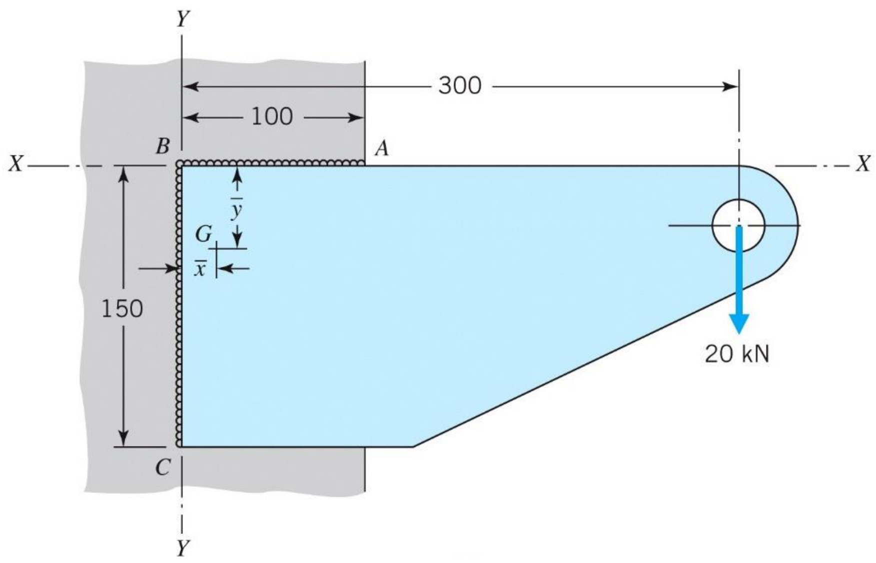
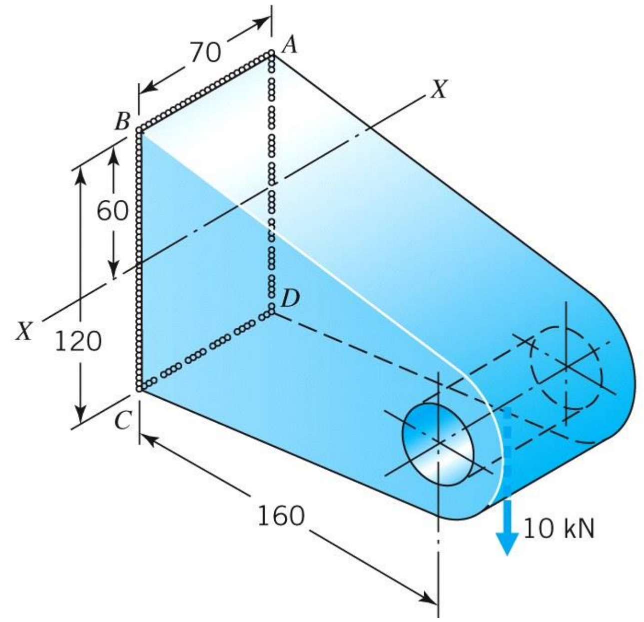
Welding

- **Fillet Weld**
  - **Bending**
- **Static Failure Criteria**
- **Fatigue Failure Criteria**

FILLET WELD: Load Orientation





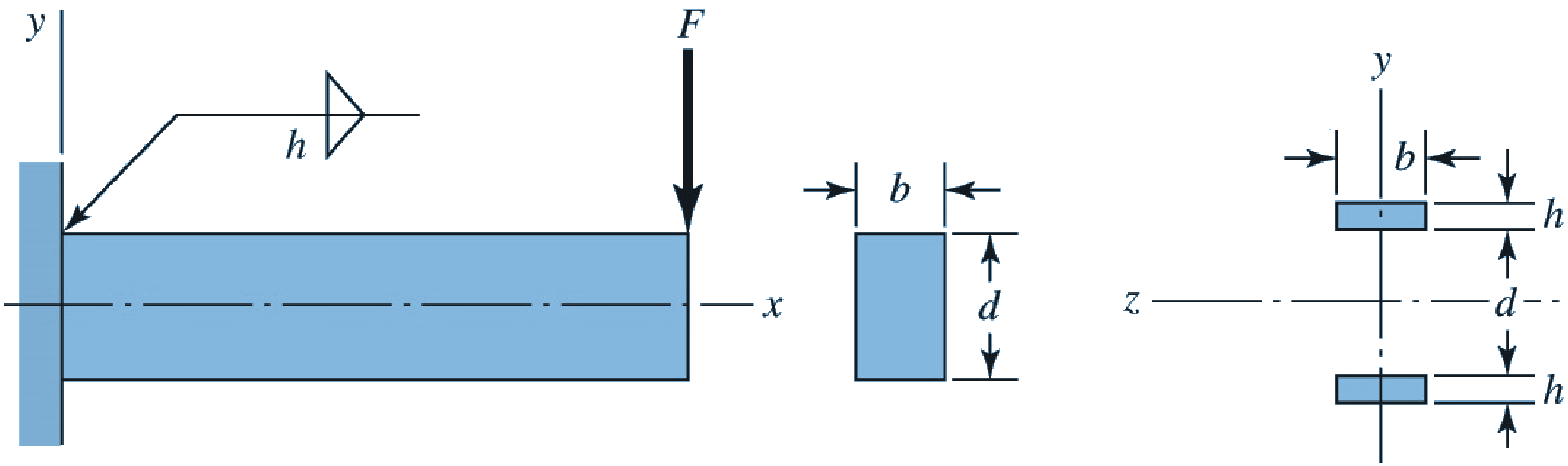
Welds in the Plane of the Load

- **Welds subjected to Torsion**
- **Welds also subjected to direct loading**

Welds out of the Plane of the Load

- **Welds subjected to Bending**
- **Welds also subjected to direct loading**

Fillet Welds Loaded in Bending

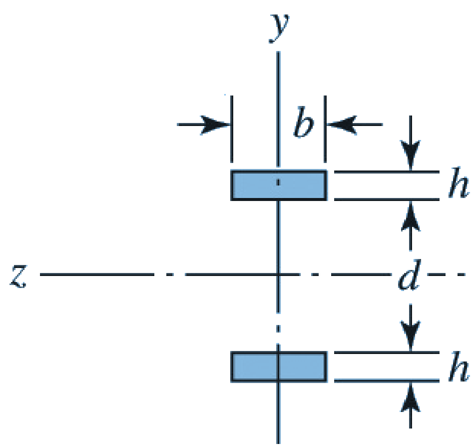


Direct Shear Stress

$$\tau' = \frac{V}{A} = \frac{F}{t \cdot b}$$

Calculating the Fillet Welds
Moment of Inertia

$$I_o = \frac{b \cdot t^3}{12}$$



$$I = I_o + A \cdot d^2 = \frac{b \cdot t^3}{12} + b \cdot t \cdot \left(\frac{d}{2}\right)^2$$

