University of Technology
Mechanical Engineering Department

Machine Design I

Third Class for All Branches

LECTURES TWENTY THREE & TWENTY FOUR

MACHINE FRAMES, BOLTED CONNECTIONS AND WELDED JOINTS

Figure (20) shows an example of an eccentrically loaded bolted joint. The motor on the extended bracket places the bolts in shear because its weight acts directly downward. But there also exists a moment equal *to (P*a)* that must be resisted. The moment tends to rotate the bracket and thus to shear the bolts. The basic approach to the analysis and design of eccentrically loaded joints is to determine the forces that act on each bolt because of all the applied loads. Then, by a process of superposition, the loads are combined vectorially to determine which bolt carries the greatest load. That bolt is then sized. The method will be illustrated in Example Problem 20-1.

The American Institute of Steel Construction (AISC) lists allowable stresses for bolts made from ASTM grade steels, as shown in Table 20-1. These data are for bolts used in standard-sized holes, (1.5875 mm) larger than the bolt.

In the design of bolted joints, you should ensure that there are no threads in the plane where shear occurs. The body of the bolt will then have a diameter equal to the major diameter of the thread. You can use the tables in Chapter 18 to select the standard size for a bolt.

FIGURE 20–4
Eccentrically loaded bolted joint

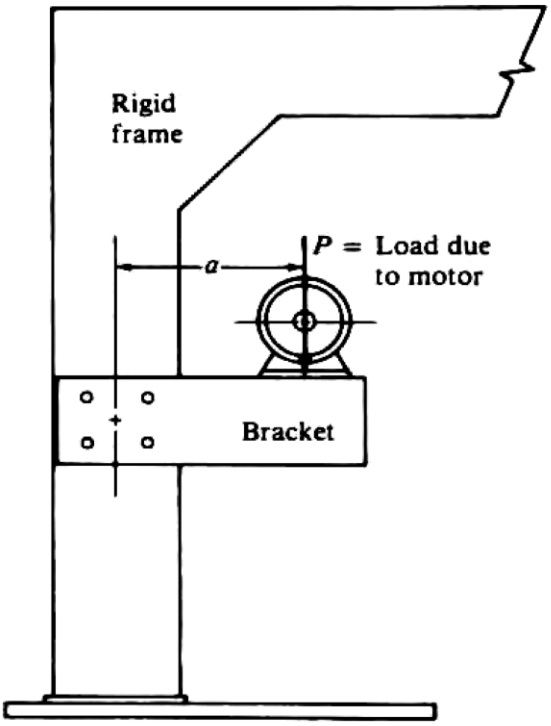
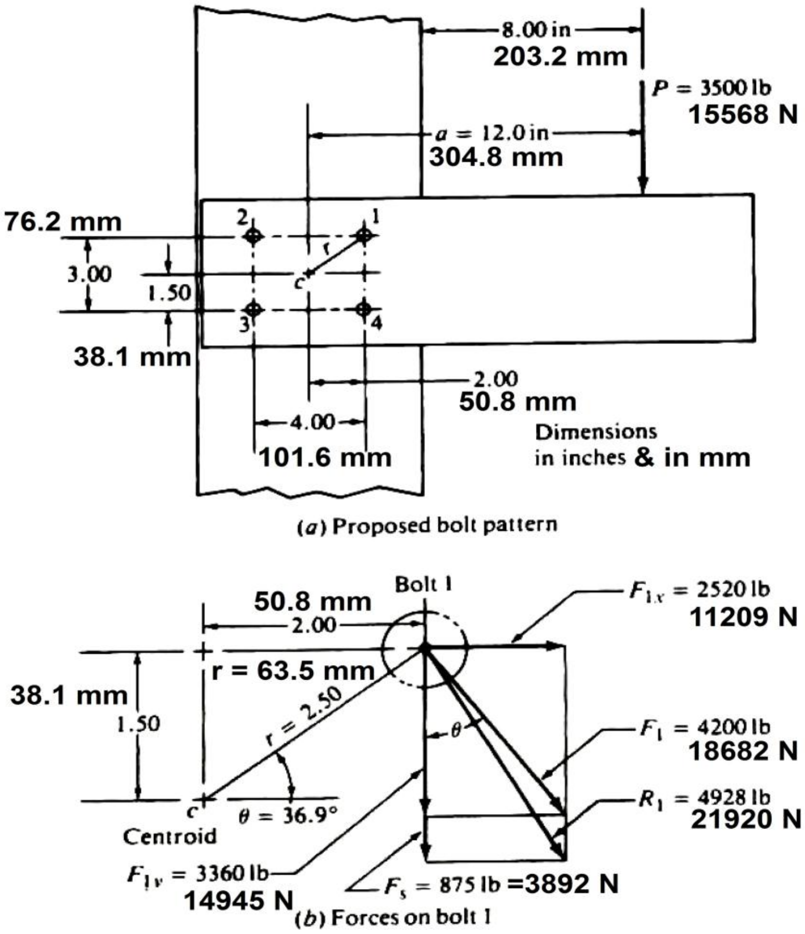


FIGURE 20–5
Geometry of bolted joint and forces on bolt 1



(a) Proposed bolt pattern

(b) Forces on bolt 1

TABLE 20–1 Allowable stresses for bolts

ASTM grade	Allowable shear stress	Allowable tensile stress
A307	10 ksi (69 MPa)	20 ksi (138 MPa)
A325 and A449	17.5 ksi (121 MPa)	44 ksi (303 MPa)
A490	22 ksi (152 MPa)	54 ksi (372 MPa)

Example Problem 20-1 (page 781)

For the bracket in Figure (20-4), assume that the total force (P) is 3500 lb (15568 N) and the distance (a) is 12 in. (304.8 mm). Design the bolted joint, including the location and number of bolts, the material (see table 20-1), and the diameter.

