_{p5}$	$A_{b5} = 2.25 \cdot in^2$
Critical Bearing Stress	$F_{pcr5} := R_y \cdot A_{b5}^{-1}$	$F_{pcr5} = 4.318 \times 10^3 \cdot lb \cdot in^{-2}$
Required Distance to Edge from Center of Hole	$l_{e5} := 2 \cdot d_{p5} \cdot F_{pcr5} \cdot F_{u5}^{-1}$	$l_{e5} = 0.223 \cdot in$
Actual distance from the free edge to center of the pin hole		$L_{e5} := 2.5 \cdot in$

Minimum Edge Distance (from Table J3.5, AISC, 9th ed., p 5-76 [1]) was also satisfied as the minimum was 0.223 in. based on a 1-1/2 in. hole and 2.5 in. actual distance.

Section 6: Weld Stress at Lug Connection

Nominal Tensile Strength of Weld Material (E7018 rod (MIG) [5])		$E_{xx6} := 70000 \cdot lb \cdot in^{-2}$
Design Factor (Design Category A)		$N_d = 2$
Distance from Lug to Weld		$d_6 := 5 \cdot in$
Height of Weld (from Figure 8, assume 10")		$d_{w6} := 10 \cdot in$
Width of Weld		$b_6 := 4.25 \cdot in$
Thickness of Weld (fillet)		$h_6 := 0.375 \cdot in$

Bending and Shear Component (Shigley & Mischke, "Mechanical Engineering Design," 5th ed., Table 3-9, p. 396 [6])

Maximum Vertical Reaction (from Multiframe, Table 1)		$R_y = 9.716 \times 10^3 \cdot lb$
Maximum Moment due to Bending	$M_{y6} := R_y \cdot d_6$	$M_{y6} = 4.858 \times 10^4 \cdot lb \cdot in$
Distance to Outer Most Fiber		$c_{y6} := d_{w6} \cdot .5$
Weld (primary shear) Area	$A_{w6} := 1.414 \cdot h_6 \cdot (b_6 + d_{w6})$	$A_{w6} = 7.556 \cdot in^2$

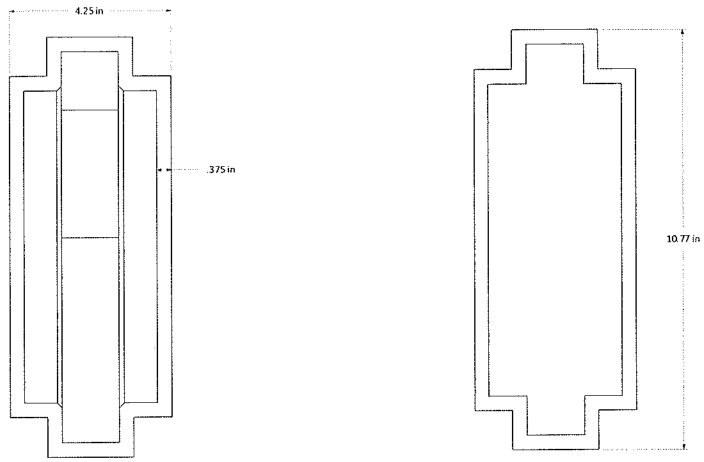

Figure 8: Welds at Lug connection to base frame.

Unit Second Moment of Area $I_{u6} := d_6^{\,2} \cdot 6^{-1} \cdot (3 \cdot b_6 + d_{w6})$ $I_{u6} = 94.792 \cdot in^3$

Moment of Inertia (from bending) $I_{xx6} := 0.707 \cdot h_6 \cdot I_{u6}$ $I_{xx6} = 25.132 \cdot in^4$

Torsional Component (Shigley & Mischke, "Mechanical Engineering Design," 5th ed., Table 9-2, p. 396 [6])

Maximum Vertical Reaction (from Multiframe, Table 1) $R_z = 8.414 \times 10^3 \cdot lb$

Maximum Moment due to Bending $M_{z6} := R_z \cdot d_6$ $M_{z6} = 4.207 \times 10^4 \cdot lb \cdot in$

Distance to Outer Most Fiber $c_{z6} := d_6 \cdot .5$

Weld (primary shear) Area $A_{j6} := 1.414 \cdot h_6 \cdot (b_6 + d_{w6})$ $A_{j6} = 7.556 \cdot in^2$

Unit Second Polar Moment of Area $J_{u6} := (b_6 + d_{w6})^3 \cdot 6^{-1}$ $J_{u6} = 482.273 \cdot in^3$

Polar Moment of Inertia (from torsion) $J_{yy6} := 0.707 \cdot h_6 \cdot J_{u6}$ $J_{yy6} = 127.863 \cdot in^4$

Maximum Combined Stress; Shear, Secondary Shear and Torsion (Shigley & Mischke, "Mechanical Engineering Design," 5th ed., p. 396 [6])

$$S_{b6} := R_y \cdot A_{w6}^{-1} + M_{y6} \cdot c_{y6} \cdot I_{xx6}^{-1} + R_z \cdot A_{j6}^{-1} + M_{z6} \cdot c_{z6} \cdot J_{yy6}^{-1} \qquad S_{b6} = 1.289 \times 10^4 \cdot lb \cdot in^{-2}$$

Allowable Stress (ASME BTH-1-2011, p. 26 [2])

$$F_{v6} := \frac{0.6 \cdot E_{xx6}}{1.20 \cdot N_d} \qquad F_{v6} = 1.75 \times 10^4 \cdot lb \cdot in^{-2}$$

Factor of Safety (nominal tensile) $FS_6 := E_{xx6} \cdot S_{b6}^{-1}$ $FS_6 = 5.432$

The shear stress in lugs is 12,890 psi and beneath the allowable of 17,500 psi with a safety factor of 5.4 based on the yield.

Stress in Structural Tubes

Dwg # F10038883, Sheet 1 - Weldment, Base Frame

Section 7: Bending Stress in Tube (Lower Back Member)

Material: ASTM A-500 Steel

Tensile Yield Strength $F_{y7} := 45000 \cdot lb \cdot in^{-2}$

Design Factor (Design Category A) $N_d = 2$

Maximum Moment (from Figure 5 and Table 2, lower back member) $M_{z7} := 67718 \cdot lb \cdot in$

Moment of Inertia (taken from ASIC, p. 1-103 [1], 6"x 3" x 1/4" tube) $I_{xx7} := 17.9 \cdot in^4$

Distance to outermost fiber $c_7 := 3 \cdot in$

Bending Stress $S_{b7} := M_{z7} \cdot c_7 \cdot I_{xx7}^{-1}$ $S_{b7} = 1.135 \times 10^4 \cdot lb \cdot in^{-2}$

Allowable Bending Stress (ASME BTH-1-2011, p. 20 [2])

$$F_{b7} := \frac{1.25 \cdot F_{y7}}{N_d} \qquad F_{b7} = 2.813 \times 10^4 \cdot \frac{lb}{in^2}$$

Factor of Safety $FS_7 := F_{y7} \cdot S_{b7}^{-1}$ $FS_7 = 3.965$

The bending stress in structural tube is11,350 psi and beneath the allowable of 28,130 psi with a safety factor of 4 based on the yield. Note that the maximum deflection of this tube is 0.062".

Section 8: Shear Stress in Tube (Lower Back Member)

Tensile Yield Strength $F_{y8} := 45000 \cdot lb \cdot in^{-2}$

Modulus of Elasticity $E_8 := 29 \cdot 10^6 \cdot lb \cdot in^{-2}$

Maximum Shear Force (Table 2) $R_{y8} := 1149 \cdot lb$

Depth of Tube $h_8 := 6 \cdot in$

Thickness of Tube $t_8 := 0.25 \cdot in$

Area (taken from ASIC, p. 1-103 [1], 6"x 3" x 1/4" tube) $A_{c8} := 4.59 \cdot in^2$

Shear Stress $S_{v8} := R_{y8} \cdot A_{c8}^{-1}$ $S_{v8} = 250.327 \cdot lb \cdot in^{-2}$

when $\frac{h_8}{t_8} = 24$ < $2.45 \cdot \sqrt{E_8 \cdot F_{y8}^{-1}} = 62.195$

Allowable Shear Stress (ASME BTH-1-2011, p. 21 [2])

$$F_{v8} := \frac{F_{y8}}{N_d \cdot \sqrt{3}} \qquad F_{v8} = 1.299 \times 10^4 \cdot \frac{lb}{in^2}$$

Factor of Safety $FS_8 := F_{y8} \cdot S_{v8}^{-1}$ $FS_8 = 179.765$

The shear stress in tubes is 250 psi and beneath the allowable of 12,990 psi with a safety factor of 180 based on the yield.

