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CHAPTER 2 MATERIALS

SOLUTION (**2.1**)

$$A_0 = \frac{\pi}{4}(12.5)^2 = 122.7 \text{ mm}^2, \quad A_f = \frac{\pi}{4}(12.5 - 0.006)^2 = 122.6 \text{ mm}^2$$

We have $\varepsilon_a = \frac{0.3}{200} = 1500\ \mu, \quad \varepsilon_t = \frac{0.006}{12.5} = 480\ \mu$

Thus

$$S_p = \frac{P}{A_0} = \frac{18(10^3)}{122.7} = 146.8 \text{ MPa}$$

$$E = \frac{S_p}{\varepsilon_a} = \frac{146.7(10^6)}{1500(10^{-6})} = 97.8 \text{ GPa}, \quad \nu = \frac{\varepsilon_t}{\varepsilon_a} = 0.32 \quad \blacktriangleleft$$

Also

$$\%\ elongation = \frac{0.3}{200}(100) = 0.15$$

$$\%\ reduction\ \ in\ area = \frac{122.7 - 122.6}{122.7}(100) = 0.082 \quad \blacktriangleleft$$

SOLUTION (**2.2**)

Normal stress is

$$\sigma = \frac{P}{A} = \frac{2200}{\frac{\pi}{4}(3.125)^2} = 286.8 \text{ MPa}$$

This is below the yield strength of 350 MPa (Table B.1).
We have

$$\varepsilon = \frac{\delta}{L} = \frac{7.5}{5600} = 0.001339 = 1339\ \mu$$

Hence

$$E = \frac{\sigma}{\varepsilon} = \frac{286.8(10^6)}{1339(10^{-6})} = 214.2 \text{ GPa} \quad \blacktriangleleft$$

SOLUTION (**2.3**)

The cross-sectional area: $A = w_o t_o = 12.7(6.1) = 77.47 \text{ mm}^2$

(**a**) Axial strain and axial stress are

$$\varepsilon_a = \frac{0.0841}{63.5} = 0.001324 = 1324\ \mu$$

$$\sigma_a = \frac{P}{A} = \frac{21{,}500}{77.47(10^{-6})} = 277.5 \text{ MPa}$$

Because $\sigma_a < S_y$ (See Table B.1), Hooke's Law is valid.

(**b**) Modulus of elasticity,

$$E = \frac{\sigma_a}{\varepsilon_a} = \frac{277.5(10^6)}{1324(10^{-6})} = 209.6 \text{ GPa}$$

(**c**) Decrease in the width and thickness

$$\Delta w = \nu w_o = 0.3(12.7) = 3.81 \text{ mm} \quad \blacktriangleleft$$

$$\Delta t = \nu t_o = 0.3(6.1) = 1.83 \text{ mm}$$

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SOLUTION (**2.4**)

Assume Hooke's Law applies. We have

$$\varepsilon_t = -\frac{1.5}{5} = -300\ \mu$$

$$\varepsilon_a = -\frac{\varepsilon_t}{\nu} = -\frac{-300}{0.34} = 822\ \mu$$

Thus,

$$\sigma = E\varepsilon_a = (105\times10^9)(822\times10^{-9}) = 92.61\ \text{MPa}$$

Since $\sigma < S_y$, our assumption is valid.

So

$$P = \sigma A = (92.61)(\pi/4)(5)^2 = 1.818\ \text{kN}$$ ◀

SOLUTION (**2.5**)

We obtain

$$L_{AC} = L_{BD} = \sqrt{15^2 + 15^2} = 21.21\ \text{mm}$$

$$\varepsilon_x = \frac{\Delta L_{AC}}{L_{AC}} = \frac{21.17 - 21.21}{21.21} = -1886\ \mu$$

$$\varepsilon_y = \frac{\Delta L_{BD}}{L_{BD}} = \frac{21.22 - 21.21}{21.21} = 471\ \mu$$

(**a**) $E = \frac{\sigma_x}{\varepsilon_x} = \frac{100\ (10^6)}{-1886\ (10^{-6})} = 53\ \text{GPa}$ ◀

(**b**) $\nu = \frac{\varepsilon_y}{\varepsilon_x} = \left|\frac{471}{1886}\right| = 0.25$ ◀

(**c**) $G = \frac{53}{2(1+0.25)} = 21.2\ \text{GPa}$ ◀

SOLUTION (**2.6**)

Use generalized Hooke's law:

$$\varepsilon_x + \varepsilon_y + \varepsilon_z = \frac{1-2\nu}{E}(\sigma_x + \sigma_y + \sigma_z) \qquad (1)$$

For a constant triaxial state of stress:

$$\varepsilon_x = \varepsilon_y = \varepsilon_z = \varepsilon, \quad \sigma_x = \sigma_y = \sigma_z = \sigma$$

Then, Eq. (1) becomes $\varepsilon = \frac{1-2\nu}{E}\sigma$. Since σ and ε must have identical signs:

$$1 - 2\nu \geq 0 \quad \text{or} \quad \nu = \frac{1}{2}$$ ◀

SOLUTION (**2.7**)

We have $\sigma_x = \frac{450(10^3)}{50(75)} = 120\ \text{MPa}$

(CONT.)

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2.7 (CONT.)

