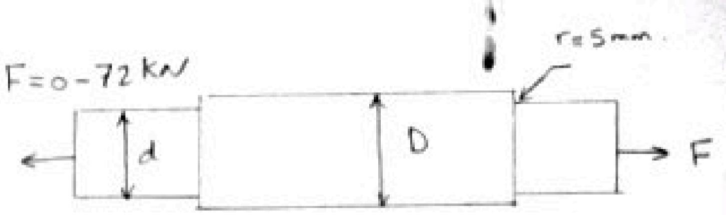
Example

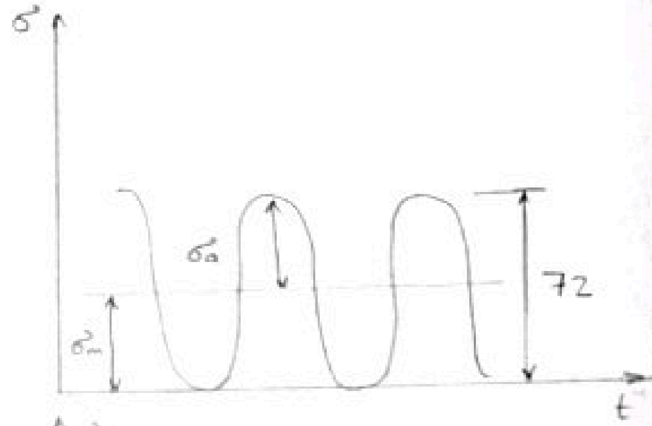
Find d of cold-drawn steel of shaft under fluctuating load



$F = 0 - 72$ KN

$S_y = 510$ MPa , $S_{ut} = 650$ MPa , $n = 2.0$

$K_t = 2.02$



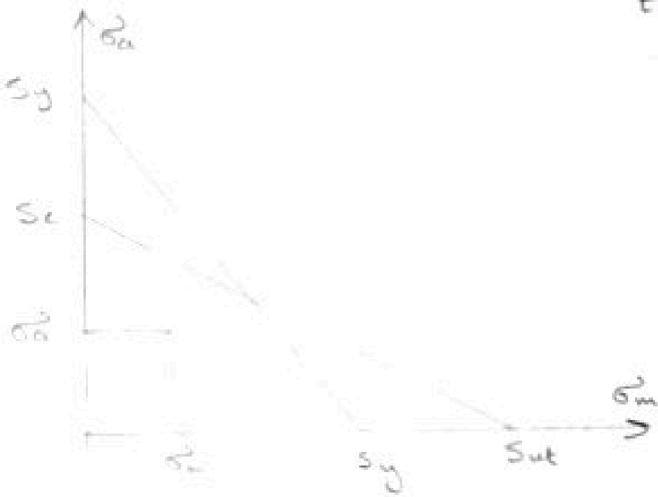
Solution:

$S_e' = 0.5\,S_{ut} = 325$ MPa.

$K_a = a\,S_{ut}^{\,b} = 4.51\,(650)^{-0.265} = 0.81$

Cold-drawn → Table [7-4]

$K_b = 1.0$ → axial load.



$K_c = 0.85$ → axial load.

$q = 0.87$ → Fig. [7-20] $r = 5$ mm

$K_f = 1 + q(K_t - 1) = 1.39$

$K_e = \frac{1}{K_f} = 0.529$.

$S_e = K_a K_b K_c K_d K_e S_e'$

$= 0.81 \times 1 \times 0.85 \times 0.529 \times 325 = 118.44$ MPa

$S_e = 225.76$ MPa

$\sqrt{a} = \frac{139}{S_{ut}}$ $\sqrt{mm}$

Table [7-8]

$F_a = F_m = \frac{72}{2} = 36$ kN.

$\sigma_a = \sigma_m = \frac{4F_a}{\pi d^2} = \frac{4F_m}{\pi d^2} = \frac{45.84 \times 10^{-3}}{d^2}$ MPa $\times K_f$

Goodman line.

$\frac{\sigma_a}{S_e} + \frac{\sigma_m}{S_{ut}} = \frac{1}{n}$

$K_f\,\frac{45.84 \times 10^{-3}}{d^2}\left(\frac{1}{S_e} + \frac{1}{S_{ut}}\right) = \frac{1}{2}$

$d = 32.15$ mm. → $\boxed{d = 33}$ mm

against yielding.

$\sigma_a + \sigma_m = \frac{S_y}{n}$

$K_f\,\frac{45.84 \times 10^{-3}}{d^2} \times 2 = \frac{510}{2}$ → $d = 26$ mm.