Section 9: Bending Stress in Tube (Lower Aisle Member)

Material: ASTM A-500 Steel

Tensile Yield Strength $F_{y9} := 45000 \cdot lb \cdot in^{-2}$

Design Factor (Design Category A) $N_d = 2$

Maximum Moment (from Figure 5 and Table 2, lower aisle member) $M_{z9} := 25615 \cdot lb \cdot in$

Moment of Inertia (taken from ASIC, p. 1-103 [1], 6"x 3" x 1/4" tube) $I_{xx9} := 17.9 \cdot in^4$

Distance to outermost fiber $c_9 := 3 \cdot in$

Bending Stress $S_{b9} := M_{z9} \cdot c_9 \cdot I_{xx9}^{-1}$ $S_{b9} = 4.293 \times 10^3 \cdot lb \cdot in^{-2}$

Allowable Bending Stress (ASME BTH-1-2011, p. 20 [2])

$$F_{b9} := \frac{1.25 \cdot F_{y9}}{N_d} \qquad F_{b9} = 2.813 \times 10^4 \cdot \frac{lb}{in^2}$$

Factor of Safety $FS_9 := F_{y9} \cdot S_{b9}^{-1}$ $FS_9 = 10.482$

The bending stress in structural tube is 4,923 psi and beneath the allowable of 28,130 psi with a safety factor of 10.5 based on the yield. Note that the maximum deflection of this tube is 0.042".

Section 10: Shear Stress in Tube (Lower Aisle Member)

Tensile Yield Strength $F_{y10} := 45000 \cdot lb \cdot in^{-2}$

Modulus of Elasticity $E_{10} := 29 \cdot 10^6 \cdot lb \cdot in^{-2}$

Maximum Shear Force (Table 2) $R_{y10} := 1015 \cdot lb$

Depth of Tube $h_{10} := 6 \cdot in$

Thickness of Tube $t_{10} := 0.25 \cdot in$

Area (taken from ASIC, p. 1-103 [1], 6"x 3" x 1/4" tube) $A_{c10} := 4.59 \cdot in^2$

Shear Stress $S_{v10} := R_{y10} \cdot A_{c10}^{-1}$ $S_{v10} = 221.133 \cdot lb \cdot in^{-2}$

when $\frac{h_{10}}{t_{10}} = 24$ < $2.45 \cdot \sqrt{E_{10} \cdot F_{y10}^{-1}} = 62.195$

Allowable Shear Stress (ASME BTH-1-2011, p. 21 [2])

$$F_{v10} := \frac{F_{y10}}{N_d \cdot \sqrt{3}} \qquad F_{v10} = 1.299 \times 10^4 \cdot \frac{lb}{in^2}$$

Factor of Safety $FS_{10} := F_{y10} \cdot S_{v10}^{-1}$ $FS_{10} = 203.498$

The shear stress in tubes is 221 psi and beneath the allowable of 12,990 psi with a safety factor of 204 based on the yield.

Section 11: Bending Stress in Tube (Lower Base Cross Member)

Material: ASTM A-500 Steel

Tensile Yield Strength $F_{y11} := 45000 \cdot lb \cdot in^{-2}$

Design Factor (Design Category A) $N_d = 2$

Maximum Moment (from Figure 5 and Table 2, cross member) $M_{z11} := 22140 \cdot lb \cdot in$

Moment of Inertia (taken from ASIC, p. 1-100 [1], 3"x 3" x 1/4" tube) $I_{yy11} := 3.16 \cdot in^4$

Distance to outermost fiber $c_{11} := 1.5 \cdot in$

Bending Stress $S_{b11} := M_{z11} \cdot c_{11} \cdot I_{yy11}^{-1}$ $S_{b11} = 1.051 \times 10^4 \cdot lb \cdot in^{-2}$

Allowable Bending Stress (ASME BTH-1-2011, p. 20 [2])

$$F_{b11} := \frac{1.25 \cdot F_{y11}}{N_d} \qquad F_{b11} = 2.813 \times 10^4 \cdot \frac{lb}{in^2}$$

Factor of Safety $FS_{11} := F_{y11} \cdot S_{b11}^{-1}$ $FS_{11} = 4.282$

The bending stress in structural tube is 10,510 psi and beneath the allowable of 28,130 psi with a safety factor of 4.3 based on the yield. Note that the maximum deflection of this tube is 0.026".

Section 12: Shear Stress in Tube (Lower Base Cross Member)

Tensile Yield Strength $F_{y12} := 45000 \cdot lb \cdot in^{-2}$

Modulus of Elasticity $E_{12} := 29 \cdot 10^6 \cdot lb \cdot in^{-2}$

Maximum Shear Force (Table 2) $R_{y12} := 565 \cdot lb$

Depth of Tube $h_{12} := 3 \cdot in$

Thickness of Tube $t_{12} := 0.25 \cdot in$

Area (taken from ASIC, p. 1-100 [1], 3"x 3" x 1/4" tube) $A_{c12} := 2.59 \cdot in^2$

Shear Stress $S_{v12} := R_{y12} \cdot A_{c12}^{-1}$ $S_{v12} = 218.147 \cdot lb \cdot in^{-2}$

$$\text{when} \quad \frac{h_{12}}{t_{12}} = 12 \quad < \quad 2.45 \cdot \sqrt{E_{12} \cdot F_{y12}^{-1}} = 62.195$$

Allowable Shear Stress (ASME BTH-1-2011, p. 21 [2])

$$F_{v12} := \frac{F_{y12}}{N_d \cdot \sqrt{3}} \qquad F_{v12} = 1.299 \times 10^4 \cdot \frac{lb}{in^2}$$

Factor of Safety $FS_{12} := F_{y12} \cdot S_{v12}^{-1}$ $FS_{12} = 206.283$

The shear stress in tubes is 218 psi and beneath the allowable of 12,990 psi with a safety factor of 206 based on the yield.

Section 13: Bending Stress in Tube (Upper Member)

Material: ASTM A-500 Steel

Tensile Yield Strength $F_{y13} := 45000 \cdot lb \cdot in^{-2}$

Design Factor (Design Category A) $N_d = 2$

Maximum Moment (from Figure 5 and Table 2, upper member) $M_{z13} := 17844 \cdot lb \cdot in$

Moment of Inertia (taken from ASIC, p. 1-96 [1], 3"x 3" x 1/4" tube) $I_{xx13} := 3.16 \cdot in^4$

Distance to outermost fiber $c_{13} := 1.5 \cdot in$

Bending Stress $S_{b13} := M_{z13} \cdot c_{13} \cdot I_{xx13}^{-1}$ $S_{b13} = 8.47 \times 10^3 \cdot lb \cdot in^{-2}$

Allowable Bending Stress (ASME BTH-1-2011, p. 20 [2])

$$F_{b13} := \frac{1.25 \cdot F_{y13}}{N_d} \qquad F_{b13} = 2.813 \times 10^4 \cdot \frac{lb}{in^2}$$

Factor of Safety $FS_{13} := F_{y13} \cdot S_{b13}^{-1}$ $FS_{13} = 5.313$

The bending stress in structural tube is 8,470 psi and beneath the allowable of 28,130 psi with a safety factor of 5.3 based on the yield. This analysis does not consider the reinforcement from the Upper Truss (a frame which is attached to the top of the Base Frame). Note that the maximum deflection of this tube is 0.036".

Section 14: Shear Stress in Tube (Upper Member)

Tensile Yield Strength $F_{y14} := 45000 \cdot lb \cdot in^{-2}$

Modulus of Elasticity $E_{14} := 29 \cdot 10^{6} \cdot lb \cdot in^{-2}$

Maximum Shear Force (Table 2) $R_{y14} := 365 \cdot lb$

Depth of Tube $h_{14} := 3 \cdot in$

Thickness of Tube $t_{14} := 0.25 \cdot in$

Area (taken from ASIC, p. 1-103 [1], 6"x 3" x 1/4" tube) $A_{c14} := 2.59 \cdot in^{2}$

Shear Stress $S_{v14} := R_{y14} \cdot A_{c14}^{-1}$ $S_{v14} = 140.927 \cdot lb \cdot in^{-2}$

$$\text{when} \quad \frac{h_{14}}{t_{14}} = 12 \quad < \quad 2.45 \cdot \sqrt{E_{14} \cdot F_{y14}^{-1}} = 62.195$$

Allowable Shear Stress (ASME BTH-1-2011, p. 21 [2])

$$F_{v14} := \frac{F_{y14}}{N_d \cdot \sqrt{3}} \qquad F_{v14} = 1.299 \times 10^{4} \cdot \frac{lb}{in^{2}}$$

Factor of Safety $FS_{14} := F_{y14} \cdot S_{v14}^{-1}$ $FS_{12} = 206.283$

The shear stress in tubes is 141 psi and beneath the allowable of 12,990 psi with a safety factor of 206 based on the yield.

Stress in Welds (Structural Tubes)

Dwg # F10038883, Sheet 2 - Weldment, Base Frame

Note that in the following paired cases (Detail A - Y) the geometry and weldments are the same with slightly different loads, Sections 15 through 20 considers the worst-case loading.

