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Author(s): Peebles, Garrett William

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Source Physics Experiment DAG

Final Design Review Lifting Equipment

Garrett Peebles
Los Alamos National Laboratory
Source Execution Team
June 27, 2017

Design Criteria

- **Lifting Structures**

- 3.5 yield strength / 5 ultimate strength (exceeds ASME BTH-1)
 - HSLA 100 – Yield 100 ksi, Ultimate 115 ksi, (Max Allowable Stress 23 ksi)
 - A36 – Yield 36 ksi, Ultimate 70 ksi, (Max Allowable Stress 10.2 ksi)
- 150 kip Load for 84” vessel
- 6 kip Load for 42”vessel

- **Bolted Joints**

- 35% Variation on Torque - [NASA-STD-5020]
- 5% Relaxation on preload - [NASA-STD-5020]
- Joint Separation Factor of Safety = 1.4 - [NASA-STD-5020]
- Tensile / Bearing Stress via allowables described in BTH-1 pg 17.
- Bolts Specifications – [ASTM A574] (170 ksi ultimate strength)

- **Testing**

- 1.25x the rated load will be tested at Holloway Houston
 - This includes the lifting structures and equalizer beam

Large Lifting Frame - 84" Vessel

Purpose

- Connect the tank to the equalizer beam
- Provide an interface for the shield

Attachments

- To Equalizer beam via 6" pin
- To the tank via 24x bolt pattern

Properties

- A36 steel / HSLA 100 for lifting lugs
- Weight ~3.4 kip

Dimensions

- Thickness of bottom ring – 6"
- Width of bottom ring – 3"
- Legs – 1.5" thick
- Outer Diameter – 90"
- Bottom to centerline of the pin hole – 58"

Analyses Large Lifting Frame

FEA Analysis

Clevis Analysis – Hand Calculations

- Lifting Lugs - HSLA 100 Steel
- Rest of structure - A36 Steel

Analysis Parameters Large Lifting Frame

Load Case	84" Vessel - Large Lifting Frame
Load Case Overview	Lifting frame attachment for the 84" Vessel Complete lifting frame viewed as one solid part. Assuming welds have base material strength. Half Symmetry
Model Fidelity / Simplifications	Bearing Load (150 kip) - This is a conservative load the nominal design weight is 126 kip. Top of Central Plate N/A
Load Type 1	Fix Constraint
Load Placement 1	Bottom Surface of Ring
Load Type 2	Multi-Pass-Adaptive
Load Placement 2	
Boundary Condition Type	
Boundary Condition Location(s)	
Run Settings	
FEA Parameters	
Component Interaction (Bonded / Contact / Free)	Welds: Single Solid
Mesh Refinement Used	Max element size: 2.0" (global)
Element Total	100326
Material	A36
Poisson's ratio	0.26 [-]
Density	0.284 lb/in ³
Modulus of Elasticity	29000 KSI
Yield Strength	36 KSI
Ultimate Strength (Tensile)	70 KSI
FEA Results	
Allowable Stress	10.2 KSI (yield strength 36 KSI @ FoS of 3.5)
Peak Stress (VM) - Entire Model	9.6 KSI
Peak Displacement - Entire Model	0.007"
Areas removed from summary	None
Reason for removal (Riser: Geometry / Load Edge / BC Edge)	N/A
Peak Stress (VM) *	N/A
Other Notes	
Date	6/22/2017
Run time	32 min
Converged on maximum order	5
Stress Error (% of Max Prin Str)	0.9%

Margin: 0.6 KSI

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Results Large Lifting Frame Body

Max Von-Mises Stress : 9.6 ksi

Max Displacement: 0.007 in

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Results Large Lifting Frame – Lifting Lugs

Lifting Frame - Pin Connection

Materials

HSLA 100 Steel $\sigma_{YS} := 100 \text{ ksi}$ $\sigma_{US} := 115 \text{ ksi}$
 A36 Steel $\sigma_Y := 36 \text{ ksi}$ $\sigma_U := 70 \text{ ksi}$

Lifting Load

$$F := \frac{150}{2} \text{ kip} = 75 \text{ kip}$$

Shigley Pinned Connection

$d := 6.125 \text{ in}$ Pin Hole Diam
 $w := 18 \text{ in}$ refer to chart
 $h := 9 \text{ in}$ refer to chart
 $t := 2 \text{ in}$ Thickness
 $d \cdot w^{-1} = 0.34$
 $k_t := 3.6$ From Chart

$$\sigma_{nom} := F \cdot ((w - d) \cdot t)^{-1} = 3.158 \text{ ksi}$$

$$\sigma_{act} := \sigma_{nom} \cdot k_t = 11.368 \text{ ksi}$$

$$n_{p_yield} := \frac{\sigma_{YS}}{\sigma_{act}} = 8.796$$

$$n_{p_ult} := \frac{\sigma_{US}}{\sigma_{act}} = 10.116$$

Welded Joint - Full Penetration Weld

$t := 2 \text{ in}$ Thickness of each plate
 $l := 18 \text{ in}$ length of weld

$$\sigma_t := \frac{F}{l \cdot t} = 2.083 \text{ ksi}$$
 Stress through the weld

$$n_o := \frac{\sigma_Y}{\sigma_t} = 17.28$$
 Factor of Safety on A36 Steel

Large Lifting Frame - Bolt Calculation

Assumptions

- $\mu_T = 0.12$, CoF (Threads)
 - [Table 5, NASA Fastener Design Manual]
- $\mu_H = 0.15$, CoF (Under Bolt Head)
 - [Table 5, NASA Fastener Design Manual]
- Torque Adjustment Factor $\pm 35\%$
 - [NASA-STD-5020]
- Preload relaxation 5%
 - [NASA-STD-5020]
- 150 kip Load Case
 - 126 kip is the nominal design weight