Solution:

The solution shown is an outline of procedure that can be used to analyze similar joints. The data of this problem illustrate the procedure:

1. Propose the number of bolts and the pattern. This is a design decision, based on your judgment and the geometry of the connected parts. Assume the No. of bolts and their orientation, so assume (4 bolts) and fixed as shown in figure (20-5).

2. Determine the direct shear force: $\left\{F_s = \frac{P}{No.of\ bolts}\right\}$. Load per bolt = $F_s = \frac{P}{4}$

$$\Rightarrow \ F_s = \frac{15568}{4} = 3892 \text{ N} \downarrow$$

3. Compute the **Moment** to be resisted by bolts pattern: the product of the overhanging load and the distance to the **centroid** of the bolt pattern. In this problem: (M=P*a = 15568*304.8 = 4.745 KN.m)

4. Compute the radial distance from the centroid of the bolt pattern to the center of each bolt. In this problem, each bolt has a radial distance of:

$$\left\{r = \sqrt{(38.1)^2 + (50.8)^2} = 63.5\ mm\right\}$$

5. Compute the sum of the squares of all radial distances to all bolts. In this problem, all the four bolts have the same (r), then

$$\sum r^2 = r_1^2 + r_2^2 + r_3^2 \;\ldots\ldots\ldots = 4\,(63.5)^2 = 16130\, mm^2$$

6. Compute the force on each bolt required to resist the bending moment from the relation:

M = P*a = $F_1\, r_1 + F_2 r_2 + F_3 r_3 + \ldots\ldots\ldots$

$F_i \;\alpha\; r_i \qquad \rightarrow \qquad \frac{F_i}{r_i} = constant = \frac{F_1}{r_1} = \frac{F_2}{r_2} = \frac{F_3}{r_3} = \quad \ldots\ldots\ldots$

M = $\frac{F_1}{r_1} * r_1^2 + \frac{F_2}{r_2} * r_2^2 + \frac{F_3}{r_3} * r_3^2 + \;\ldots\ldots = \frac{F_i}{r_i}\,(r_1^2 + r_2^2 + r_3^2 + \;\ldots\ldots)$

$$F_i = \frac{M\, r_i}{r_1^2 + r_2^2 + r_3^2 + r_4^2} = \frac{M\, r_i}{\sum r^2} \quad \ldots\ldots\ldots (20-3)$$

r_i = radial distance from the centriod of the bolt pattern to the i^{th} bolt

F_i = Force on the i^{th} bolt due to moment. The force acts perpendicular to the reduis.

In this problem, all such forces are equal. For example, for bolt 1:

$$F_1 = \frac{4745\ \text{N.m} * 63.5\ \text{mm}}{16130} = 18682\ \text{N}$$

7. Determine the resultant of all forces acting on each bolt. A vector summation can be performed either analytically or graphically, or each force can be resolved into horizontal and vertical components. The components can be summed and then the resultant can be computed.
Let us use the letter approach for this problem. The shear force acts directly downward, in the y- direction. The x- and y- components of F_i are:

$F_{1x} = F_1 \sin\theta = 18682 \sin 36.9 = 11209$ N

$F_{1y} = F_1 \cos\theta = 18682 \cos 36.9 = 14945$ N

Total force in Y-direction

$F_{1T)y} = F_{1y} + F_s = 14945 + 3892 = 18837$ N

R_1 = Resultant force on bolt 1 = $\sqrt{(11209)^2 + (18837)^2} = 21920\, N$

8. Specify the bolt material; compute the required area for the bolt; and select an appropriate size. For this problem, let us specify ASTM A325 steel for the

bolts having an allowable shear stress of (121 MPa) from table (20-1). Then the required area for the bolt is:

Allowable shear stress = $\tau_a = 121\ MPa = \frac{R_1}{A_s} = \frac{21920}{\frac{\pi D^2}{4}} \quad \rightarrow \quad D = 15.215\ mm$

Now choose 4 bolts with M16*2 from table 18-5 or use table 18-4 choose size

5/8 = 0.625 inch = 15.875 mm

WELDED JOINTS

References:

Machine Elements in Mechanical Design by Robert L. Mott, P.E. (Chapter 20)

Note: Read section (20-4) (Page 783)

Introduction:

The design of welded joints requires:

- Manner of loading on the joint.
- The type of materials in weld and in the member to be joined.
- The geometry of the joint itself.

