Design/Evaluation of Overhead Lifing Lugs

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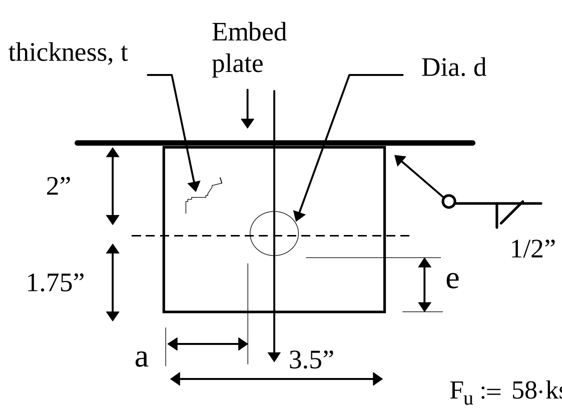
Introduction

Design guidance for the design of lifting lugs are provided in References 1 and 3. Since the eye of the lifting lug can be considered a pin-connected member, provisions of Reference 2 are applicable also. ANSI N14.6 (Ref. 5) requires a design factor of 3 on yield strength and 5 on ultimate strength. References 1 and 3 also achieve these design factors indirectly.

In the following evaluation example, a single alowable stress is used consistently based on the lower of the yield strength divided by 3 or the ultimate strength divided by 5 while applying the guidance in References 1, 2, and 3.

Although the following lesson illustrates an overhead lifting lug, the associated engineering principles can be applied to evaluate lifting lugs attached to a spreader beam, lifted load, etc.

Example of an Overhead Lifting Lug



$kip \equiv 1000 \cdot lb$

$t := 1.25 \cdot in$

$ksi \equiv 1000 \cdot \frac{lb}{in \cdot in}$

$d := 1.25 \cdot in$

$a := 1.125 \cdot in$

$e := 1.125 \cdot in$

$F_u := 58 \cdot ksi$ ultimate strength

$F_y := 36 \cdot ksi$ yield strength

$F_{weldu} := 70 \cdot ksi$ weld ultimate strength

$F_{weldy} := 57 \cdot ksi$ weld yield strength

$h_{weld} := 0.5 \cdot in$ weld size

$d_{pin} := d - 0.5 \cdot in$ pin diameter

Alllowable stress, $F_a := \min\left(\frac{F_u}{5}, \frac{F_y}{3}\right) = 11.6 \cdot ksi$

Geometric Guidelines:

There are some geometric guidelines to be considered as recommended in Reference 1. They will be called Rule 1 and Rule 2.

Rule 1:

The dimension "a" must be greater than or equal to half the hole diameter, d.
i.e. a $\geq$ 1/2 * d
For this example, a = 1.125" and since it is greater than 1/2*d which is 0.625". Rule 1 is satisfied.

$$Rule\_1 := \text{if}(a \geq 0.5 \cdot d, \text{"OK"}, \text{"NG"}) \qquad Rule\_1 = \text{"OK"}$$

Note: This rule also states that "a" must be greater than twice the thickness of the lug, t. In this example "a" needs to be more than 2.5 ins. Since other rules that follow require an effective value of "a" less than the actual value of "a", this part of the rule is not applied here.

Rule 2:

The dimension "e" must be greater than or equal to 0.67 times the hole diameter, d.
Thus, e $\geq$ 0.67 * d
For this example, e = 1.125" and since it is greater than 0.67*d which is 0.8375". Rule 2 is satisfied.

$$Rule\_2 := \text{if}(e \geq 0.67 \cdot d, \text{"OK"}, \text{"NG"}) \qquad Rule\_2 = \text{"OK"}$$

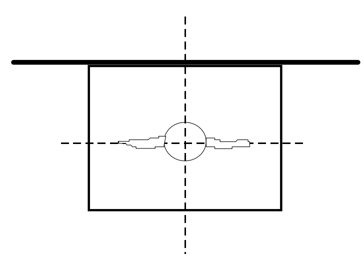
Evaluation based on Failure Modes:

Failure Mode 1:

This failure mode involves tension failure on both sides of the hole. Therefore, the maximum working load is given by:

$$P_{w1} := 2 \cdot a \cdot t \cdot F_a$$

$$P_{w1} = 32.625 \cdot kip$$



ASME BTH-1 (Ref. 4) provides an alternative method for calculating the capacity based on this failure mode.