For both areas

0

$$I_{tot} = 2 \cdot \left[\frac{b \cdot t^3}{12} + b \cdot t \cdot \left(\frac{d}{2}\right)^2\right] = \frac{b \cdot t^3}{6} + \frac{b \cdot t \cdot d^2}{2}$$

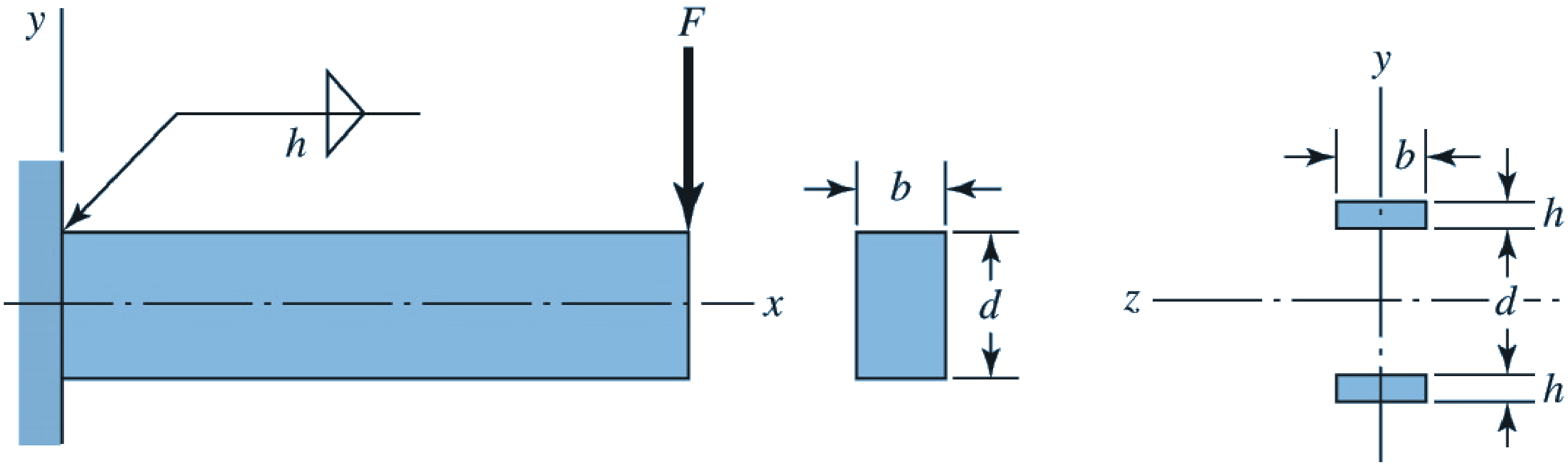
$$\boxed{I_{tot} = t \cdot I_u} = 0.7071 \cdot h \cdot I_u = t \cdot \frac{b \cdot d^2}{2}$$

$$t = 0.7071 \cdot h$$

$$I_u = \frac{b \cdot d^2}{2}$$

$$\boxed{\begin{array}{l} I = t \cdot I_u = 0.7071 \cdot h \cdot I_u \\ \\ t = 0.7071 \cdot h \end{array}}$$

Fillet Welds Loaded in Bending



Direct Shear

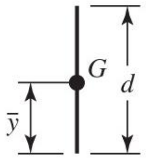
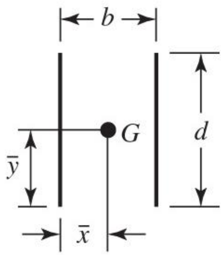
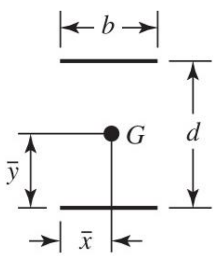
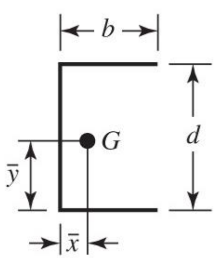
$$\tau' = \frac{V}{A} = \frac{F}{t \cdot b}$$

Indirect Shear: Bending

$$\tau''' = \frac{M \cdot c}{I} = \frac{M \cdot {}^{d}\!/\!{}_{2}}{0.7071 \cdot h \cdot b \cdot d^2 /\!{}_{2}} = \frac{1.414 \cdot M}{h \cdot b \cdot d}$$

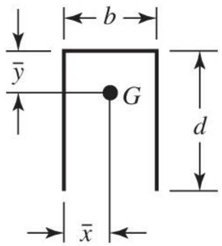
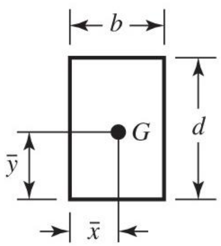
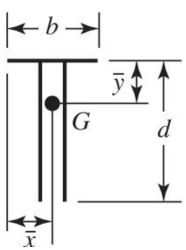
Bending Properties of Fillet Welds

Shigley 10th, Table 9-2

Weld	Throat Area	Location of G	Unit Second Moment of Area
1. 	$A = 0.707hd$	$\bar{x} = 0$ $\bar{y} = d/2$	$I_u = \dfrac{d^3}{12}$
2. 	$A = 1.414hd$	$\bar{x} = b/2$ $\bar{y} = d/2$	$I_u = \dfrac{d^3}{6}$
3. 	$A = 1.414hb$	$\bar{x} = b/2$ $\bar{y} = d/2$	$I_u = \dfrac{bd^2}{2}$
4. 	$A = 0.707h(2b + d)$	$\bar{x} = \dfrac{b^2}{2b + d}$ $\bar{y} = d/2$	$I_u = \dfrac{d^2}{12}(6b + d)$

