UNIVERSITY OF TORONTO

FACULTY OF APPLIED SCIENCE AND ENGINEERING

FINAL EXAMINATION, APRIL 2001
MMS 350H1 S - MATERIALS DESIGN & ENGINEERING

EXAMINERS: D. D. PEROVIC AND B.G. YACOBI

[Answer all 5 questions]

[All 5 questions are of equal value]
[Marks for individual questions are as indicated]

Exam Type: A

1. Briefly answer the following questions:

(a) Explain why covalently bonded materials are generally less dense than ionically or metallically bonded solids. **(4 marks)**

(b) Explain why the properties of polycrystalline materials are most often isotropic. **(4 marks)**

(c) Would you expect a material in which the atomic bonding is predominantly ionic in nature to be more or less likely to form a noncrystalline solid upon solidification than a covalent material? **(4 marks)**

(d) For a face-centred cubic solid, would you expect the surface energy for a (100) plane to be greater or less than that for a (111) plane? Why? **(4 marks)**

(e) Explain why small-angle grain boundaries are not as effective in increasing the yield stress of a material as are high-angle grain boundaries. **(4 marks)**

2.(a) Gaseous hydrogen at a constant pressure of 1.013 MPa (10 atm) is to flow within the interior of a thin-walled cylindrical tube of nickel that has a radius of 0.1 m. The temperature of the tube is to be 300 C and the pressure of hydrogen outside the tube will be maintained at 0.01013 (0.1 atm). Calculate the minimum wall thickness if the diffusion flux is to be no greater than 1×10^{-7} mol/m^2 sec. The concentration of hydrogen in nickel (C_H), in moles hydrogen per m^3 of nickel, is a function of hydrogen pressure, p_{H2} (in MPa) and absolute temperature (T) according to:

$$C_H = 30.8\,(p_{H2})^{1/2}\ \exp(-Q_C/RT) \text{ where } Q_C = 12.3 \text{ kJ/mol.}$$

Furthermore, the diffusivity of H in Ni is given by:

D_H (m^2/sec) = 4.76 × 10^{-7} exp ($-Q_D$ /RT) where Q_D = 39.56 kJ/mol. **(5 marks)**

(b) For thin-walled cylindrical tubes that are pressurized, the circumferential stress (σ) is a function of the pressure difference across the wall (Δp), cylinder radius (r) and tube thickness (Δx) as given by: $\sigma = r(\Delta p)/4(\Delta x)$. Compute the circumferential stress to which the walls of this pressurized cylinder are exposed. **(5 marks)**

(c) The room-temperature yield strength (σ_y) of Ni is 100 MPa and decreases about 5 MPa for every 50 C increase in temperature. Would you expect the wall thickness computed in **(b)** to be suitable for this Ni cylinder at 300 C? Why or why not? **(5 marks)**

(d) If this thickness is found to be suitable, compute the minimum thickness that could be used without any deformation of the tube walls. How much would the diffusion flux increase with this reduction in thickness? On the other hand, if the thickness determined in **(c)** is found to be unsuitable, then specify a minimum thickness that you would use. In this case how much of a reduction in diffusion flux would result? **(5 marks)**

3.(a) Consider a hypothetical phase diagram for a lead-free A-B alloy to be used in microelectronics assembly and packaging. The diagram is similar in form to the Pb-Sn system. Assume that: (i) α and β solid solution phases exist at the A and B extremities of the phase diagram, respectively; (ii) the eutectic composition is 47 wt.%B-53 wt.%A; and (iii) the composition of the β phase at the eutectic temperature is 92.6 wt.%B-7.4 wt.%A. Determine the composition of an alloy that will yield primary α and total α mass fractions of 0.356 and 0.693, respectively. **(10 marks)**

(b) A microelectronic component is manufactured from the A-B alloy which has been determined to have a *plane strain* fracture toughness of 35 MPa$\sqrt{m}$. It is known from thermal cycling tests that fracture results at a stress of 250 MPa when the maximum internal flaw size is 2.0 mm. For this same component and alloy, will fracture occur at a stress level of 325 MPa when the maximum internal flaw size is 1.0 mm? Why or why not? [Recall that: $K_c = Y\sigma(\pi a)^{1/2}$ where Y is a dimensionless parameter that depends on specimen size, geometry and stress state (e.g. plane strain conditions)]. **(10 marks)**

4. Outline briefly (i) the changes in the properties at the nanoscale and (ii) the major advantages of nanostructures, as related to:
(a) Electronic properties **(10 marks)**
(b) Mechanical properties **(10 marks)**
In your answer, specifically, consider such applications as (i) quantum dot lasers and (ii) high-surface area materials.

5. You have been asked to design the ultimate airplane wing. The wing section is assumed to be hollow (variable wall thickness= t) and ellipsoidal is cross-section. The wing is loaded as a cantilever beam with a uniformly distributed force along the length (l) of the wing. Using the information attached answer the following questions:

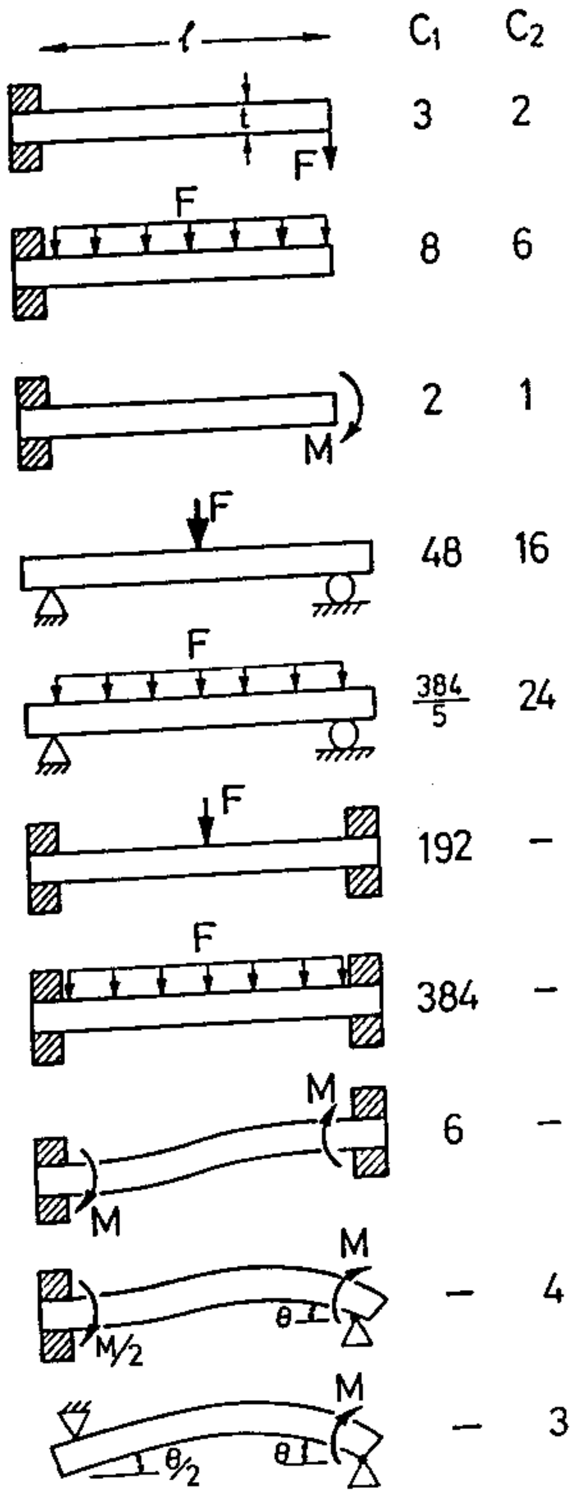
(a) Select the best engineering material to achieve the maximum stiffness for least weight if cost is no object. **(5 marks)**