Take

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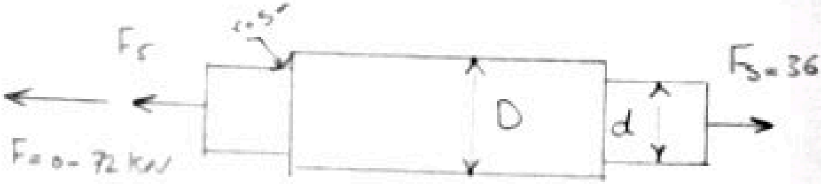
Find (d) of cold-drawn steel shaft

$S_y = 510$ MPa, $S_{ut} = 650$ MPa

Tensile preload, $F_s = 36$ kN

Fluctuating load, $F = 0 - 72$ kN.

For $n = 2.0$, $K_t = 2.02$, $r = 5$ mm



Solution:

$S_e' = 0.5\, S_{ut} = 325$ MPa

$K_a = a\, S_{ut}^{\,b} = 4.51\,(650)^{-0.265} = 0.81 \rightarrow$ cold-drawn steel

$K_b = 1.0$ axial loading, $\underline{K_c} = 0.923 \rightarrow$ axial loading $S_{ut} < 1520$ MPa.

$K_f = 1 + q\,(K_t - 1)$, $q = 0.87$, $K_f = 1.89$, $K_e = \dfrac{1}{K_f} = 0.529$.

$S_e = K_a K_b K_c K_d K_e S_e' = 0.81 \times 1 \times 0.923 \times 0.529 \times 325 = 128.53$ MPa.

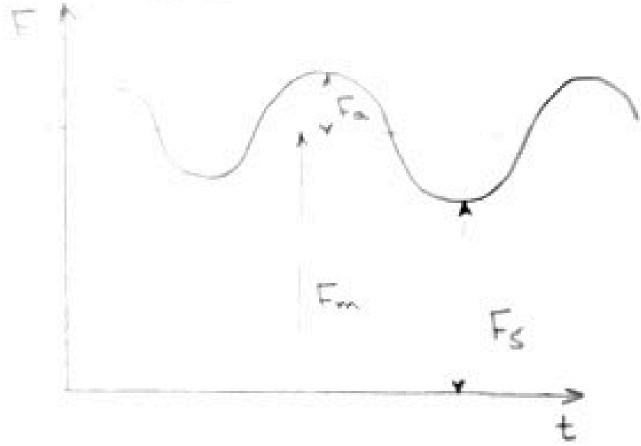
$S_e\,[K_c = 1] = 118.44$

$F_a = \dfrac{72}{2} = 36$ kN

$F_m = F_s + F_a = 72$ kN

$\sigma_m' = \dfrac{4F_m}{\pi d^2} = \dfrac{91.67 \times 10^{3}}{d^2}$ Pa

$\sigma_a' = \dfrac{4F_a}{\pi d^2} = \dfrac{45.84 \times 10^{3}}{d^2}$ Pa



Goodman line: $\dfrac{\sigma_m'}{S_{ut}} + \dfrac{\sigma_a'}{S_e} = \dfrac{1}{n}$

$\dfrac{\sigma_a}{\sigma_m} = 0.5$

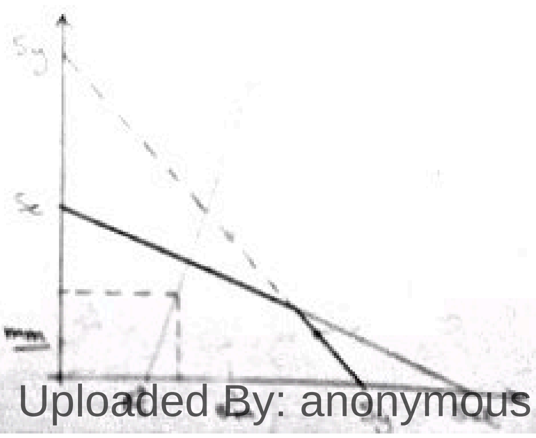
$S_m = \dfrac{S_{ut}\, S_e}{S_e + \left(\dfrac{\sigma_a}{\sigma_m}\right) S_{ut}} = 184.215$ MPa. $\Rightarrow n = \dfrac{S_m}{\sigma_m'} = 2.0$

$\Rightarrow d = 31.55$ mm.

For axial loading: $\underline{K_b = 1.0}$

Yielding line:

$\sigma_m + \sigma_a = S_y \Rightarrow n = \dfrac{S_y}{\sigma_m + \sigma_a} \Rightarrow d = 23$ mm



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$$n = \frac{S_a}{\sigma_a}$$

$$S_a = \frac{S_{ut} - \sigma_s'}{\frac{1}{m} + \frac{S_{ut}}{S_c}}$$

$$m = \frac{K_f \sigma_a}{K_f \sigma_m - \sigma_s'} = 1.0$$

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$$= 0.254 [S_{ut} - \sigma_s']$$

$$n = \frac{S_a}{\sigma_a} = 2 \rightarrow 2 = \frac{0.254 [S_{ut} - \sigma_s']}{\sigma_a} = 7.81 \sigma_a = S_{ut} - \sigma_s$$

$$\sigma_a = \sigma_s' \Rightarrow 8.8 \sigma_a = S_{ut} \rightarrow 8.8 K_f \frac{45 \times 10^{+3}}{d^2} = S_{ut} \rightarrow d = 34.2 \text{ mm}.$$

yielding.