Bending Properties of Fillet Welds

Shigley 10th, Table 9-2

Weld	Throat Area	Location of *G*	Unit Second Moment of Area
5. 	$A = 0.707h(b + 2d)$	$\bar{x} = b/2$ $\bar{y} = \dfrac{d^2}{b + 2d}$	$I_u = \dfrac{2d^3}{3} - 2d^2\bar{y} + (b + 2d)\bar{y}^2$
6. 	$A = 1.414h(b + d)$	$\bar{x} = b/2$ $\bar{y} = d/2$	$I_u = \dfrac{d^2}{6}(3b + d)$
7. 	$A = 0.707h(b + 2d)$	$\bar{x} = b/2$ $\bar{y} = \dfrac{d^2}{b + 2d}$	$I_u = \dfrac{2d^3}{3} - 2d^2\bar{y} + (b + 2d)\bar{y}^2$

Minimum Weld-Metal Properties

Shigley 10th, Table 9-3

AWS Electrode Number*	Tensile Strength kpsi (MPa)	Yield Strength, kpsi (MPa)	Percent Elongation
E60xx	62 (427)	50 (345)	17–25
E70xx	70 (482)	57 (393)	22
E80xx	80 (551)	67 (462)	19
E90xx	90 (620)	77 (531)	14–17
E100xx	100 (689)	87 (600)	13–16
E120xx	120 (827)	107 (737)	14

*The American Welding Society (AWS) specification code numbering system for electrodes. This system uses an E prefixed to a four- or five-digit numbering system in which the first two or three digits designate the approximate tensile strength. The last digit includes variables in the welding technique, such as current supply. The next-to-last digit indicates the welding position, as, for example, flat, or vertical, or overhead. The complete set of specifications may be obtained from the AWS upon request.

Stresses Permitted by Code

Shigley 10th, Table 9-4

Type of Loading	Type of Weld	Permissible Stress	n*
Tension	Butt	$0.60S_y$	1.67
Bearing	Butt	$0.90S_y$	1.11
Bending	Butt	$0.60–0.66S_y$	1.52–1.67
Simple compression	Butt	$0.60S_y$	1.67
Shear	Butt or fillet	$0.30S_{ut}^{\dagger}$	

*The factor of safety n has been computed by using the distortion-energy theory.

†Shear stress on base metal should not exceed $0.40S_y$ of base metal.

Allowable Load or Various Sizes of Fillet Welds

Shigley 10th, Table 9-6

Strength Level of Weld Metal (EXX)							
	60*	70*	80	90*	100	110*	120
Allowable shear stress on throat, ksi (1000 psi) of fillet weld or partial penetration groove weld							
$\tau =$	18.0	21.0	24.0	27.0	30.0	33.0	36.0
Allowable Unit Force on Fillet Weld, kip/linear in							
$^{\dagger}f =$	$12.73h$	$14.85h$	$16.97h$	$19.09h$	$21.21h$	$23.33h$	$25.45h$
Leg Size h, in	Allowable Unit Force for Various Sizes of Fillet Welds kip/linear in						
1	12.73	14.85	16.97	19.09	21.21	23.33	25.45
7/8	11.14	12.99	14.85	16.70	18.57	20.41	22.27
3/4	9.55	11.14	12.73	14.32	15.92	17.50	19.09
5/8	7.96	9.28	10.61	11.93	13.27	14.58	15.91
1/2	6.37	7.42	8.48	9.54	10.61	11.67	12.73
7/16	5.57	6.50	7.42	8.35	9.28	10.21	11.14
3/8	4.77	5.57	6.36	7.16	7.95	8.75	9.54
5/16	3.98	4.64	5.30	5.97	6.63	7.29	7.95
1/4	3.18	3.71	4.24	4.77	5.30	5.83	6.36
3/16	2.39	2.78	3.18	3.58	3.98	4.38	4.77
1/8	1.59	1.86	2.12	2.39	2.65	2.92	3.18
1/16	0.795	0.930	1.06	1.19	1.33	1.46	1.59

*Fillet welds actually tested by the joint AISC-AWS Task Committee.
$^{\dagger}f = 0.707h\,\tau_{\text{all}}$.

Schedule A: Allowable Load for Various Sizes of Fillet Welds

Strength Level of Weld Metal (EXX)							
	60*	70*	80	90*	100	110*	120
Allowable shear stress on throat, MPa of fillet weld or partial penetration groove weld							
$\tau =$	124	145	165	186	207	228	248
Allowable Unit Force on Fillet Weld, N/mm							
$^{\dagger}f =$	$87.67h$	$102.52h$	$116.66h$	$131.5h$	$146.35h$	$161.2h$	$175.34h$
Leg Size h, mm	Allowable Unit Force for Various Sizes of Fillet Welds N/mm						
25	2192	2563	2916	3288	3659	4030	4383
22	1929	2255	2566	2893	3220	3546	3857
20	1753	2050	2333	2630	2927	3224	3506
16	1403	1640	1866	2104	2342	2579	2805
12	1052	1230	1400	1578	1756	1934	2104
11	964	1127	1283	1447	1610	1773	1927
10	877	1025	1167	1315	1463	1612	1753
8	701	820	933	1052	1171	1290	1403
6	526	615	700	789	878	967	1052
5	438	513	583	658	732	806	877
3	263	308	350	395	439	484	526
2	175	205	233	263	293	322	351

*Fillet welds actually tested by the joint AISC-AWS Task Committee.
$^{\dagger}f = 0.707\text{h}\,\tau_{\text{all}}$.

Minimum Fillet Weld Size, h

Shigley 10th, Table 9-6

Material Thickness of Thicker Part Joined, in		Weld Size, in
*To $\frac{1}{4}$ incl.		$\frac{1}{8}$
Over $\frac{1}{4}$	To $\frac{1}{2}$	$\frac{3}{16}$
Over $\frac{1}{2}$	To $\frac{3}{4}$	$\frac{1}{4}$
†Over $\frac{3}{4}$	To $1\frac{1}{2}$	$\frac{5}{16}$
Over $1\frac{1}{2}$	To $2\frac{1}{4}$	$\frac{3}{8}$
Over $2\frac{1}{4}$	To 6	$\frac{1}{2}$
Over 6		$\frac{5}{8}$

Not to exceed the thickness of the thinner part.