Strength reduction factor: $C_r := \text{if}\left(\frac{d_{pin}}{d} \geq 0.9, 1.0, 1 - 0.275 \cdot \sqrt{1 - \frac{d_{pin}^{\,2}}{d^2}}\right) = 0.78$ (Eq. 3-46 of Ref.4)

Calculate a_e per Eq. 3-47 & 3-48 of Ref. 4:

$$a_e := \min\left(a, 4 \cdot t, a \cdot 0.6 \cdot \frac{F_u}{F_y} \cdot \sqrt{\frac{d}{a}}\right) \qquad a_e = 1.125 \cdot in$$

$$P_{w1.1} := C_r \cdot 2 \cdot t \cdot a_e \cdot F_a$$

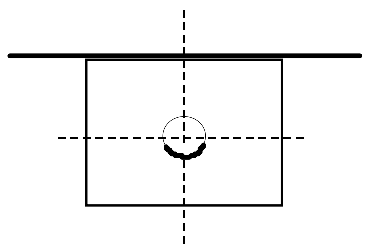
$$P_{w1.1} = 25.448 \cdot kip$$

Failure Mode 2:

This failure mode involves bearing failure at the pin/lifting lug interface. Often the pin diameter is much less than the hole diameter. For the following example, it is assumed that the pin diameter is 1/2" less than the hole diameter. Using a bearing stress of F_a over the bearing area of t x d_{pin}:

$$P_{w2} := F_a \cdot t \cdot d_{pin}$$

$$P_{w2} = 10.875 \cdot kip$$



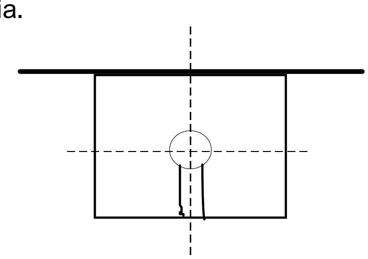
It should be noted that Reference 1 requires checking bearing capacity only if the pin is "snug fit" in the hole and that Reference 4 provides for a 25% increase in the bearing stress allowable.

Failure Mode 3:

This failure mode involves shear failure as the pin tries to push out a block of steel through the edge of the lug plate. The shear area is twice the cross-sectional area beyond the hole for the pin (2et). For shear failure, the allowable stress F_a will be divided by $\sqrt{3}$ consistent with von Mises failure criteria.

$$P_{w3} := \frac{2 \cdot F_a \cdot e \cdot t}{\sqrt{3}}$$

$$P_{w3} = 18.836 \cdot kip$$



ASME BTH-1 (Ref. 4) refers to this failure as double plane fracture failure and provides an alternate method for calculating the shear area:

$$\phi := 55 \cdot deg \cdot \frac{d_{pin}}{d} = 33 \cdot deg$$ (Eq. 3-52 of Ref. 4)

$$A_v := 2 \cdot \left[e + \frac{d_{pin}}{2} \cdot (1 - \cos(\phi)) \right] \cdot t = 2.964 \cdot in^2$$ (Eq. 3-51 of Ref. 4)

$$P_{w3.1} := \frac{A_v \cdot F_a}{\sqrt{3}}$$

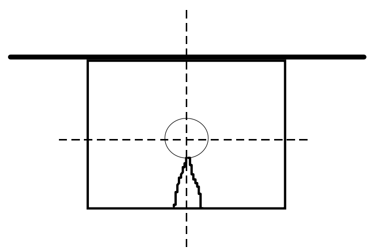
$$P_{w3.1} = 19.849 \cdot kip$$

Failure Mode 4:

This failure mode involves tensile failure as the pin tries to push out a block of steel through the edge of the lug plate. Assuming a block of steel 0.8d in length, allowable load is given by (See Note 1):

$$P_{w4} := 1.67 \cdot F_a \cdot e^2 \cdot \frac{t}{d}$$

$$P_{w4} = 24.518 \cdot kip$$



ASME BTH-1 (Ref. 4) refers to this failure as single plane fracture failure and provides an alternate method for calculating the tensile strength based on beyond the pin hole section:

$$A_{fracture} := C_r \cdot \left(1.13 \cdot e + \frac{0.92 \cdot a}{1 + \frac{a}{d}} \right) \cdot t = 1.771 \cdot in^2$$ (Based on Eq. 3-49 of Ref. 4)

$$P_{w4.1} := A_{fracture} \cdot F_a$$

$$P_{w4.1} = 20.539 \cdot kip$$

Failure Mode 5:

This failure mode involves the out-of-plane buckling failure of the lug. Per Ref. 1, this failure is prevented by ensuring a minimum thickness of lug of 0.5 inches and 0.25 times the hole diameter d.

In this example, since 0.25 x 1.25 = 0.3125" and the thickness of the lug is 1.25", this failure mode does not control.

$$Rule\_3 := if(t \geq 0.25 \cdot d, "OK", "NG") \quad Rule\_3 = "OK"$$

$$Rule\_4 := if(t \geq 0.5 \cdot in, "OK", "NG") \quad Rule\_4 = "OK"$$

AISC Code Checks per Section D.5.2

The above section of AISC Code has two separate geometry checks that can be applied to the lifting lug. If these requirements are not met, a smaller value for "a", should be used for the calculation of tensile capacity (a_{eff}).