$$S_a = \frac{S_y - \sigma_s'}{\frac{1}{m} + \frac{S_y}{S_y}} = \frac{S_y - \sigma_s}{2}$$

$$n = \frac{S_a}{\sigma_a} = 2$$

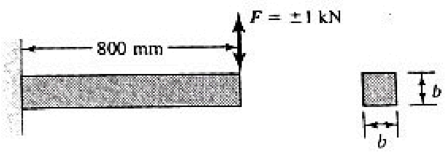
$$2 = \frac{S_y - \sigma_s}{2 \sigma_a} \rightarrow 5 \sigma_a = S_y$$

$$d = 21.2 \text{ m}$$

7-9

Hot Rolled

HR



$f = 0.9$

$n = 1.5$

$N = 10^4$ cycles

For AISI 1045 HR steel, $S_{ut} = 570$ MPa and $S_y = 310$ MPa

$$S'_e = 0.504(570 \text{ MPa}) = 287.3 \text{ MPa}$$

Find an initial guess based on yielding:

$$\sigma_a = \sigma_{\max} = \frac{Mc}{I} = \frac{M(b/2)}{b(b^3)/12} = \frac{6M}{b^3}$$

$$M_{\max} = (1 \text{ kN})(800 \text{ mm}) = 800 \text{ N} \cdot \text{m}$$

$$\sigma_{\max} = \frac{S_y}{n} \quad \Rightarrow \quad \frac{6(800 \times 10^3 \text{ N} \cdot \text{mm})}{b^3} = \frac{310 \text{ N/mm}^2}{1.5}$$

$$b = 28.5 \text{ mm}$$

Eq. (7-24): $\quad d_e = 0.808b$

Eq. (7-19): $\quad k_b = \left(\dfrac{0.808b}{7.62}\right)^{-0.107} = 1.2714b^{-0.107}$

$$k_b = 0.888$$

$$\sigma = \frac{6M}{b^3} = \frac{6 \times 800}{b^3}$$

$K_a = 0.606$

$K_b = 1.0$ —— assumed

$K_c = 1.0$

$S_e = 0.606 \times 287.3 = 174$ MPa

$S_f = 343.9$ MPa

$$n = \frac{S_f}{\sigma} = 1.5 \qquad \frac{343.9}{1.5} = \frac{4800}{b^3}$$

$b = 27.6$ mm

$d_e = 0.808\, b = 22.27$ mm

$$K_b = \left(\frac{d}{7.62}\right)^{-0.107} = 0.89$$

$S_e = 0.606 \times 0.89 \times 287.3 = 155.13$ MPa

$$b = \frac{1}{3} \log \frac{0.9 \times S_{ut}}{S_e} = -0.173$$

$$c = \log \frac{(0.9 S_{ut})^2}{S_e} = 3.23$$

$S_f = 345.14$ MPa.

$$n = \frac{S_f}{\sigma} \rightarrow b = \left(\frac{1.5 \times 4800}{231.74}\right)^{1/3} = 31.4$$

$$n = \frac{S_f b^3}{6M} \qquad b = \left(\frac{n\, 6M}{S_f}\right)^{1/3} = 27.5 \text{ mm}$$

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Combined loading

General case of stress :

Bending stress : σ_a , σ_m

Torsional stress : τ_a , τ_m

Axial stress : $(\sigma_a)_{axial}$, $(\sigma_m)_{axial}$

Design procedure:

1- Find endurance limit (S_e) , assume $(K_c = 1)$

2- Multiply the alternating component by the corresponding stress concentration factor

$$K_f \, \sigma_a \;,\; K_{fs} \, \tau_a \;,\; (K_f)_{axial} \, (\sigma_a)_{axial}.$$

3- For axial loading , multiply the alternating component by $\dfrac{1}{(K_c)_{axial}}$

$$\Rightarrow \frac{1}{(K_c)_{axial}} (\sigma_a)_{axial}$$

4- Find the principal stress for alternating and mean component

$$(\sigma_{1a} , \sigma_{2a}) \text{ and } (\sigma_{1m} , \sigma_{2m})$$

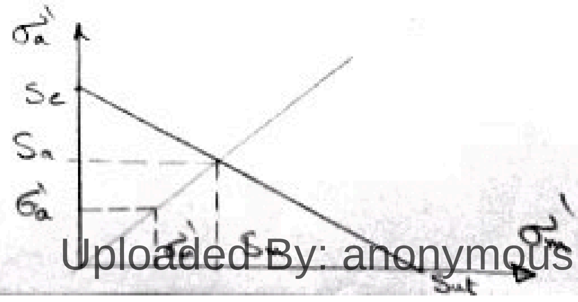
5- Find the von-mises stresses , the critical stresses according to DET

$$\sigma_m' = \sqrt{\sigma_{1m}^2 - \sigma_{1m}\sigma_{2m} + \sigma_{2m}^2}$$

$$\sigma_a' = \sqrt{\sigma_{1a}^2 - \sigma_{1a}\sigma_{2a} + \sigma_{2a}^2}$$

6- Draw $(\sigma_m' - \sigma_a')$ diagram using Goodman line.