*Minimum size for bridge application does not go below $\frac{3}{16}$ in.

†For minimum fillet weld size, schedule does not go above $\frac{5}{16}$ in fillet weld for every $\frac{3}{4}$ in material.

Schedule B: Minimum Fillet Weld Size, *h*

Material Thickness of Thicker Part Joined, mm		Weld Size, mm
*To 6 incl.		3
Over 6	To 12	5
Over 12	To 20	6
†Over 20	To 38	8
Over 38	To 58	10
Over 58	To 150	12
Over 150		16

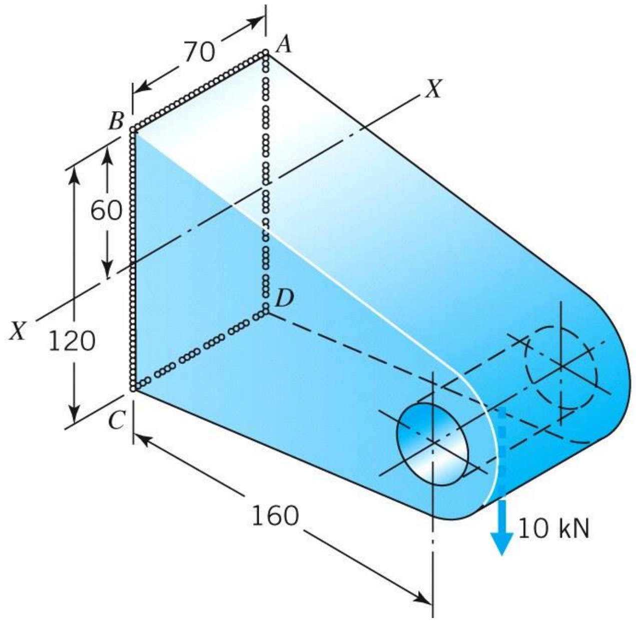
Not to exceed the thickness of the thinner part.

*Minimum size for bridge application does not go below 5 mm.

†For minimum fillet weld size, schedule does not go above 8 mm fillet weld for every 20 mm material.

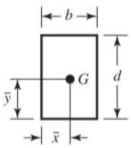
Example

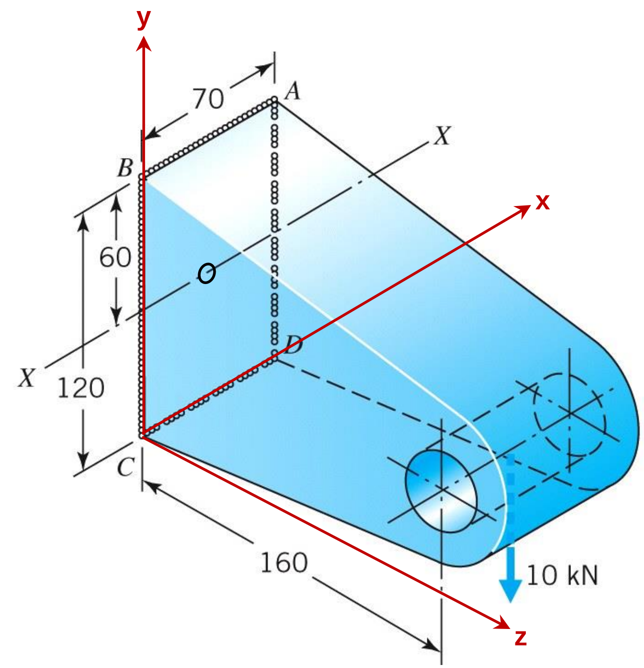
Determine the weld size for the structure shown below using E60 weld Rod (S_y=345 MPa) and for a safety factor of 3 off the yield stress.



Solution

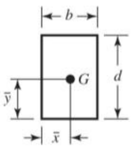
Shigley 10th, Table 9-2

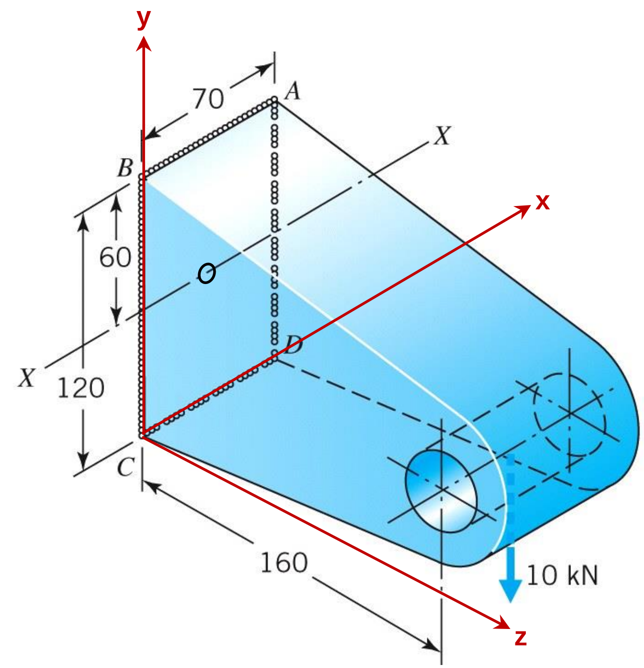
Weld	Throat Area	Location of G	Unit Second Moment of Area
6. 	$A = 1.414h(b + d)$	$\bar{x} = b/2$ $\bar{y} = d/2$	$I_u = \frac{d^2}{6}(3b + d)$



Solution

Shigley 10th, Table 9-2

Weld	Throat Area	Location of G	Unit Second Moment of Area
6. 	$A = 1.414h(b+d)$	$\bar{x} = b/2$ $\bar{y} = d/2$	$I_u = \frac{d^2}{6}(3b+d)$