Section 15: Weld Stress at Connection (Details B & C)

Nominal Tensile Strength of Weld Material (E7018 rod (MIG) [5]) $E_{xx15} := 70000 \cdot lb \cdot in^{-2}$

Design Factor (Design Category A) $N_d = 2$

Height of Weld (from Figure 9(a)) $d_{w15} := 3 \cdot in$

Width of Weld $b_{15} := 3 \cdot in$

Thickness of Weld (fillet) $h_{15} := 0.25 \cdot in$

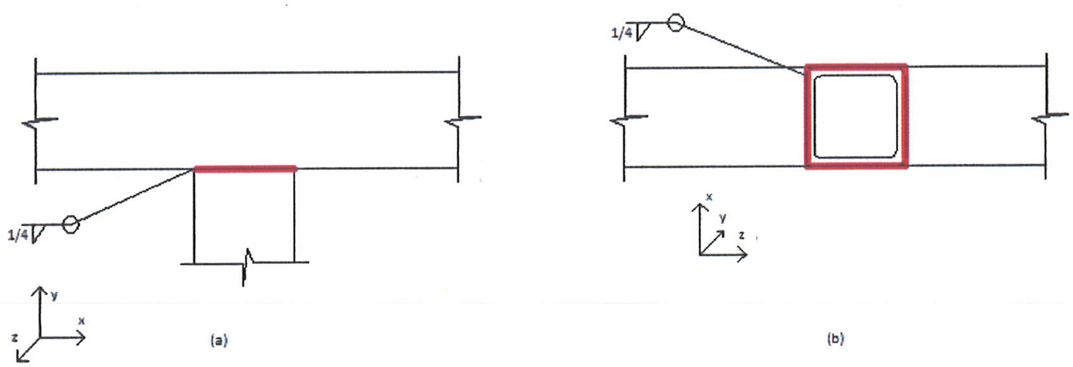

Figure 9(a): Longitudinal view of upper-mid weldment. **9(b):** Bottom-view of same weldment.

Bending and Shear Component (Shigley & Mischke, "Mechanical Engineering Design," 5th ed., Table 3-9, p. 396 [6])

Maximum Vertical Reaction (from Multiframe, Table 3) $R_{y15} := 130 \cdot lb$

Maximum Moment due to Bending $M_{y15} := R_{y15} \cdot d_{w15}$ $M_{y15} = 390 \cdot lb \cdot in$

Distance to Outer Most Fiber $c_{y15} := d_{w15} \cdot .5$

Weld (primary shear) Area $A_{w15} := 1.414 \cdot h_{15} \cdot (b_{15} + d_{w15})$ $A_{w15} = 2.121 \cdot in^2$

Unit Second Moment of Area $I_{u15} := d_{w15}^{\,2} \cdot 6^{-1} \cdot (3 \cdot b_{15} + d_{w15})$ $I_{u15} = 18 \cdot in^3$

Moment of Inertia (from bending) $I_{xx15} := 0.707 \cdot h_{15} \cdot I_{u15}$ $I_{xx15} = 3.181 \cdot in^4$

Torsional Component (Shigley & Mischke, "Mechanical Engineering Design," 5th ed., Table 9-2, p. 396 [6])

Maximum Longitudinal Reaction (Table 3) $R_{z15} := 4252 \cdot lb$

Maximum Moment due to Bending $M_{z15} := 2125.5 \cdot lb \cdot in$

Distance to Outer Most Fiber $c_{z15} := d_{w15} \cdot .5$

Weld (primary shear) Area $A_{j15} := 1.414 \cdot h_{15} \cdot (b_{15} + d_{w15})$ $A_{j15} = 2.121 \cdot in^2$

Unit Second Polar Moment of Area $J_{u15} := (b_{15} + d_{w15})^3 \cdot 6^{-1}$ $J_{u15} = 36 \cdot in^3$

Polar Moment of Inertia (from torsion) $J_{yy15} := 0.707 \cdot h_{15} \cdot J_{u15}$ $J_{yy15} = 6.363 \cdot in^4$

Maximum Combined Stress; Shear, Secondary Shear and Torsion (Shigley & Mischke, "Mechanical Engineering Design," 5th ed., p. 396 [6])

$$S_{b15} := R_{y15} \cdot A_{w15}^{\,-1} + M_{y15} \cdot c_{y15} \cdot I_{xx15}^{\,-1} + R_{z15} \cdot A_{j15}^{\,-1} + M_{z15} \cdot c_{z15} \cdot J_{yy15}^{\,-1}$$

$$S_{b15} = 2.751 \times 10^3 \cdot lb \cdot in^{-2}$$

Allowable Stress (ASME BTH-1-2011, p. 27 [2])

$$F_{v15} := \frac{0.6 \cdot E_{xx15}}{1.20 \cdot N_d} \qquad F_{v15} = 1.75 \times 10^4 \cdot lb \cdot in^{-2}$$

Factor of Safety (nominal tensile) $FS_{15} := E_{xx15} \cdot S_{b15}^{-1}$ $FS_{15} = 25.446$

The combined stress in weldment is 2,751 psi and beneath the allowable of 17,500 psi with a safety factor of 25.5 based on the rod strength.

Section 16: Weld Stress at Connection (Details D, G, L & P)

Nominal Tensile Strength of Weld Material (E7018 rod (MIG) [5]) $E_{xx16} := 70000 \cdot lb \cdot in^{-2}$

Design Factor (Design Category A) $N_d = 2$

Height of Weld (from Figure 10(a)) $d_{w16} := 6 \cdot in$

Width of Weld $b_{16} := 3 \cdot in$

Thickness of Weld (fillet) $h_{16} := 0.25 \cdot in$

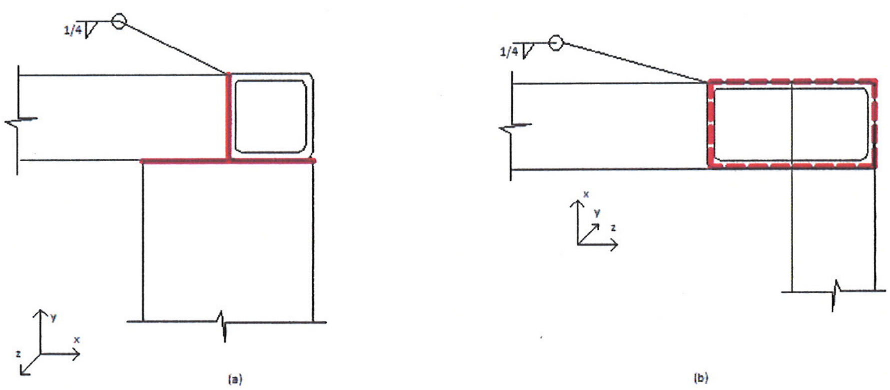

Figure 10(a): Longitudinal view of upper-end weldment. 10**(b):** Bottom-view of same weldment.

Bending and Shear Component (Shigley & Mischke, "Mechanical Engineering Design," 5th ed., Table 3-9, p. 396 [6])

Maximum Vertical Reaction (from Multiframe, Table 3) $R_{y16} := 73 \cdot lb$

Maximum Moment due to Bending $M_{y16} := R_{y16} \cdot d_{w16}$ $M_{y16} = 438 \cdot lb \cdot in$

Distance to Outer Most Fiber $c_{y16} := d_{w16} \cdot .5$

Weld (primary shear) Area $A_{w16} := 1.414 \cdot h_{16} \cdot (b_{16} + d_{w16})$ $A_{w16} = 3.181 \cdot in^2$

Unit Second Moment of Area $I_{u16} := d_{w16}^{2} \cdot 6^{-1} \cdot (3 \cdot b_{16} + d_{w16})$ $I_{u16} = 90 \cdot in^3$

Moment of Inertia (from bending) $I_{xx16} := 0.707 \cdot h_{16} \cdot I_{u16}$ $I_{xx16} = 15.907 \cdot in^4$

Torsional Component (Shigley & Mischke, "Mechanical Engineering Design," 5th ed., Table 9-2, p. 396 [6])

Maximum Longitudinal Reaction (Table 3) $R_{z16} := 4252.4 \cdot lb$

Maximum Moment due to Bending $M_{z16} := 737.7 \cdot lb \cdot in$

Distance to Outer Most Fiber $c_{z16} := d_{w15} \cdot .5$

Weld (primary shear) Area $A_{j16} := 1.414 \cdot h_{16} \cdot (b_{16} + d_{w16})$ $A_{j16} = 3.181 \cdot in^2$

Unit Second Polar Moment of Area $J_{u16} := (b_{16} + d_{w16})^3 \cdot 6^{-1}$ $J_{u16} = 121.5 \cdot in^3$

Polar Moment of Inertia (from torsion) $J_{yy16} := 0.707 \cdot h_{16} \cdot J_{u16}$ $J_{yy16} = 21.475 \cdot in^4$

Maximum Combined Stress; Shear, Secondary Shear and Torsion (Shigley & Mischke, "Mechanical Engineering Design," 5th ed., p. 396 [6])

$$S_{b16} := R_{y16} \cdot A_{w16}^{-1} + M_{y16} \cdot c_{y16} \cdot I_{xx16}^{-1} + R_{z16} \cdot A_{j16}^{-1} + M_{z16} \cdot c_{z16} \cdot J_{yy16}^{-1}$$

$$S_{b16} = 1.494 \times 10^3 \cdot lb \cdot in^{-2}$$

Allowable Stress (ASME BTH-1-2011, p. 27 [2])

$$F_{v16} := \frac{0.6 \cdot E_{xx16}}{1.20 \cdot N_d} \qquad F_{v16} = 1.75 \times 10^4 \cdot lb \cdot in^{-2}$$

Factor of Safety (nominal tensile) $FS_{16} := E_{xx16} \cdot S_{b16}^{-1}$ $FS_{16} = 46.864$

The combined stress in weldment is 1,494 psi and beneath the allowable of 17,500 psi with a safety factor of 46.9 based on the rod strength.

