

The Effect of Eccentricity on Brace-to-gusset Angles

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INTRODUCTION

Claw angles are used in many bracing connections as shown in Figure 1. Normally these angles and their connections are designed for direct load only without consideration of the fact that the connections are to opposite legs of the angles and of the eccentricities thereby induced. It is the purpose of this note to demonstrate that this practice is generally acceptable, and to produce some guidance as to when it is not.

THEORY

Consider the single claw angle shown in Figure 2. The applied load is P . The other forces shown in Figure 2, i.e., H_1 , H_2 , M_{A_1} , M_{B_1} , M_{A_2} , and M_{B_2} , are possible. Two additional couples, M_{A_3} , and M_{B_3} , are also possible but are never necessary for equilibrium and therefore can be assumed to not exist (have identically zero value). The forces shown in Figure 2 must satisfy equilibrium, as represented by the following three equations.

$$Pg_1 = LH_1 + M_{A_2} + M_{B_2} \quad (1)$$

$$Pg_2 = LH_2 + M_{A_1} + M_{B_1} \quad (2)$$

$$H_1g_2 = H_2g_1 \quad (3)$$

Any set of forces which satisfies these three equations is said to be admissible. There are obviously an infinite number of admissible sets of forces which satisfy Equations 1-3. Each admissible set, when made to satisfy the various yield and fracture limit states associated with the angle and bolts, will result in an allowable value for P . In the sense of the Lower Bound Theorem of Limit Analysis, the admissible set which produces the largest allowable value for P is the set which most closely approximates the true solution, which satisfies compatibility in addition to equilibrium and the limit state criteria. Therefore, of all the possible admissible sets of forces which also satisfy the limit states, the one which maximizes P provides the best approximation for the capacity of the connection.

Admissible Force Sets

Of the many possible admissible force sets, three will be

singled out for further study. One of these three will usually produce a capacity close to the greatest lower bound value of P .

Admissible Set No. 1:

$$H_1 = H_2 = 0$$

$$M_{A_1} = M_{B_1} = 0$$

$$Pg_1 = M_{A_2}$$

$$Pg_2 = M_{B_2}$$

This set is shown in Figure 3. It is the set that first comes to mind when the question of eccentricity is first raised with claw angle connections. It places the applied load P at the heel of the angle. Thus, in addition to axial force, the angle section midway between the connections is subjected to biaxial bending moments.

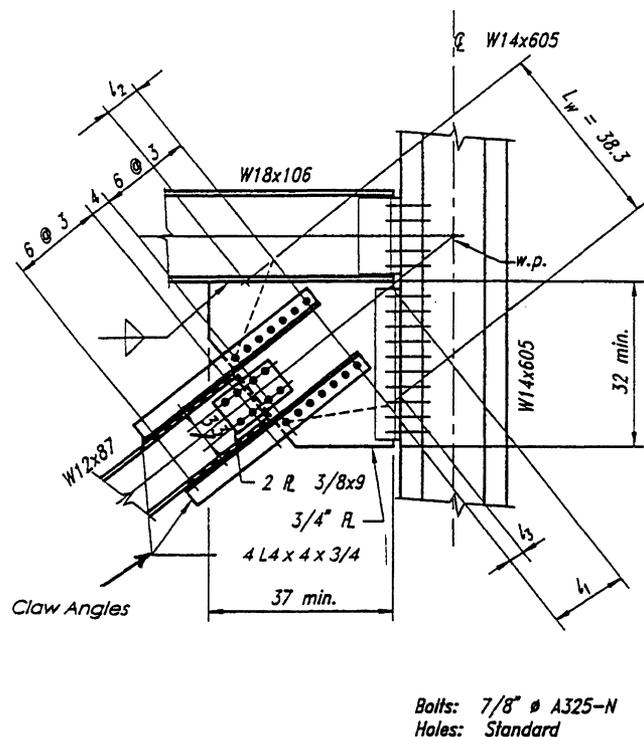


Fig. 1. Typical bracing connection with claw angles (from AISC 1992, pg. 7-114).

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Admissible set No. 2:

$$M_{A_1} = M_{A_2} = M_{B_1} = M_{B_2} = 0$$

$$Pg_1 = LH_1$$

$$Pg_2 = LH_2$$

This set is shown in Figure 4. It will generally produce the greatest value of P except for short connections with light angles. Note that this distribution causes the resultant force on the bolt groups A and B to pass very close to the centroid of the angle on the cross-section midway between the centroids of the two groups. Thus, the assumption that the angle is axially loaded is closely approximated.