(b) Does your conclusion in **(a)** change if material cost is a constraint? **(2 marks)**

(c) Would your conclusion in **(a)** change if the wing were to be constructed from a solid ellipsoidal section where the minor axis dimension (b) is variable? **(5 marks)**

(d) Select the ultimate material for maximum resistance to full plasticity, where a "plastic hinge" develops prior to plastic collapse, at minimum weight. (N.B. For simplicity assume the wing has a rectangular cross-section with a variable thickness (b)). **(5 marks)**

(e) Is the material selected in case **(d)** ideal for resistance to catastrophic fracture? If not, select the best material for fracture resistance. **(3 marks)**



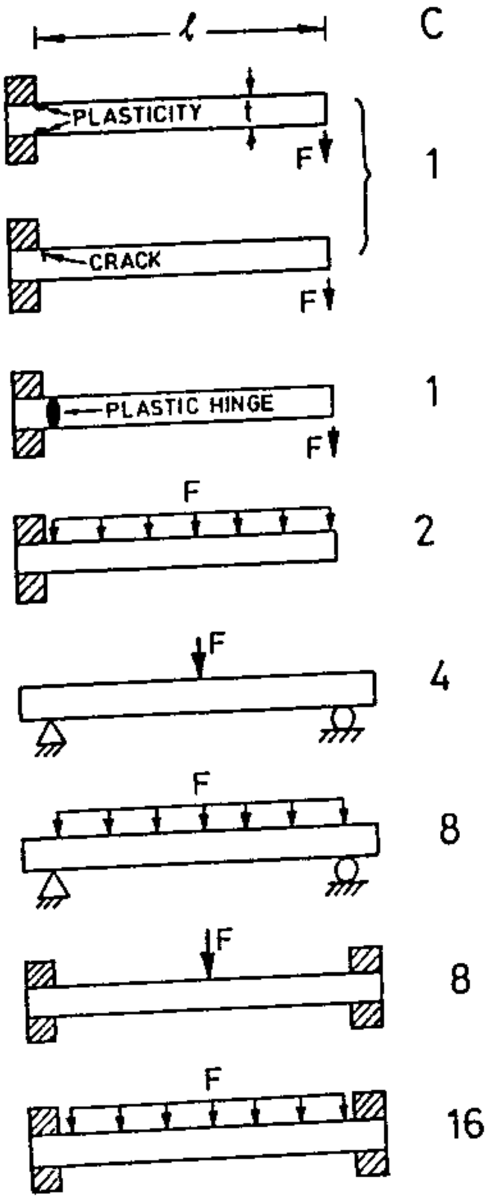
$$\delta = \frac{F\ell^3}{C_1 E I} = \frac{M\ell^2}{C_1 E I}$$

$$\theta = \frac{F\ell^2}{C_2 E I} = \frac{M\ell}{C_2 E I}$$

E = YOUNGS MODULUS (N/m^2)
δ = DEFLECTION (m)
F = FORCE (N)
M = MOMENT (Nm)
ℓ = LENGTH (m)
b = WIDTH (m)
t = DEPTH (m)
θ = END SLOPE (–)
I = SEE TABLE 2 (m^4)
y = DISTANCE FROM N.A.(m)
R = RADIUS OF CURVATURE (m)

$$\frac{\sigma}{y} = \frac{M}{I} = \frac{E}{R}$$

FIG. A3 Deflection of beams.



$$M_f = \left(\frac{I}{y_m}\right) \sigma^* \text{ (ONSET)}$$

$$M_f = H\sigma_y \text{ (FULL PLASTICITY)}$$

$$F_f = C\left(\frac{I}{y_m}\right)\frac{\sigma^*}{\ell} \text{ (ONSET)}$$

$$F_f = \frac{CH\sigma_y}{\ell} \text{ (FULL PLASTICITY)}$$

M_f = FAILURE MOMENT (Nm)

F_f = FORCE AT FAILURE (N)

ℓ = LENGTH (m)

t = DEPTH (m)

b = WIDTH (m)

I = SEE TABLE 2 (m^4)

$\frac{I}{y_m}$ = SEE TABLE 2 (m^3)

H = SEE TABLE 2 (m^3)

σ_y = YIELD STRENGTH (N/m^2)

σ_f = MODULUS OF RUPTURE (N/m^2)

σ^* = σ_y (PLASTIC MATERIAL)

= σ_f (BRITTLE MATERIAL)

FIG. A4 Failure of beams.