Table (20-2) below shows material of weld and allowable stresses:

TABLE 20–2 Allowable shear stresses on fillet welds

A. Steel

Electrode type	Typical metals joined (ASTM grade)	Allowable shear stress
E60	A36, A500	18 ksi (124 MPa)
E70	A242, A441	21 ksi (145 MPa)
E80	A572, Grade 65	24 ksi (165 MPa)
E90		27 ksi (186 MPa)
E100		30 ksi (207 MPa)
E110		33 ksi (228 MPa)

B. Aluminum

	Filler Alloy							
	1100		4043		5356		5556	
	Allowable Shear Stress							
Metal joined	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
1100	3.2	22	4.8	33				
3003	3.2	22	5.0	34				
6061			5.0	34	7.0	48	8.5	59
6063			5.0	34	6.5	45	6.5	45

For steel welded by electric arc method, the type of electrode is an indication of the tensile strength for filler metal. For example, E70 electrode has Su ≥ 70 Ksi (483 MPa). More information can be found from:

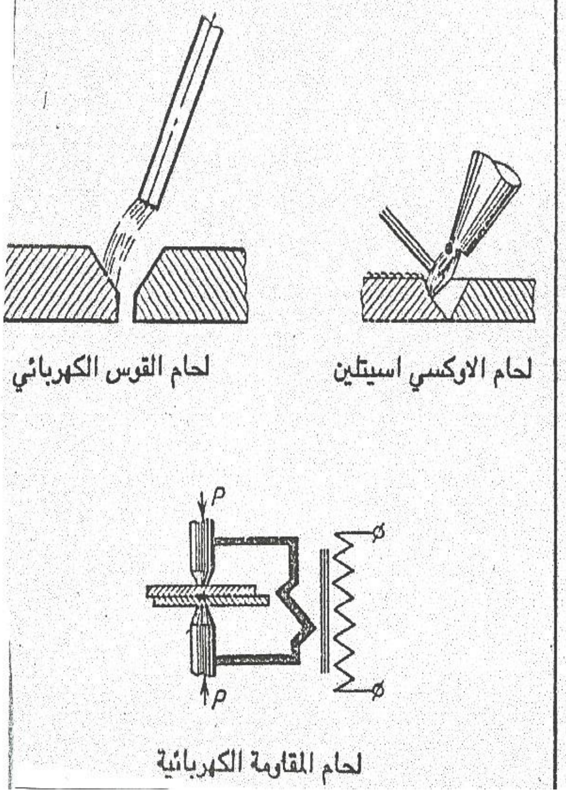
American Welding Society (AWS)
American Institute for Steel Construction (AISC)
Aluminum Association (AA)

See internal sites 3 & 7 in Robert L. Mott (Ch. 20)

<u>Type of Joints, Type of Welds, and size of weld:</u>

في العام الماضي قد تعلمت في موضوع الرسم الميكانيكي وفي الفصل الثامن عن اللحام مايلي:

نبذة مختصرة عن اللحام ، تمثيل اللحام على الرسم ، الرموز الاساسية ، وضع الابعاد ، وغيرها من المواضيع وفيما يلي بعض فقط للتذكرة تم اخذها من كتاب الاستاذ عبد الرسول الخفاف.



لقد تزايد استعمال اللحام في السنوات الاخيرة لربط الاجزاء بدلا من البراغي والبراشيم وغيرها . ويستعمل اللحام في تصنيع ابدان المكائن واجزائها . ويستعمل بنطاق واسع في بناء السفن وانشاء الهياكل الحديدية المستعمله في البناء الحديدي .

تتميز المنتجات الملحومة عن المنتجات المسبوكة برخص كلفتها في حالة انتاج وحدات قليلة ومحدودة لان اللحام لا يتطلب التجهيزات اللازمة للسباكة مثل قوالب الصب وغيرها .

توجد ثلاثة طرق رئيسية للحام وهي :

1 - لحام الاوكسي اسيتيلين ويعرف بـ لحام الغاز (Gas welding) .

ان حرق غاز الاسيتيلين مع الاوكسجين يولد لهب ذو درجة حرارية عالية تكفي لصهر المعادن ولحامها . ويمكن استعمال هذه الحرارة ايضا لقطع المعادن .

2 - لحام القوس الكهربائي ويعرف بـ لحام القوس (Arc welding) .

تستخدم الحرارة الناتجه من القوس الكهربائي لغرض صهر المعادن ولحامها .

3- لحام المقاومة الكهربائية ويعرف بـ لحام المقاومة (Resistance welding) .

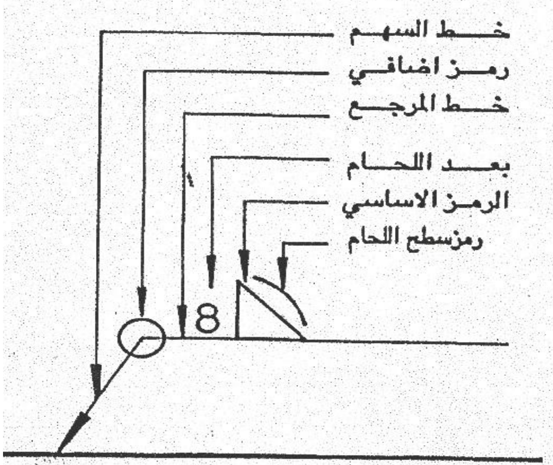
عند لحام المقاومة تمسك قطعتان من المعدن تحت ضغط معين ثم يتم امرار كمية كبيرة من التيار الكهربائي خلال الجزئين حيث تنتج مقاومة المعدن لامرار التيار الكهربائي حرارة عاليه عند مناطق الاتصال مما تسبب لحام القطعتين مع بعضهما .