Admissible Set No. 3.

Forces H_1 and H_2 are taken as large as the thickness of the angle leg allows, but not to exceed the tension/shear interaction expression for the bolts. Let these values of H_1 and H_2 be denoted by $H_{1_{max}}$ and $H_{2_{max}}$. Then, setting $M_{A_1} = M_{B_2} = 0$ (these will add extra tension on the bolts if non zero).

$$Pg_1 = LH_{1_{max}} + M_{A_2}$$

$$Pg_2 = LH_{2_{max}} + M_{B_1}$$

$$H_{1_{max}}g_2 = H_{2_{max}}g_1$$

This set is much more complex than either of the first two, but will produce a larger value for P than sets 1 or 2 for very short connections with light angles.

APPLICATIONS

As stated in the introduction, claw angle connections are normally designed for direct load (P) only, with no consideration of the eccentricities. This has been the practice of many designers for many years and has been incorporated

into the latest AISC Manuals on Connection Design (AISC 1992, AISC 1994B). Consider the following two examples from the Manuals. For these two examples, admissible set No. 2 will be used. From Figure 4, it can be seen that Bolts A are subjected to forces

$$shear = \sqrt{P^2 + H_1^2}$$

$$tension = H_2$$

while Bolts B are subjected to forces

$$shear = \sqrt{P^2 + H_2^2}$$

$$tension = H_1$$

Note that P is assumed to be tension. This is the critical case. When P is compression, the "tensions" H_1 and H_2 are compressions and are transmitted by bearing and not by the bolts.

The notation used in these examples is that of AISC (1989) if not defined herein.

Example 1

AISC Manual Vol. II (ASD/LRFD 1992) p. 7-111, Ex. 16.; Ex. 11-2 of the AISC Manual Vol. II (LRFD 1994) p. 11-27, is similar.

This is the claw angle of the connection of Figure 1.

$$g_1 = g_2 = g = 2\frac{1}{2}$$

$$L = 22$$

$$P = 173/2 = 86.5k$$

$$H_1 = H_2 = H = \frac{86.5 \times 2.5}{22} = 9.83k$$

L's4x4x3/4

Material A36

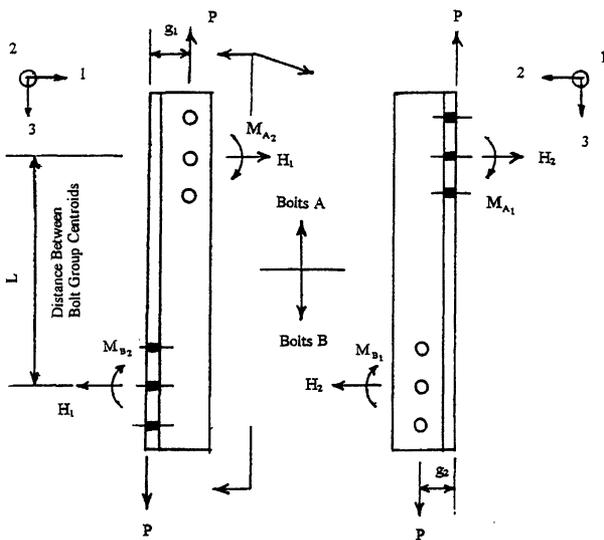


Fig. 2. Most general set of claw angle forces.

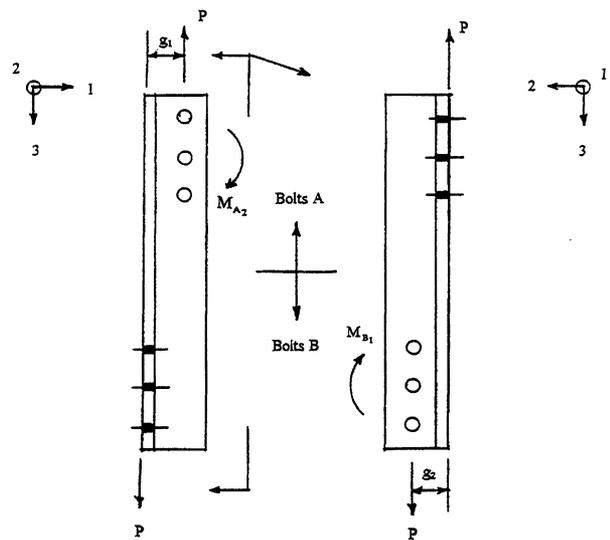


Fig. 3. Forces for admissible set No. 1.