Locating the Centroids

$$\bar{x} = \frac{b}{2} = \frac{70\,mm}{2} = 35\,mm$$

$$\bar{y} = \frac{b}{2} = \frac{120\,mm}{2} = 60\,mm$$

Throat Area from Table 9-2

$$t = 0.7071 \cdot h$$

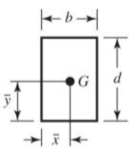
$$A = 1.414 \cdot h \cdot (b+d) = 2 \cdot t \cdot (b+d) = 2 \cdot t \cdot (70\,mm + 120\,mm) = 380\,mm \cdot t$$

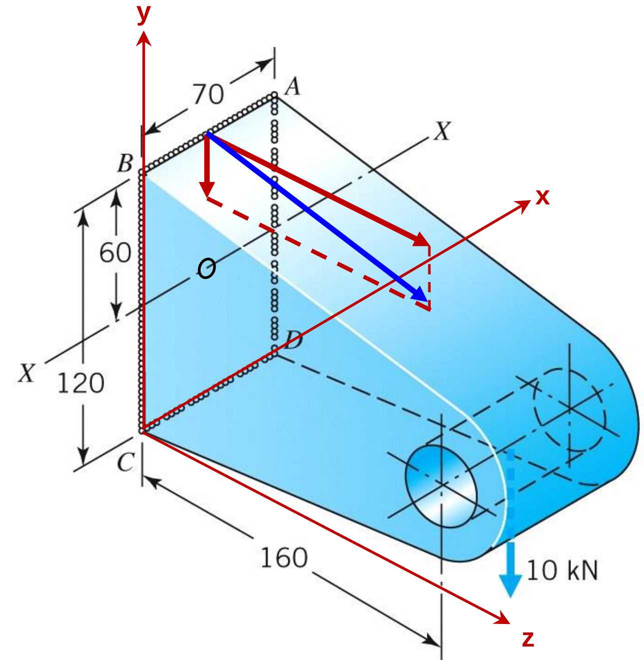
Direct Shear

$$\tau' = \frac{V}{A_T} = \frac{V}{3 \cdot b + d} = \frac{10\,000\,N}{0.380\,m \cdot t} = \frac{26.3 \times 10^3\ \frac{N}{m}}{t}$$

Solution

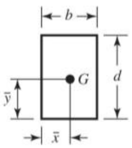
Shigley 10th, Table 9-2

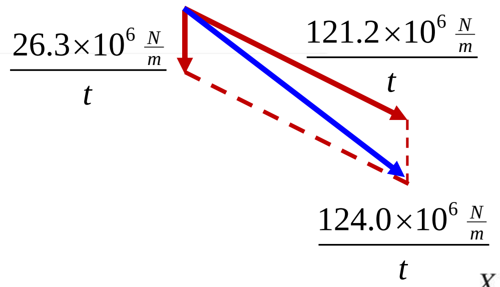
Weld	Throat Area	Location of *G*	Unit Second Moment of Area
6. 	$A = 1.414h(b + d)$	$\bar{x} = b/2$ $\bar{y} = d/2$	$I_u = \dfrac{d^2}{6}(3b + d)$

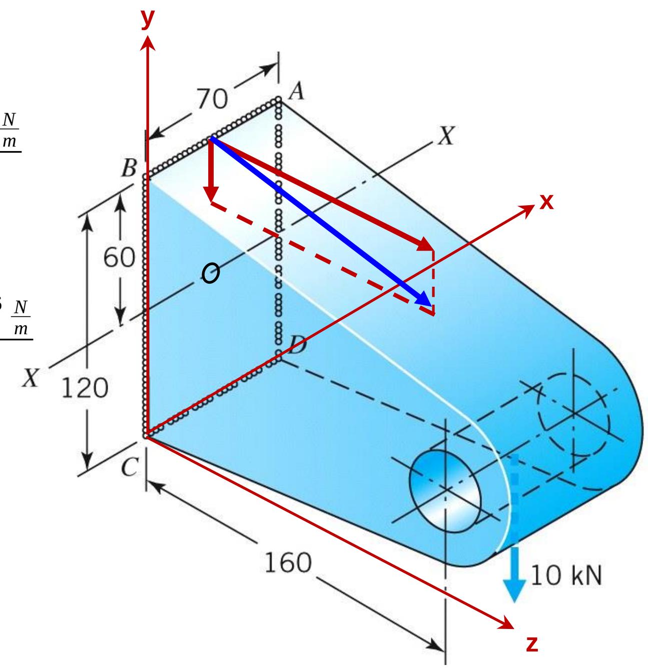


Solution

Shigley 10th, Table 9-2

Weld	Throat Area	Location of G	Unit Second Moment of Area
6. 	$A = 1.414h(b+d)$	$\bar{x} = b/2$ $\bar{y} = d/2$	$I_u = \frac{d^2}{6}(3b+d)$





From Previous Page

$$\tau' = \frac{V}{A_T} = \frac{V}{2\cdot b+d} = \frac{10\,000\,N}{0.380\,m\cdot t} = \frac{26.3\times10^3\ \frac{N}{m}}{t}$$

Bending Shear

$$M = P\cdot l = 10\,000\,N\cdot 0.160\,m = 1600\,N\cdot m$$

Unit Second Moment of Area

$$I_u = \frac{d^2}{6}\cdot(3\cdot b+d) = \frac{(0.120\,m)^2}{6}\cdot(3\cdot 0.070\,m + 0.120\,m)$$

$$= 0.792\times10^{-3}\ m^3$$

$$I_{xx} = t\cdot I_u = 0.792\times10^{-3}\ m^3\cdot t$$

Secondary Shear

$$\tau'' = \frac{M\cdot c}{I_{xx}} = \frac{(1600\,N\cdot m)\cdot(0.06\,m)}{(0.792\times10^{-3}\ m^3)\cdot t} = \frac{121.2\times10^3\ \frac{N}{m}}{t}$$

Resultant

$$\tau_R = \sqrt{\tau' + \tau''} = \sqrt{\left(\frac{26.3\times10^3\ \frac{N}{m}}{t}\right)^2 + \left(\frac{121.2\times10^3\ \frac{N}{m}}{t}\right)^2} = \frac{124.0\times10^3\ \frac{N}{m}}{t}$$