Specifications

- Torque – (350 ± 10) ft*lbs
- Preload Range (14.5 – 33.7) kips

Bolt Pattern

- (24x) UNC 1"-8 x 10"
 - Bolts - ASTM A574 (ult strength -170 ksi)

Load Case	Bolt			Clamped Part			Joint	
	SF _{Tensile Yielding}	SF _{Overload}	SF _{Shear Stress}	SF _{Bearing}	SF _{Pull Through}	SF _{Shear Stress}	SF _{Joint Sep}	SF _{Min. Thread Eng.}
Nominal	56.04	172.71	16.18	1.94	17.23	4.57	4.09	1.39
Upper Limit	56.04	142.76	11.69	1.40	12.45	3.30	5.69	
Lower Limit	56.04	203.56	26.74	3.20	28.48	7.55	2.46	
BTH-1 (>1)			BTH-1 (>1)			NASA - STD- 5020 (>1.4)		

Small Vessel Lifting Frame

Purpose:

- Connect the tank to the equalizer beam
- Provide an interface for shield

Attachments:

- To Equalizer beam via 6" pin
- To the tank via 12x bolt pattern

Properties:

- A36 steel
- Weight ~182 lbs

Dimensions:

- Thickness of bottom ring – 6"
- Width of bottom ring – 2.5"
- Legs – 1" thick
- Outer Diameter – 48"
- Bottom to centerline of the pin hole – 42"

Analysis:

- Max Stress – 2.2 ksi
- Safety Factor - 4.36 on yield

Margin: 8 KSI

Equalizer Beam

Purpose

- Attaches all the lifting structures to the pendants

Properties

- HSLA 100
- Weight ~725 lbs

Equalizer Beam Analysis Parameters

Load Case	Equalizer Beam
Load Case Overview	Tilted Equalizer Beam lifting senario. The 4.125" pin holes are 18" spaced vertically.
Model Fidelity / Simplifications	Fixed boundaries at the lower 4.125" hole Bearing Load (150 kip) at the 6.125" pin location- This is a conservative load the nominal design weight is 126 kip.
Load Type 1	The Bearing Load on the 6.125" pin acts at 22° off the vertical axis. The off set of load is used to represent the 18 inch height difference between 4.125" pins.
Load Placement 1	Bearing Load 87.64 kip at the upper 4.125" pin
Load Type 2	The Bearing Load on the 4.125" pin acts at 22° off the vertical axis, opposite to the direction of the load on the 6.125" pin. The off set of load is used to represent the 18 inch height difference between 4.125" pins
Load Placement 2	Fix Constraint
Boundary Condition Type	At the lower 4.125" pin hole
Boundary Condition Location(s)	Multi-Pass-Adaptive
Run Settings	
FEA Parameters	
Component Interaction (Bonded / Contact / Free)	Contact
Mesh Refinement Used	Max element size: 2.0" (global)
Element Total	68916
Material	HSLA 100
Poisson's ratio	0.28 [-]
Density	0.282 lb/in^3
Modulus of Elasticity	29700 KSI
Yield Strength	100 KSI
Ultimate Strength (Tensile)	115 KSI
FEA Results	
Allowable Stress	23 KSI
Peak Stress (VM) - Entire Model	22.9 KSI
Peak Displacement - Entire Model	0.06"
Areas removed from summary	None
Reason for removal (Riser: Geometry / Load Edge / BC Edge)	N/A
Peak Stress (VM) *	N/A
Other Notes	
Date	6/24/2017
Run time	~7 min
Converged on maximum order	4
Stress Error (% of Max Prin Str)	0.2%

Margin: 0.1 KSI

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Equalizer Beam FEA Results

Stress (ksi) (WCS)
Loadset: LoadSet1 : DAG1_LLB

22.9367
23.0000
17.2500
11.5000
5.75000
0.00000
0.00106

Max Von-Mises Stress : 22.9 ksi

Displacement (in) (WCS)
Max Disp 6.4366E-02
Loadset: LoadSet1 : DAG1_LLB

0.06437
0.10000
0.07500
0.05000
0.02500
0.00000
0.00000

Max Displacement: 0.06 in

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Summary

- **Large Lifting Frame**

- Max Stress – 9.8 ksi
 - Max Allowable – 10.2
- FoS on joint separation – 2.4

- **Small Lifting Frame**

- Max Stress - 2.2 ksi
 - Max Allowable– 10.2 ksi
- FoS on Joint separation – 5.76

- **Equalizer Beam**

- Max Stress – 22.9 ksi
 - Max Allowable – 23 ksi

Appendix

Large Lifting Frame Pin Connection BTH-1

BTH-1 Guide Lines Big Pin

$D_h := 6.125 \text{ in}$ Hole Diameter
 $D_p := 6 \text{ in}$ Pin Diameter
 $t := 2.5 \text{ in}$ Thickness of Plate
 $N_d := 2$ Category A lift parameter
 $R := 9 \text{ in}$ Distance from the center of the hole to the edge of the plate in the direction of the applied load
 $b_e := 9 \text{ in}$ Edge of hole to the edge of the plate
 $a := 9 \text{ in}$