تمثيل اللحام على الرسم

ليس من السهل رسم الشكل الحقيقي للحام وتوضيح معالمه . لذا يجب استعمال رموز خاصه بذلك . ينبغي ان تعطي الرموز جميع البيانات الضرورية التي تخص اللحام المطلوب تنفيذه بصورة مبسطه وواضحة دون الحاجه الى استعمال الملاحظات الكثيرة او رسم مساقط اضافيه ، وقد وضعت هيئة المواصفات الدولية مواصفه خاصه برموز اللحام (ISO 2253) .

تشمل الرموز ما يلي :

- خط المرجع
- خط السهم
- الرمز الاساس
- رمز سطح اللحام
- ابعاد اللحام
- رموز اضافية

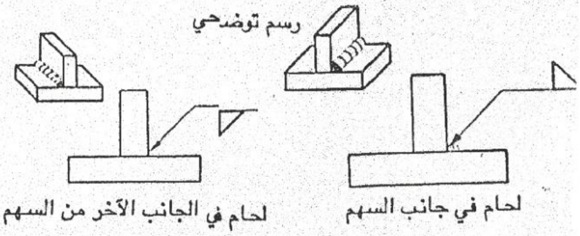


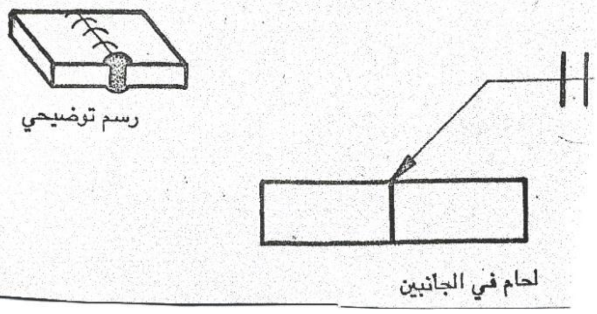
يبين هذا الشكل العناصر الاساسية التي تستعمل عند وضع بيانات اللحام.

موقع الرمز نسبة الى خط المرجع

يوضع الرمز مع خط المرجع كما يلي :

- فوق خط المرجع اذا كان اللحام في جانب لسهم (لحام ظاهر)
- تحت خط المرجع اذا كان اللحام في الجانب الاخر (لحام مخفي)
- عبر خط المرجع اذا كان اللحام في كلا الجنبين



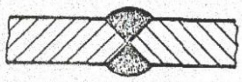
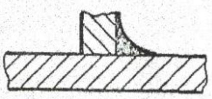
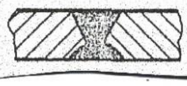


رموز سطح اللحام

تبين رموز سطح اللحام شكل السطح الخارجي للحام . الجدول التالي يبين هذه الرموز .

الرمز	شكل سطح اللحام
—	مسطح
⌒	محدب
‿	مقعر

- امثلة لاستعمال رموز اللحام

الرمز	رسم توضيحي	التفسير
		لحام الحرف V مسطح
		لحام الحرف V في الجانبين محدب
		لحام مثلث مقعر
		لحام الحرف V في الجانب الأول ولحام الظهارة في الجانب الآخر مسطح في الجانبين .

Figures (20-6) and (20-7) shows types and size of welded joints.

FIGURE 20–6 Types of weld joints

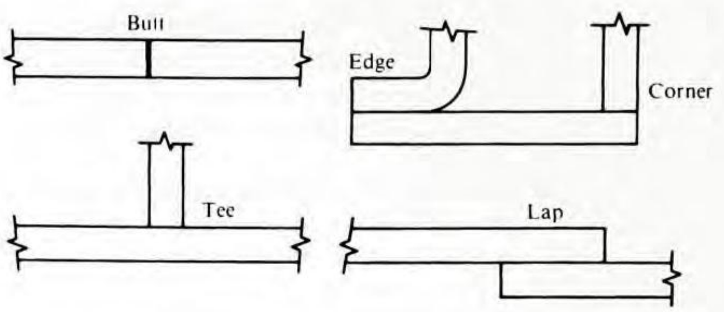
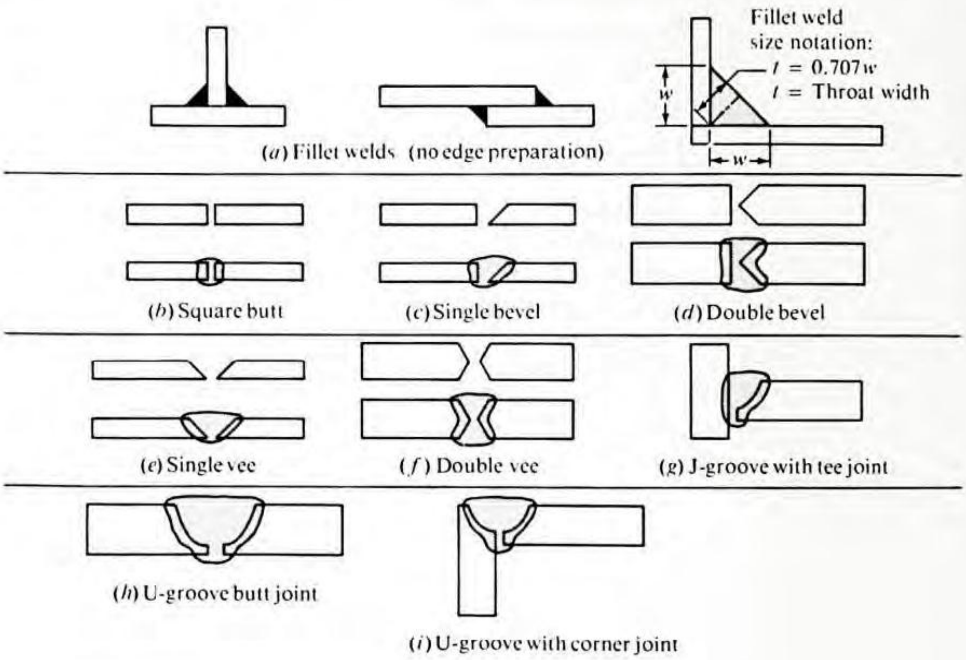