Requirement 1:

The minimum length of a_{eff} shall not be less than 2t+0.63 in but not more than actual distance from edge of hole to edge of lug measured in a direction normal to the applied force.

2t+0.63 in is 2 x 1.25 +0.63 = 3.13". This is much greater than actual value of 1.125". Therefore, this requirement is satisfied.

Requirement 2:

This requirement states that the extension, e, beyond end of pin hole shall not be less than 1.33 times a.

Actual a is 1.125. Therefore 1.33 x 1.125 = 1.496". This is greater than dimension, e, which is also 1.125. Therefore, this requirement is not satisfied. Therefore, the tensile capacity of the lug must be based on a reduced "a" dimension to satisfy this requirement, a_{eff}.

Combining these two requirements into a single "formula" we have:

$$AISC_{min} := \left(a \quad \frac{e}{1.33} \quad 2 \cdot t + 0.63 \cdot in \right)$$

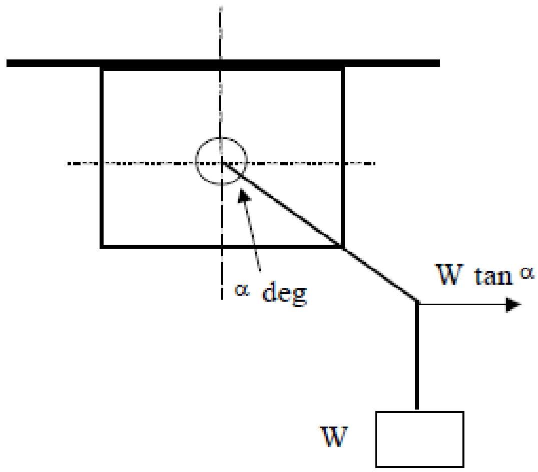
$$a_{eff} := \min\left(AISC_{min}\right) = 0.846 \cdot in$$

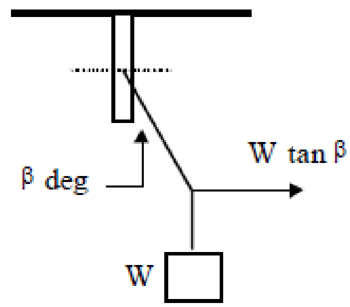
Therefore, load capacity based on AISC is given by:

$$P_{w5} := 2 \cdot a_{eff} \cdot t \cdot F_a \qquad P_{w5} = 24.53 \cdot kip$$

Weld between Lug and Baseplate:

This is the typically the weak link in an overhead lifitng lug, due to off-set loading. In general, the lug is rarely directly over the item to be rigged and a certain amount of side pull is necessary to facilitate rigging. Conservatively, let us assume that the off-set is a maximum of 45 degrees in the plane of the lug and 20 degrees normal to the plane of the lug. The additional loads due to off-set can be determined by statics to be as follows:





Therefore, the maximum load W that can be applied can be calculated as follows:

$W := 1 \cdot kip$ This is an initial guess for Mathcad

$t_w := 1.25 \cdot in$ Length of welds along lug thickness

$l := 2 \cdot in$ lever arm

$w := 3.5 \cdot in$ Length of weld along lug width

Allowable weld load per inch of 1/2" fillet size is calculated as follows:

$$Throat\_stress\_allow := \min\left(\frac{F_{weldu}}{5 \cdot \sqrt{3}}, \frac{F_{weldy}}{3 \cdot \sqrt{3}}\right) = 8.083 \cdot ksi$$

$\alpha := 45$

$\beta := 20$

$$f_{max} := 0.707 \cdot h_{weld} \cdot Throat\_stress\_allow$$

$$f_{max} = 2857 \cdot \frac{lb}{in}$$

$$f_1(W) := \frac{W}{(w + t_w)\cdot 2} + \frac{W\cdot\tan(\beta\cdot deg)\cdot l}{\left(w\cdot t_w + \frac{t_w^{\,2}}{3}\right)} + \frac{W\cdot\tan(\alpha\cdot deg)\cdot l}{\left(w\cdot t_w + \frac{w^2}{3}\right)}$$ See Note 2

$$f_2(W) := \frac{W\cdot\tan(\beta\cdot deg)}{2\cdot(w + t_w)}$$

$$f_3(W) := \frac{W\cdot\tan(\alpha\cdot deg)}{2\cdot(w + t_w)}$$

$$P_{w6} := root\left[\left(f_1(W)^2 + f_2(W)^2 + f_3(W)^2\right)^{0.5} - f_{max}, W\right]$$