$\theta := 55 \text{ deg} \cdot \frac{D_p}{D_h} = 53.878 \text{ deg}$ Shear plane locating angle

$b_{eff,1} := 4 \cdot t = 10 \text{ in}$

$b_{eff,2} := b_e \cdot 0.6 \cdot \frac{\sigma_{YS}}{\sigma_{US}} \cdot \left(\frac{D_h}{b_e} \right)^{0.5} = 3.874 \text{ in}$

$b_{eff} := \min(b_{eff,1}, b_{eff,2}) = 3.874 \text{ in}$ Effective Width to each side of the pin hole

$C_r := 1 - 0.275 \cdot \left(1 - \frac{D_p^2}{D_h^2} \right)^{0.5} = 0.945$

$P_t := C_r \cdot \frac{\sigma_{US}}{1.2 \cdot N_d} \cdot 2 \cdot t \cdot b_{eff} = 876.779 \text{ kip}$ Allowable Tensile Load

$P_b := C_r \cdot \frac{\sigma_{US}}{1.2 \cdot N_d} \cdot \left(1.13 \cdot \left(R - \frac{D_h}{2} \right) + \frac{0.92 \cdot b_e}{1 + \frac{b_e}{D_h}} \right) \cdot t = (1.139 \cdot 10^3) \text{ kip}$ Allowable single plane fracture strength beyond the pinhole

$A_v := 2 \cdot \left(a + \frac{D_p}{2} \cdot (1 - \cos(\theta)) \right) \cdot t = 51.157 \text{ in}^2$

$P_v := \frac{0.7 \cdot \sigma_{US}}{1.2 \cdot N_d} \cdot A_v = (1.716 \cdot 10^3) \text{ kip}$ Allowable double plane shear strength beyond the pinhole

$F_p := \frac{1.25 \cdot \sigma_{YS}}{N_d} = 62.5 \text{ ksi}$ Max Allowable Bearing Strength for static loads

$F_p := \frac{0.63 \cdot \sigma_{YS}}{N_d} = 31.5 \text{ ksi}$ Max Allowable Bearing Strength for cyclic loads/dynamic

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Bolt Calculation Large Lifting Frame

Bolt Calculator - Large Lifting Frame

[INPUTS]

Loading

$F_E \equiv 150 \text{ kip}$ External Load on jointed assembly
 $n \equiv 24$ Number of bolts
 $T \equiv 350 \text{ lbf} \cdot \text{ft}$ Applied Torque
 +

Clamp properties

$t_1 \equiv 6 \text{ in}$ Thickness of clamped material
 $t_2 \equiv 6 \text{ in}$ Thickness of threaded material

Threaded/clamped material properties (same material)

$E \equiv 29000 \text{ ksi}$ $\sigma_y \equiv 36 \text{ ksi}$ $\sigma_u \equiv 70 \text{ ksi}$ $\sigma_{uT} \equiv 70 \text{ ksi}$

UN threaded Bolt

$d \equiv 1 \text{ in}$ Nominal Diameter
 $d_w \equiv 2.5 \text{ in}$ Bolt Head/Washer Diameter
 $t \equiv 0.126 \text{ in}$ Washer thickness
 $L \equiv 10 \text{ in}$ Bolt Length
 $L_T \equiv 2.5 \text{ in}$ Threaded length
 $N_b \equiv 8$ Threads per Inch
 $S_p \equiv 130 \text{ ksi}$ Minimum Proof Strength
 $S_t \equiv 170 \text{ ksi}$ Minimum Tensile Strength
 $S_y \equiv 170 \cdot 0.9 \text{ ksi}$ Minimum Yield Strength

Friction Values

$f \equiv 0.12$ Coefficient of Friction (threads)
 $f_c \equiv 0.14$ Coefficient of Friction (head)

[OUTPUTS]

Bolt Parameters [UN Thread Only]

$N := N_b \text{ in}^{-1}$ Threads per inch
 $p := N^{-1} = 0.125 \text{ in}$ Pitch
 $d_m := d - 0.5 \cdot p = 0.938 \text{ in}$ Average Bolt Diameter
 $d_r := d - 1.299038 \cdot p = 0.838 \text{ in}$ Minor Diameter
 $d_p := d - 0.649519 \cdot p = 0.919 \text{ in}$ Pitch Diameter
 $d_t := 0.5 \cdot (d_p + d_r) = 0.878 \text{ in}$ Tensile-Stress Area Diameter
 $A_r := 0.25 \cdot \pi \cdot d_r^2 = 0.551 \text{ in}^2$ Minor Diameter
 $A_t := 0.25 \cdot \pi \cdot d_t^2 = 0.606 \text{ in}^2$ Tensile Stress Area (Threaded Portion of bolt)
 $A_d := 0.25 \cdot \pi \cdot d^2 = 0.785 \text{ in}^2$ Area of unthreaded portion
 $\alpha \equiv 30 \text{ deg}$ Shigley p.428, can vary between 25° and 33°

$\lambda := \text{atan}\left(1 \cdot p \cdot (\pi \cdot d_m)^{-1}\right) = 2.43 \text{ deg}$ Lead Angle