FIGURE 20–7 Some types of welds showing edge preparation



- The length of line from root of the weld = 0.707 W (W: leg dimension).
- The objective of the design of fillet welded joint is to specify the length of fillet, so the weld is treated as a line having no thickness.
- Fig. (20-3) gives the allowable force per (inch or mm) of leg.

TABLE 20–3 Allowable shear stresses and forces on welds

Base metal ASTM grade	Electrode	Allowable shear stress	Allowable force per inch of leg
Building-type structures:			
A36, A441	E60	13 600 psi	9600 lb/in
A36, A441	E70	15 800 psi	11 200 lb/in
Bridge-type structures:			
A36	E60	12 400 psi	8800 lb/in
A441, A242	E70	14 700 psi	10 400 lb/in

- Four different types of loading are considered here when the weld treated as a line:

The relationships used are summarized next:

Type of Loading	*Formula (and Equation Number) for Force per Inch of Weld*	
Direct tension or compression	$f = P/A_w$	**(20-4)**
Direct vertical shear	$f = V/A_w$	**(20-5)**
Bending	$f = M/S_w$	**(20-6)**
Twisting	$f = Tc/J_w$	**(20-7)**

- Fig. (20-8) Page 786 shows geometry factors for weld analysis.

Example: use class 5 in fig. (20-8) with b=101.6 mm, d=152.4 mm. find A_w, J_w , $\bar{X}$

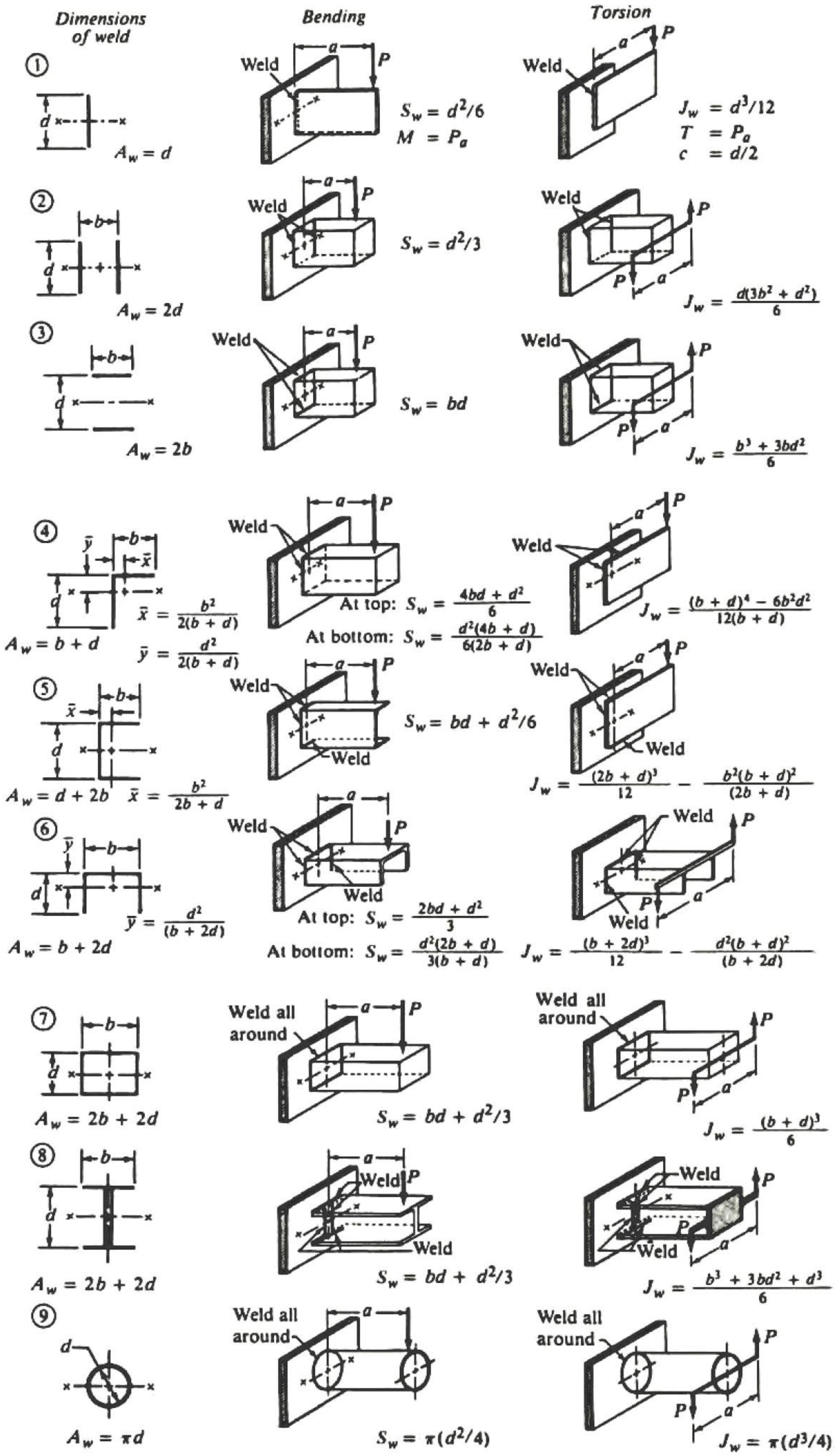
Sol: A_w = d +2b = 152.4+ (2*101.6) = 355.6 mm (with no thickness)