$$\frac{\sigma_a'}{S_e} + \frac{\sigma_m'}{S_{ut}} = \frac{1}{n} \Rightarrow \boxed{n = \frac{S_{ut}}{\sigma_m' + \left(\frac{S_{ut}}{S_e}\right)\sigma_a'}}$$



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For pure shear [Torsion]:

$$\sigma'_x = \sigma'_y = 0 .$$

Torsional stresses; τ_a, τ_m

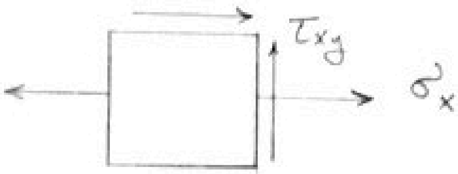
For yielding: $$n = \frac{S_{sy}}{\tau_{max}} = \frac{S_{sy}}{\tau_m + \tau_a}$$

For Fatigue: $$\frac{\tau_a}{S_{se}} + \frac{\tau_m}{S_{su}} = \frac{1}{n}$$

For a state of stress of single axial and Torsional stress (σ_x, τ_{xy})

$$\sigma_x = \sigma_a, \sigma_m$$

$$\tau_{xy} = \tau_a, \tau_m$$



DET

$$\sigma'_m = \sqrt{\sigma_m^2 + 3\tau_m^2}$$

$$\sigma'_a = \sqrt{\sigma_a^2 + 3\tau_a^2}$$

For combined loading the factor of safety against yielding:

$$n = \frac{S_y}{\sigma'_{max}} = \frac{S_y}{\sigma'_a + \sigma'_m}$$

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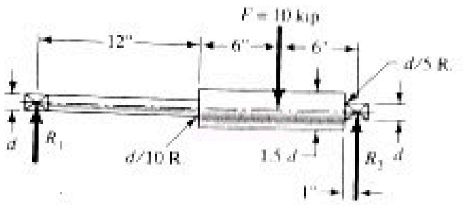
DESIGN

7–11 Bearing reactions R_1 and R_2 are exerted on the shaft shown in the figure, which rotates at 1150 rev/min and supports a 10-kip bending force. Use a 1095 steel. Specify a diameter d using a design factor of $n_d = 1.6$ for a life of 3 min. The surfaces are machined.

Problem 7–11



7-11 A priori design decisions:

The design decision will be: d

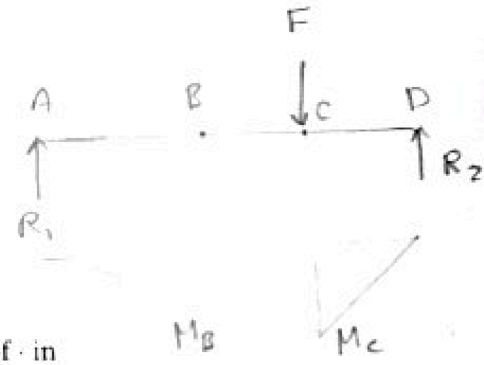
Material and condition: 1095 HR and from Table A-20 $S_{ut} = 120$, $S_y = 66$ kpsi.

Design factor: $n_f = 1.6$ per problem statement.

Life: (1150)(3) = 3450 cycles

Function: carry 10 000 lbf load

Preliminaries to iterative solution:



$M_c = 45$ kip.in

$M_B = 30$ kip.in

$\sigma = \frac{32M}{\pi d^3}$

$$S'_e = 0.504(120) = 60.5 \text{ kpsi}$$

$$k_a = 2.70(120)^{-0.265} = 0.759$$

$$\frac{I}{c} = \frac{\pi d^3}{32} = 0.098\,17d^3$$

$$M(\text{crit.}) = \left(\frac{6}{24}\right)(10\,000)(12) = 30\,000 \text{ lbf} \cdot \text{in}$$

$\sigma_C = \frac{135.8}{d^3}$

$\sigma_B = \frac{305.57}{d^3}$

$\sigma_B > \sigma_C$

The critical location is in the middle of the shaft at the shoulder. From Fig. A-15-9: $D/d = 1.5$, $r/d = 0.10$, and $K_t = 1.68$. With no direct information concerning f, use $f = 0.9$.