Section 17: Weld Stress at Connection (Details M, R & T)

Nominal Tensile Strength of Weld Material (E7018 rod (MIG) [5]) $E_{xx17} := 70000 \cdot lb \cdot in^{-2}$

Design Factor (Design Category A) $N_d = 2$

Height of Weld (from Figure 11(a)) $d_{w17} := 6 \cdot in$

Width of Weld $b_{17} := 3 \cdot in$

Thickness of Weld (fillet) $h_{17} := 0.25 \cdot in$

Bending and Shear Component (Shigley & Mischke, "Mechanical Engineering Design," 5th ed., Table 3-9, p. 396 [6])

Maximum Vertical Reaction (from Multiframe, Table 3) $R_{y17} := 1001 \cdot lb$

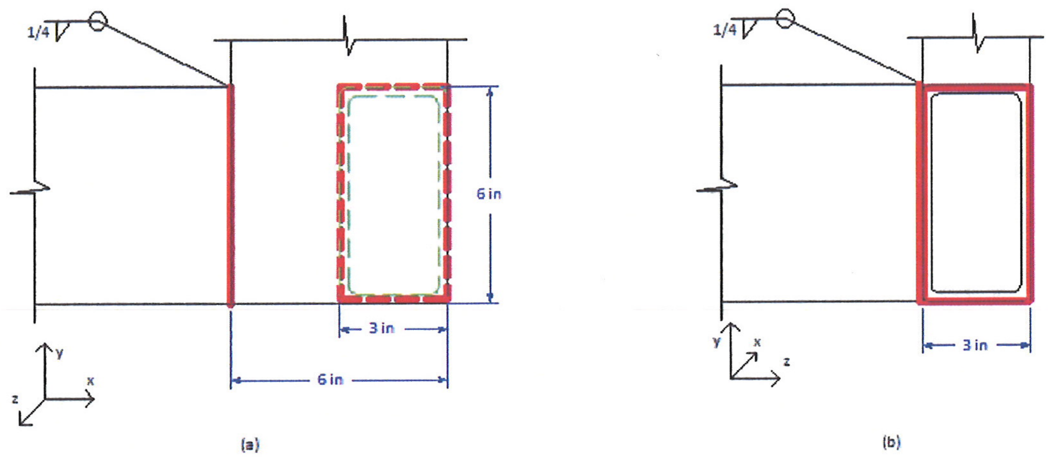

Figure 11(a): Longitudinal view of lower end weldment. **11(b):** Transverse view of same weldment.

Maximum Moment due to Bending $M_{y17} := R_{y17} \cdot d_{w17}$ $M_{y17} = 6.006 \times 10^3 \cdot lb \cdot in$

Distance to Outer Most Fiber $c_{y17} := d_{w17} \cdot .5$

Weld (primary shear) Area $A_{w17} := 1.414 \cdot h_{17} \cdot (b_{17} + d_{w17})$ $A_{w17} = 3.181 \cdot in^2$

Unit Second Moment of Area $I_{u17} := d_{w17}^{2} \cdot 6^{-1} \cdot (3 \cdot b_{17} + d_{w17})$ $I_{u17} = 90 \cdot in^3$

Moment of Inertia (from bending) $I_{xx17} := 0.707 \cdot h_{17} \cdot I_{u17}$ $I_{xx17} = 15.907 \cdot in^4$

Torsional Component (Shigley & Mischke, "Mechanical Engineering Design," 5th ed., Table 9-2, p. 396 [6])

Maximum Longitudinal Reaction (Table 3) $R_{z17} := 1517.6 \cdot lb$

Maximum Moment due to Bending $M_{z17} := 8177 \cdot lb \cdot in$

Distance to Outer Most Fiber $c_{z17} := d_{w17} \cdot .5$

Weld (primary shear) Area $A_{j17} := 1.414 \cdot h_{17} \cdot (b_{17} + d_{w17})$ $A_{j17} = 3.181 \cdot in^2$

Unit Second Polar Moment of Area $J_{u17} := (b_{17} + d_{w17})^{3} \cdot 6^{-1}$ $J_{u17} = 121.5 \cdot in^3$

Polar Moment of Inertia (from torsion) $J_{yy17} := 0.707 \cdot h_{17} \cdot J_{u17}$ $J_{yy17} = 21.475 \cdot in^4$

Maximum Combined Stress; Shear, Secondary Shear and Torsion (Shigley & Mischke, "Mechanical Engineering Design," 5th ed., p. 396 [6])

$$S_{b17} := R_{y17} \cdot A_{w17}^{-1} + M_{y17} \cdot c_{y17} \cdot I_{xx17}^{-1} + R_{z17} \cdot A_{j17}^{-1} + M_{z17} \cdot c_{z17} \cdot J_{yy17}^{-1}$$

$S_{b17} = 3.067 \times 10^3 \cdot lb \cdot in^{-2}$

Allowable Stress (ASME BTH-1-2011, p. 27 [2])

$$F_{v17} := \frac{0.6 \cdot E_{xx17}}{1.20 \cdot N_d} \qquad F_{v17} = 1.75 \times 10^4 \cdot lb \cdot in^{-2}$$

Factor of Safety (nominal tensile) $\quad FS_{17} := E_{xx17} \cdot S_{b17}^{-1} \qquad FS_{17} = 22.827$

The combined stress in weldment is 3,067 psi and beneath the allowable of 17,500 psi with a safety factor of 22.8 based on the rod strength.

Section 18: Weld Stress at Connection (Details N, V & W)

Nominal Tensile Strength of Weld Material (E7018 rod (MIG) [5]) $\quad E_{xx18} := 70000 \cdot lb \cdot in^{-2}$

Design Factor (Design Category A) $\quad N_d = 2$

Height of Weld (from Figure 12(b)) $\quad d_{w18} := 3 \cdot in$

Width of Weld $\quad b_{18} := 3 \cdot in$

Thickness of Weld (fillet) $\quad h_{18} := 0.25 \cdot in$

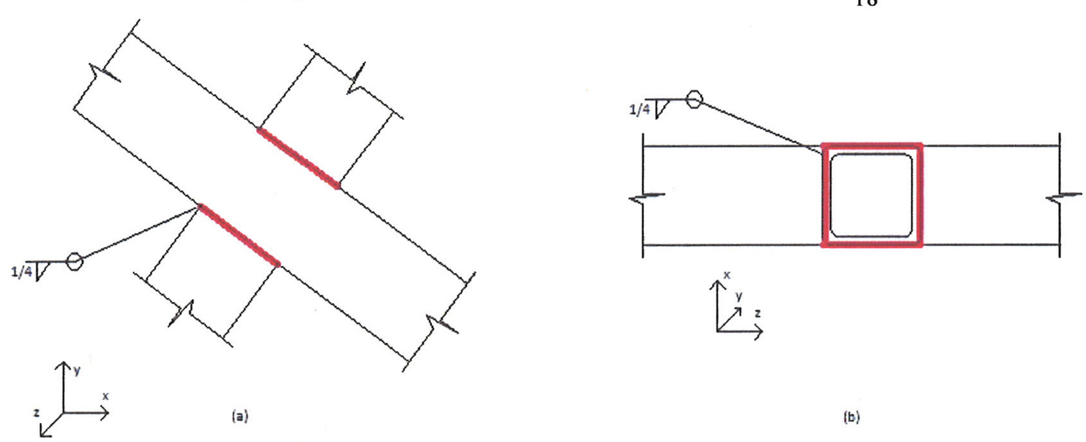

Figure 12(a): Longitudinal view of mid weldment. **12(b):** Transverse view of same weldment.