$$J_w = \frac{(2b+d)^3}{12} - \frac{b^2\,(b+d)}{(2b+d)} = \frac{355.6^3}{12} - \frac{10323\,(254)^2}{355.6} = 1.876 * 10^{-3}\ m^3$$

$$\bar{X} = \frac{b^2}{2b+d} = \frac{10323}{355.6} = 28.956\ mm$$

$$S_w = bd + \frac{d^2}{6} = (101.6)(152.4) + \frac{152.4^2}{6} = 1963\ mm^2$$

FIGURE 20–8
Geometry factors for weld analysis



General Procedure for Designing Welded Joints:

1. Propose the geometry of the joint and the design of the members to be joined.
2. Identify the types of stresses to which the joint is subjected (bending, twisting, vertical shear, direct tension, or compression).
3. Analyze the joint to determine the magnitude and the direction of the force on the weld due to each type of load.
4. Combine the forces vectorially at the point or points of the weld where the forces appear to be maximum.
5. Divide the maximum force on the weld by the allowable force from Table 20-3 to determine the required leg size for the weld. Note that when thick plates are welded, there are minimum acceptable sizes for the welds as listed in Table 20-4.

TABLE 20–4 Minimum weld sizes for thick plates

Plate thickness (in)	Minimum leg size for fillet weld (in)
≤1/2	3/16
>1/2–3/4	1/4
>3/4–1½	5/16
>1½–2¼	3/8
>2¼–6	1/2
>6	5/8

Example Problem 20–2 Design a bracket similar to that in Figure 20-4, but use welding to attach the bracket to the column. The bracket is 6.00 in high and is made from ASTM A36 steel having a thickness of 1/2 in. The column is also made from A36 steel and is 8.00 in wide.

Solution ***Step 1.*** The proposed geometry is a design decision and may have to be subjected to some iteration to achieve an optimum design. For a first trial, let's use the C-shaped weld pattern shown in Figure 20–9.

Step 2. The weld will be subjected to direct vertical shear and twisting caused by the 3500-lb load on the bracket.

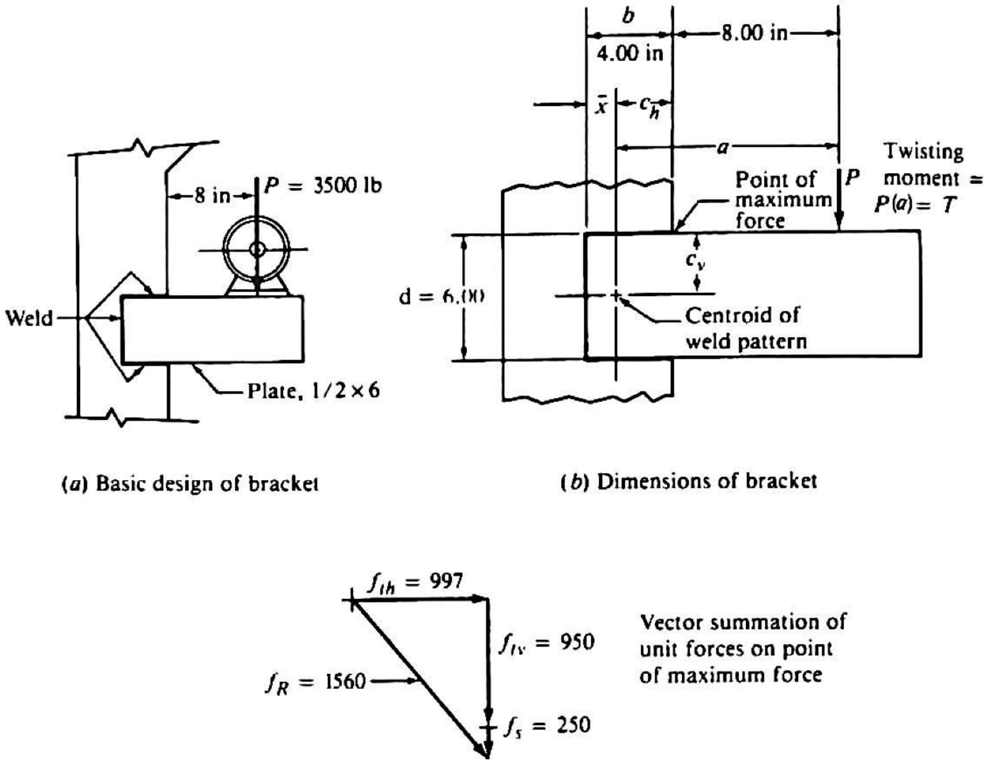
Step 3. To compute the forces on the weld, we must know the geometry factors A_w and J_w. Also, the location of the centroid of the weld pattern must be computed [see Figure 20–9(b)]. Use Case 5 in Figure 20–8.