For an initial trial, set $d = 2.00$ in

$$k_b = \left(\frac{2.00}{0.30}\right)^{-0.107} = 0.816$$

$$S_e = 0.759(0.816)(60.5) = 37.5 \text{ kpsi}$$

$$a = \frac{[0.9(120)]^2}{37.5} = 311.0$$

$c = \log \frac{(0.9 S_{ut})^2}{S_e} = 2.49$

$$b = -\frac{1}{3}\log\frac{0.9(120)}{37.5} = -0.1531$$

$Sf = N^b 10^c$

$$S_f = 311.0(3450)^{-0.1531} = 89.3$$

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$$\sigma_0 = \frac{M}{I/c} = \frac{30}{0.098\,17d^3} = \frac{305.6}{d^3}$$

$$= \frac{305.6}{2^3} = 38.2 \text{ kpsi}$$

$$q = \frac{1}{1+\frac{\sqrt{a}}{\sqrt{r}}}$$

$$r = \frac{d}{10} = \frac{2}{10} = 0.2$$

$$K_f = \frac{1.68}{1 + (2/\sqrt{0.2})[(1.68-1)/1.68](4/120)} = 1.584$$

$$a = \frac{1}{kf} =$$

$$b = -\frac{1}{3}\log\frac{1}{kf}$$

$$kf' = aN^b$$

$$= \frac{1}{1.584}(3450)^{0.066}$$

$$=$$

Eq. (7-37):

$$(K_f)_{10^3} = 1 - (\underset{Kf}{1.584} - 1)[0.18 - 0.43(10^{-2})\underset{Sut}{120} + 0.45(10^{-5})\underset{Sut^2}{120^2}]$$

$$= 1.158$$

Eq. (7-38):

$$(K_f)_N = K_{3450} = \frac{\overset{(Kf_{10^3})^2}{1.158^2}}{\underset{kf}{1.584}}\overset{N}{(3450)}^{-(1/3)\log(\overset{Kf_{10^3}}{1.158}/\underset{kf}{1.584})}$$

$$= 1.225$$

$$b = -0.063$$

$$aN^b$$

$$\sigma_0 = \frac{305.6}{2^3} = 38.2 \text{ kpsi}$$

$$\sigma_a = (K_f)_N\sigma_0 = 1.225(38.2) = 46.8 \text{ kpsi}$$

$$n_f = \frac{(S_f)_{3450}}{\sigma_a} = \frac{89.3}{46.8} = 1.91$$

The design is satisfactory. Reducing the diameter will reduce n, but the resulting preferred size will be $d = 2.00$ in.

7-12

$$\sigma_a' = 172 \text{ MPa}, \quad \sigma_m' = \sqrt{3}\tau_m = \sqrt{3}(103) = 178.4 \text{ MPa}$$

Yield:
$$172 + 178.4 = \frac{S_y}{n_y} = \frac{413}{n_y} \quad \Rightarrow \quad n_y = 1.18 \quad \textit{Ans.}$$

(a) Modified Goodman, Table 7-9

$$n_f = \frac{1}{(172/276) + (178.4/551)} = 1.06 \quad \textit{Ans.}$$

(b) Gerber, Table 7-10

$$n_f = \frac{1}{2}\left(\frac{551}{178.4}\right)^2\left(\frac{172}{276}\right)\left\{-1 + \sqrt{1 + \left[\frac{2(178.4)(276)}{551(172)}\right]^2}\right\} = 1.31 \quad \textit{Ans.}$$

(c) ASME-Elliptic, Table 7-11

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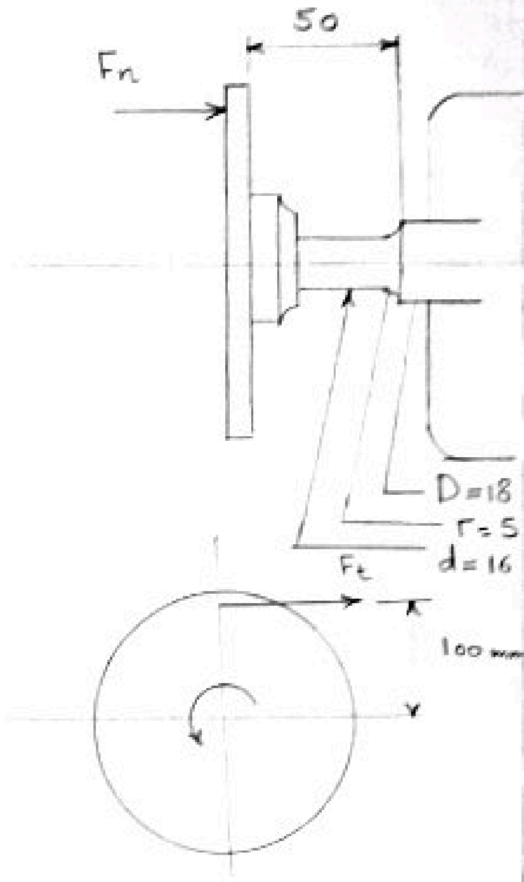
Example: Disk sander.