Bolts A325 N $\frac{7}{8}$ ϕ

Holes STD $1\frac{5}{16}$ ϕ

Since $g_1 = g_2$, both sets of bolts see the same loads

$$shear = \sqrt{86.5^2 + 9.83^2} = 87.1k$$

$$tension = 9.83k$$

$$shear \text{ per bolt} = V = \frac{87.1}{7} = 12.4k < 12.6k \quad \text{o.k.}$$

$$tension \text{ per bolt} = T = \frac{9.83}{7} = 1.4k$$

Allowable tension per bolt = $B =$

$$\sqrt{44^2 - 4.39 \left(\frac{12.4}{.6013} \right)^2} \times .6013 = 5.0k > 1.4k \quad \text{o.k.}$$

Check bending of angle leg under tension load $H = 9.83k$
(Prying Action)

$$b = 2.5 - .75 = 1.75$$

$$a = 4 - 2.5 = 1.5 < 1.25b \quad \text{o.k.}$$

$$b' = 1.75 - \frac{.875}{2} = 1.31$$

$$a' = 1.5 + \frac{.875}{2} = 1.94$$

$$\rho = .68$$

$$\delta = 1 - \frac{.9375}{3} = .69$$

$$t_c = \sqrt{\frac{8 \times 5.0 \times 1.31}{3 \times 36}} = .70$$

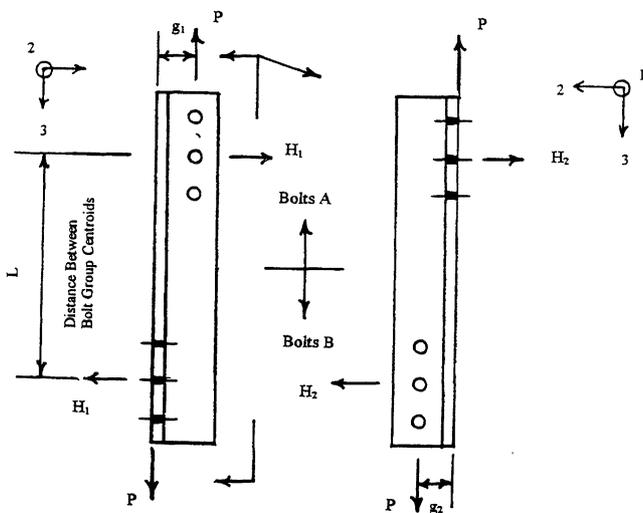


Fig. 4. Forces for admissible set No. 2.

$$\alpha' = \frac{1}{.69 \times 1.68} \left[\left(\frac{.70}{.75} \right)^2 - 1 \right] = -.11$$

$$T_{allow} = 5.0k > 1.4k \quad \text{o.k.}$$

\therefore Bolts and claw angles are **o.k.**

The angles and bolts were originally designed (AISC 1992, AISC 1994B) only for $P = 86.5k$, with the extra shear and tension of $9.83k$ ignored. The original design was very close to the limit on the bolts, i.e. $86.5/7 = 12.36k < 12.6k$, i.e. within 1.9 percent of the allowable load. Nevertheless, the extra shear and tension do not cause the design to be unsatisfactory.

Example 2

AISC Manual Vol. II (ASD/LRFD 1992) p. 7-160, Ex.24. Figure 5 shows the configuration where

$$g_1 = g_2 = g = 2\frac{1}{2}$$

$$L = 13.25$$

$$P = 28.1k$$

$$H = \frac{28.1 \times 2.5}{13.25} = 5.30$$

L \times S4 \times 4 \times $\frac{3}{8}$

Material A36

Bolts A325SC - A - N $\frac{7}{8}$ ϕ

Note: This is a shorthand way to say the bolts are slip critical with surface Class A, and with threads in the shear plane(s).

Holes STD $1\frac{5}{16}$ ϕ

Since $g_1 = g_2$, both sets of bolts see the same loads

$$shear = \sqrt{28.1^2 + 5.30^2} = 28.6k$$

$$tension = 5.30k$$

$$shear \text{ per bolt} = V = \frac{28.6}{3} = 9.53k < 10.2k \quad \text{o.k.}$$

$$tension \text{ per bolt} = T = \frac{5.30}{3} = 1.77k$$

$$\begin{aligned} \text{allowable tension per bolt} &= B = 39 \left(1 - \frac{9.53}{10.2} \right) \\ &= 2.56k > 1.77k \quad \text{o.k.} \end{aligned}$$

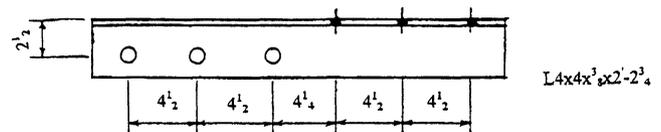


Fig. 5. Claw angle for Example 2.