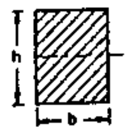
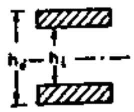
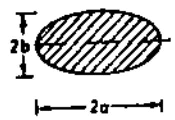
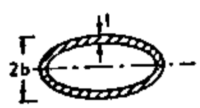
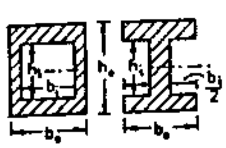
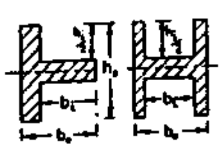
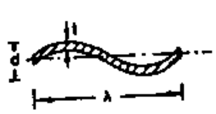
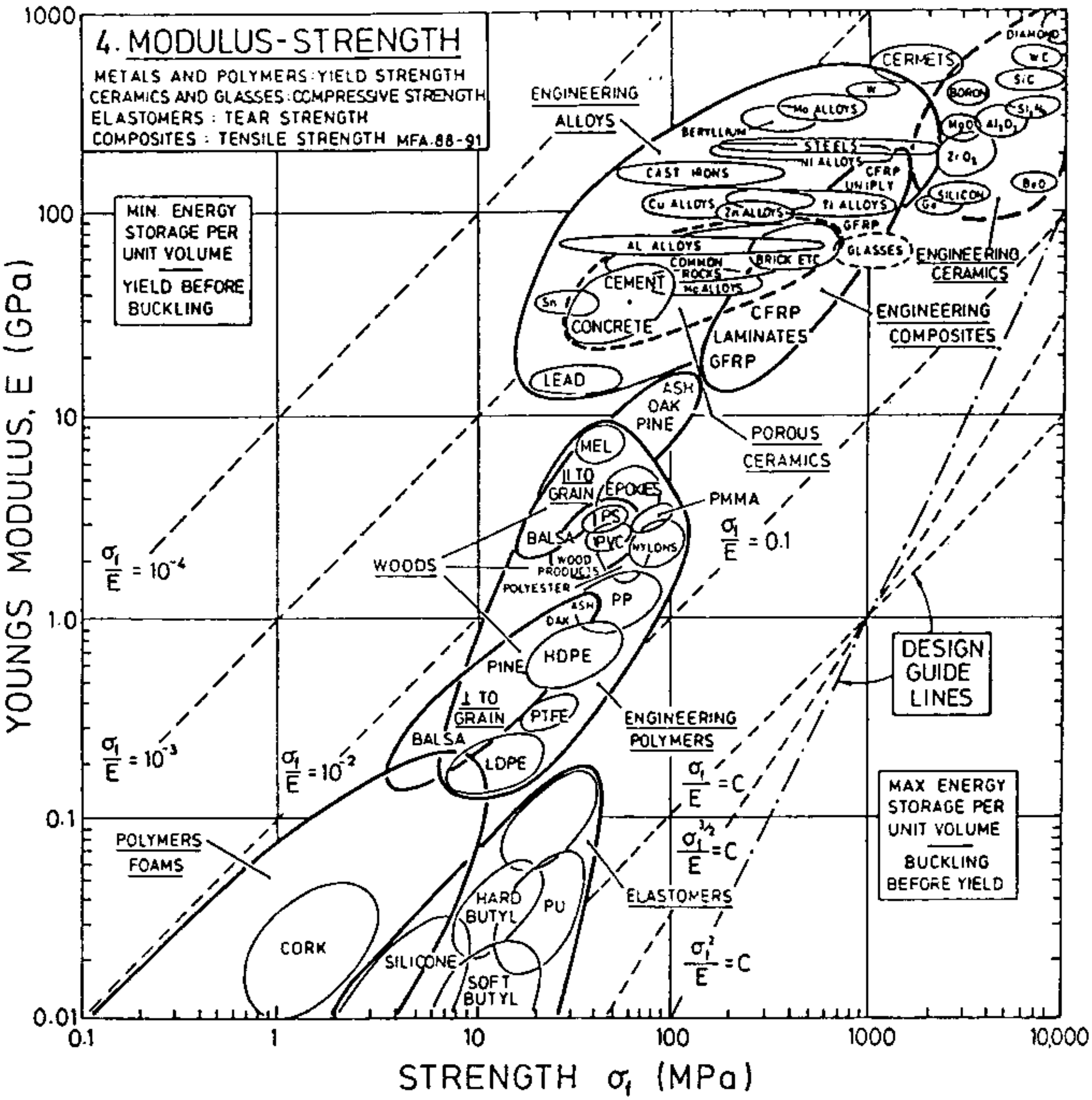
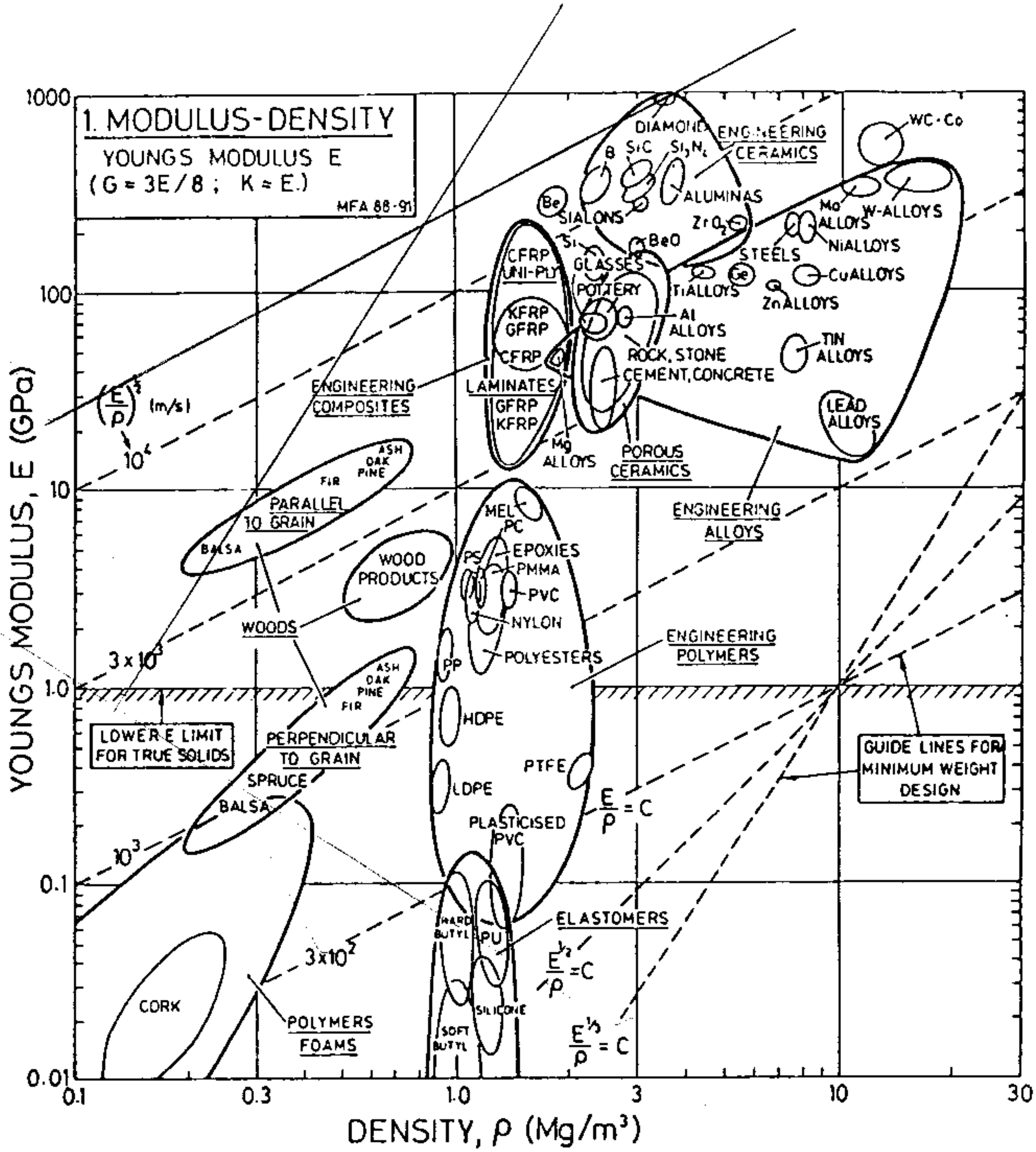
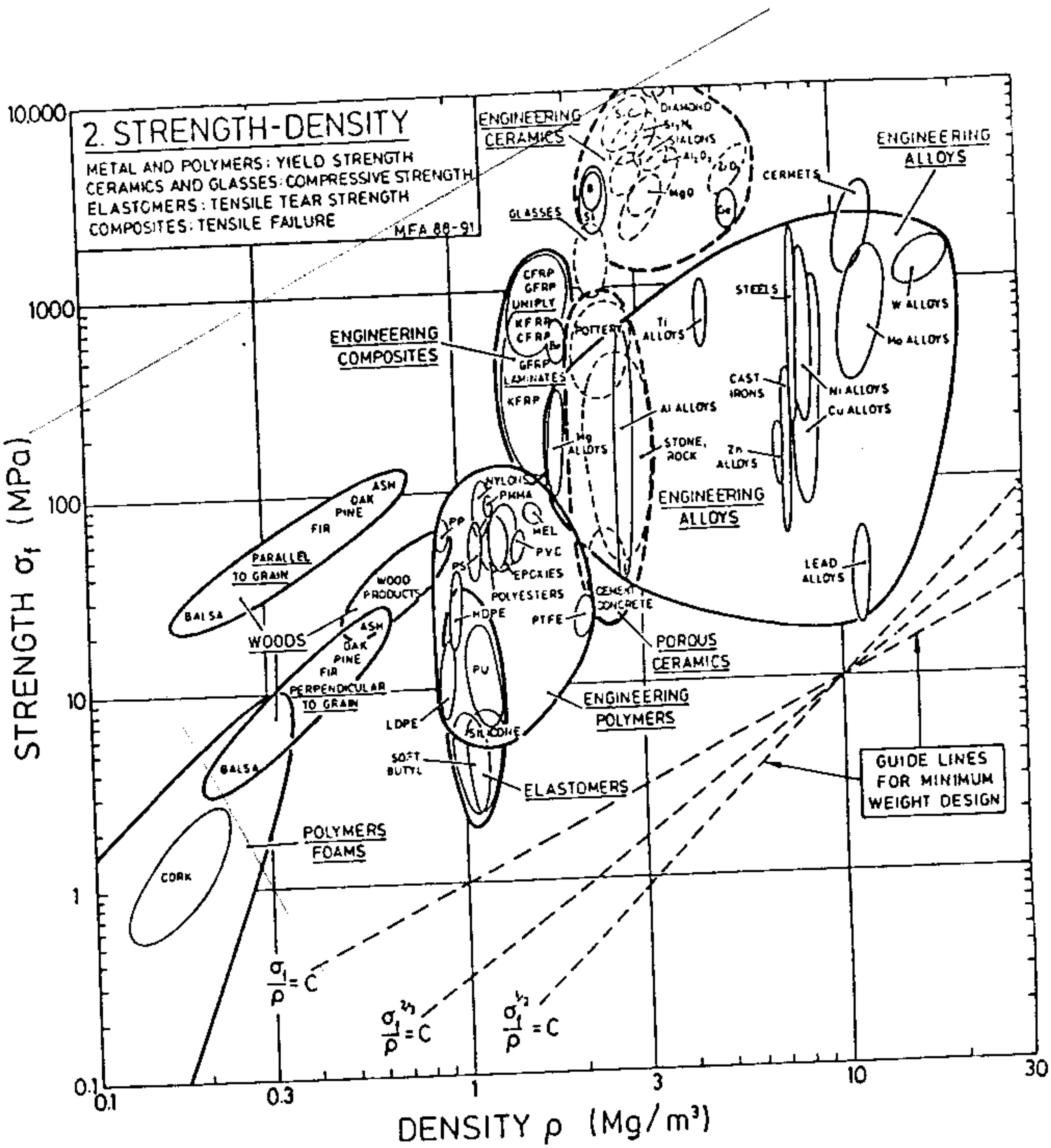
SECTION	$A (m^2)$	$I (m^4)$	$K (m^4)$	$I/y_m (m^3)$	$H (m^3)$
	bh	$\frac{bh^3}{12}$	$\frac{16}{3} hb^3 \left(1 - 0.58\frac{b}{h}\right)$	$\frac{bh^2}{6}$	$\frac{bh^2}{4}$
	$b(h_o - h_i)$	$\frac{b}{12}(h_o^3 - h_i^3)$	—	$\frac{b}{12h_o}(h_o^3 - h_i^3)$	$\frac{b}{4}(h_o^2 - h_i^2)$
	$\frac{\sqrt{3}}{4} a^2$	$\frac{a^4}{32\sqrt{3}}$	$\frac{a^4\sqrt{3}}{80}$	$\frac{a^3}{32}$	—
	$\frac{\pi d^2}{4}$	$\frac{\pi}{64} d^4$	$\frac{\pi}{32} d^4$	$\frac{\pi}{32} d^3$	$\frac{1}{6} d^3$