(**a**) $\varepsilon_x = \frac{0.5}{250} = 2000\ \mu, \quad \varepsilon_y = -\frac{0.025}{50} = -500\ \mu$

$\nu = \left|\frac{500}{2000}\right| = 0.25$ ◀

(**b**) $E = \frac{\sigma_x}{\varepsilon_x} = \frac{120(10^6)}{2000(10^{-6})} = 60\ \text{GPa}$ ◀

(**c**) $\varepsilon_z = -\frac{\nu\sigma_x}{E} = -0.25\frac{120(10^6)}{60(10^9)} = -500\ \mu$

$\Delta a = -500(10^{-6})75 = -37.5(10^{-3})\ \text{mm}; \qquad a' = 75 - 0.0375 = 74.9625\ \text{mm}$ ◀

(**d**) $G = \frac{60(10^9)}{2(1+0.25)} = 24\ \text{GPa}$ ◀

SOLUTION (**2.8**)

We have

$$\varepsilon_y = \varepsilon_z = 0 \qquad \sigma_x = \frac{25(10^3)}{20\times10(10^{-6})} = 125 \quad \text{MPa}$$

Thus

$$\varepsilon_y = 0 = \frac{1}{E}[\sigma_y - \nu(\sigma_x + \sigma_z)] \tag{1}$$

$$\varepsilon_z = 0 = \frac{1}{E}[\sigma_z - \nu(\sigma_x + \sigma_y)] \tag{2}$$

$$\varepsilon_x = \frac{1}{E}[\sigma_x - \nu(\sigma_y + \sigma_z)] \tag{3}$$

Equations (1) and (2) become

$$\sigma_y - \nu\sigma_z = \nu\sigma_x \tag{1'}$$

$$\sigma_z - \nu\sigma_y = \nu\sigma_x \tag{2'}$$

Adding : $\nu(\sigma_y + \sigma_z) = 2\nu^2\sigma_x/(1-\nu)$. Then, Eq. (3):

$$\varepsilon_x = \frac{1-\nu-2\nu^2}{1-\nu}\frac{\sigma_x}{E}$$ ◀

Substituting the data:

$$\varepsilon_x = \frac{1-0.3-0.18}{0.7}\frac{125(10^6)}{70(10^9)} = 1327\ \mu$$ ◀

SOLUTION (**2.9**)

<u>Hooke's Law.</u> We have $\sigma_y = 0$ and

$$\varepsilon_x = \frac{\sigma_x}{E} - \frac{\nu\sigma_y}{E} - \frac{\nu\sigma_z}{E}$$

$$= \frac{10^6}{72\times10^9}[(80) - 0 - 0.3(140)] = 0.000528 = 528\ \mu$$

$$\varepsilon_y = -\frac{\nu\sigma_x}{E} + \frac{\sigma_y}{E} - \frac{\nu\sigma_z}{E}$$

$$= \frac{10^6}{72\times10^9}[-0.3(80) + 0 - 0.3(140)] = -917\ \mu$$

$$\varepsilon_z = -\frac{\nu\sigma_x}{E} - \frac{\nu\sigma_y}{E} + \frac{\sigma_z}{E}$$

$$= \frac{10^6}{72\times10^9}[-0.3(80) - 0 + 140] = 1611\ \mu$$

(CONT.)

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2.9 (CONT.)

(**a**) Change in length $\Delta L_{AB} = \varepsilon_x a$,

$$\Delta L_{AB} = (528\times10^{-6})(320) = 0.169 \text{ mm}$$ ◀

(**b**) Change in thickness

$$\Delta t = \varepsilon_y t = (-917\times10^{-6})(15) = -0.014 \text{ mm}$$ ◀

(**c**) Change in volume,

$$e = \varepsilon_x + \varepsilon_y + \varepsilon_z = 528 - 917 + 1611 = 1.222$$

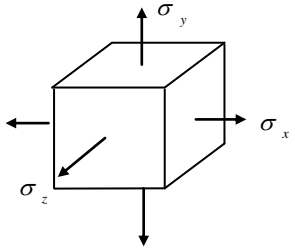
$$\Delta V = eV_o = 1.222(320\times320\times15) = 1.877 \text{ mm}^3$$ ◀

SOLUTION (**2.10**)

By assumptions, rubber in triaxial stress:

$$\sigma_x = \sigma_z = -p, \quad \sigma_y = -\frac{F}{\pi d^2/4} = -\frac{4F}{\pi d^2}$$

Stains are $\varepsilon_x = \varepsilon_z = 0$. Hooke's law gives



$$\varepsilon_x = 0 = \frac{1}{E}[\sigma_x - \nu(\sigma_y + \sigma_z)]$$

or

$$0 = p - \nu\frac{4F}{\pi d^2(1-\nu)}$$

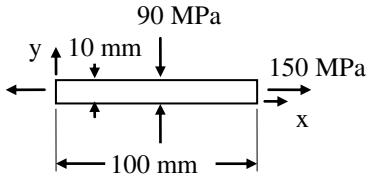
Solving,

$$p = \frac{4\nu F}{\pi d^2(1-\nu)}$$ Q.E.D. ◀

Substitute the data:

$$p = \frac{4(0.5)(10\times10^3)}{\pi(62.5)^2(1-0.5)} = 3.26 \text{ MPa} \quad \text{(C)}$$ ◀

SOLUTION (**2.11**)



Hooke's law gives

$$\varepsilon_x = \frac{1}{E}(\sigma_x - \nu\sigma_y) = \frac{10^6}{100\,(10^9)}(150 + \frac{90}{3}) = 1800 \quad \mu$$

$$\varepsilon_y = \frac{1}{E}(\sigma_y - \nu\sigma_x) = \frac{10^6}{100(10^9)}(-90 - \frac{150}{3}) = -1400 \ \mu$$

$$\varepsilon_z = -\frac{\nu}{E}(\sigma_x + \sigma_y) = -\frac{(1/3)10^6}{100\,(10^9)}(150 - 90) = -200 \quad \mu$$

Thus

$$\Delta L = 1800 \ \mu(100) = 180 \ \mu\text{m}$$

$$\Delta a = -1400 \ \mu(50) = -70 \ \mu\text{m}$$

$$\Delta b = -200 \ \mu(10) = -2 \ \mu\text{m}$$

and

$$L' = 100.018 \text{ mm}, \quad a' = 49.993 \text{ mm}, \quad b' = 9.9998 \text{ mm}$$ ◀

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SOLUTION (**2.12**)

We have

$$\sigma_x = \sigma_y = \sigma_z = -p$$

Gen. Hooke's law:

$$\varepsilon_x = \varepsilon_y = \varepsilon_z = -\frac{p}{E}(1-2\nu) = -\frac{120\,(10^6)}{100\,(10^9)}\frac{1}{3} = -400 \quad \mu$$