$$A_w = 2b + d = 2(4) + 6 = 14 \text{ in}$$

$$J_w = \frac{(2b+d)^3}{12} - \frac{b^2(b+d)^2}{(2b+d)} = \frac{(14)^3}{12} - \frac{16(10)^2}{14} = 114.4 \text{ in}^3$$

$$\bar{x} = \frac{b^2}{2b+d} = \frac{16}{14} = 1.14 \text{ in}$$

FIGURE 20–9
C-shaped weld bracket



(*a*) Basic design of bracket

(*b*) Dimensions of bracket

(*c*) Analysis of forces

Force Due to Vertical Shear

$$V = P = 3500 \text{ lb}$$
$$f_s = P/A_w = (3500 \text{ lb})/14 \text{ in} = 250 \text{ lb/in}$$

This force acts vertically downward on all parts of the weld.

Forces Due to the Twisting Moment

$$T = P[8.00 + (b - \bar{x})] = 3500[8.00 + (4.00 - 1.14)]$$
$$T = 3500(10.86) = 38\,010 \text{ lb·in}$$

The twisting moment causes a force to be exerted on the weld that is perpendicular to a radial line from the centroid of the weld pattern to the point of interest. In this case, the end of the weld to the upper right experiences the greatest force. It is most convenient to break the force down into horizontal and vertical components and then subsequently recombine all such components to compute the resultant force:

$$f_{th} = \frac{Tc_v}{J_w} = \frac{(38\,010)(3.00)}{114.4} = 997 \text{ lb/in}$$
$$f_{tv} = \frac{Tc_h}{J_w} = \frac{(38\,010)(2.86)}{114.4} = 950 \text{ lb/in}$$

Step 4. The vectorial combination of the forces on the weld is shown in Figure 20–9(c). Thus, the maximum force is 1560 lb/in.

Step 5. Selecting an E60 electrode for the welding, we find that the allowable force per inch of weld leg size is 9600 lb/in (Table 20–3). Then the required weld leg size is

$$w = \frac{1560 \text{ lb/in}}{9600 \text{ lb/in per in of leg}} = 0.163 \text{ in}$$

Table 20–4 shows that the minimum size weld for a 1/2-in plate is 3/16 in (0.188 in). That size should be specified.

Example Problem 20–3 A steel strap, 1/4 in thick, is to be welded to a rigid frame to carry a dead load of 12 500 lb, as shown in Figure 20–10. Design the strap and its weld.

Solution The basic objectives of the design are to specify a suitable material for the strap, the welding electrode, the size of the weld, and the dimensions W and h, as shown in Figure 20–10.

Let's specify that the strap is to be made from ASTM A441 structural steel and that it is to be welded with an E70 electrode, using the minimum size weld, 3/16 in. Appendix 7 gives the yield strength of the A441 steel as 42 000 psi. Using a design factor of 2, we can compute an allowable stress of

$$\sigma_a = 42\,000/2 = 21\,000 \text{ psi}$$

Then the required area of the strap is

$$A = \frac{P}{\sigma_a} = \frac{12\,500 \text{ lb}}{21\,000 \text{ lb/in}^2} = 0.595 \text{ in}^2$$

But the area is $W \times t$, where $t = 0.25$ in. Then the required width W is

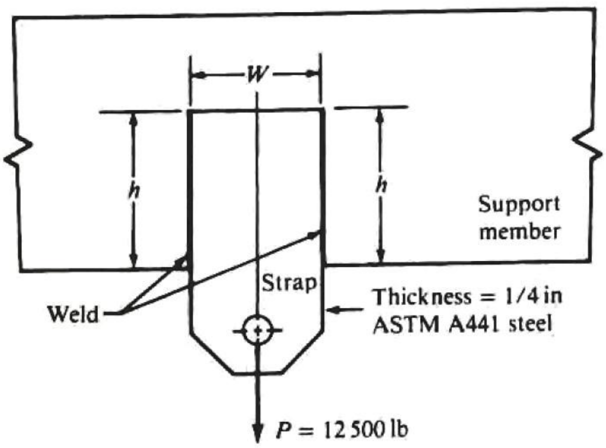
$$W = A/t = 0.595/0.25 = 2.38 \text{ in}$$

Let's specify that $W = 2.50$ in.

To compute the required length of the weld h, we need the allowable force on the 3/16-in weld. Table 20–3 indicates the allowable force on the A441 steel welded with an E70 electrode to be 11 200 lb/in per in of leg size. Then

$$f_a = \frac{11\,200 \text{ lb/in}}{1.0 \text{ in leg}} \times 0.188 \text{ in leg} = 2100 \text{ lb/in}$$

FIGURE 20–10
Steel strap



The actual force on the weld is

$$f_a = P/A_w = P/2h$$

Then solving for h gives

$$h = \frac{P}{2(f_a)} = \frac{12\,500\text{ lb}}{2(2100\text{ lb/in})} = 2.98\text{ in}$$

Let's specify $h = 3.00$ in.