	$\frac{\pi}{4}(d_o^2 - d_i^2)$	$\frac{\pi}{64}(d_o^4 - d_i^4)$	$\frac{\pi}{32}(d_o^4 - d_i^4)$	$\frac{\pi}{32 d_o}(d_o^4 - d_i^4)$	$\frac{1}{6}(d_o^3 - d_i^3)$
	$\pi a b$	$\frac{\pi}{4} a b^3$	$\frac{\pi a^3 b^3}{a^2 + b^2}$	$\frac{\pi}{2} a b^2$	—
	$2\pi (ab)^{1/2} t$	$\frac{\pi}{4} a b^3 t \left(\frac{1}{a} + \frac{3}{b}\right)$	$\frac{4\pi t a^2 b^2}{(a+b)}$	$\frac{\pi a b^2 t}{2}\left(\frac{1}{a} + \frac{3}{b}\right)$	—
	$h_o b_o - h_i b_i$	$\frac{1}{12}(b_o h_o^3 - b_i h_i^3)$	—	$\frac{1}{12 h_o}(b_o h_o^3 - b_i h_i^3)$	$\frac{1}{4}(b_o h_o^2 - b_i h_i^2)$
	$h_o b_i + h_i b_o$	$\frac{1}{12}(b_i h_o^3 + b_o h_i^3)$	—	$\frac{1}{12 h_o}(b_i h_o^3 + b_o h_i^3)$	$\frac{1}{4}(b_o h_o^2 + b_i h_i^2 - 2b h_i h_o)$
	$t\lambda\left(1 + \left(\frac{\pi d}{2\lambda}\right)^2\right)$	$\frac{t\lambda d^2}{8}\left(1 - \frac{0.81}{1 + 2.5\left(\frac{d}{2\lambda}\right)^2}\right)$	—	—	—