Thus

$$\Delta L = -400\ \mu(100) = -40 \ \mu\text{m}$$

$$\Delta a = -400\ \mu(50) = -20 \ \mu\text{m}$$

$$\Delta b = -400\ \mu(10) = -4 \ \mu\text{m}$$

and

$$L' = 99.96 \ \text{mm}, \quad a' = 49.98 \ \text{mm}, \quad b' = 9.996 \ \text{mm}$$ ◀

SOLUTION (**2.13**)

We have

$\sigma_x = \sigma_y = \sigma_z = -p$. The volume is

$$V_o = \frac{4}{3}\pi r^3 = \frac{4\pi}{3}(125)^3 = 8.181(10^6) \ \text{mm}^3$$

(**a**) $\varepsilon_x = -\frac{1}{E}[\sigma - \nu(\sigma+\sigma)] = -\frac{\sigma}{E}(1-2\nu)$

$$= \frac{168(10^6)}{70(10^9)}(1-0.5) = -1200 \ \mu$$

Change in diameter,

$$\Delta d = \varepsilon_x d = -1200(10^{-6})250 = -0.3 \ \text{mm}$$

Decrease in circumference:

$$\pi(\Delta d) = -0.3\pi = -0.9425 \ \text{mm}$$ ◀

(**b**) $\Delta V = eV_o = (1-2\nu)\varepsilon_x V_o$

$$= (0.5)(-1200\times10^{-6})(8.181\times10^6) = -4909 \ \text{mm}^3$$ ◀

SOLUTION (**2.14**)

From Fig.2.3b and Eq.2.20:

$$U_t = \frac{S_y + S_u}{2}\varepsilon_f \approx \frac{250+440}{2}(0.27) \approx 93 \ \text{MPa}$$ ◀

We have $L_f = 50 + 50(0.27) = 63.5 \ \text{mm}$

Using Eq.(2.1): $\%\ elongation = \frac{63.5-50}{50}(100) = 27\ \%$ ◀

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SOLUTION (**2.15**)

Table B.1: $S_y = 260$ MPa , $E = 70$ GPa

We have

$$V = AL = \frac{\pi}{4}(0.005)^2(3) = 58.9 \times 10^{-6} \text{ m}^3$$

$$U_r = \frac{S_y^2}{2E} = \frac{(260 \times 10^6)^2}{2(70 \times 10^9)} = 482.9 \text{ kJ/m}^3$$

$$U_{app} = U_r V = 482.9 \times 10^3 (58.9 \times 10^{-6}) = 28.44 \text{ J}$$

For $U_{app} = 9$ J :

$$n = \frac{28.44}{9} = 3.16$$ ◀

SOLUTION (**2.16**)

(**a**) ASTM-A242. $E = 200$ GPa and $\sigma_y = 345$ MPa

$$U_o = \frac{S_y^2}{2E} = \frac{(345 \times 10^6)^2}{2(200 \times 10^9)} = 298 \frac{\text{kJ}}{\text{m}^3}$$ ◀

(**b**) Stainless (302). $E = 190$ GPa and $S_y = 520$ MPa

$$U_o = \frac{S_y^2}{2E} = \frac{(520 \times 10^6)^2}{2(200 \times 10^9)} = 712 \frac{\text{kJ}}{\text{m}^3}$$ ◀

SOLUTION (**2.17**)

(**a**) Aluminum 2014-T6. $E = 72$ GPa and $\sigma_y = 410$ MPa

$$U_o = \frac{S_y^2}{2E} = \frac{(410 \times 10^6)^2}{2(72 \times 10^9)}$$

$$= 1167 \frac{kJ}{m^3}$$ ◀

(**b**) Annealed yellow brass. $E = 105$ GPa and $S_y = 105$ MPa

$$U_o = \frac{S_y^2}{2E} = \frac{(105 \times 10^6)^2}{2(105 \times 10^9)} = 52.5 \frac{\text{kJ}}{\text{m}^3}$$ ◀

SOLUTION (**2.18**)

Referring to Fig. P2.18: $E = \frac{105(10^6)}{0.0025} = 42$ GPa, $S_y = 192.5$ MPa

(**a**) $U_o = \frac{S_y^2}{2E} = \frac{(192.5 \times 10^6)^2}{2(42 \times 10^9)} = 441.5 \text{ kJ/m}^3$ ◀

(**b**) Total area under $\sigma - \varepsilon$ diagram:

$$U_t \approx 262.5(10^6)(0.176) = 46.2 \text{ MJ/m}^3$$ ◀

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SOLUTION (**2.19**)

(**a**) $V = 50 \times 50 \times 1{,}500 = 3.75\,(10^{6})\ \text{mm}^3$

Thus $nU = \frac{S_y^2}{2E} V$

or $S_y = \left[\frac{2EnU}{V}\right]^{\frac{1}{2}}$

$= \left[\frac{2 \times 200 \times 10^{9} \times 1.5 \times 400}{3.75\,(10^{-3})}\right]^{\frac{1}{2}} = 253 \text{ MPa}$ ◄

(**b**) $U_r = \frac{S_y^2}{2E} = \frac{(253 \times 10^{6})^2}{2(200 \times 10^{9})} = 160 \text{ kPa}$ ◄

SOLUTION (**2.20**)

Table B.1: $S_y = 250 \text{ MPa}, \quad E = 200 \text{ GPa}$

We have

$U = nU_{app} = 5(17) = 85 \text{ N} \cdot \text{m}$

$U_r = \frac{S_y^2}{2E} = \frac{(250 \times 10^{6})^2}{2(200 \times 10^{9})} = 156.25 \text{ kN} \cdot \text{m}/\text{m}^3$

Therefore

$V = \frac{U}{U_r} = \frac{85}{156.25\,(10^{3})} = 0.544\,(10^{-3})\ \text{m}^3$

Also $V = AL: \quad 0.544\,(10^{-3}) = \frac{\pi}{4} d^2\,(2.4)$

or

$d = 0.017 \text{ m} = 17 \text{ mm}$ ◄

SOLUTION (**2.21**)