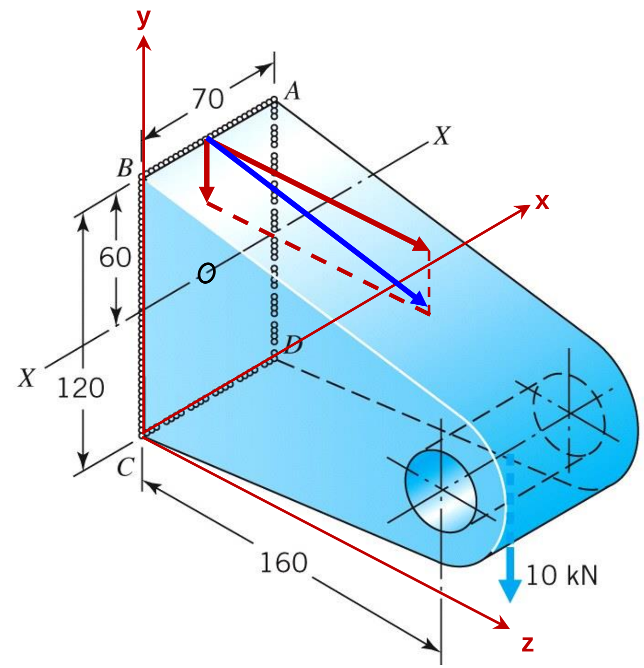
Solution

Shigley 10th, Table 9-3

AWS Electrode Number*	Tensile Strength kpsi (MPa)	Yield Strength, kpsi (MPa)	Percent Elongation
E60xx	62 (427)	50 (345)	17–25

Shigley 10th, Table 9-4

Type of Loading	Type of Weld	Permissible Stress	n^*
Shear	Butt or fillet	$0.30S_{ut}^{\dagger}$	



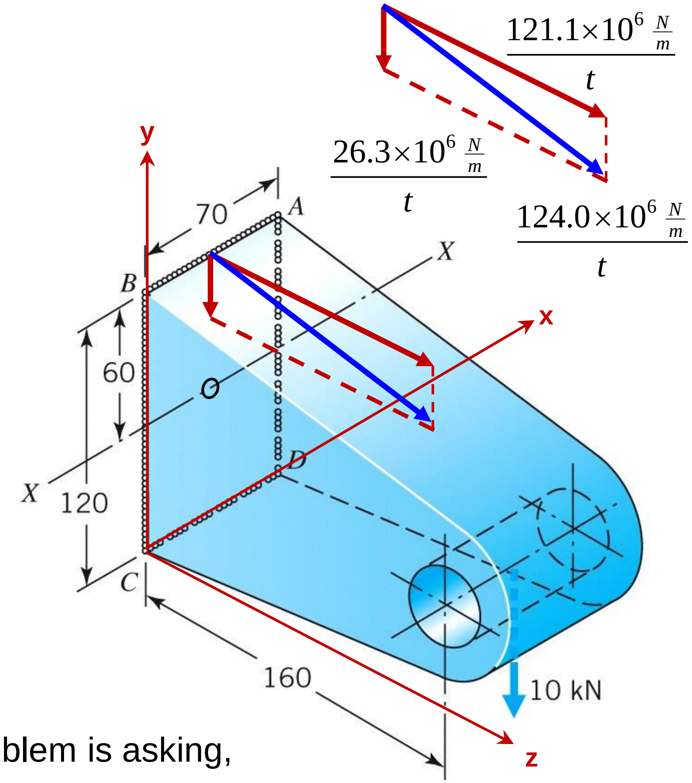
Solution

Shigley 10th, Table 9-3

AWS Electrode Number*	Tensile Strength kpsi (MPa)	Yield Strength, kpsi (MPa)	Percent Elongation
E60xx	62 (427)	50 (345)	17–25

Shigley 10th, Table 9-4

Type of Loading	Type of Weld	Permissible Stress	n*
Shear	Butt or fillet	$0.30S_{ut}^{\dagger}$	



From Previous Page

$$\tau_R = \frac{124.0\times10^{3}\ \frac{N}{m}}{t}$$

Given E60xx Weld Rod (Table 9-3) and the Permissible Stress State in Table 9-4

$$\tau_{per} = 0.30\cdot S_{ut} = 0.30\cdot(427MPa) = 128.1MPa$$

Given the Standard Factor of Safety in

$$\tau_R = \tau_{per} \quad \Rightarrow \quad \frac{124.0\times10^{3}\ \frac{N}{m}}{t} = 128.1\times10^{6}\ \frac{N}{m^2}$$

$$t = 0.968\times10^{-3}\ m = 0.968\,mm$$

Now consider what the problem is asking, a Factor of Safety of 3 off the Shear Yield Stress. From the Distortional Energy Theory $S_{sy}=0.577\cdot S_y$

$$\tau_R = \tau_{per} \quad \Rightarrow \tau_R = \frac{S_y\cdot(0.577)}{3}$$

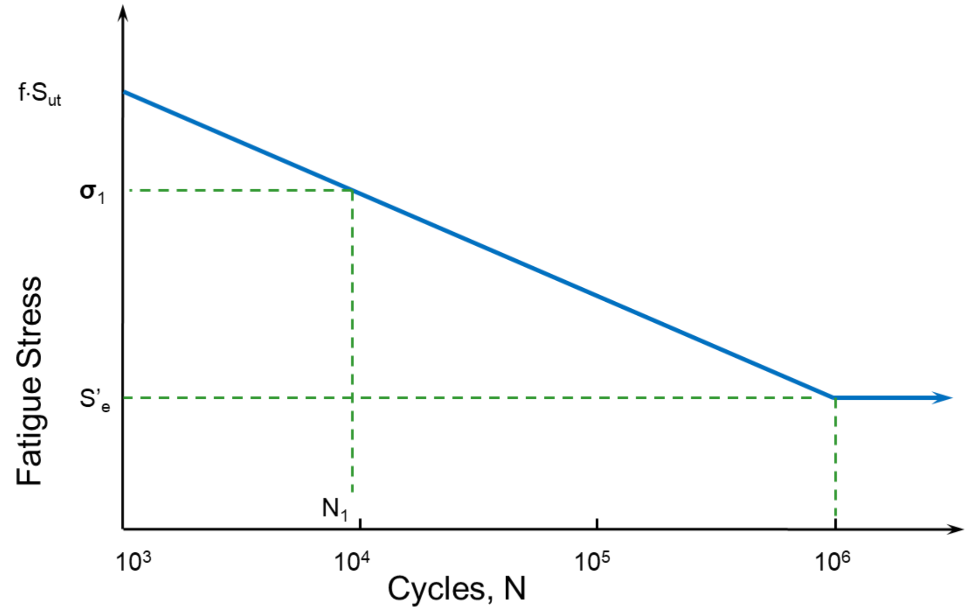
$$\Rightarrow \quad \frac{124.0\times10^{3}\ \frac{N}{m}}{t} = \frac{\left(345\times10^{6}\ \frac{N}{m^2}\right)\cdot(0.577)}{3}$$

$$t = 1.869\times10^{-3}\ m = 1.869\,mm \quad \Rightarrow \quad h = 1.414\cdot t = \boxed{2.64\,mm}$$