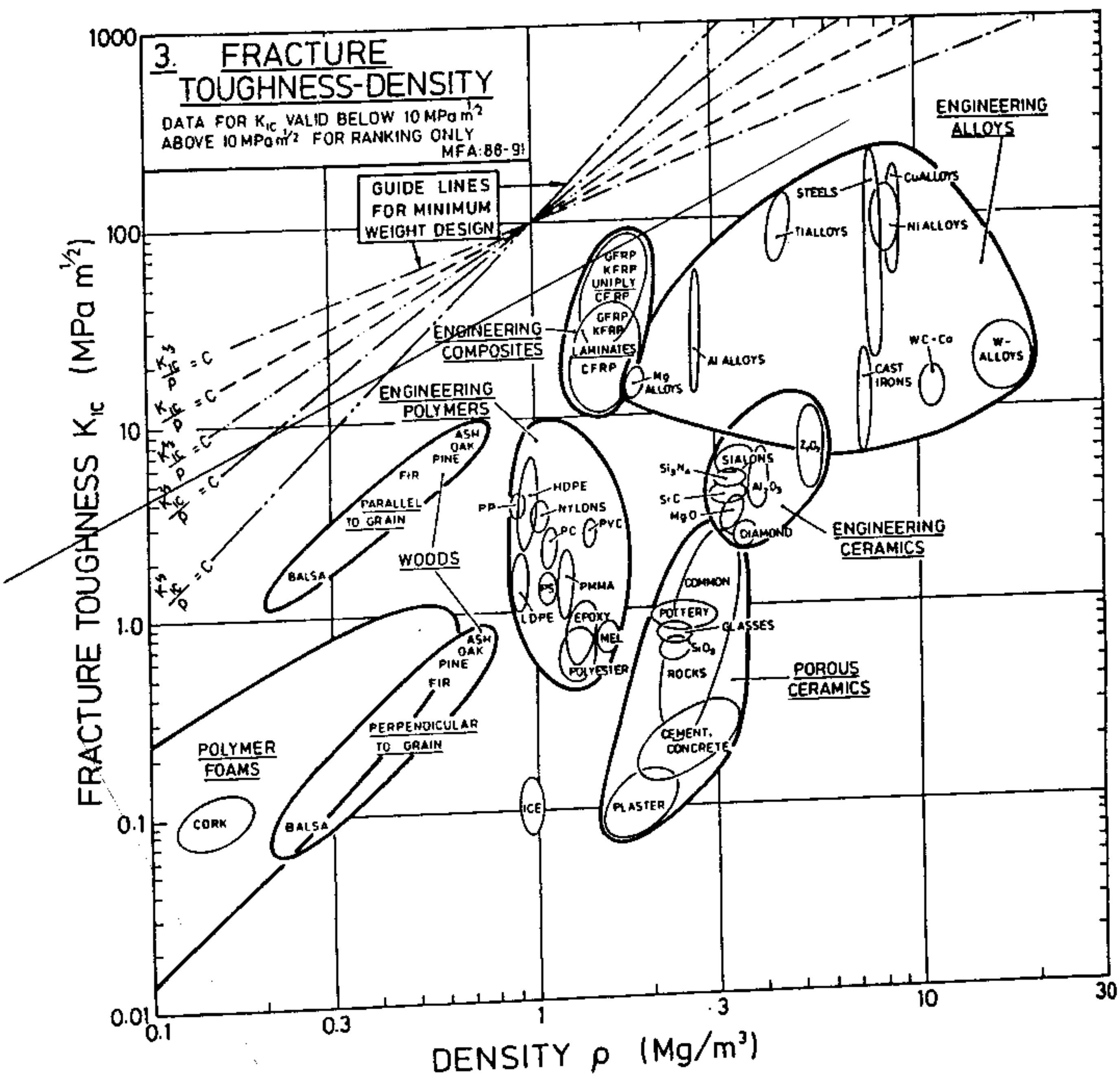
FIG. A2 Moments of sections.