Washer/Bolt Head Parameters

$A_w := 0.25 \cdot \pi \cdot (d - d_w)^2 = 1.767 \text{ in}^2$ Outer washer/bolt head area

Clamp Grip Parameters

$h := t_1 + t = 6.126 \text{ in}$ Thickness of washer and clamped material
 $l := \text{if } t_2 < d \text{ then } 6.626 \text{ in}$ Grip Length

$$\begin{cases} h + \frac{t_2}{2} \\ \text{else} \\ h + \frac{d}{2} \end{cases}$$

$L_E := 2 \cdot A_t \cdot (0.5 \cdot \pi \cdot (d + p - 0.64952 \cdot p))^{-1} = 0.739 \text{ in}$ Ratio of Tensile Strengths
 $J := S_t \cdot \sigma_u^{-1} = 2.429$ Minimum Thread Engagement
 $L_E := L_E \cdot J = 1.794 \text{ in}$

$l_d := L - L_T = 7.5 \text{ in}$ Length of unthreaded portion in grip
 $l_t := \text{abs}(l - l_d) = 0.874 \text{ in}$ Length of threaded portion in grip

External Thread (Bolt) Properties

$A_{E_t} := 0.625 \cdot \pi \cdot d_p \cdot L_T = 4.51 \text{ in}^2$ Thread Shear Area (External)

Internal Thread (Threaded Material) Properties

$d_{pi} := d - 0.64951905 \cdot N^{-1} = 0.919 \text{ in}$ (ASME B1.1 Section 8.3) Pitch diameter Internal Threads
 $A_{E_i} := 0.75 \cdot \pi \cdot d_{pi} \cdot L_T = 5.412 \text{ in}^2$ Thread Shear Area (Internal)
 $A_p := 0.25 \cdot \pi \cdot d_w \cdot t_1 = 11.781 \text{ in}^2$ Pull Through Area

Bolt Calculation Bolt Calculation Large Cont...

[OUTPUTS CONT...]

Suggested Pre-loads / Tightening Torque

$$F_p := A_t \cdot S_p = 78.747 \text{ kip} \quad \text{Proof Load}$$

$$F_i := 0.9 \cdot F_p = 70.872 \text{ kip} \quad \text{Suggested Preload for Permanent Joint}$$

$$K := \frac{d_m}{2 \cdot d} \cdot \frac{\tan(\lambda) + f \cdot \sec(\alpha)}{1 - f \cdot \tan(\lambda) \cdot \sec(\alpha)} + 0.625 \cdot f_e = 0.173 \quad \text{Torque Coefficient}$$

$$T_s := F_i \cdot K \cdot d = (1.021 \cdot 10^3) \text{ lbf} \cdot \text{ft} \quad \text{Suggested Torque for Permanent Joint}$$

Stiffness Values

$$k_t := \frac{A_t \cdot E}{l_t} = (2.412 \cdot 10^8) \frac{\text{lbf}}{\text{ft}} \quad \text{Threaded portion stiffness of bolt}$$

$$k_d := \frac{A_d \cdot E}{l_d} = (3.644 \cdot 10^7) \frac{\text{lbf}}{\text{ft}} \quad \text{Unthreaded portion stiffness of bolt}$$

$$k_b := \frac{A_d \cdot A_t \cdot E}{A_d \cdot l_t + A_t \cdot l_d} = (3.166 \cdot 10^7) \frac{\text{lbf}}{\text{ft}} \quad \text{Fastener stiffness}$$

$$k_m := \frac{\pi \cdot \tan(\alpha) \cdot E \cdot d}{2 \ln \left(\frac{(l \cdot \tan(\alpha) + d_w - d) \cdot (d_w + d)}{(l \cdot \tan(\alpha) + d_w + d) \cdot (d_w - d)} \right)} = (5.972 \cdot 10^8) \frac{\text{lbf}}{\text{ft}} \quad \text{Joint Stiffness}$$

$$C := \frac{k_b}{k_b + k_m} = 0.05 \quad \text{Fraction of external load carried by the bolt}$$

Load Parameters

$$F_L := F_E \cdot n^{-1} = 6.25 \text{ kip} \quad \text{Load per bolt}$$

$$F_i := T \cdot (K \cdot d)^{-1} = 24.299 \text{ kip} \quad \text{Preload Force}$$

$$F_T := (C \cdot F_L + F_i) = 24.613 \text{ kip} \quad \text{Total Tensile Force}$$

$$P_b := F_L \cdot C = 0.315 \text{ kip} \quad \text{Portion of ext. load carried by a bolt}$$

$$P_m := F_L - P_b = 5.935 \text{ kip} \quad \text{Portion of load taken by members}$$

$$F_b := C \cdot F_E + F_i = 31.85 \text{ kip} \quad \text{Resultant bolt load}$$

$$F_m := (1 - C) \cdot F_E - F_i = 118.15 \text{ kip} \quad \text{Resultant load on the connected members}$$

BTH-1 Parameters

$$N_d := 2 \quad \text{Category A - lifting safety factor}$$

Stresses

Bolt

$$\sigma_i := F_i \cdot A_t^{-1} = 40.114 \text{ ksi} \quad \text{Preload Stress}$$

$$\sigma_b := F_T \cdot A_t^{-1} = 40.633 \text{ ksi} \quad \text{Tensile Stress}$$

$$\tau_s := F_T \cdot A_{te}^{-1} = 5.457 \text{ ksi} \quad \text{Shear Stress}$$