Check bending of angle leg (prying action)

$$b = 2.5 - .375 = 2.125$$

$$a = 1.5 < 1.25b \quad \text{o.k.}$$

$$b' = 1.69$$

$$a' = 1.94$$

$$\rho = .87$$

$$\delta = 1 - \frac{.9375}{4.5} = .79$$

$$t_c = \sqrt{\frac{8 \times 2.56 \times 1.69}{4.5 \times 36}} = .462$$

$$\alpha' = \frac{1}{.79 \times 1.87} \left[\left(\frac{.462}{.375} \right)^2 - 1 \right] = .35$$

$$T_{allow} = 2.56 \left(\frac{.375}{.462} \right)^2 (1 + .35 \times .79) = 2.15k > 1.77k \quad \text{o.k.}$$

∴ bolts and claw angles are **o.k.**

Example 3

As a "worst case" situation, consider the claw angle of Figure 6. This is a very short angle, of fairly light weight, and with strong bolts (A325N $\frac{7}{8}$ φ).

a. Solution via Admissible Set No. 1 (Both sets of bolts see the same loads so subscripts are unnecessary).

$$M = 2.5P$$

AISC Manual (ASD 9th) p. 4-62 Table XI

$$n = 2 \quad l = 2.5 \quad c = 1.03$$

$$P = 1.03 \times 12.6 = 13.0k$$

b. Solution via Admissible Set No. 2.

$$H = 2.5P/6.5 = .385P$$

$$b = 2.5 - .375 = 2.125$$

$$a = 1.5 < 1.25b = 2.656 \quad \text{o.k.}$$

$$b' = 2.125 - .875/2 = 1.6875$$

$$a' = 1.5 + .875/2 = 1.9375$$

$$\rho = .871$$

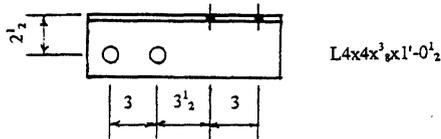


Fig. 6. Claw angle for Example 3.

$$\delta = 1 - .9375/3 = .6875$$

At max bolt shear, $F_v = 21$ ksi, the allowable bolt tensile stress $F_t = 55 - 1.8 \times 21 = 17.2$ ksi, and the max allowable bolt tensile force $B = 17.2 \times .6013 = 10.34k$. Note that the tension/shear interaction equation used here is the "three straight lines" version rather than the ellipse. This is acceptable per the AISC specification as mentioned in the commentary (AISC 1994A).

Thus

$$t_c = \sqrt{\frac{8 \times 10.34 \times 1.6875}{3 \times 36}} = 1.137$$

$$\alpha' = \frac{1}{.6875 \times 1.871} \left[\left(\frac{1.137}{.375} \right)^2 - 1 \right] = 6.37$$

use $\alpha' = 1$

$$T_{allow} = 10.34 \left(\frac{.375}{1.137} \right)^2 \times 1.6875 = 1.90k$$

Based on T_{allow} , $H_{max} = 2 \times 1.90 = 3.80k$

Setting $H_{max} = 3.80 = .385P$, $P = 9.87k$. With $P = 9.87k$, the shear per bolt is

$$\sqrt{\left(\frac{9.87}{2} \right)^2 + \left(\frac{3.80}{2} \right)^2} = 5.29k < 12.6k \quad \text{o.k.}$$

Thus the maximum load by Admissible Set No. 2 is 9.87k

c. Solution via Admissible Set No. 3.

The solution given by Admissible Set No. 1 assumes that $H = 0$, i.e. angle legs and bolts can take no tension. Alternately, the solution given by Admissible Set No. 2 assumes that $M = 0$, i.e. that the couple on the bolt group is zero. The present set allows both H and M to exist. Its genesis lies in the fact that with Set No. 2 the bolt shear is only 5.29k. Since this is the case allowing the couple M to exist will increase capacity. The relevant equilibrium equation is

$$2.5P = HL + M$$

from which it can be seen that a non zero M will increase P . Set $H = H_{max} = 3.80k$ from the Set No. 2 calculations. Then, with $L = 6.5$

$$M = 2.5P - 24.7$$

and the resultant load on the critical bolt is

$$R = \sqrt{\left(\frac{P}{2} \right)^2 + \left(\frac{H_{max}}{2} + \frac{M}{3} \right)^2}$$