Typically not practical to apply a weld leg h less than 1/8in or 3mm.

Fatigue Modifying Factors

- $S_e = k_a k_b k_c k_d k_e k_f S'_e$
  - k_a-surface factor
  - k_b-size factor
  - k_c-load factor
  - k_d-temperature factor
  - k_e-reliability factor
  - k_f-miscellaneous effects factor



- k_a – Surface factor

  $$k_a = a \cdot S_{ut}^b$$

Surface Finish	Factor a S_{ut}, kpsi	Factor a S_{ut}, MPa	Exponent b
As-forged	39.9	272.	−0.995

- k_b=Size Facto = 1
- k_c- Loading Factor
  - Torsion/Shear: 0.59
  - Bending: 1.0
  - Axial: 0.85
- $S_{su} = 0.6 \cdot S_{ut}$

Fatigue Stress Concentration Factors

Shigley 10th, Table 9-5

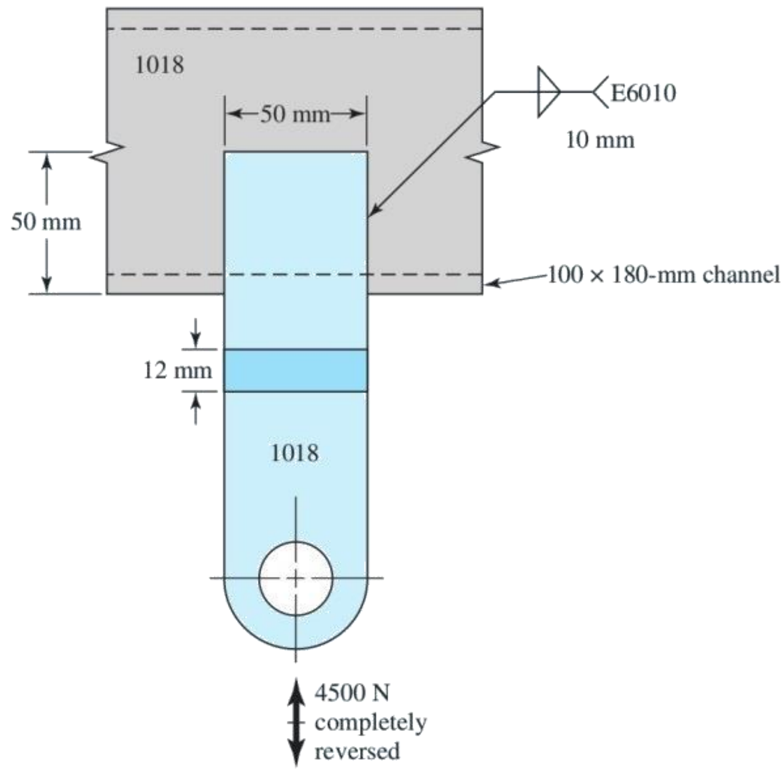
Type of Weld	K_{fs}
Reinforced butt weld	1.2
Toe of transverse fillet weld	1.5
End of parallel fillet weld	2.7
T-butt joint with sharp corners	2.0

Fatigue Stress-Concentration Factors, K_{fs}

- **K_{fs} appropriate for application to shear stresses**
- **Use for parent metal and for weld metal**

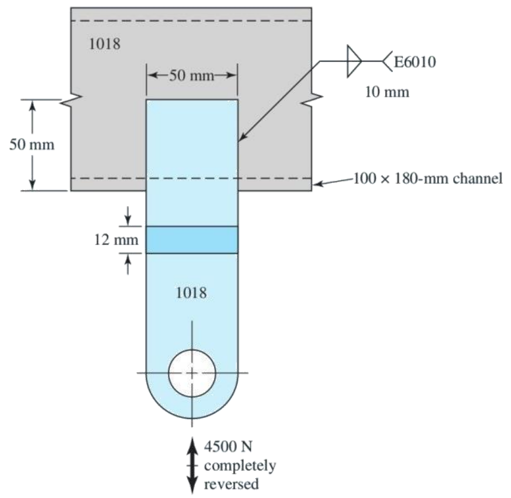
Example

The AISI 1018 HR steel (S_y=220MPa=32ksi, S_{ut}=400MPa=58ksi) strap shown has a 4500-N, completely reversed load applied. Determine the factor of safety of the weldment for infinite life.



Solution

- **Given**
  - **AISI 1018 HR Steel**
    - **S_{ut} = 400 MPa**
    - **S_y = 220 MPa**



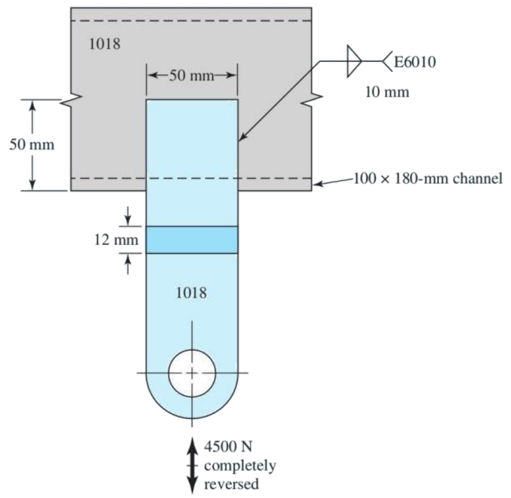
Shigley 10th Table 6-2

Surface Finish	Factor a S_{ut}, kpsi	Factor a S_{ut}, MPa	Exponent b
As-forged	39.9	272.	−0.995