Clamped Parts

$$\sigma_z := F_T \cdot A_w^{-1} = 13.928 \text{ ksi} \quad \text{Stress - Bearing}$$

$$\sigma_p := F_T \cdot A_p^{-1} = 2.089 \text{ ksi} \quad \text{Pull Through Stress}$$

$$\tau_{s_part} := F_T \cdot A_{ti}^{-1} = 4.548 \text{ ksi} \quad \text{Shear Stress}$$

BTH-1 Parameters - [pg. 17]

$$F_{p1} := \frac{1.8 \cdot \sigma_y}{1.2 \cdot N_d} = 27 \text{ ksi} \quad \text{Max Allowable Bearing Load}$$

$$F_{t1} := \frac{\sigma_u}{1.2 \cdot N_d} = 29.167 \text{ ksi} \quad \text{Max Allowable Tensile Stress in the bolt}$$

$$F_{v1} := \frac{0.62 \cdot \sigma_u}{1.2 \cdot N_d} = 18.083 \text{ ksi} \quad \text{Max Allowable Shear Stress in the bolt}$$

$$F_{t_prime} := C \cdot F_L \cdot A_t^{-1} = 0.519 \text{ ksi} \quad \text{Allowable Tensile Stress - Excluding Preload}$$

Safety Factors

Bolt

$$n_p := F_{t1} \cdot F_{t_prime}^{-1} = 56.153 \quad \text{Yielding (Must be >1, BTH-1)}$$

$$n_L := (S_p \cdot A_t - F_i) \cdot (C \cdot F_L)^{-1} = 173.053 \quad \text{Overload}$$

$$n_0 := F_i \cdot (F_L \cdot (1 - C))^{-1} = 4.094 \quad \text{Joint Separation}$$

$$n_t := 0.577 \cdot S_y \cdot \tau_s^{-1} = 16.177 \quad \text{Shear Stress}$$

Clamped Parts

$$n_z := F_{p1} \cdot \sigma_z^{-1} = 1.938 \quad \text{Bearing (Must be >1, BTH-1)}$$

$$n_s := \sigma_y \cdot \sigma_p^{-1} = 17.231 \quad \text{Pull Through}$$

$$n_{s_part} := 0.577 \cdot \sigma_y \cdot \tau_{s_part}^{-1} = 4.568 \quad \text{Shear Stress}$$

Joint

$$n_e := L_T \cdot L_E^{-1} = 1.393 \quad \text{Minimum Thread Engagement}$$

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Bolt Calculation - Variance Factors

Description	Symbol	Adjustment used when calculating maximum preload	Adjustment used when calculating minimum preload
Short-term relaxation of preload (embedment of imperfectly matched surfaces); see Appendix A.3	P_{pr}	Zero	5% of minimum initial preload for joints with all-metallic clamped parts, test-derived value for joints with any non-metallic parts or coatings

II

Maximum initial preload for strength and fatigue analyses is calculated as

$$P_{pi-max} = c_{max}(1+\Gamma)P_{pi-nom} \quad (6-4)$$

where P_{pi-nom} is the nominal (mean) preload applicable to installation, Γ is the preload variation, and c_{max} is a factor that accounts for the maximum value of the controlled installation parameter, as allowed by the specified tolerance. For example, if torque control is used and the effective torque is specified as 40 ± 2 N·m, then $c_{max} = (40 + 2)/40 = 1.05$.

For use in separation analysis of separation-critical joints and for fatigue analysis, minimum initial preload is calculated as

$$P_{pi-min} = c_{min}(1-\Gamma)P_{pi-nom} \quad (6-5a)$$

III

In absence of applicable data showing otherwise, $\Gamma = 25$ percent for fasteners lubricated at assembly, and $\Gamma = 35$ percent for non-lubricated and as-received. If the actual extreme variation found in the tests performed per paragraph 6.1.b exceeds the Γ values stated above, then the actual extreme variation should be used or methods for reducing the preload variation should be pursued. A fastener is considered to be lubricated if a solid-film, grease, or liquid lubricant is applied to the threads and to the turning bearing surfaces of the nut or the bolt head (or to the washer under the nut or the bolt head).

NASA-STD-5020

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Small Vessel – Lifting Frame

Load Case	Small Lifting Frame
Load Case Overview	Lifting frame attachment for the 42" Vessel Complete lifting frame viewed as one solid part. Assuming welds have base material strength
Model Fidelity / Simplifications	Bearing Load (6 kip) - This is a conservative load the nominal design weight is 4.4 kip .
Load Type 1	At top pin connection to equalizer beam
Load Placement 1	N/A
Load Type 2	Fix Constraint
Load Placement 2	At each bolt hole (12x)
Boundary Condition Type	Multi-Pass-Adaptive
Boundary Condition Location(s)	
Run Settings	
FEA Parameters	
Component Interaction (Bonded / Contact / Free)	Welds: Single Solid
Mesh Refinement Used	Max element size: 2.0" (global)
Element Total	70418
Material	A36
Poisson's ratio	0.26 [-]
Density	0.284 lb/in ³
Modulus of Elasticity	29000 KSI
Yield Strength	36 KSI
Ultimate Strength (Tensile)	70 KSI
FEA Results	
Allowable Stress	10.2 KSI (yield strength 36 KSI @ FoS of 3.5)
Peak Stress (VM) - Entire Model	2.2 KSI
Peak Displacement - Entire Model	0.0005"
Areas removed from summary	None
Reason for removal (Riser: Geometry / Load Edge / BC Edge)	N/A
Peak Stress (VM) *	N/A
Other Notes	
Date	6/23/2017
Run time	~10 min
Converged on maximum order	7
Stress Error (% of Max Prin Str)	0.4%