The shaf is made of steel machine finished. $S_{ut} = 900$ MPa, $S_y = 750$ MPa



The friction torque developed by force Ft at (100 mm radius), $T = 12$ N.m

$\mu = 0.6$ between the object and the disk.

Find factor of safety (n) against fatigue failure.

Solution:

1- $T = F_t R = F_t (0.1)$

$\Rightarrow F_t = 120$ N

$F_t = \mu F_n \Rightarrow F_n = \frac{F_t}{\mu} = \frac{120}{0.6} = 200$ N.

Torque $T = 12$ N.m

axial force: $P = 200$ N axial force.

Bending: Horizontal plane, $M_h = 120\,N \times 50$ mm

Vertical plane, $M_v = 200 \times 100$ mm

$M = \sqrt{M_h^2 + M_v^2}$

$M = 20{,}900$ N.m.

2- Stress concentration:

$K_t = 1.28$, $K_{ts} = 1.1$, $(K_t)_a = 1.28$

For $r = 5$ mm, $S_{ut} = 900$ MPa. $\Rightarrow q = 0.91$ (axial and bending)

$q_s = 0.93$ (Torsion).

$\Rightarrow K_{f_s} = 1.09$

$K_f = 1.25$

$(K_f)_a = 1.25$

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3- Stresses at fillet :

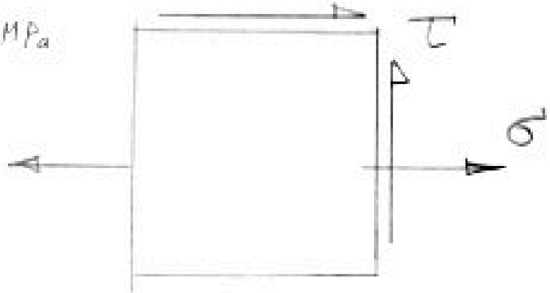
$$\tau_m = \frac{16 T_m}{\pi d^3} K_{fs} , \quad \tau_a = \frac{16 T_m}{\pi d^3} = 0$$

$$(\sigma_m)_{axial} = \frac{P}{A} = \frac{4P}{\pi d^3} K_{f\,axial} , \quad (\sigma_a)_b = \frac{32 M}{\pi d^3} , \quad (\sigma_m)_b = 0$$

$$\sigma_m = (\sigma_m)_{axial} , \quad (\sigma_a)_{axial} = 0$$

4- Mises stress

$$\sigma_m' = \sqrt{\sigma_m^2 + 3\tau_m^2}$$



$$\sigma_m = (\sigma_m)_{axial} = \frac{4P}{\pi d^2} = \frac{4(200)}{\pi (16)^2} \times 1.25 = 1.25 \text{ MPa}$$

$$\tau_m = \frac{16T}{\pi d^3} K_f = 16.35 \text{ MPa}$$

$$\sigma_m' = \sqrt{\sigma_m^2 + 3\tau_m^2} = 28.34 \text{ MPa}$$

$$\sigma_a' = \sqrt{\sigma_a^2 + 3\tau_a^2}$$

$$\sigma_a = \sigma_b = K_f \frac{32 M}{\pi d^3} = 1.25 \frac{32(20.900)}{\pi (16)^3} = 65 \text{ MPa}$$

$$\tau_a = 0$$

$$\sigma_a' = 65 \text{ MPa}$$

5- $S_e' = 0.5\, S_{ut} = 450$ MPa

$$K_a = a\, S_{ut}^{b} = 4.45 (900)^{-0.265} = 0.73$$

$$K_b = \left(\frac{d}{7.62}\right)^{-0.107} = 0.923$$

$K_c = 1.0$

$K_e = 1.0$, $K_d = 1.0$

$$S_e = 0.73 \times 0.923 \times 450 = 303.43 \text{ MPa}$$

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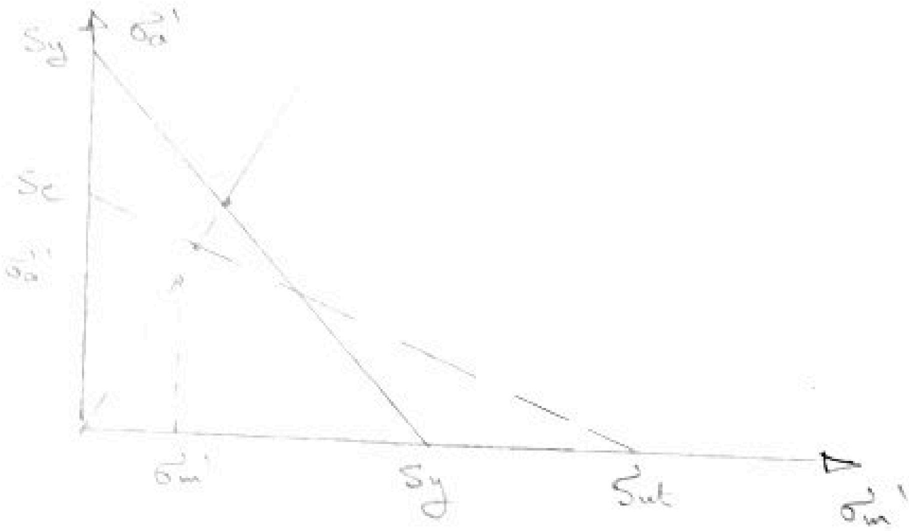
6- Goodman line.