Refer to Fig. P2.21. We have

$E = \frac{190(10^{6})}{0.001} = 190 \text{ GPa}, \quad S_y \approx 245 \text{ MPa}$

(**a**) $U_o = \frac{S_y^2}{2E} = \frac{(245 \times 10^{3})^2}{2(190 \times 10^{9})} = 158 \ \frac{\text{kJ}}{\text{m}^3}$ ◄

(**b**) Total area under $\sigma - \varepsilon$ diagram:

$U_t \approx 350 \times 10^{3}(0.28) = 98 \ \frac{\text{MJ}}{\text{m}^3}$ ◄

SOLUTION (**2.22**)

$V = (0.05)(0.05)(1.2) = 0.003\ m^3$ and $S_y \approx S_p$

(**a**) $n \cdot U = \frac{S_p^2}{2E} V, \quad S_p^2 = \frac{nU(2E)}{V}$

Substituting the data given,

(CONT.)

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2.22 (CONT.)

$$S_p^{\,2} = \frac{1.8(150)(2\times210\times10^9)}{0.003} = 37.8\times10^{15}$$ ◀

or

$$S_p = 194.4 \text{ MPa}$$

(**b**) $U_o = \frac{S_p^{\,2}}{2E} = \frac{37.8\times10^{15}}{2(210\times10^9)} = 90 \ \frac{\text{kJ}}{\text{m}^3}$ ◀

SOLUTION (**2.23**)

Applying Eq. (2.22), we find

$$S_u = 3.45H_B \text{ MPa} = 3.45(149) = 514 \text{ MPa}$$ ◀

Equation (2.24):

$$S_y = 3.62(149) - 207 = 332.4 \text{ MPa}$$ ◀

SOLUTION (**2.24**)

Using Eq. (2.22),

$$S_u = 3.45H_B \text{ MPa} = 3.45(179) = 618 \text{ MPa}$$ ◀

Formula (2.24):

$$S_y = 3.62(179) - 207 = 441 \text{ MPa}$$ ◀

SOLUTION (**2.25**)

Formula (2.22),

$$S_u = 3.45H_B \text{ MPa} = 3.45(156) = 538 \text{ MPa}$$ ◀

Equation (2.24):

$$S_y = 3.62(156) - 207 = 378 \text{ MPa}$$ ◀

SOLUTION (**2.26**)

Equation (2.22) gives

$$S_u = 3.45H_B \text{ MPa} = 3.45(293) = 1010.9 \text{ MPa}$$ ◀

Formula (2.24):

$$S_y = 3.62(293) - 207 = 853.7 \text{ MPa}$$ ◀

End of Chapter 2

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Figure 2.1
Tensile loading machine with automatic data-processing system. (Courtesy of MTS Systems Corp.)

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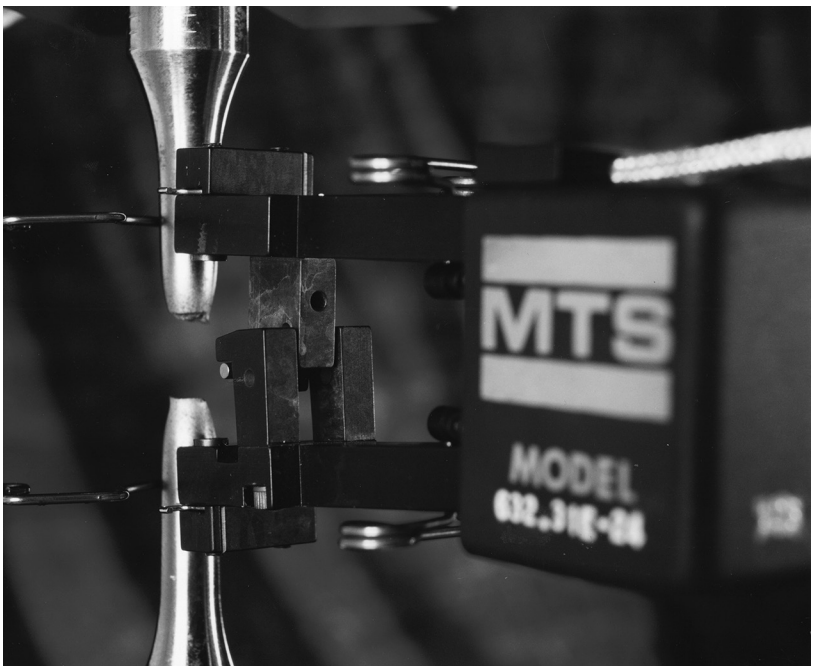


Figure 2.2
A tensile test specimen with extensometer attached; the specimen has fractured. (Courtesy of MTS Systems Corp.)

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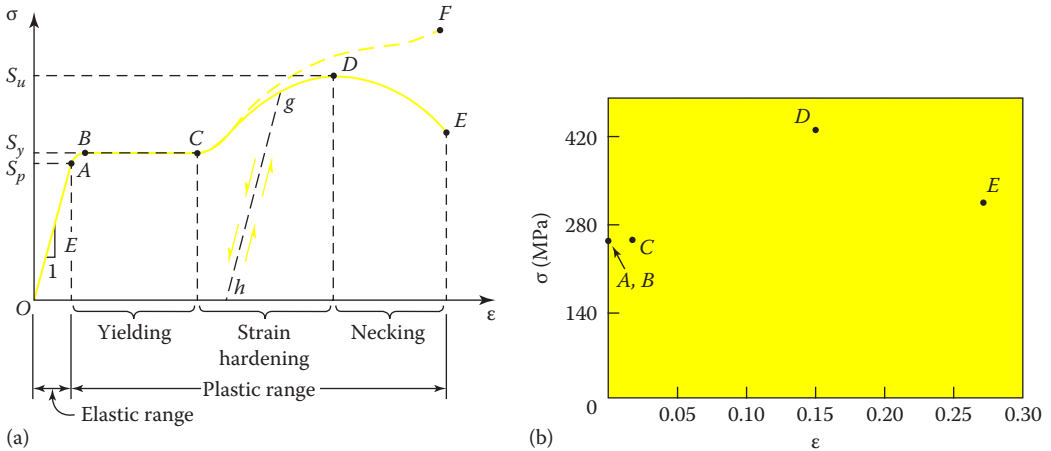


Figure 2.3
Stress–strain diagram for a typical structural steel in tension: (a) drawn not to scale and (b) drawn to scale.