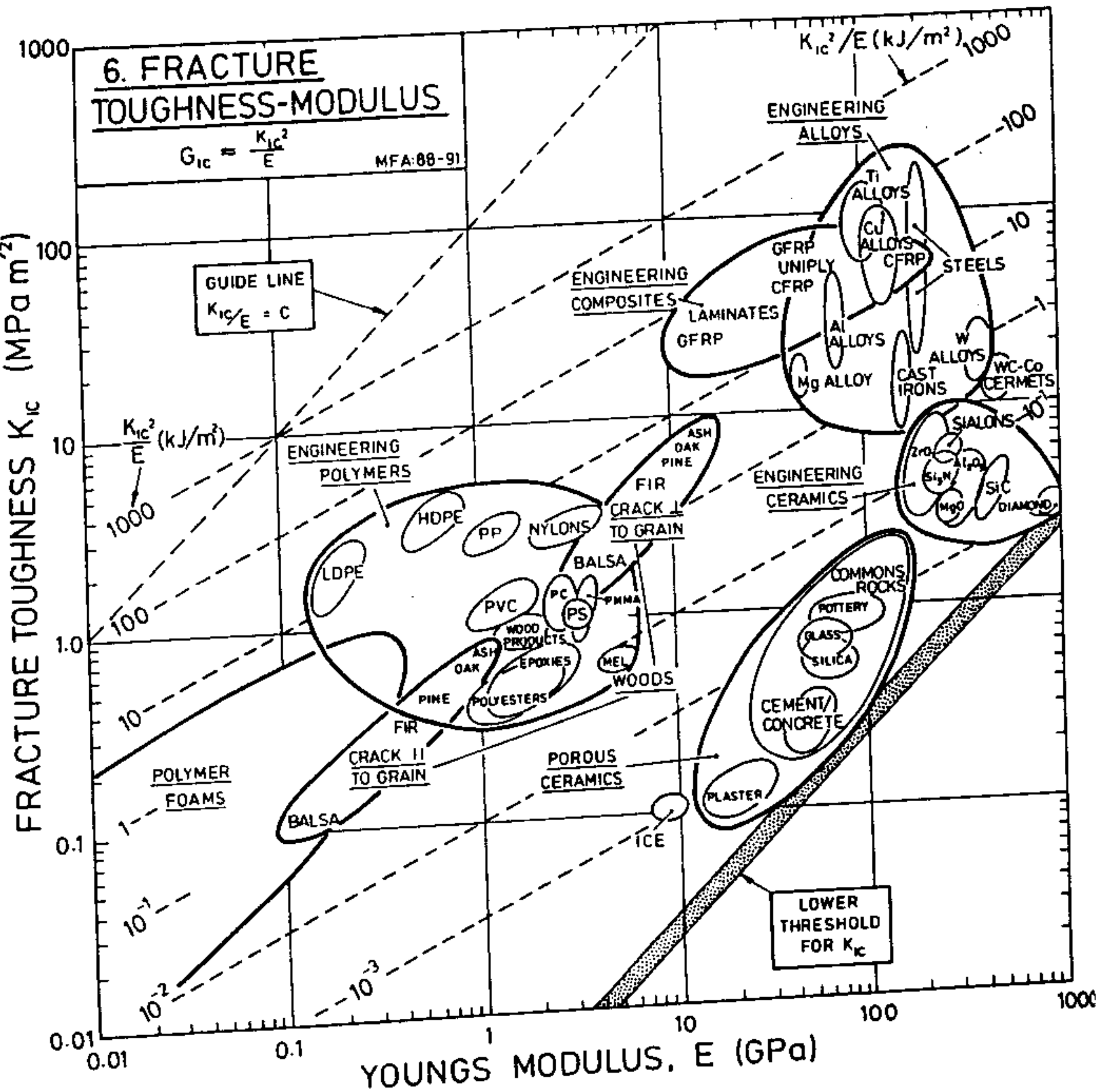


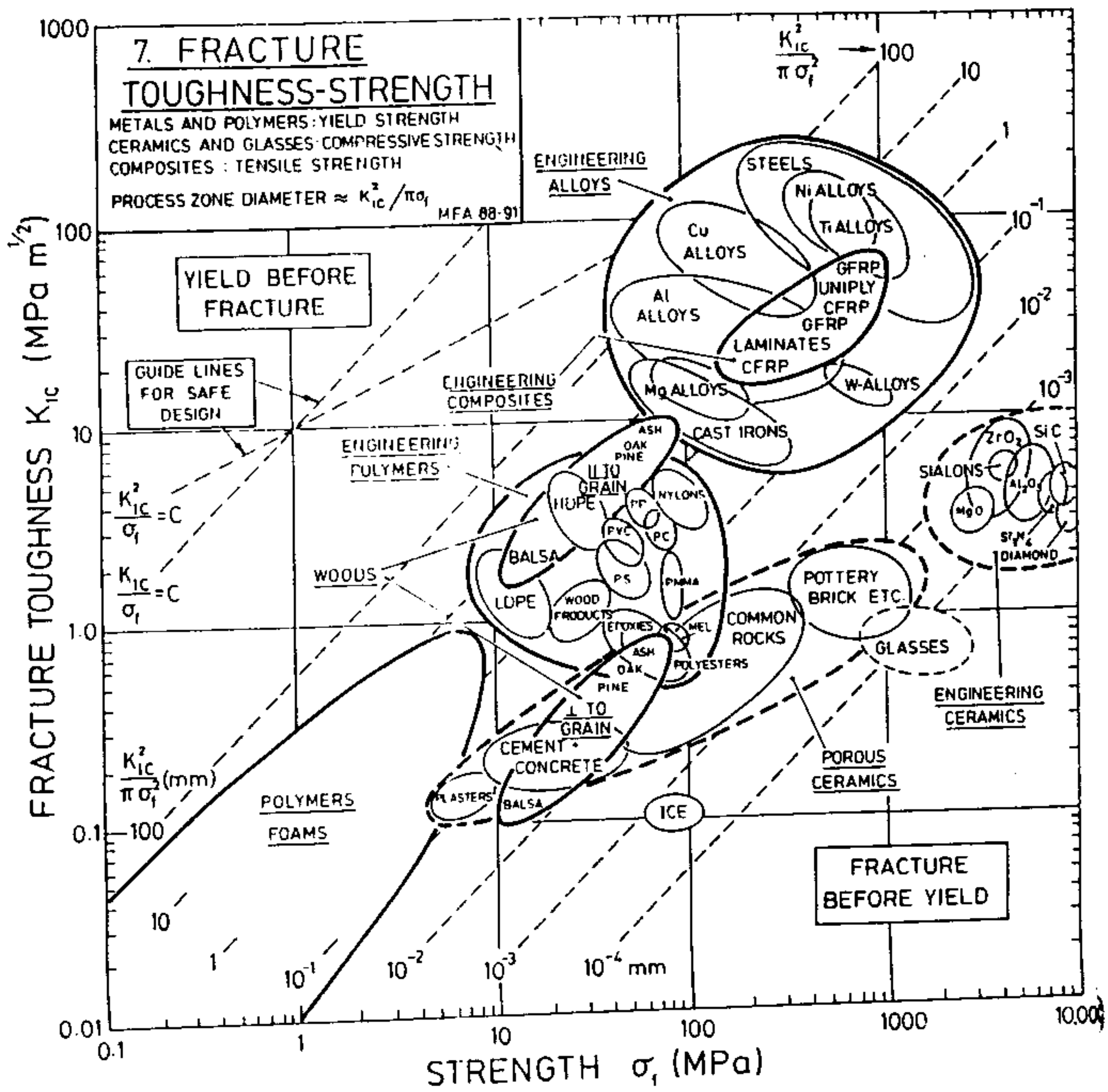
4. MODULUS-STRENGTH
METALS AND POLYMERS: YIELD STRENGTH
CERAMICS AND GLASSES: COMPRESSIVE STRENGTH
ELASTOMERS : TEAR STRENGTH
COMPOSITES : TENSILE STRENGTH MFA 88-91
MIN. ENERGY STORAGE PER UNIT VOLUME
YIELD BEFORE BUCKLING
MAX ENERGY STORAGE PER UNIT VOLUME
BUCKLING BEFORE YIELD
DESIGN GUIDE LINES
ENGINEERING ALLOYS
ENGINEERING CERAMICS
ENGINEERING COMPOSITES
POROUS CERAMICS
ENGINEERING POLYMERS
ELASTOMERS
POLYMERS FOAMS
WOODS
CFRP LAMINATES GFRP
CERMETS
DIAMOND
WC
SiC
BORON
MgO
Al_2O_3
Si_3N_4
ZrO_2
BeO
SILICON
Ge
W
Mo ALLOYS
BERYLLIUM
STEELS
NI ALLOYS
CAST IRONS
CFRP UNIPLY
Cu ALLOYS
Zn ALLOYS
Ti ALLOYS
GFRP
AL ALLOYS
GLASSES
BRICK ETC
COMMON ROCKS
Mg ALLOYS
CEMENT
Sn
CONCRETE
LEAD
ASH OAK PINE
MEL
∥ TO GRAIN
EPOXIES
PMMA
PS
PVC
NYLONS
BALSA
WOOD PRODUCTS
POLYESTER
PP
ASH
OAK
PINE
HDPE
⊥ TO GRAIN
PTFE
BALSA
LDPE
CORK
SILICONE
HARD BUTYL
PU
SOFT BUTYL
$\frac{\sigma_f}{E} = 10^{-4}$
$\frac{\sigma_f}{E} = 10^{-3}$
$\frac{\sigma_f}{E} = 10^{-2}$
$\frac{\sigma_f}{E} = 0.1$
$\frac{\sigma_f}{E} = C$
$\frac{\sigma_f^{3/2}}{E} = C$
$\frac{\sigma_f^{2}}{E} = C$
YOUNGS MODULUS, E (GPa)
STRENGTH σ_f (MPa)
1000
100
10
1.0
0.1
0.01
0.1
1
10
100
1000
10,000