$$\frac{\sigma_m'}{S_{ut}} + \frac{\sigma_a'}{S_e} = \frac{1}{n} \Rightarrow n = \frac{S_{ut}}{\sigma_m' + \left(\frac{S_{ut}}{S_e}\right)\sigma_a'}$$

$n = 4.16$

7- Factor of safety against yielding.

$$n = \frac{S_y}{\sigma_a' + \sigma_m'} = \frac{750}{65 + 28.34} = 8.03$$



$$\frac{\sigma_a}{\sigma_m} = 0.5$$

$$S_m = \frac{S_e\, S_{ut}}{S_e + \left(\frac{\sigma_a}{\sigma_m}\right) S_{ut}} = 184.\ \text{MPa.}$$

$$n = \frac{S_m}{\sigma_m} = \frac{184}{\frac{91.67 \times 10^{-3}}{d^2}} = 2.0 \Rightarrow d = 31.5 \text{ mm}$$

$$\frac{\sigma_a}{S_e} + \frac{\sigma_m}{S_{ut}} = \frac{1}{n} \Rightarrow \frac{45.84 \times 10^{-3}}{(128.5)\, d^2} + \frac{91.67 \times 10^{-3}}{650\, d^2} = \frac{1}{2}$$

$d = 31.55$ mm.

use $d = 32.0$ mm.

Yielding:

$$\sigma_m + \sigma_a = \frac{S_y}{n}$$

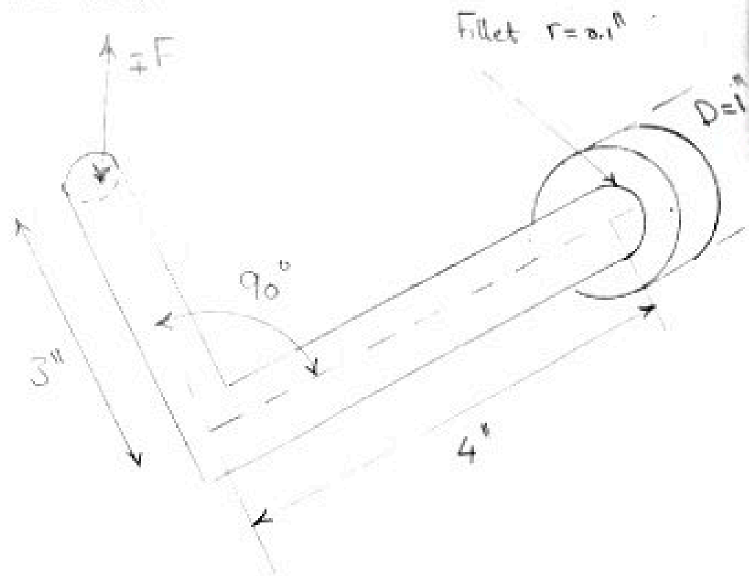
$$\frac{(45.84 + 91.67) \times 10^{-3}}{d^2} = \frac{510}{2}$$

$$\Rightarrow d = 23 \text{ mm}$$

Example

a) The shown steel bar, $d = \frac{1}{2}$", is machine finished having, $S_{ut} = 90$ kpsi, $S_y = 55$ kpsi. Find the value of alternating force $\underline{F}$ which would just sufficient to cause fatigue failure of the bar.

b) If the previous bar is subjected to constant load $F = 50$ lb. Find the alternating superimposed F_a just sufficient to cause failure.