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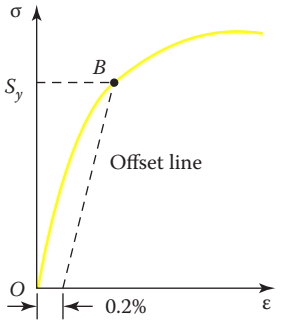


Figure 2.4
Determination of yield strength by the offset method.

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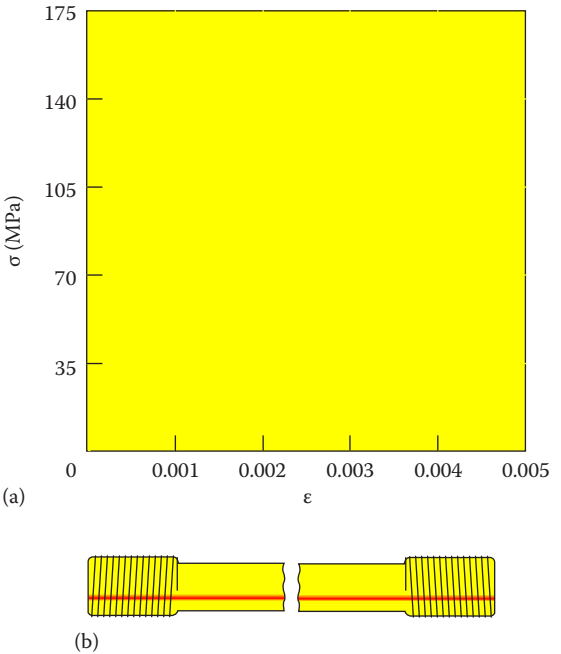


Figure 2.5
Gray cast iron in tension: (a) stress–strain diagram and (b) fractured specimen.

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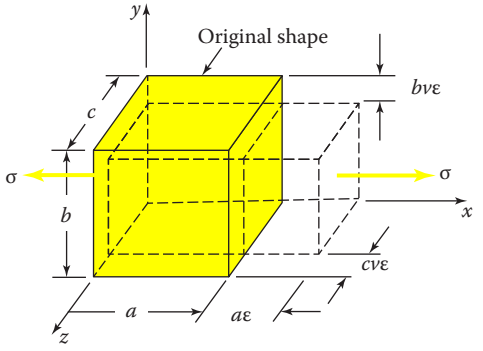


Figure 2.6
Axial elongation and lateral contraction of an element in tension (Poisson's effect).

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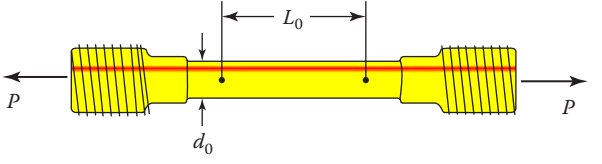


Figure 2.7
Example 2.1. A tensile specimen.

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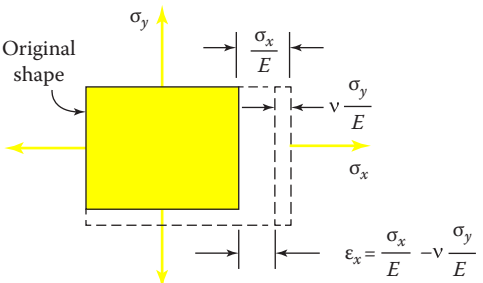


Figure 2.8
Element deformations caused by biaxial stress.

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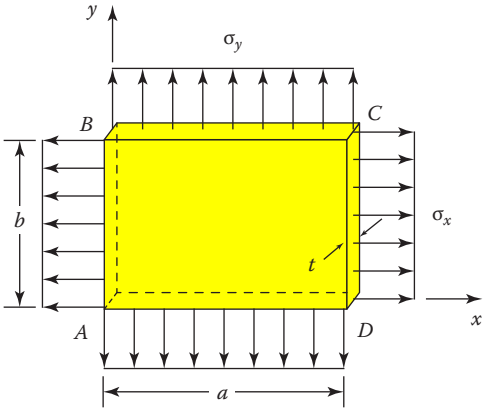


Figure 2.9
Example 2.2. Plate in biaxial stress.

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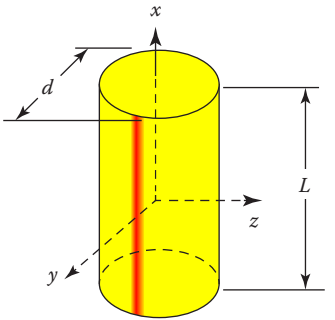


Figure 2.10
Example 2.3. A solid cylinder.

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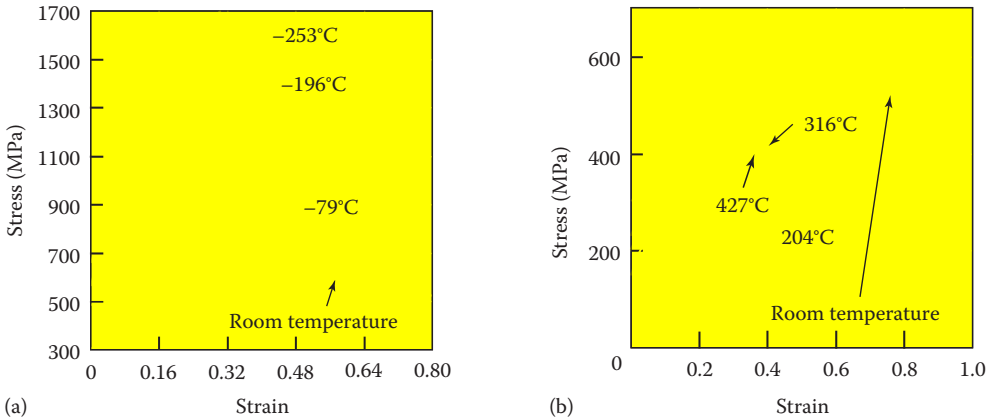


Figure 2.11
Stress–strain diagrams for AISI type 304 stainless steel in tension: (a) at low temperatures and (b) at elevated temperatures.