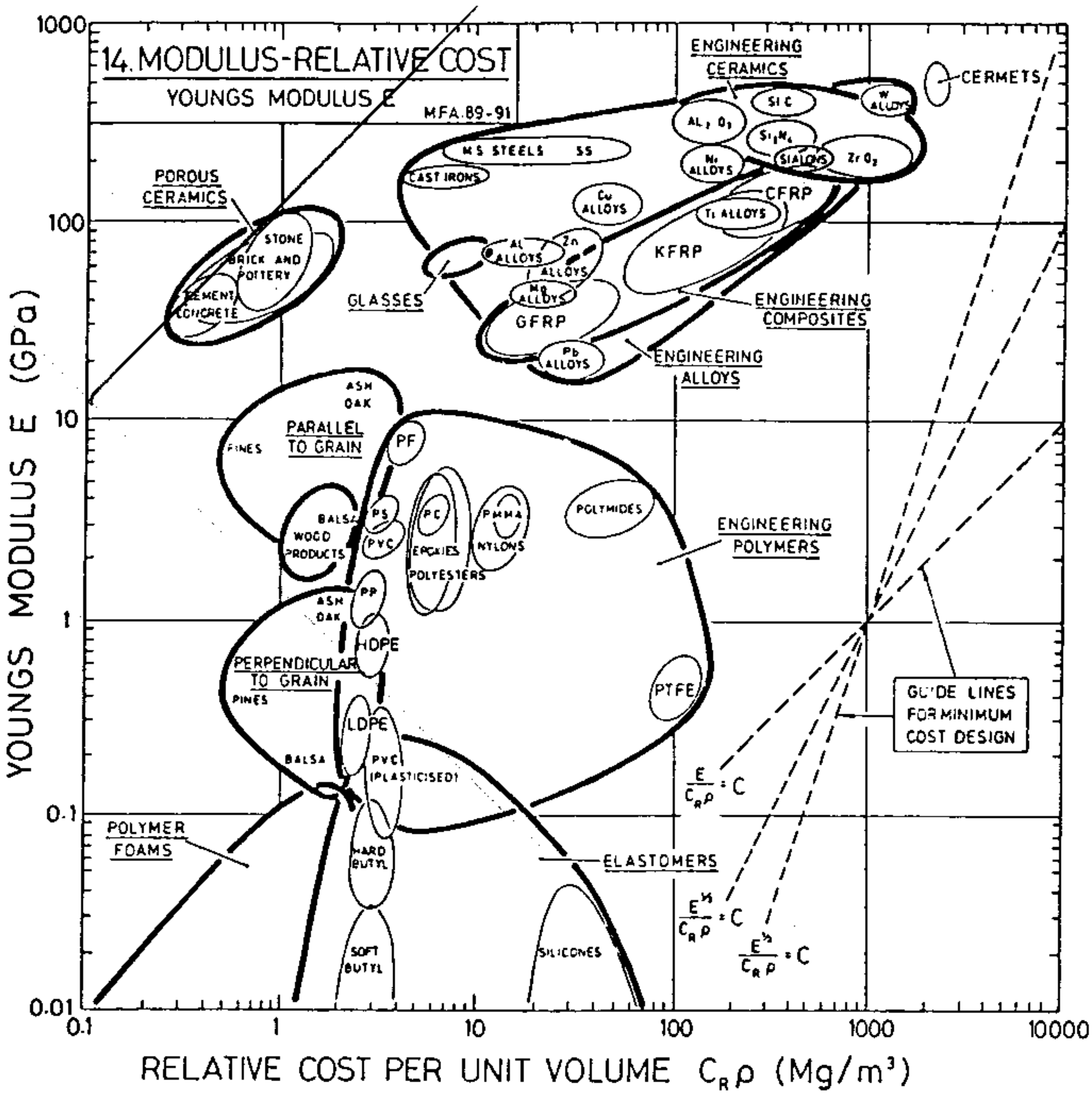

1. MODULUS-DENSITY
YOUNGS MODULUS E
(G = 3E/8 ; K = E.)
MFA 88-91
YOUNGS MODULUS, E (GPa)
DENSITY, ρ (Mg/m³)
1000
100
10
1.0
0.1
0.01
0.1
0.3
1.0
3
10
30
DIAMOND
ENGINEERING CERAMICS
B
SiC
Si3N4
ALUMINAS
Be
SIALONS
ZrO2
BeO
Si
GLASSES
POTTERY
CFRP UNI-PLY
KFRP GFRP
CFRP
ENGINEERING COMPOSITES
LAMINATES GFRP KFRP
Mg ALLOYS
POROUS CERAMICS
ROCK, STONE CEMENT, CONCRETE
Al ALLOYS
Ti ALLOYS
Ge
STEELS
Zn ALLOYS
Cu ALLOYS
Ni ALLOYS
Mo ALLOYS
W-ALLOYS
WC-Co
TIN ALLOYS
LEAD ALLOYS
ENGINEERING ALLOYS
(E/ρ)^½ (m/s)
10⁴
3 x 10³
10³
3x10²
ASH OAK PINE
FIR
BALSA
PARALLEL TO GRAIN
WOOD PRODUCTS
WOODS
PERPENDICULAR TO GRAIN
SPRUCE
LOWER E LIMIT FOR TRUE SOLIDS
MEL
PC
PS
EPOXIES
PMMA
PVC
NYLON
POLYESTERS
PP
HDPE
LDPE
PTFE
PLASTICISED PVC
ENGINEERING POLYMERS
HARD BUTYL
PU
SILICONE
SOFT BUTYL
ELASTOMERS
CORK
POLYMERS FOAMS
E/ρ = C
E^½/ρ = C
E^⅓/ρ = C
GUIDE LINES FOR MINIMUM WEIGHT DESIGN