$P_{w6} = 5.68\cdot kip$

Lug Basematerial:

The analysis is similar to the weld above except that there is no interaction between tension and shear. The capacity is based on the maximum tensile stress at the base of the lug:

$W := 1\cdot kip$

$f_{max} := F_a$ $l_w := 2\cdot a + d$ Lug width

$$f_1(W) := \frac{W}{l_w\cdot t} + \frac{W\cdot\tan(\beta\cdot deg)\cdot l}{\left(l_w\cdot\frac{t^2}{6}\right)} + \frac{W\cdot\tan(\alpha\cdot deg)\cdot l}{\left(\frac{l_w^{\,2}}{6}\cdot t\right)}$$ See Note 3

$$P_{w7} := root\left[\left(f_1(W)\right) - f_{max}, W\right]$$

$P_{w7} = 6.406\cdot kip$

Conclusion:

$$Capacity := \left(P_{w1}\ \ P_{w1.1}\ \ P_{w2}\ \ P_{w3}\ \ P_{w3.1}\ \ P_{w4}\ \ P_{w4.1}\ \ P_{w5}\ \ P_{w6}\ \ P_{w7}\right)$$

$Cap_{allow} := \min(Capacity)$

$Cap_{allow} = 5.68\cdot kip$

Note variation in capacities for each attribute

$P_{w1} = 32.625 \cdot kip$ $P_{w1.1} = 25.448 \cdot kip$

$P_{w2} = 10.875 \cdot kip$ $P_{w3} = 18.836 \cdot kip$

$P_{w3.1} = 19.849 \cdot kip$ $P_{w4} = 24.518 \cdot kip$

$P_{w4.1} = 20.539 \cdot kip$ $P_{w5} = 24.53 \cdot kip$

$P_{w6} = 5.68 \cdot kip$ $P_{w7} = 6.406 \cdot kip$

If additional capacity is desired, the angles α and β can be restricted as needed to increase the capacity of the lug. In the above example, if these angles are made equal to zero, the maximum capacity will increase to 10.875 kips.

References:

1. David T. Ricker, "Design and Construction of Lifting Beams", Engineering Journal, Fourth Quarter 1991.

2. AISC Manual of Steel Construction, 13th Edition, 2005

3. Omer Blodgett, "Design of Welded Structures", 1966

4. ASME BTH-1-2014, "Design of Below the Hook Liftng Devices", 2014

5. ANSI N14.6, "Standard for Special Lifting Devices for Shipping Containers weighing 10,000 lbs or more for Nuclear Materials", 1993

Notes:

1. Section modulus of the section of the lug below the hole is $\frac{t \cdot e^2}{6}$.

Using F_a as the allowable stress, the maximum allowable bending moment would be $\frac{F_a \cdot t \cdot e^2}{6}$. Maximum bending moment caused by loading P_{w4} over a span of 0.8 d would be $\frac{P_{w4} \cdot 0.8 \cdot d}{8}$ assuming P_{w4} acts a uniformly distributed load. Equating these two expressions, we have:

$$\frac{P_{w4} \cdot 0.8 \cdot d}{8} = \frac{F_a \cdot t \cdot e^2}{6}$$

Simplifying the above equation, we have:

$$P_{w4} := 1.67 \cdot F_a \cdot e^2 \cdot \frac{t}{d}$$

2. The geometric properties of welds per Ref. 3 are as follows:

$L_w := (w + t_w) \cdot 2$ (Length of weld)

$S_{weak} := w \cdot t_w + \frac{t_w^2}{3}$ (Weak axis section moduls of rectangular weld)

$S_{strong} := w \cdot t_w + \frac{w^2}{3}$ (Strong axis section modulus of rectangular weld)

Axial Force on weld is W. Weak axis moment, M_{weak}, is the weak axis component multiplied by lever arm (W x tanβ x l). Strong axis moment, M_{strong}, is the strong axis component multiplied by lever arm (W x tanα x l). Therefore, maximum unit force on weld is given by:

$W/L_w + M_{weak}/S_{weak} + M_{strong}/S_{strong}$.

Substituting for L_w, S_{weak}, and S_{strong} above:

$$\frac{W}{(w + t_w) \cdot 2} + \frac{W \cdot \tan(\beta \cdot deg) \cdot l}{\left(w \cdot t_w + \frac{t_w^2}{3}\right)} + \frac{W \cdot \tan(\alpha \cdot deg) \cdot l}{\left(w \cdot t_w + \frac{w^2}{3}\right)}$$

3. Similar to the above except that the full section of the lug is used for geometric properties.