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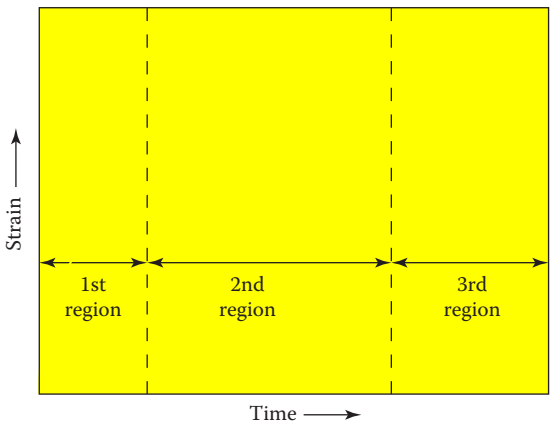


Figure 2.12
Creep curve for structural steel in tension at high temperatures.

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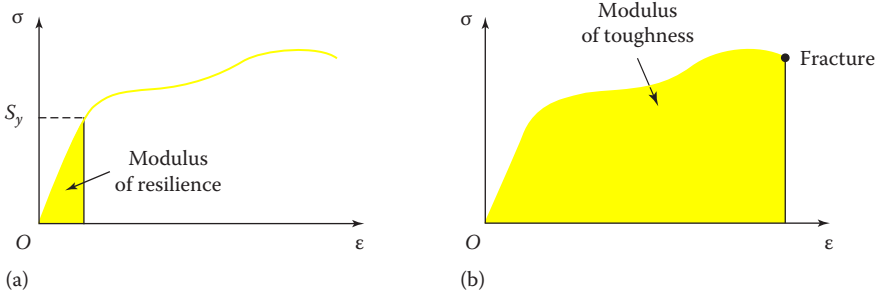


Figure 2.13
Stress–strain diagram: (a) modulus of resilience and (b) modulus of toughness.

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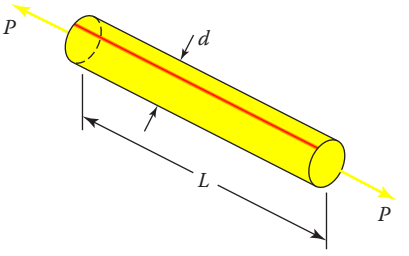


Figure 2.14
Example 2.4. Prismatic bar in tension.

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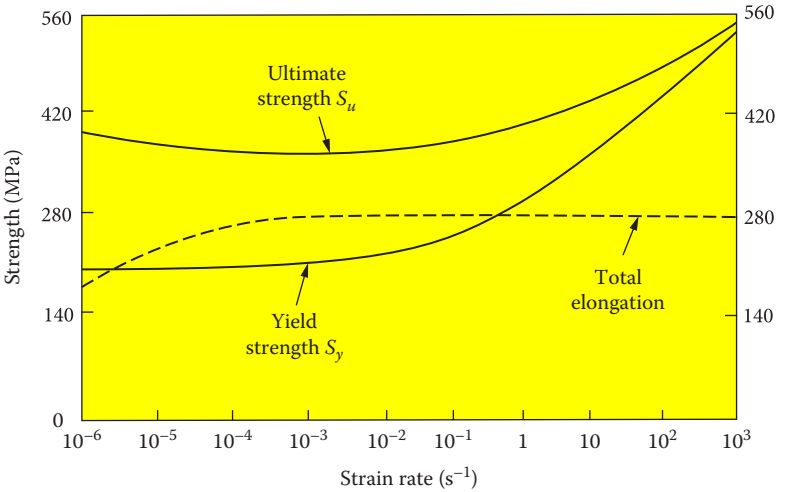


Figure 2.15
Influence of strain rate on tensile properties of a mild steel at room temperature.

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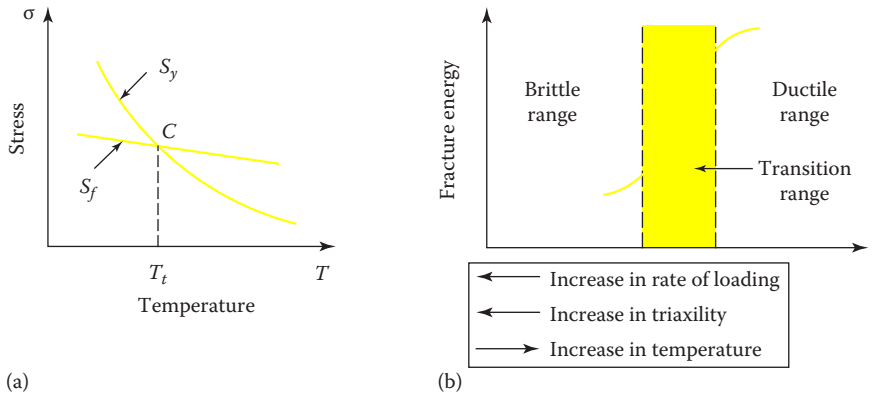


Figure 2.16
Typical transition curves for metals: (a) variation of yield strength S_y and fracture strength S_f with temperature and (b) effects of loading rate, stress around a notch, and temperature on impact toughness.

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Figure 2.17
Depiction of Titanic sinking. (Courtesy of google.com.)