AWS Electrode Number*	Tensile Strength kpsi (MPa)	Yield Strength, kpsi (MPa)	Percent Elongation
E60xx	62 (427)	50 (345)	17–25
E70xx	70 (482)	57 (393)	22
E80xx	80 (551)	67 (462)	19
E90xx	90 (620)	77 (531)	14–17
E100xx	100 (689)	87 (600)	13–16
E120xx	120 (827)	107 (737)	14

Solution

- **Given**
  - **AISI 1018 HR Steel**
    - **S_{ut} = 400 MPa**
    - **S_y = 220 MPa**
  - **4500 N completely reversed load**
    - **F_m = 0 N**
    - **F_a = 4500 N**



- **$S_e = k_a k_b k_c k_d k_e k_f S'_e = k_a k_b k_c k_d k_e k_f \cdot 0.5 \cdot S_{ut}$**

- **Fatigue Factors**
  - **k_a – Surface factor**

$$k_a = a \cdot S_{ut}^b$$

$$= 272 \cdot (500)^{-0.995} = 0.561$$

  - **k_b=Size Factor = 1**
  - **k_c- Loading Factor = 0.59**

Shigley 10th Table 6-2

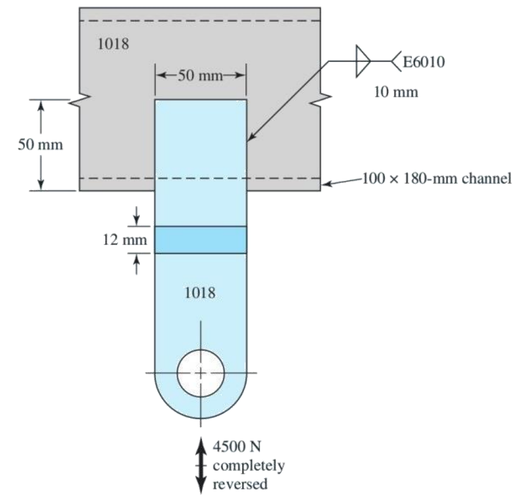
Surface Finish	Factor a S_{ut}, kpsi	Factor a S_{ut}, MPa	Exponent b
As-forged	39.9	272.	−0.995

AWS Electrode Number*	Tensile Strength kpsi (MPa)	Yield Strength, kpsi (MPa)	Percent Elongation
E60xx	62 (427)	50 (345)	17–25
E70xx	70 (482)	57 (393)	22
E80xx	80 (551)	67 (462)	19
E90xx	90 (620)	77 (531)	14–17
E100xx	100 (689)	87 (600)	13–16
E120xx	120 (827)	107 (737)	14

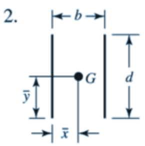
- $$S_e = (0.561) \cdot (1.0) \cdot (0.59) \cdot (0.5) \cdot (400\,MPa) = 66.2MPa$$

Solution

- **Previous Results**
  - **AISI 1018 HR Steel**
    - **S_{ut} = 400 MPa**
    - **S_y = 220 Mpa**
  - $S_e = 66.2\,MPa$
  - **F_m = 0 N**
  - **F_a = 4500 N**



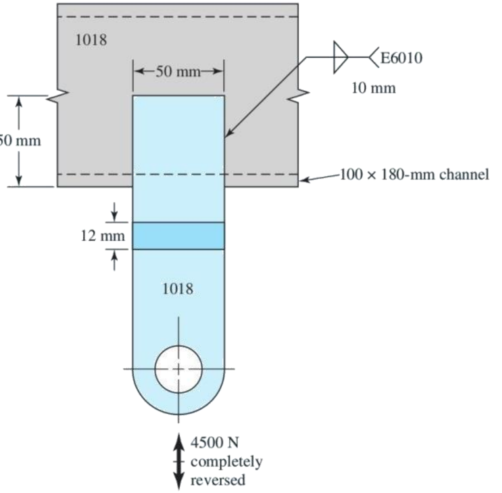
Shigley 10th Table 9-1

Weld	Throat Area	Location of G	Unit Second Polar Moment of Area
2. 	$A = 1.414\,hd$	$\bar{x} = b/2$ $\bar{y} = d/2$	$J_u = \dfrac{d(3b^2 + d^2)}{6}$

Shigley 10th Table 9-5

Type of Weld	K_{fs}
End of parallel fillet weld	2.7

Solution



- **Previous Result**
  - $S_e = 66.2\,MPa$
  - **F_m = 0 N**
  - **F_a = 4500 N**

- **There is only Primary Shear, Secondary Shear**
  - **Throat Area**

$$A = 1.414 \cdot h \cdot d$$
$$= 1.414 \cdot (0.01 m) \cdot (0.05\,m)$$
$$= 707.0 \times 10^{-6}\; m^2$$

  - **Fatigue Stress Concentration Factor**

$$K_{fs} = 2.7$$

  - **Only Primary Shear Present**

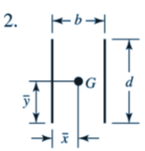
$$\tau_a' = \frac{K_{fs} \cdot F_a}{A} = \frac{2.7 \cdot (4500\ N)}{707.0 \times 10^{-6}\ m^2} = 17.18\,MPa$$

$$\tau_m' = \frac{K_{fs} \cdot F_m}{A} = \frac{2.7 \cdot (0\ N)}{707.0 \times 10^{-6}\ m^2} = 0\,MPa$$

  - **Fatigue Factor of Safety**

$$n_f = \frac{S_{se}}{\tau_a'} = \frac{66.2\,MPa}{17.18\,MPa} = 3.85$$

Shigley 10th Table 9-1

Weld	Throat Area	Location of G	Unit Second Polar Moment of Area
2. 	$A = 1.414\,hd$	$\bar{x} = b/2$ $\bar{y} = d/2$	$J_u = \frac{d(3b^2 + d^2)}{6}$

Shigley 10th Table 9-5

Type of Weld	K_{fs}
End of parallel fillet weld	2.7