Example Problem 20–4 Evaluate the design shown in Figure 20–11 with regard to stress in the welds. All parts of the assembly are made of ASTM A36 structural steel and are welded with an E60 electrode. The 2500-lb load is a dead load.

Solution The critical point would be the weld at the top of the tube where it is joined to the vertical surface. At this point, there is a three-dimensional force system acting on the weld as shown in Figure 20–12. The offset location of the load causes a twisting on the weld that produces a force f_t on the weld toward the left in the y-direction. The bending produces a force f_b acting outward along the x-axis. The vertical shear force f_s acts downward along the z-axis.

FIGURE 20–11
Bracket assembly

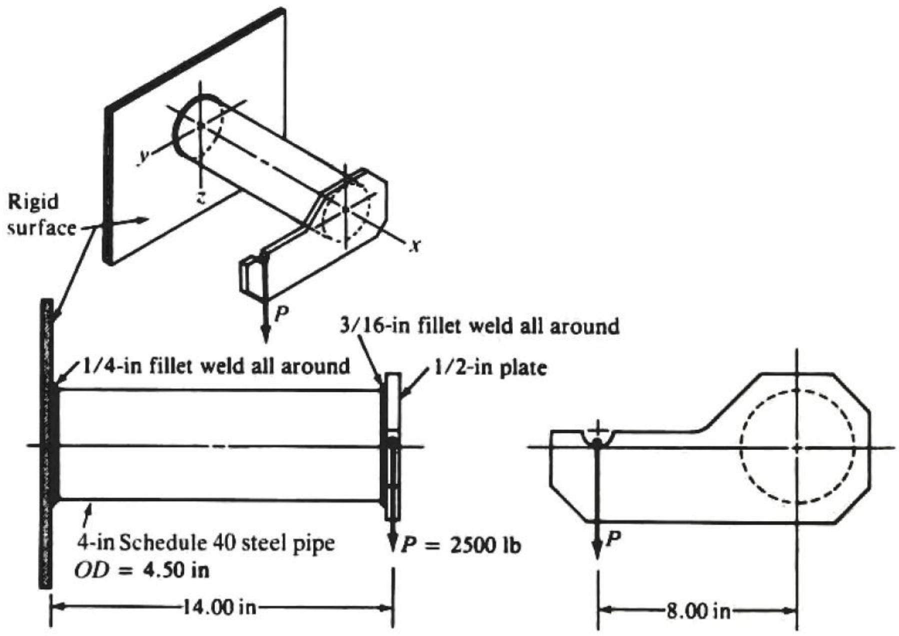
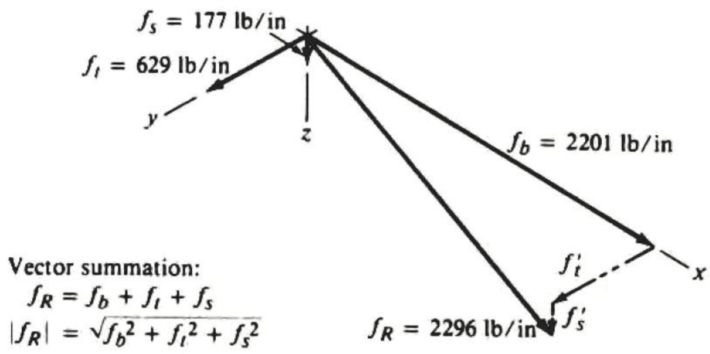


FIGURE 20–12
Force vectors



From statics, the resultant of the three force components would be

$$f_R = \sqrt{f_t^2 + f_b^2 + f_s^2}$$

Now each component force on the weld will be computed.

Twisting Force, f_t

$$f_t = \frac{Tc}{J_w}$$

$$T = (2500\text{ lb})(8.00\text{ in}) = 20\,000\text{ lb}\cdot\text{in}$$

$$c = OD/2 = 4.500/2 = 2.25\text{ in}$$

$$J_w = (\pi)(OD)^3/4 = (\pi)(4.500)^3/4 = 71.57\text{ in}^3$$

Then

$$f_t = \frac{Tc}{J_w} = \frac{(20\,000)(2.25)}{71.57} = 629\text{ lb/in}$$

Bending Force, f_b

$$f_b = \frac{M}{S_w}$$

$$M = (2500\text{ lb})(14.00\text{ in}) = 35\,000\text{ lb}\cdot\text{in}$$

$$S_w = (\pi)(OD)^2/4 = (\pi)(4.500)^2/4 = 15.90\text{ in}^2$$

Then

$$f_b = \frac{M}{S_w} = \frac{35\,000}{15.90} = 2201\text{ lb/in}$$

Vertical Shear Force, f_s

$$f_s = \frac{P}{A_w}$$

$$A_w = (\pi)(OD) = (\pi)(4.500\text{ in}) = 14.14\text{ in}$$

$$f_s = \frac{P}{A_w} = \frac{2500}{14.14} = 177\text{ lb/in}$$

Now the resultant can be computed:

$$f_R = \sqrt{f_t^2 + f_b^2 + f_s^2}$$

$$f_R = \sqrt{629^2 + 2201^2 + 177^2} = 2296\text{ lb/in}$$

Comparing this with the allowable force on a 1.0-in weld gives

$$w = \frac{2296\text{ lb/in}}{9600\text{ lb/in per in of leg size}} = 0.239\text{ in}$$

The 1/4-in fillet specified in Figure 20–11 is satisfactory.