Bending and Shear Component (Shigley & Mischke, "Mechanical Engineering Design," 5th ed., Table 3-9, p. 396 [6])

Maximum Vertical Reaction (from Multiframe, Table 3) $\quad R_{y18} := 340 \cdot lb$

Maximum Moment due to Bending $\quad M_{y18} := R_{y18} \cdot d_{w18} \qquad M_{y18} = 1.02 \times 10^3 \cdot lb \cdot in$

Distance to Outer Most Fiber $\quad c_{y18} := d_{w18} \cdot .5$

Weld (primary shear) Area $\quad A_{w18} := 1.414 \cdot h_{18} \cdot (b_{18} + d_{w18}) \qquad A_{w18} = 2.121 \cdot in^2$

Unit Second Moment of Area $I_{u18} := d_{w18}^{2} \cdot 6^{-1} \cdot (3 \cdot b_{18} + d_{w18})$ $I_{u18} = 18 \cdot in^{3}$

Moment of Inertia (from bending) $I_{xx18} := 0.707 \cdot h_{18} \cdot I_{u18}$ $I_{xx18} = 3.181 \cdot in^{4}$

Torsional Component (Shigley & Mischke, "Mechanical Engineering Design," 5th ed., Table 9-2, p. 396 [6])

Maximum Longitudinal Reaction (Table 3) $R_{z18} := 5122.4 \cdot lb$

Maximum Moment due to Bending $M_{z18} := 4608 \cdot lb \cdot in$

Distance to Outer Most Fiber $c_{z18} := d_{w18} \cdot .5$

Weld (primary shear) Area $A_{j18} := 1.414 \cdot h_{18} \cdot (b_{18} + d_{w18})$ $A_{j18} = 2.121 \cdot in^{2}$

Unit Second Polar Moment of Area $J_{u18} := (b_{18} + d_{w18})^{3} \cdot 6^{-1}$ $J_{u18} = 36 \cdot in^{3}$

Polar Moment of Inertia (from torsion) $J_{yy18} := 0.707 \cdot h_{18} \cdot J_{u18}$ $J_{yy18} = 6.363 \cdot in^{4}$

Maximum Combined Stress; Shear, Secondary Shear and Torsion (Shigley & Mischke, "Mechanical Engineering Design," 5th ed., p. 396 [6])

$$S_{b18} := R_{y18} \cdot A_{w18}^{-1} + M_{y18} \cdot c_{y18} \cdot I_{xx18}^{-1} + R_{z18} \cdot A_{j18}^{-1} + M_{z18} \cdot c_{z18} \cdot J_{yy18}^{-1}$$

$$S_{b18} = 4.143 \times 10^{3} \cdot lb \cdot in^{-2}$$

Allowable Stress (ASME BTH-1-2011, p. 27 [2])

$$F_{v18} := \frac{0.6 \cdot E_{xx18}}{1.20 \cdot N_d} \qquad F_{v18} = 1.75 \times 10^{4} \cdot lb \cdot in^{-2}$$

Factor of Safety (nominal tensile) $FS_{18} := E_{xx18} \cdot S_{b18}^{-1}$ $FS_{18} = 16.898$

The combined stress in weldment is 4,143 psi and beneath the allowable of 17,500 psi with a safety factor of 16.9 based on the rod strength.

Section 19: Weld Stress at Connection (Details U & Y)

Nominal Tensile Strength of Weld Material (E7018 rod (MIG) [5]) $E_{xx19} := 70000 \cdot lb \cdot in^{-2}$

Design Factor (Design Category A) $N_d = 2$

Height of Weld (from Figure 13(a)) $d_{w19} := 3 \cdot in$

Width of Weld $b_{19} := 3 \cdot in$

Thickness of Weld (fillet) $h_{19} := 0.25 \cdot in$

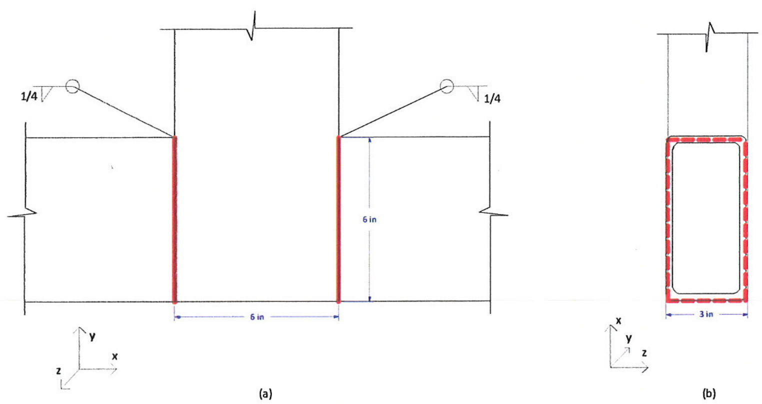

Figure 13(a): Longitudinal view of mid weldment. 13**(b):** Transverse view of same weldment.

Bending and Shear Component (Shigley & Mischke, "Mechanical Engineering Design," 5th ed., Table 3-9, p. 396 [6])

Maximum Vertical Reaction (from Multiframe, Table 3) $R_{y19} := 1110 \cdot lb$

Maximum Moment due to Bending $M_{y19} := R_{y19} \cdot d_{w19}$ $M_{y19} = 3.33 \times 10^{3} \cdot lb \cdot in$

Distance to Outer Most Fiber $c_{y19} := d_{w19} \cdot .5$

Weld (primary shear) Area $A_{w19} := 1.414 \cdot h_{19} \cdot (b_{19} + d_{w19})$ $A_{w19} = 2.121 \cdot in^{2}$

Unit Second Moment of Area $I_{u19} := d_{w19}^{\;2} \cdot 6^{-1} \cdot (3 \cdot b_{19} + d_{w19})$ $I_{u19} = 18 \cdot in^{3}$

Moment of Inertia (from bending) $I_{xx19} := 0.707 \cdot h_{19} \cdot I_{u19}$ $I_{xx19} = 3.181 \cdot in^{4}$

Torsional Component (Shigley & Mischke, "Mechanical Engineering Design," 5th ed., Table 9-2, p. 396 [6])

Maximum Longitudinal Reaction (Table 3) $R_{z19} := 1830 \cdot lb$

Maximum Moment due to Bending $M_{z19} := 5630 \cdot lb \cdot in$

Distance to Outer Most Fiber $c_{z19} := d_{w19} \cdot .5$

Weld (primary shear) Area $A_{j19} := 1.414 \cdot h_{19} \cdot (b_{19} + d_{w19})$ $A_{j19} = 2.121 \cdot in^{2}$

Unit Second Polar Moment of Area $J_{u19} := (b_{19} + d_{w19})^{3} \cdot 6^{-1}$ $J_{u19} = 36 \cdot in^{3}$

Polar Moment of Inertia (from torsion) $J_{yy19} := 0.707 \cdot h_{19} \cdot J_{u19}$ $J_{yy19} = 6.363 \cdot in^{4}$

Maximum Combined Stress; Shear, Secondary Shear and Torsion (Shigley & Mischke, "Mechanical Engineering Design," 5th ed., p. 396 [6])

$$S_{b19} := R_{y19} \cdot A_{w19}^{-1} + M_{y19} \cdot c_{y19} \cdot I_{xx19}^{-1} + R_{z19} \cdot A_{j19}^{-1} + M_{z19} \cdot c_{z19} \cdot J_{yy19}^{-1}$$

$S_{b19} = 4.283 \times 10^{3} \cdot lb \cdot in^{-2}$

Allowable Stress (ASME BTH-1-2011, p. 27 [2])

$F_{v19} := \frac{0.6 \cdot E_{xx19}}{1.20 \cdot N_d}$ $\quad F_{v19} = 1.75 \times 10^{4} \cdot lb \cdot in^{-2}$

Factor of Safety (nominal tensile) $\quad FS_{19} := E_{xx19} \cdot S_{b19}^{-1}$ $\quad FS_{19} = 16.342$

The combined stress in weldment is 4,283 psi and beneath the allowable of 17,500 psi with a safety factor of 16.3 based on the rod strength.

Section 20: Weld Stress at Connection (Detail)

Nominal Tensile Strength of Weld Material (E7018 rod (MIG) [5]) $\quad E_{xx20} := 70000 \cdot lb \cdot in^{-2}$

Design Factor (Design Category A) $\quad N_d = 2$

Width of Isolator (span from Isolator Fixture and Base Frame) $\quad d_{20} := 4 \cdot in$

Height of Weld (from Figure 14) $\quad d_{w20} := 6 \cdot in$

Width of Weld $\quad b_{20} := 15 \cdot in$

Thickness of Weld (fillet) $\quad h_{20} := 0.25 \cdot in$

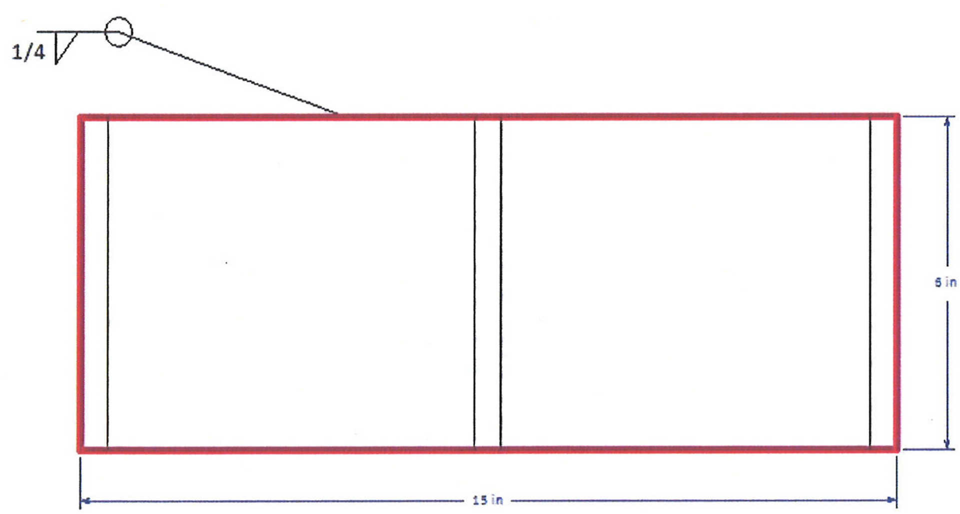

Figure 14: Front view of isolator connection weldment.