Solution:

1- $S_e' = 0.5\, S_{ut} = 45$ kpsi

$K_a = a S_{ut}^{\,b} = 2.7\,(90)^{-0.265} = 0.819$

$K_b = \left(\frac{d}{0.3}\right)^{-0.1133}$

non-rotating shaft:

$d_e = 0.37\, d = 0.185''$ $\Rightarrow K_b = \left(\frac{0.185}{0.3}\right)^{-0.1133} = 1.056$

$K_c = 1.0$ combined loading

$K_e = 1.0$

$K_d = 1.0$

$\Rightarrow S_e = 0.819 \times 1.056 \times 1 \times 1 \times 45 = 40$ kpsi

2- Stress concentration at (A):

Bending:

$K_t = 1.43$ $q = 0.82$

$K_f = 1 + q\,(K_t - 1) = 1.35$

Torsion:

$K_{ts} = 1.28$ $q_s = 0.85$

$K_{fs} = 1 + q_s\,(K_{ts} - 1) = 1.238$

3- Completely reversed stress:

Bending: $\sigma_a = K_f \frac{32 M}{\pi d^3} = 1.35 \frac{(4F)}{\pi (0.5)^3} = 440\, F$

Torsion: $\tau_a = K_{fs} \frac{16 T}{\pi d^3} = \frac{16\,(3F)}{\pi (0.5)^3}(1.24) = 151\, F$

4- $\sigma_a' = \sqrt{\sigma_a^2 + 3\tau_a^2} = 512\, F$

5- completely reversed bending: $n = \frac{S_e}{\sigma_a'} = 1.0 \Rightarrow 512\, F = 39 \times 10^3$

$\boxed{F = 76 \text{ lb}}$

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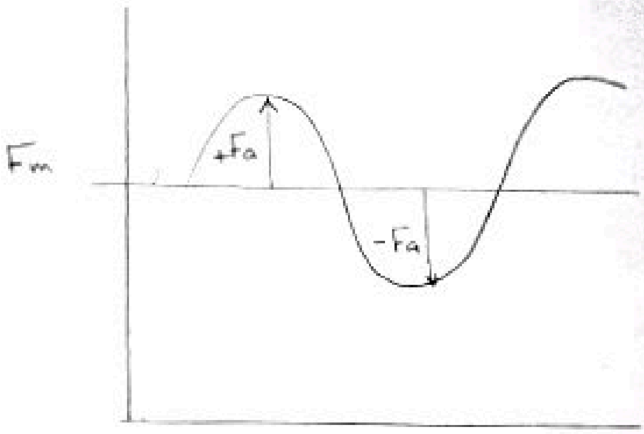
$F_m = 50 \text{ lb}$ $\quad F_a = F$

$F_{max} = F_s + F_a$

$F_{min} = F_s - F_a$

$F = F_s \mp F_a$



$M_a = 4F$ $\quad M_m = 4 \times 50$

$T_a = 3F$ $\quad T_m = 3 \times 50$

Stresses

$$\sigma_a = K_f \frac{32(4F)}{\pi d^3} = 440F$$

$$\sigma_m = K_f \frac{(32)(200)}{\pi d^3} = 22 \text{ kpsi}$$

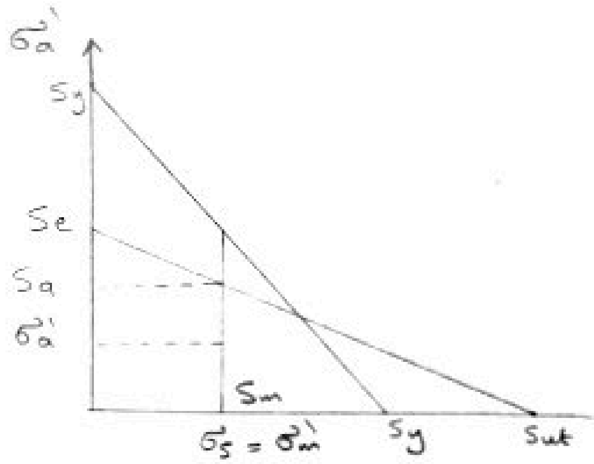
$$\tau_a = K_{f_s} \frac{16(3F)}{\pi d^3} = 151F$$

$$\tau_m = K_{f_s} \frac{16(150)}{\pi d^3} = 7.55 \text{ kpsi}$$

Von-mises stress

$$\sigma_a' = \sqrt{\sigma_a^2 + 3\tau_a^2} = 512F$$

$$\sigma_m' = \sqrt{\sigma_m^2 + 3\tau_m^2} = 25.6 \text{ kpsi}$$



goodman line:

$$\frac{\sigma_a'}{S_e} + \frac{\sigma_m'}{S_{ut}} = \frac{1}{n}$$

$$S_m = \sigma_m \rightarrow \frac{S_a}{S_e} + \frac{\sigma_m}{S_{ut}} = 1 \rightarrow S_a = S_e\left(1 - \frac{\sigma_m}{S_{ut}}\right) = 28.6 \text{ kpsi}$$

$$n = \frac{S_a}{\sigma_a} = 1.0 \rightarrow S_a = \sigma_a = 512F \Rightarrow F = 55.9 \text{ lb.}$$

Yielding line:

$$S_a + S_m = S_y \Rightarrow S_a = S_y - S_m = S_y - \sigma_m = 55 - 25.6 = 29.4$$

$$S_a = \sigma_a = 512F \Rightarrow F = 57.4 \text{ lb.}$$

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