2. STRENGTH-DENSITY
METAL AND POLYMERS: YIELD STRENGTH
CERAMICS AND GLASSES: COMPRESSIVE STRENGTH
ELASTOMERS: TENSILE TEAR STRENGTH
COMPOSITES: TENSILE FAILURE
MFA 88-91
ENGINEERING CERAMICS
ENGINEERING ALLOYS
ENGINEERING COMPOSITES
ENGINEERING POLYMERS
POROUS CERAMICS
ELASTOMERS
WOODS
POLYMERS FOAMS
GUIDE LINES FOR MINIMUM WEIGHT DESIGN
STRENGTH σf (MPa)
DENSITY ρ (Mg/m³)


3. FRACTURE TOUGHNESS-DENSITY
DATA FOR K_{IC} VALID BELOW 10 MPa m$^{1/2}$
ABOVE 10 MPa m$^{1/2}$ FOR RANKING ONLY
MFA:88-91
GUIDE LINES FOR MINIMUM WEIGHT DESIGN
ENGINEERING ALLOYS
ENGINEERING COMPOSITES
ENGINEERING POLYMERS
ENGINEERING CERAMICS
POROUS CERAMICS
POLYMER FOAMS
WOODS
PARALLEL TO GRAIN
PERPENDICULAR TO GRAIN
FRACTURE TOUGHNESS K_{IC} (MPa m$^{1/2}$)
DENSITY ρ (Mg/m^3)


6. FRACTURE TOUGHNESS-MODULUS
$G_{Ic} = \frac{K_{Ic}^2}{E}$
MFA:88-91
GUIDE LINE $K_{Ic}/E = C$
K_{Ic}^2/E (kJ/m²)
ENGINEERING ALLOYS
Ti ALLOYS
Cu ALLOYS
CFRP
STEELS
GFRP UNIPLY CFRP
ENGINEERING COMPOSITES
LAMINATES
GFRP
Al ALLOYS
W ALLOYS
WC-Co CERMETS
Mg ALLOY
CAST IRONS
SIALONS
ZrO₂
Al₂O₃
Si₃N₄
SiC
MgO
DIAMOND
ENGINEERING CERAMICS
ENGINEERING POLYMERS
HDPE
PP
NYLONS
LDPE
PVC
PC
PS
PMMA
WOOD PRODUCTS
EPOXIES
MEL
POLYESTERS
ASH OAK PINE
FIR CRACK ⊥ TO GRAIN
BALSA
WOODS
FIR CRACK ∥ TO GRAIN
COMMONS ROCKS
POTTERY
GLASS
SILICA
CEMENT/CONCRETE
POROUS CERAMICS
PLASTER
ICE
POLYMER FOAMS
LOWER THRESHOLD FOR K_{Ic}
FRACTURE TOUGHNESS K_{Ic} (MPa m^½)
YOUNGS MODULUS, E (GPa)


7. FRACTURE TOUGHNESS-STRENGTH
METALS AND POLYMERS: YIELD STRENGTH
CERAMICS AND GLASSES: COMPRESSIVE STRENGTH
COMPOSITES : TENSILE STRENGTH
PROCESS ZONE DIAMETER ≈ $K_{IC}^2/\pi\sigma_f$
MFA 88-91
YIELD BEFORE FRACTURE
GUIDE LINES FOR SAFE DESIGN
$\frac{K_{IC}^2}{\sigma_f} = C$
$\frac{K_{IC}}{\sigma_f} = C$
$\frac{K_{IC}^2}{\pi\sigma_f^2}$ (mm)
ENGINEERING ALLOYS
STEELS
Ni ALLOYS
Ti ALLOYS
Cu ALLOYS
Al ALLOYS
GFRP
UNIPLY CFRP
GFRP
LAMINATES CFRP
Mg ALLOYS
W-ALLOYS
CAST IRONS
ENGINEERING COMPOSITES
ENGINEERING POLYMERS
WOODS
ASH
OAK
PINE
∥ TO GRAIN
HDPE
PP
NYLONS
PVC
PC
BALSA
PS
PMMA
LDPE
WOOD PRODUCTS
EPOXIES
MEL
POLYESTERS
ASH
OAK
PINE
⊥ TO GRAIN
CEMENT + CONCRETE
PLASTERS
BALSA
ICE
COMMON ROCKS
POTTERY BRICK ETC.
GLASSES
POROUS CERAMICS
ENGINEERING CERAMICS
SIALONS
ZrO_2
SiC
Al_2O_3
MgO
Si_3N_4
DIAMOND
POLYMERS FOAMS
FRACTURE BEFORE YIELD
$\frac{K_{IC}^2}{\pi\sigma_f^2}$ → 100
10
1
10^{-1}
10^{-2}
10^{-3}
100
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4} mm
FRACTURE TOUGHNESS K_{IC} (MPa $m^{1/2}$)
1000
100
10
1.0
0.1
0.01
STRENGTH σ_f (MPa)
0.1
1
10
100
1000
10,000


14. MODULUS-RELATIVE COST
YOUNGS MODULUS E
MFA 89-91
ENGINEERING CERAMICS
CERMETS
SiC
W ALLOYS
Al_2O_3
Si_3N_4
SIALONS
ZrO_2
Ni ALLOYS
MS STEELS
SS
CAST IRONS
POROUS CERAMICS
STONE
BRICK AND POTTERY
CEMENT CONCRETE
Cu ALLOYS
CFRP
Ti ALLOYS
KFRP
Al ALLOYS
Zn ALLOYS
Mg ALLOYS
GLASSES
GFRP
Pb ALLOYS
ENGINEERING COMPOSITES
ENGINEERING ALLOYS
ASH OAK
PARALLEL TO GRAIN
PINES
PF
BALSA
WOOD PRODUCTS
PS
PVC
PC
EPOXIES
POLYESTERS
PMMA
NYLONS
POLYMIDES
ENGINEERING POLYMERS
PP
ASH OAK
HDPE
PERPENDICULAR TO GRAIN
PINES
PTFE
LDPE
BALSA
PVC (PLASTICISED)
HARD BUTYL
SOFT BUTYL
SILICONES
POLYMER FOAMS
ELASTOMERS
GUIDE LINES FOR MINIMUM COST DESIGN
$\frac{E}{C_R \rho} = C$
$\frac{E^{1/2}}{C_R \rho} = C$
$\frac{E^{1/3}}{C_R \rho} = C$
YOUNGS MODULUS E (GPa)
RELATIVE COST PER UNIT VOLUME $C_R \rho$ (Mg/m^3)
1000
100
10
1
0.1
0.01
0.1
1
10
100
1000
10000