Bending and Shear Component (Shigley & Mischke, "Mechanical Engineering Design," 5th ed., Table 3-9, p. 396 [6])

The maximum load of 915 lbs per isolator considers the design load of the isolator fixture 21,105 lbs plus the rated load of 36,000 lbs minus the estimated load of 31,500 lbs. Also, during the isolator tuning process it is estimated that (32) isolators will be needed. However, this number could be as low as (28) given shock and vibration tuning. Therefore, the rated load per ioslator is (21,105 + (36,000- 31,500))/28 or 914 lbs.

Maximum Vertical Reaction

$$R_{y20} := \frac{[21105 + (36000 - 31500)] \cdot lb}{28} \qquad R_{y20} = 914 \cdot lb$$

Maximum Moment due to Bending $M_{y20} := R_{y20} \cdot d_{20}$ $\qquad M_{y20} = 3.658 \times 10^3 \cdot lb \cdot in$

Distance to Outer Most Fiber $\qquad c_{y20} := d_{w20} \cdot .5$

Weld (primary shear) Area $A_{w20} := 1.414 \cdot h_{20} \cdot (b_{20} + d_{w20})$ $\qquad A_{w20} = 7.423 \cdot in^2$

Unit Second Moment of Area $I_{u20} := d_{w20}^{2} \cdot 6^{-1} \cdot (3 \cdot b_{20} + d_{w20})$ $\qquad I_{u20} = 306 \cdot in^3$

Moment of Inertia (from bending) $I_{xx20} := 0.707 \cdot h_{20} \cdot I_{u20}$ $\qquad I_{xx20} = 54.085 \cdot in^4$

Torsional Component (Shigley & Mischke, "Mechanical Engineering Design," 5th ed., Table 9-2, p. 396 [6])

Maximum Combined Stress; Shear, Secondary Shear and Torsion (Shigley & Mischke, "Mechanical Engineering Design," 5th ed., p. 396 [6])

$$S_{b20} := R_{y20} \cdot A_{w20}^{-1} + M_{y20} \cdot c_{y20} \cdot I_{xx20}^{-1} \qquad S_{b20} = 326.078 \cdot lb \cdot in^{-2}$$

Allowable Stress (ASME BTH-1-2011, p. 27 [2])

$$F_{v20} := \frac{0.6 \cdot E_{xx20}}{1.20 \cdot N_d} \qquad F_{v20} = 1.75 \times 10^4 \cdot lb \cdot in^{-2}$$

Factor of Safety (nominal tensile) $FS_{20} := E_{xx20} \cdot S_{b20}^{-1}$ $\qquad FS_{20} = 214.672$

The combined stress in weldment is 326 psi and beneath the allowable of 17,500 psi with a safety factor of 215 based on the rod strength.

Component Stress Analysis for Isolation Fixture

Multiframe Isolation Fixture Results

The Isolation Fixture is considered in the following sections, beginning with the MultiFrame analysis. In a similar manner, a load of 914 lbs (shown in Figure 15) is defined at (28) different locations (which correspond to the isolator device attachment points). Note that the proposed case for transport involves a load of 660 lbs, distributed along (32) locations. The four attachment points for the cryomodule are constrained and the static case is solved for within MultiFrame. The results are shown in Figures 16, 17 and 18.

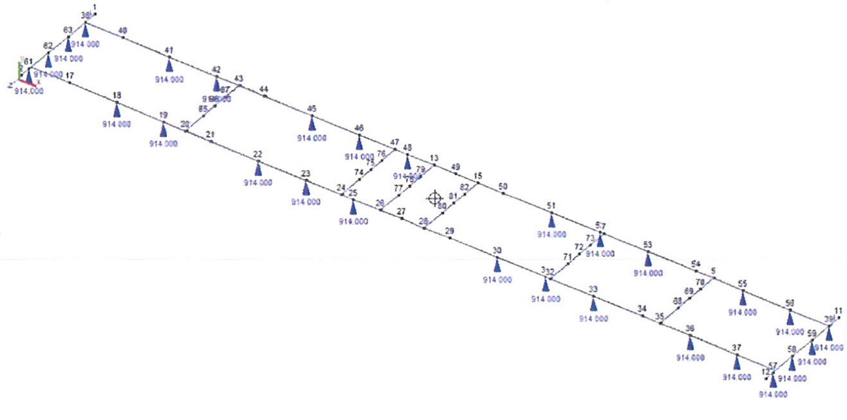

Figure 15: Multiframe loading of Isolation Fixture.

MultiFrame 15 V8i Model Moments, Shear Forces and Displacements:

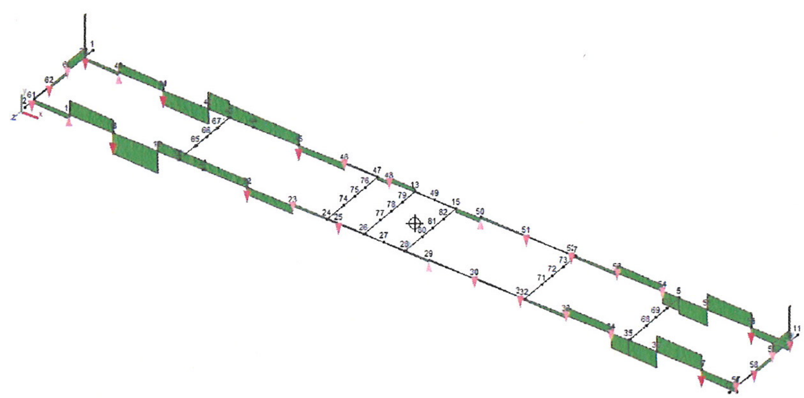

Figure 16: Multiframe vertical shear results.

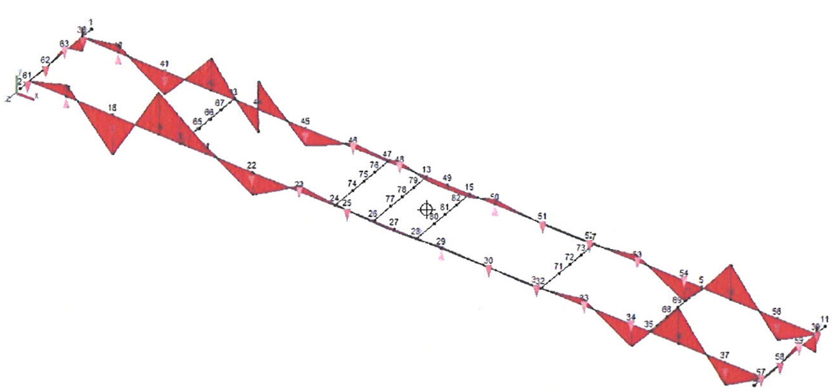

Figure 17: Multiframe moment (about z) results.

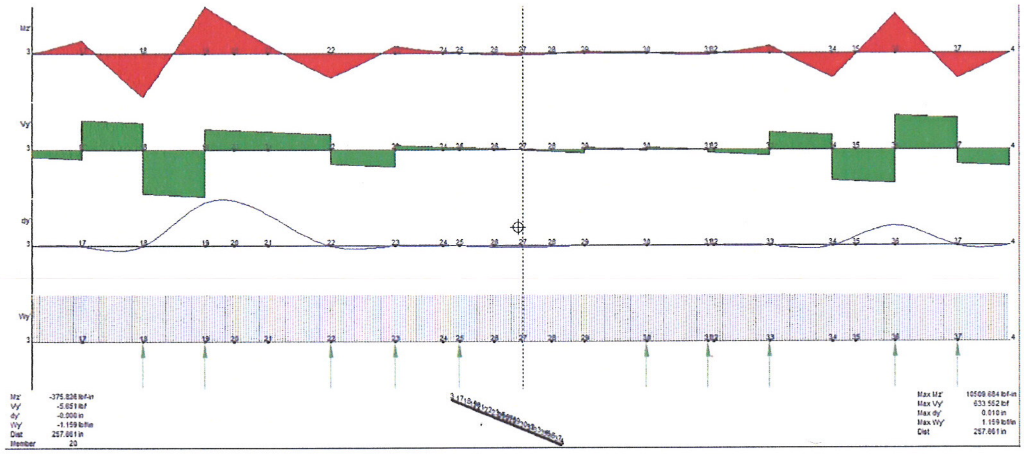

Figure 18: Multiframe results for lower 6" x 3" x 1/4" member (back-side).