Table 1.
Summary for Results for Examples 3 and 4
(A325N $7/8$ bolts, A36 angles, capacities in kips)

Ex. No.	Angle Size	L / g	Capacity Based on Admissible Set			Estimated Capacity	Direct load Capacity	% Reduction (Eccentric Effect)
			No. 1	No. 2	No. 3			
3	4x4x $3/8$	2.6	13.0	9.87	18.1	18.1	25.2	28.2
3	4x4x $1/2$	2.6	13.0	19.0	22.0	22.0	25.2	12.7
3	4x4x $3/4$	2.6	13.0	23.5	23.5 ⁽¹⁾	23.5	25.2	6.75
4	4x4x $3/8$	3.8	16.0	23.0	24.2	24.2	25.2	3.97

⁽¹⁾Set 3 does not increase capacity over that of Set 2 because $H_{max} = 17.0k$ for the 4x4x $3/4$ angle cannot be reached. The maximum achievable H is 9.05k and is reached when $M = 0$.

Substituting numerical values into Equation 4 and setting $R = 12.6$ yields

$$\left(\frac{P}{2}\right) + (.833P - 6.33)^2 = 12.6^2$$

$P = 18.1$ kips

Table 1 summarizes the results. From these three admissible sets, the estimated capacity is 19.4 kips. The direct load or no-eccentricity capacity is 25.2 kips, so the eccentricity causes a reduction not more than 28.2 percent. Additional admissible distributions may exist which make the reduction smaller than 28.2 percent. Also shown in Table 1 is the effect of increasing the angle leg thickness. When 4x4x $3/4$ angles are used, the maximum reduction is only 6.7 percent.

The reductions given in Table 1 are from the direct capacity based on bolt shear strength. Normally, there will be some slack between the applied load and the capacity, because an integer number of bolts must be used. Thus, the effect of eccentricity will generally be less than 28.2 percent even for this worst case example.

Example 4

Consider the angle of Example 3 but with the bolt pitch increased to 4 $1/2$ inches and the distance between bolt groups increased to 2 $1/4$ + 2 $1/4$ + $1/2$ = 5.

a. Admissible Set 1.

From AISC Manual (9th) p. 4-62 Table XI

For $b = 3$, $n = 2$, $l = 2.5$ $c = 1.03$

For $b = 6$, $n = 2$, $l = 2.5$ $c = 1.51$

For $b = 4\frac{1}{2}$ $c = (1.03 + 1.51)/2 = 1.27$

$P = 1.27 \times 12.6 = 16.0k$

b. Admissible Set 2.

$L = 4.5 + 5 = 9.5$

$H = 2.5P/9.5 = .263P$

$\delta = 1 - .9375/4.5 = .792$

$$t_c = \sqrt{\frac{8 \times 10.34 \times 1.6875}{4.5 \times 36}} = .928$$

$$\alpha' = \frac{1}{.792 \times 1.871} \left[\left(\frac{.928}{.375} \right)^2 - 1 \right] = 3.46$$

use $\alpha' = 1$

$$T_{allow} = 10.34 \left(\frac{.375}{.928} \right)^2 \times 1.792 = 3.03k$$

$$H_{max} = 2 \times 3.03 = 6.06k$$

$$P = 6.06/.263 = 23.0k$$

Check maximum bolt shear

$$\sqrt{\left(\frac{23.0}{2}\right)^2 + \left(\frac{6.06}{2}\right)^2} = 11.89k < 12.6k \quad \text{o.k.}$$

c. Admissible Set 3.

$$M = 2.5P - 6.06 \times 9.5 = 2.5P - 57.6$$

The resultant load on the critical bolt is

$$R = \sqrt{\left(\frac{P}{2}\right)^2 + \left(\frac{H_{max}}{2} + \frac{M}{4.5}\right)^2}$$

Thus

$$\left(\frac{P}{2}\right)^2 + (.56P - 9.77)^2 = 12.6^2$$

$P = 24.2k$

These results are also shown in Table 1. It can be seen that a small increase in the length of the claw angle, by increasing the pitch from 3 to 4 $1/2$ inches, yields a great reduction in the effect of eccentricity.

CONCLUSION

The examples given show that the eccentric effect of the connections to opposite angle legs is very small except for very short connections ($L/g < 4$), and can safely be ignored. For short connections, consideration should be given to eccentricity by performing the calculations outlined in this note, or short connections should be avoided by keeping $L/g \geq 4$, approximately.

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