Margin: 8 KSI

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42" Vessel – Small Lifting Frame Results

Stress
(ksi)
Loadset: LoadSet1 : DAG_SMALL_MAD_MAX

Max Von-Mises Stress 2.2 ksi

Displacement
(in)
Max Disp 5.6335E-04
Loadset: LoadSet1 : DAG_SMALL_MAD_MAX

Max Displacement: 0.0005 in

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Small Lifting Frame – Bolt Calculation

Assumptions

- $\mu_T = 0.12$, CoF (Threads)
 - [Table 5, NASA Fastener Design Manual]
- $\mu_H = 0.15$, CoF (Under Bolt Head)
 - [Table 5, NASA Fastener Design Manual]
- Torque Adjustment Factor $\pm 35\%$
 - [NASA-STD-5020]
- Preload relaxation 5%
 - [NASA-STD-5020]
- 6 kip Load Case
 - 4.4 kip is the nominal design weight

Specifications

- Torque - (50 ± 10) ft*lbs
- Preload Range (2.7 – 8.9) kips

Bolt Pattern

- 12x - UNC 5/8"-11 x 8"
 - Bolts - ASTM A574 (ult strength -170 ksi)

Load Case	Bolt			Clamped Part			Joint	
	SF _{Tensile Yielding}	SF _{Overload}	SF _{Shear Stress}	SF _{Bearing}	SF _{Shear Stress}	SF _{Full Through}	SF _{Joint Sep}	SF _{Min. Thread Eng}
Nominal	212.80	771.91	31.21	1.82	15.27	8.81	11.66	1.64
Upper Limit	212.80	662.42	19.31	1.13	18.37	5.45	18.89	
Lower Limit	212.80	861.26	62.81	3.66	111.00	17.74	5.76	
	BTH-1 (>1)			BTH-1 (>1)			NASA - STD- 5020 (>1.4)	

Slide 20

Bolt Calculation Small Lifting Frame

Bolt Calculator - Small Lifting Frame

[INPUTS]

Loading

$F_B \equiv 6 \text{ kip}$ External Load on jointed assembly
 $n \equiv 12$ Number of bolts
 $T \equiv 50 \text{ lbf} \cdot \text{ft}$ Applied Torque

Clamp properties

$t_1 \equiv 6 \text{ in}$ Thickness of clamped material
 $t_2 \equiv 4 \text{ in}$ Thickness of threaded material

Threaded/clamped material properties (same material)

$E \equiv 29000 \text{ ksi}$ $\sigma_y \equiv 36 \text{ ksi}$ $\sigma_u \equiv 70 \text{ ksi}$

UN threaded Bolt

$d \equiv 0.625 \text{ in}$ Nominal Diameter
 $d_w \equiv 1.312 \text{ in}$ Bolt Head/Washer Diameter
 $t \equiv 0.074 \text{ in}$ Washer thickness
 $L \equiv 8 \text{ in}$ Bolt Length
 $L_T \equiv 1.75 \text{ in}$ Threaded length
 $N_b \equiv 11$ Threads per Inch
 $S_p \equiv 130 \text{ ksi}$ Minimum Proof Strength
 $S_t \equiv 170 \text{ ksi}$ Minimum Tensile Strength
 $S_y \equiv 170 \cdot 0.9 \text{ ksi}$ Minimum Yield Strength

Friction Values

$f \equiv 0.12$ Coefficient of Friction (threads)
 $f_c \equiv 0.14$ Coefficient of Friction (head)

[OUTPUTS]

Bolt Parameters [UN Thread Only]

$N := N_b \text{ in}^{-1}$ Threads per inch
 $p := N^{-1} = 0.091 \text{ in}$ Pitch
 $d_m := d - 0.5 \cdot p = 0.58 \text{ in}$ Average Bolt Diameter
 $d_p := d - 1.299038 \cdot p = 0.507 \text{ in}$ Minor Diameter
 $d_r := d - 0.649519 \cdot p = 0.566 \text{ in}$ Pitch Diameter
 $d_t := 0.5 \cdot (d_p + d_r) = 0.536 \text{ in}$ Tensile-Stress Area Diameter
 $A_r := 0.25 \cdot \pi \cdot d_r^2 = 0.202 \text{ in}^2$ Minor Diameter
 $A_t := 0.25 \cdot \pi \cdot d_t^2 = 0.226 \text{ in}^2$ Tensile Stress Area (Threaded Portion of bolt)
 $A_d := 0.25 \cdot \pi \cdot d^2 = 0.307 \text{ in}^2$ Area of unthreaded portion
 $\alpha \equiv 30 \text{ deg}$ Shigley p.428, can vary between 25° and 33°

$\lambda := \arctan \left(1 \cdot p \cdot (\pi \cdot d_m)^{-1} \right) = 2.858 \text{ deg}$ Lead Angle

Washer/Bolt Head Parameters

$A_w := 0.25 \cdot \pi \cdot (d - d_w)^2 = 0.371 \text{ in}^2$ Outer washer/bolt head area