Table 4: Summary of maximum loads of Multiframe structual member type for Isolation Fixture.

Location	Member	M_z'/ M_x' (lbs-in)	V_y' (lbs)	d_y' (in)
Iso Back Member	TS 6" x 3" x ¼"	50,490	4,230	0.028
Cross Member	TS 8" x 4" x ¼"	58,243	4,996	0.035
Weldment	TS 8" x 4" x ¼"	42,340	4,996	---

Stress in Structural Tubes of Isolation Fixture

Dwg # F10039628, Weldment, Base Frame

Section 21: Bending Stress in Tube (Longitudinal Member)

Material: ASTM A-500 Steel

Tensile Yield Strength $F_{y21} := 45000 \cdot lb \cdot in^{-2}$

Design Factor (Design Category A) $N_d = 2$

Maximum Moment (Table 4, Iso Back Member) $M_{z21} := 50490 \cdot lb \cdot in$

Moment of Inertia (taken from ASIC, p. 1-103 [1], 6"x 3" x 1/4" tube) $I_{xx21} := 17.9 \cdot in^4$

Distance to outermost fiber $c_{21} := 3 \cdot in$

Bending Stress $S_{b21} := M_{z21} \cdot c_{21} \cdot I_{xx21}^{-1}$ $S_{b21} = 8.462 \times 10^3 \cdot lb \cdot in^{-2}$

Allowable Bending Stress (ASME BTH-1-2011, p. 19 [2])

$$F_{b21} := \left(1.25 \cdot F_{y21}\right) \cdot N_d^{-1} \qquad F_{b21} = 2.813 \times 10^4 \cdot \frac{lb}{in^2}$$

Factor of Safety $FS_{21} := F_{y21} \cdot S_{b21}^{-1}$ $FS_{21} = 5.318$

The bending stress in structural tube is 8,462 psi and beneath the allowable of 28,130 psi with a safety factor of 5.3 based on the yield. Note that the maximum deflection of this tube is 0.028".

Section 22: Shear Stress in Tube (Longitudinal Member)

Tensile Yield Strength		$F_{y22} := 45000 \cdot lb \cdot in^{-2}$
Modulus of Elasticity		$E_{22} := 29 \cdot 10^{6} \cdot lb \cdot in^{-2}$
Maximum Shear Force (Table 4)		$R_{y22} := 4230 \cdot lb$
Depth of Tube		$h_{22} := 6 \cdot in$
Thickness of Tube		$t_{22} := 0.25 \cdot in$
Area (taken from ASIC, p. 1-103 [1], 6"x 3" x 1/4" tube)		$A_{c22} := 4.59 \cdot in^{2}$
Shear Stress	$S_{v22} := R_{y22} \cdot A_{c22}^{-1}$	$S_{v22} = 921.569 \cdot lb \cdot in^{-2}$

$$\text{when} \quad \frac{h_{22}}{t_{22}} = 24 \quad < \quad 2.45 \cdot \sqrt{E_{22} \cdot F_{y22}^{-1}} = 62.195$$

Allowable Shear Stress (ASME BTH-1-2011, p. 21 [2])

$$F_{v22} := \frac{F_{y22}}{N_d \cdot \sqrt{3}} \qquad F_{v22} = 1.299 \times 10^{4} \cdot \frac{lb}{in^{2}}$$

Factor of Safety $\quad FS_{22} := F_{y22} \cdot S_{v22}^{-1} \quad FS_{22} = 48.83$

The shear stress in tubes is 922 psi and beneath the allowable of 12,990 psi with a safety factor of 49 based on the yield.

Section 23: Bending Stress in Tube (Isolation Cross Member)

Material: ASTM A-500 Steel

Tensile Yield Strength		$F_{y23} := 45000 \cdot lb \cdot in^{-2}$
Design Factor (Design Category A)		$N_d = 2$
Maximum Moment (from Table 4, Cross Member)		$M_{x23} := 58243 \cdot lb \cdot in$
Moment of Inertia (taken from ASIC, p. 1-101 [1], 8"x 4" x 1/4" tube)		$I_{yy23} := 15.3 \cdot in^{4}$
Distance to outermost fiber		$c_{23} := 1.5 \cdot in$
Bending Stress	$S_{b23} := M_{x23} \cdot c_{23} \cdot I_{yy23}^{-1}$	$S_{b23} = 5.71 \times 10^{3} \cdot lb \cdot in^{-2}$

Allowable Bending Stress (ASME BTH-1-2011, p. 21 [2])

$$F_{b23} := \frac{1.25 \cdot F_{y23}}{N_d} \qquad F_{b23} = 2.813 \times 10^4 \cdot \frac{lb}{in^2}$$

Factor of Safety $\quad FS_{23} := F_{y23} \cdot S_{b23}^{-1} \qquad FS_{23} = 7.881$

The bending stress in structural tube is 5,710 psi and beneath the allowable of 28,130 psi with a safety factor of 7.9 based on the yield. Note that the maximum deflection of this tube is 0.026".

Section 24: Shear Stress in Tube (Isolation Cross Member)

Tensile Yield Strength $\quad F_{y24} := 45000 \cdot lb \cdot in^{-2}$

Modulus of Elasticity $\quad E_{24} := 29 \cdot 10^6 \cdot lb \cdot in^{-2}$

Maximum Shear Force (Table 4) $\quad R_{y24} := 4230 \cdot lb$

Depth of Tube $\quad h_{24} := 3 \cdot in$

Thickness of Tube $\quad t_{24} := 0.25 \cdot in$

Area (taken from ASIC, p. 1-101 [1], 8"x 4" x 1/4" tube) $\quad A_{c24} := 5.59 \cdot in^2$

Shear Stress $\quad S_{v24} := R_{y24} \cdot A_{c24}^{-1} \qquad S_{v24} = 756.708 \cdot lb \cdot in^{-2}$

$$\text{when} \quad \frac{h_{24}}{t_{24}} = 12 \quad < \quad 2.45 \cdot \sqrt{E_{24} \cdot F_{y24}^{-1}} = 62.195$$

Allowable Shear Stress (ASME BTH-1-2011, p. 21 [2])

$$F_{v24} := \frac{F_{y24}}{N_d \cdot \sqrt{3}} \qquad F_{v24} = 1.299 \times 10^4 \cdot \frac{lb}{in^2}$$

Factor of Safety $\quad FS_{24} := F_{y24} \cdot S_{v24}^{-1} \qquad FS_{24} = 59.468$

The shear stress in tubes is 757 psi and beneath the allowable of 12,990 psi with a safety factor of 60 based on the yield.

Section 25: Weld Stress at Connection (Detail)

Nominal Tensile Strength of Weld Material (E7018 rod (MIG) [5]) $\quad E_{xx25} := 70000 \cdot lb \cdot in^{-2}$

Design Factor (Design Category A) $\quad N_d = 2$

Height of Weld (from Figure 19) $\quad d_{w25} := 4 \cdot in$

Width of Weld $\quad b_{25} := 8 \cdot in$

Thickness of Weld (fillet) $\quad h_{25} := 0.25 \cdot in$

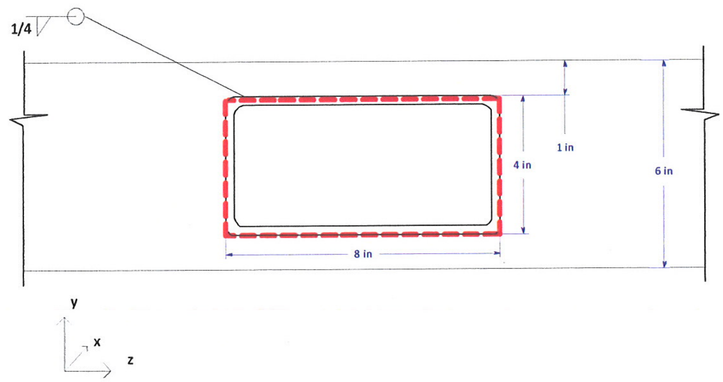

Figure 19: Longitudinal view of lower weldment.