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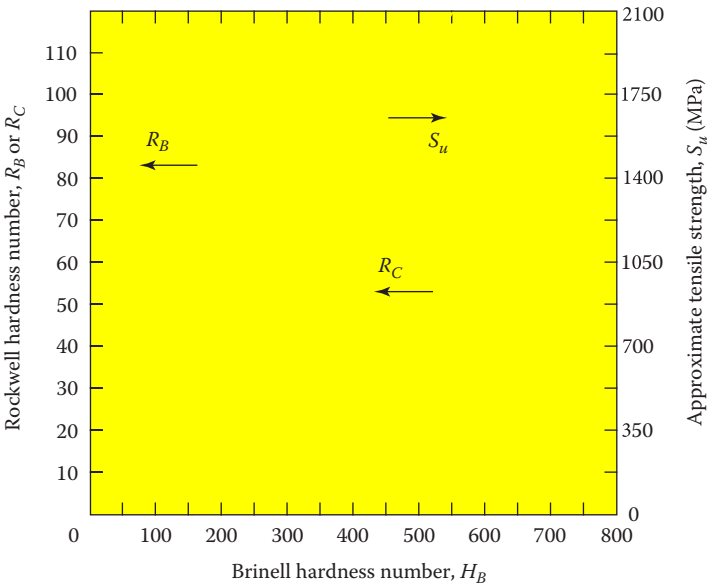


Figure 2.18
Hardness conversion to ultimate strength in tension of steel.

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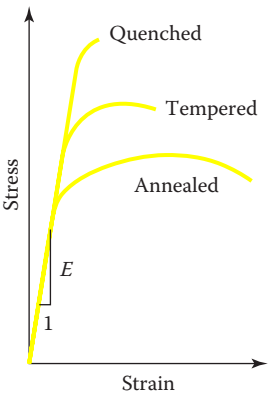


Figure 2.19
Stress–strain diagrams for annealed, quenched, and tempered steel.

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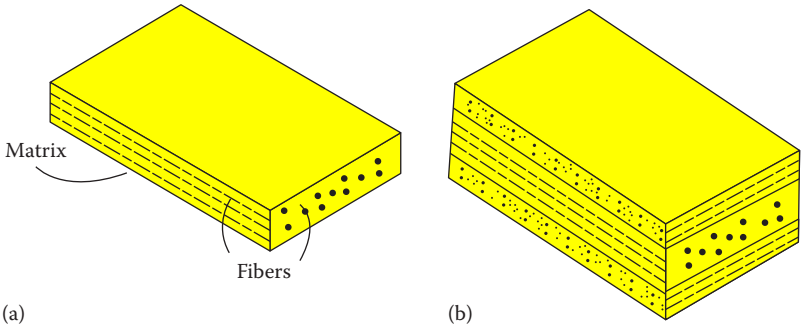


Figure 2.20
Fiber-reinforced materials: (a) single layer and (b) three-cross layer.

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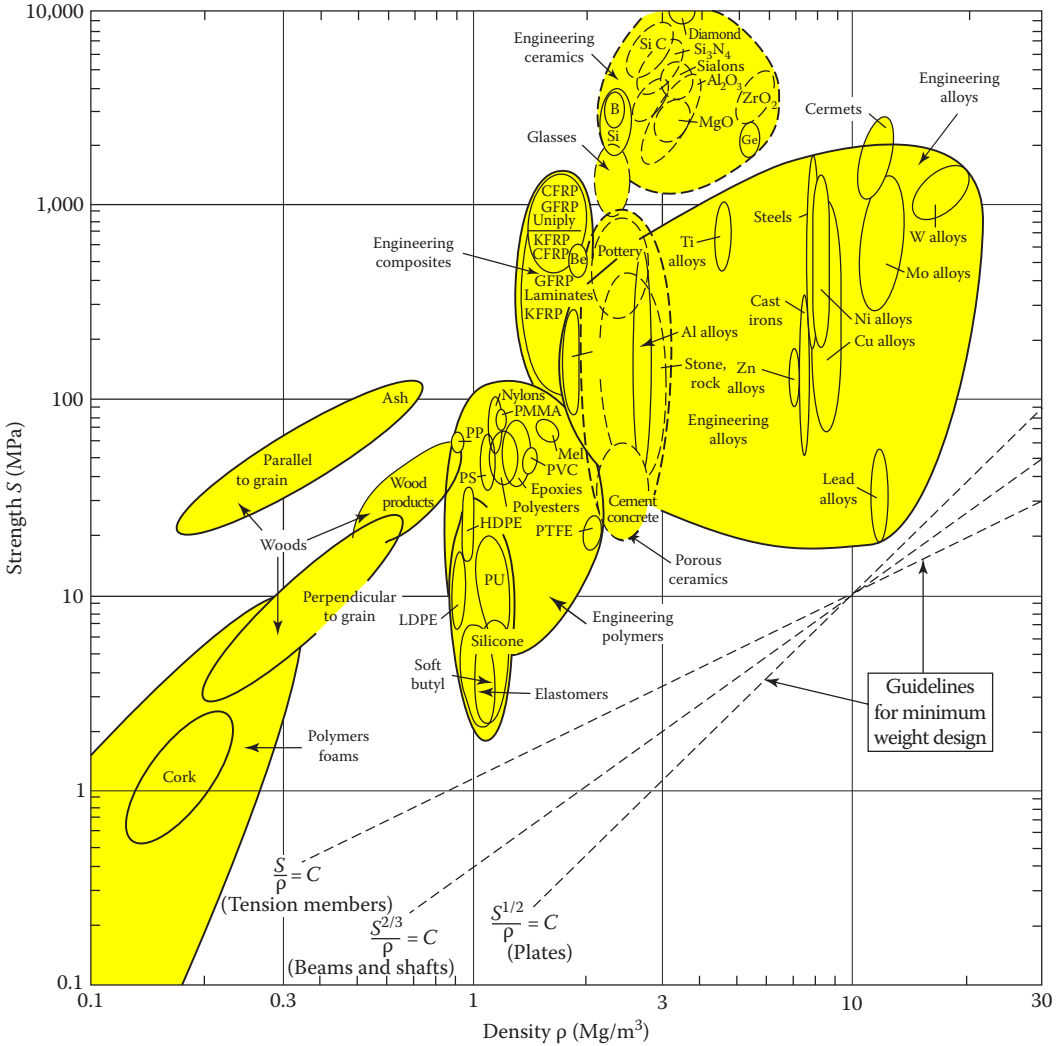


Figure 2.21
Strength versus density for engineering materials. The envelopes enclose data for a prescribed class of material. (From Ashby, M.J., *Material Selection in Mechanical Design*, 4th ed., Butterworth Heinemann, Oxford, U.K., 2011.)