Clamp Grip Parameters

$h := t_1 + t = 6.074 \text{ in}$ Thickness of washer and clamped material
 $l := \text{if } t_2 < d \mid = 6.387 \text{ in}$ Grip Length

$$\begin{cases} h + \frac{t_2}{2} \\ \text{else} \\ h + \frac{d}{2} \end{cases}$$

$L_E := 2 \cdot A_t \cdot (0.5 \cdot \pi \cdot (d + p - 0.64952 \cdot p))^{-1} = 0.438 \text{ in}$

$J := S_t \cdot \sigma_u^{-1} = 2.429$ Ratio of Tensile Strengths
 $L_E := L_E \cdot J = 1.064 \text{ in}$ Minimum Thread Engagement

$l_d := L - L_T = 6.25 \text{ in}$ Length of unthreaded portion in grip
 $l_t := \text{abs}(l - l_d) = 0.137 \text{ in}$ Length of threaded portion in grip

External Thread (Bolt) Properties

$A_{te} := 0.625 \cdot \pi \cdot d_p \cdot L_T = 1.945 \text{ in}^2$ Thread Shear Area (External)

Internal Thread (Threaded Material) Properties

$d_{pi} := d - 0.64951905 \cdot N^{-1} = 0.566 \text{ in}$ (ASME B1.1 Section 8.3) Pitch diameter Internal Threads
 $A_{ti} := 0.75 \cdot \pi \cdot d_{pi} \cdot L_T = 2.334 \text{ in}^2$ Thread Shear Area (Internal)
 $A_p := 0.25 \cdot \pi \cdot d_w \cdot t_1 = 6.183 \text{ in}^2$ Pull Through Area

Bolt Calculation Small Lifting Frame Cont...

[OUTPUTS CONT...]

Suggested Pre-loads / Tightening Torque

$$F_p := A_t \cdot S_p = 29.38 \text{ kip} \quad \text{Proof Load}$$

$$F_i := 0.9 \cdot F_p = 26.442 \text{ kip} \quad \text{Suggested Preload for Permanent Joint}$$

$$K := \frac{d_m}{2 \cdot d} \cdot \frac{\tan(\lambda) + f \cdot \sec(\alpha)}{1 - f \cdot \tan(\lambda) \cdot \sec(\alpha)} + 0.625 \cdot f_c = 0.176 \quad \text{Torque Coefficient}$$

$$T_s := F_i \cdot K \cdot d = 241.703 \text{ lbf} \cdot \text{ft} \quad \text{Suggested Torque for Permanent Joint}$$

Stiffness Values

$$k_t := \frac{A_t \cdot E}{l_t} = (5.762 \cdot 10^8) \frac{\text{lbf}}{\text{ft}} \quad \text{Threaded portion stiffness of bolt}$$

$$k_d := \frac{A_d \cdot E}{l_d} = (1.708 \cdot 10^7) \frac{\text{lbf}}{\text{ft}} \quad \text{Unthreaded portion stiffness of bolt}$$

$$k_b := \frac{A_d \cdot A_t \cdot E}{A_d \cdot l_t + A_t \cdot l_d} = (1.659 \cdot 10^7) \frac{\text{lbf}}{\text{ft}} \quad \text{Fastener stiffness}$$

$$k_m := \frac{\pi \cdot \tan(\alpha) \cdot E \cdot d}{2 \ln \left(\frac{(l \cdot \tan(\alpha) + d_w - d) \cdot (d_w + d)}{(l \cdot \tan(\alpha) + d_w + d) \cdot (d_w - d)} \right)} = (2.512 \cdot 10^8) \frac{\text{lbf}}{\text{ft}} \quad \text{Joint Stiffness}$$

$$C := \frac{k_b}{k_b + k_m} = 0.062 \quad \text{Fraction of external load carried by the bolt}$$

Load Parameters

$$F_L := F_E \cdot n^{-1} = 0.5 \text{ kip} \quad \text{Load per bolt}$$

$$F_i := T \cdot (K \cdot d)^{-1} = 5.47 \text{ kip} \quad \text{Preload Force}$$

$$F_T := (C \cdot F_L + F_i) = 5.501 \text{ kip} \quad \text{Total Tensile Force}$$

$$P_b := F_L \cdot C = 0.031 \text{ kip} \quad \text{Portion of ext. load carried by a bolt}$$

$$P_m := F_L - P_b = 0.469 \text{ kip} \quad \text{Portion of load taken by members}$$

$$F_b := C \cdot F_T + F_i = 5.842 \text{ kip} \quad \text{Resultant bolt load}$$

$$F_m := (1 - C) \cdot F_E - F_i = 0.158 \text{ kip} \quad \text{Resultant load on the connected members}$$

BTH-1 Parameters

$$N_d := 2 \quad \text{Category A - lifting safety factor}$$

Stesses

Bolt

$$\sigma_i := F_i \cdot A_t^{-1} = 24.203 \text{ ksi} \quad \text{Preload Stress}$$

$$\sigma_b := F_T \cdot A_t^{-1} = 24.34 \text{ ksi} \quad \text{Tensile Stress}$$

$$\tau_s := F_T \cdot A_{te}^{-1} = 2.829 \text{ ksi} \quad \text{Shear Stress}$$