Bending and Shear Component (Shigley & Mischke, "Mechanical Engineering Design," 5th ed., Table 3-9, p. 396 [6])

Maximum Vertical Reaction (from Multiframe, Table 3) $R_{y25} := 4996 \cdot lb$

Maximum Moment due to Bending $M_{y25} := R_{y25} \cdot d_{w25}$ $M_{y25} = 1.998 \times 10^4 \cdot lb \cdot in$

Distance to Outer Most Fiber $c_{y25} := d_{w25} \cdot .5$

Weld (primary shear) Area $A_{w25} := 1.414 \cdot h_{25} \cdot \left(b_{25} + d_{w25}\right)$ $A_{w25} = 4.242 \cdot in^2$

Unit Second Moment of Area $I_{u25} := d_{w25}^{\;2} \cdot 6^{-1} \cdot \left(3 \cdot b_{25} + d_{w25}\right)$ $I_{u25} = 74.667 \cdot in^3$

Moment of Inertia (from bending) $I_{xx25} := 0.707 \cdot h_{25} \cdot I_{u25}$ $I_{xx25} = 13.197 \cdot in^4$

Torsional Component (Shigley & Mischke, "Mechanical Engineering Design," 5th ed., Table 9-2, p. 396 [6])

Maximum Moment due to Bending $M_{z25} := 42340 \cdot lb \cdot in$

Distance to Outer Most Fiber $c_{z25} := d_{w25} \cdot .5$

Weld (primary shear) Area $A_{j25} := 1.414 \cdot h_{25} \cdot \left(b_{25} + d_{w25}\right)$ $A_{j25} = 4.242 \cdot in^2$

Unit Second Polar Moment of Area $J_{u25} := \left(b_{25} + d_{w25}\right)^3 \cdot 6^{-1}$ $J_{u25} = 288 \cdot in^3$

Polar Moment of Inertia (from torsion) $J_{yy25} := 0.707 \cdot h_{25} \cdot J_{u25}$ $J_{yy25} = 50.904 \cdot in^4$

Maximum Combined Stress; Shear, Secondary Shear and Torsion (Shigley & Mischke, "Mechanical Engineering Design," 5th ed., p. 396 [6])

$$S_{b25} := R_{y25} \cdot A_{w25}^{\;-1} + M_{y25} \cdot c_{y25} \cdot I_{xx25}^{\;-1} + M_{z25} \cdot c_{z25} \cdot J_{yy25}^{\;-1}$$

$$S_{b25} = 5.87 \times 10^{3} \cdot lb \cdot in^{-2}$$

Allowable Stress (ASME BTH-1-2011, p. 27 [2])

$$F_{v25} := \frac{0.6 \cdot E_{xx25}}{1.20 \cdot N_d} \qquad F_{v25} = 1.75 \times 10^{4} \cdot lb \cdot in^{-2}$$

Factor of Safety (nominal tensile) $\quad FS_{25} := E_{xx25} \cdot S_{b25}^{-1} \qquad FS_{25} = 11.926$

The combined stress in weldment is 5,870 psi and beneath the allowable of 17,500 psi with a safety factor of 12 based on the rod strength.

Component Stress Analysis for Upper Truss

Introduction

The upper truss frame design originated from a simple three 3" x 3" x 1/4" steel tube, cross-member concept. A new design was considered, since there was a possibility for either injury to personnel or equipment damage. Another improvement involves using the 10-ton strongback lifting fixture (normally used to move a cryomodule) to attach and remove the upper truss frame from the transport base frame as shown in Figure 20. The upper truss frame weighs roughly 500 lbs. With this design change there exists a possibility of loading the upper truss frame with the 10-ton strongback lifting fixture tare weight of 3.52 tons. This may occur if the crane operator lowers or unloads the crane instead of lifting the upper truss frame from the transport base frame. The upper cryomodule exists just inches below the upper truss frame, therefore protection against this accident case is reasonable to consider. Otherwise, the upper truss is a protective feature regarding the transport system and is not meant to provide structural reinforcment of the base frame.

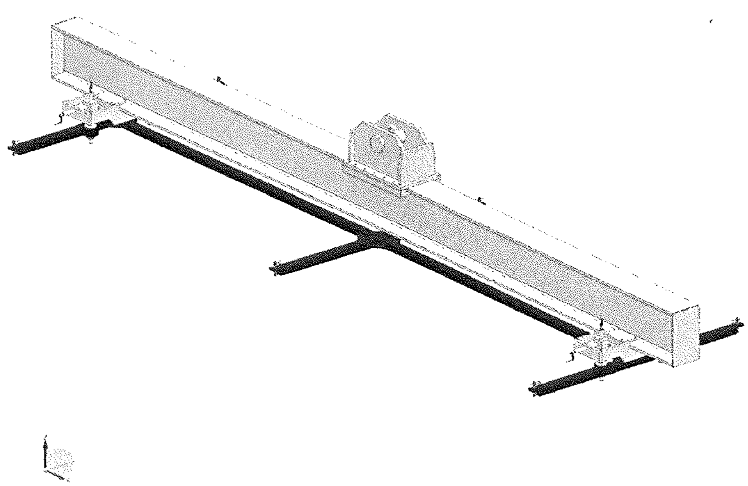

Figure 20: Use of 10-ton strongback lifting fixture to remove the upper truss frame.

Allowable Stresses

The upper truss frame structural design is made of A-500 Grade B Steel tube. The structural upper truss frame meets the AISC Manual of Steel Construction requirements for Allowable Stress Design [1]. The maximum primary stress shall be beneath 0.6Fy = 27.6 Ksi (in bending), 0.4Fy = 18.4 Ksi (in shear), where the Tensile Yield Strength (Fy) is 46 Ksi [1].

Geometry and Loading

The basic structure consists of four horizontal 3" x 3" steel tube members welded together; (3) transverse members (3/16" thick) and (2) connecting longitudinal members (1/4" thick). The loading onto the upper truss frame was based on the tare weight of the 10-ton strongback lifting fixture increased (rounded up) to 4 tons. Therefore, a 1 ton vertical load was applied to each connection point on the upper truss frame.

Finite Element Analysis

ANSYS Workbench 15 was implemented in order to consider transport upper truss frame stresses and deflections. Figure 21 provides the maximum vertical deflection downward of 0.071". Figure 22 shows the stress intensity over the frame. The maximum stress intensity of 26.5 Ksi was found on the connecting longitudinal member in bending.

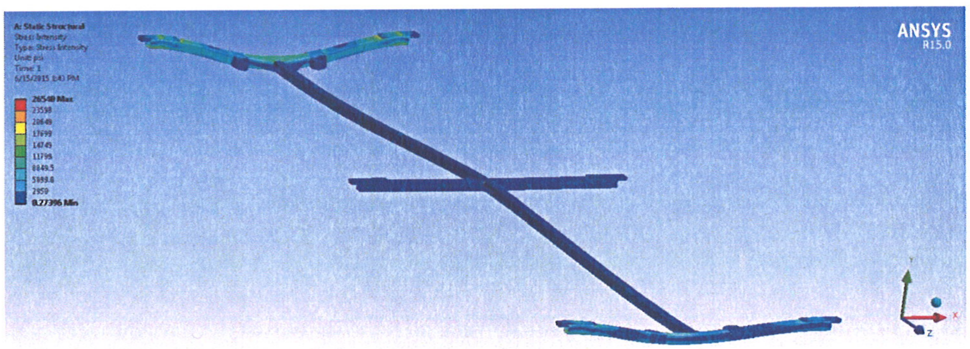

Figure 21: Vertical deflection.

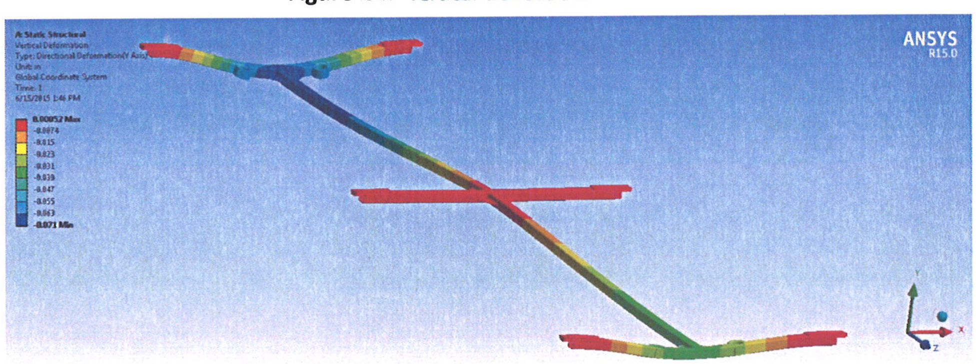

Figure 22: Stress intensity plot from ANSYS.

The transport system upper truss frame design analyzed in this report met the AISC Allowable Stress Design requirements. The maximum stress intensity within the structural tube estimated by using ANSYS was roughly 26.5 Ksi (in bending) and the allowable stresses were 27.6 Ksi (for bending) and 18.4 Ksi (for shear) [1].

References

[1] American Institue of Steel Construction (AISC) Standards, "Steel Construction Manual," 9th Ed.

[2] ASME Design of Below-the-Hook Lifting Devices, ASME BTH-1-2011.

[3] McGee, M., "LCLS-II 1.3 GHz Cryomodule Transport System," Fermilab TeamCenter # ED0002675.

[4] ASTM-A36.

[5] http://www.red-d-arc.com/pdf/Welding%20Electrode%20Classifications.pdf

[6] Shigley & Mischke, "Mechanical Engineering Design," 5th ed.