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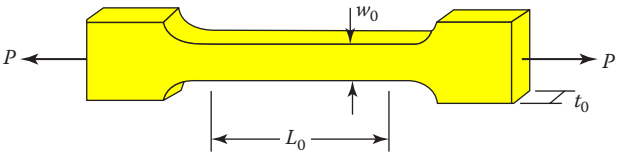


Figure P2.3

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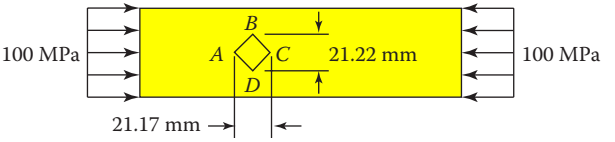


Figure P2.5

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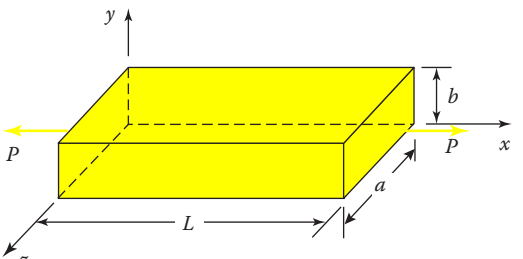


Figure P2.7

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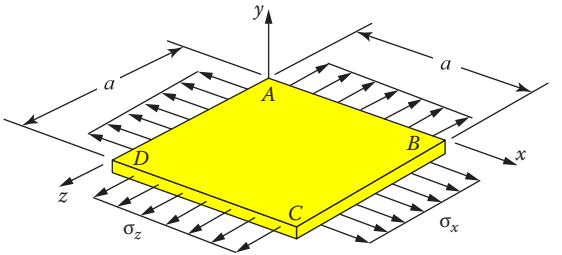


Figure P2.9

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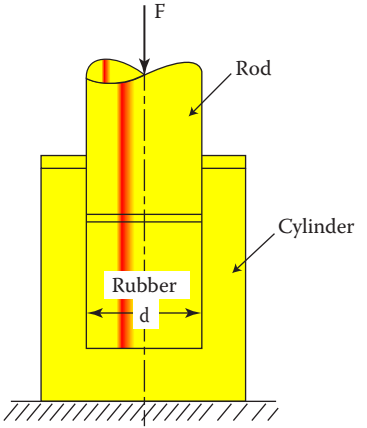


Figure P2.10

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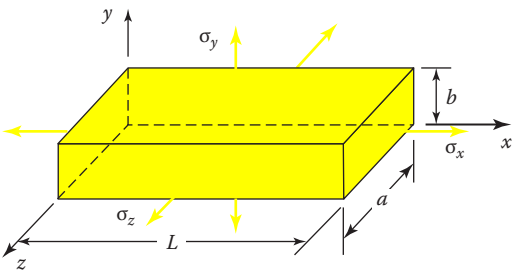


Figure P2.11

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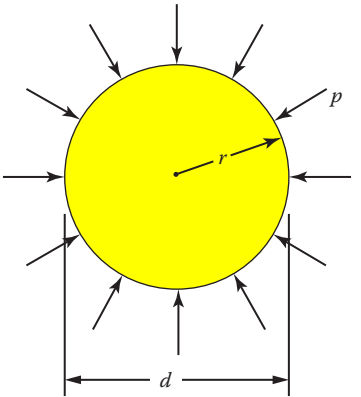


Figure P2.13

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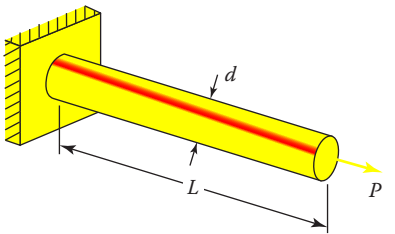


Figure P2.15

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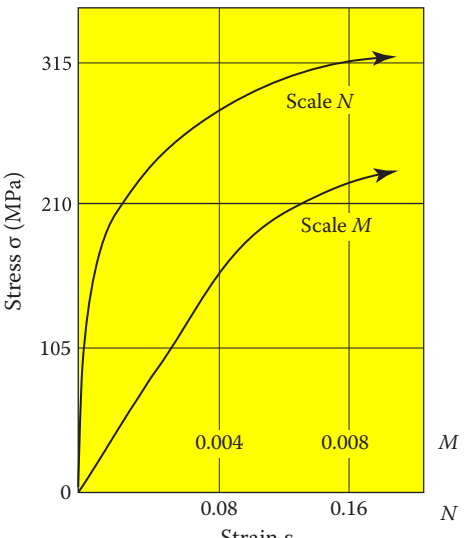


Figure P2.18

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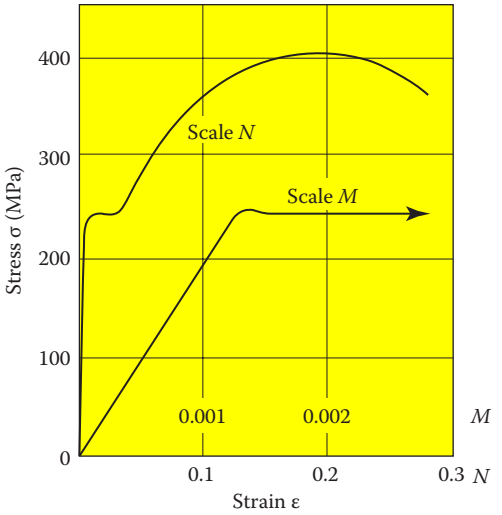


Figure P2.21

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