Clamped Parts

$$\sigma_z := F_T \cdot A_w^{-1} = 14.84 \text{ ksi} \quad \text{Stress - Bearing}$$

$$\sigma_p := F_T \cdot A_p^{-1} = 0.89 \text{ ksi} \quad \text{Pull Through Stress}$$

$$\tau_{s_part} := F_T \cdot A_{ti}^{-1} = 2.357 \text{ ksi} \quad \text{Shear Stress}$$

BTH-1 Parameters - [pg. 17]

$$F_{p1} := \frac{1.8 \cdot \sigma_y}{1.2 \cdot N_d} = 27 \text{ ksi} \quad \text{Max Allowable Bearing Load}$$

$$F_{t1} := \frac{\sigma_u}{1.2 \cdot N_d} = 29.167 \text{ ksi} \quad \text{Max Allowable Tensile Stress in the bolt}$$

$$F_{v1} := \frac{0.62 \cdot \sigma_u}{1.2 \cdot N_d} = 18.083 \text{ ksi} \quad \text{Max Allowable Shear Stress in the bolt}$$

$$F_{t_prime} := C \cdot F_L \cdot A_t^{-1} = 0.137 \text{ ksi} \quad \text{Allowable Tensile Stress - Excluding Preload}$$

Safety Factors

Bolt

$$n_p := F_{t1} \cdot F_{t_prime}^{-1} = 212.804 \quad \text{Yeilding (Must be >1, BTH-1)}$$

$$n_L := (S_p \cdot A_t - F_i) \cdot (C \cdot F_L)^{-1} = 771.906 \quad \text{Overload}$$

$$n_0 := F_i \cdot (F_L \cdot (1 - C))^{-1} = 11.663 \quad \text{Joint Separation}$$

$$n_t := 0.577 \cdot S_y \cdot \tau_s^{-1} = 31.209 \quad \text{Shear Stress}$$

Clamped Parts

$$n_z := F_{p1} \cdot \sigma_z^{-1} = 1.819 \quad \text{Bearing (Must be >1, BTH-1)}$$

$$n_s := \sigma_y \cdot \sigma_p^{-1} = 40.461 \quad \text{Shear Stress}$$

$$n_{s_part} := 0.577 \cdot \sigma_y \cdot \tau_{s_part}^{-1} = 8.812 \quad \text{Pull Through}$$

Joint

$$n_e := L_T \cdot L_E^{-1} = 1.645 \quad \text{Minimum Thread Engagement}$$

Slide 22

Equalizer Beam – Tolerance Stack

Equalizer Beam – Tilt Calculation

MAXIMUM LOADING CASE - TILTING [Based on $L_{max} = Y_R + Y_L$]

$L_{max} := 18 \text{ in}$ Tol Max
 $F_Y := 150 \text{ kip}$ Max Load

Level Dimensions

$a := 48 \text{ in}$

$b := 10 \text{ in}$

$c := \sqrt{\left(\frac{a}{2}\right)^2 + b^2} = 26 \text{ in}$

$\alpha := 2 \cdot \arcsin\left(\frac{a}{2 \cdot c}\right) = 134.76 \text{ deg}$

Angle of Tilt

$y_R := c \cdot \cos\left(\frac{\alpha}{2} - \theta\right) - b$

$y_L := b - c \cdot \cos\left(\frac{\alpha}{2} + \theta\right)$

$L_{max} = y_R + y_L$

$L_{max} = \left(c \cdot \cos\left(\frac{\alpha}{2} - \theta\right) - b\right) + \left(b - c \cdot \cos\left(\frac{\alpha}{2} + \theta\right)\right)$ $\frac{L_{max}}{c} = \cos\left(\frac{\alpha}{2} - \theta\right) - \cos\left(\frac{\alpha}{2} + \theta\right)$

$\frac{L_{max}}{c} = \left(\cos\left(\frac{\alpha}{2}\right) \cdot \cos(\theta) + \sin\left(\frac{\alpha}{2}\right) \cdot \sin(\theta)\right) - \left(\cos\left(\frac{\alpha}{2}\right) \cdot \cos(\theta) - \sin\left(\frac{\alpha}{2}\right) \cdot \sin(\theta)\right)$

$\theta := \arcsin\left(\frac{L_{max}}{2 \cdot c \cdot \sin\left(\frac{\alpha}{2}\right)}\right) = 22.024 \text{ deg}$ Angle of deflection

x & y displacements

$y_R := c \cdot \cos\left(\frac{\alpha}{2} - \theta\right) - b = 8.27 \text{ in}$

$x_R := \sqrt{c^2 - (b + y_R)^2} = 18.499 \text{ in}$

$y_L := b - c \cdot \cos\left(\frac{\alpha}{2} + \theta\right) = 9.73 \text{ in}$

$x_L := \sqrt{c^2 - (b - y_L)^2} = 25.999 \text{ in}$

Sum Forces [+Y]

$F_Y = R_L + R_R$

Sum Moments about F_Y

$R_L \cdot x_L = R_R \cdot x_R$

Solve

$F_Y = \frac{R_R \cdot x_R}{x_L} + R_R$

$R_L = \frac{R_R \cdot x_R}{x_L}$

$R_R = F_Y \cdot \left(\frac{x_R}{x_L} + 1\right)^{-1} = 87.641 \text{ kip}$

$R_L = F_Y - R_R = 62.359 \text{ kip}$