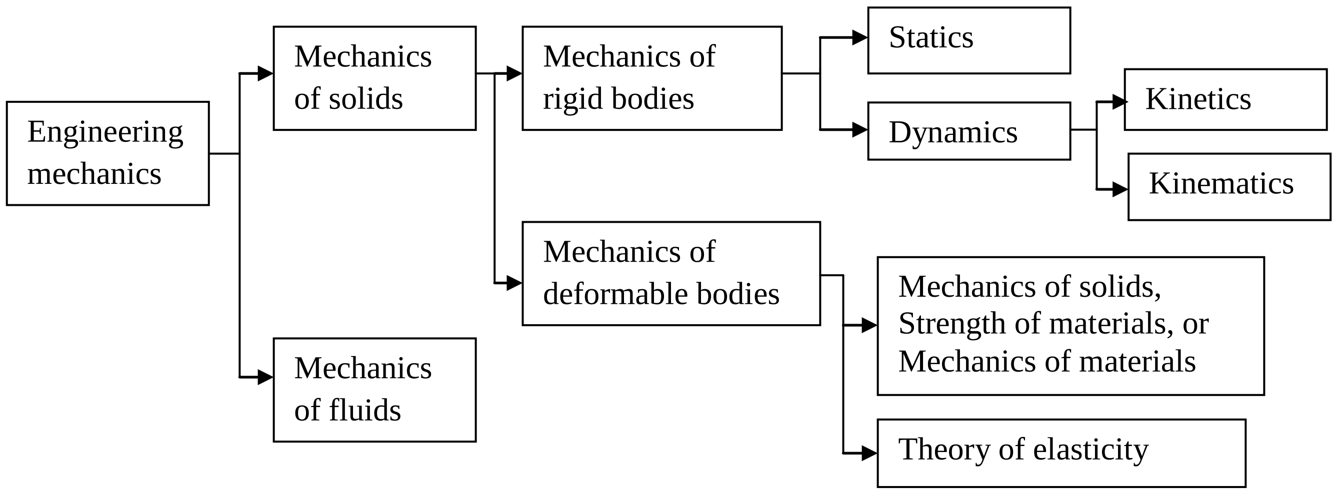
STRENGTH OF MATERIALS

UNIT 0.1 - INTRODUCTION

1. **Define Engineering.**
   Engineering is the profession in which the knowledge of mathematics and natural sciences, gained by study, practice and experience, is applied with judgment, in order to develop ways to utilize, economically, the materials and forces of nature, for the benefit of mankind.
2. **Sketch the family tree of engineering mechanics.**



3. **What is strength of materials?**
   Strength of materials or Mechanics of Materials is a branch of applied mechanics that deals with the behavior of solid bodies subjected to various types of loading.
   Strength of materials deals with the stresses, strains and deformations occurring in deformable bodies (both elastic and plastic) under the action of external forces.
4. **What is the objective of mechanics of materials?**
   The principal objective of mechanics of materials is to determine the stresses, strains and displacements in structures due to the loads acting on them.
5. **Why should we study mechanics of materials?**
   An understanding of mechanical behavior of materials is essential for the safe design of all types of structures, whether airplanes and antennas, buildings and bridges, machines and motors or ships and spacecraft.
   Statics and dynamics are also essential, but those subjects deal primarily with the forces and motions associated with particles and rigid bodies.

6. Explain the aspects of solid mechanics.

At the foundation of Solid Mechanics is the study of the **rigid body**, an ideal material in which the distance between any two particles remains fixed, a good approximation in some applications. Rigid body mechanics is usually subdivided into

- **statics**, the mechanics of materials at rest, for example of a road taking the weight of a car
- **dynamics**, the study of bodies which are changing speed, for example of a pulley rotating at ever increasing speed

Following on from statics and dynamics usually comes the topic of **Mechanics of Materials** (or **Strength of Materials**). This is the study of some elementary but relevant deformable materials and structures, for example beams and pressure vessels. **Elasticity theory** is used, in which a material is assumed to undergo *small* deformations when loaded and, when unloaded, *returns to its original shape*. The theory well approximates the behaviour of most real solid materials at low loads, and the behaviour of the "engineering materials", for example steel and concrete, right up to fairly high loads.

More advanced theories of deformable solid materials include

- **plasticity theory**, which is used to model the behaviour of materials which undergo *permanent* deformations, for example metals and soils.
- **viscoelasticity theory**, which models well materials which exhibit many "fluid-like" properties, for example plastics
- **viscoplasticity theory**, which is a combination of viscoelasticity and plasticity

Some other topics embraced by Solid Mechanics, some of which could be described as "advanced", are

i. **rods, beams, shells and membranes**, the study of material components which can be approximated by various model geometries, such as "very thin"
ii. **vibrations of solids and structures**
iii. **composite materials**, the study of components made up of more than one material, for example fibre-glass reinforced plastics
iv. **geomechanics**, the study of materials such as rock, soil and ice
v. **contact mechanics**, the study of materials in contact, for example a set of gears
vi. **fracture and damage mechanics**, the mechanics of crack-growth and damage in materials
vii. **stability of structures**
viii. **large deformation mechanics**, the study of materials such as rubber and muscle tissue, which stretch fairly easily
ix. **biomechanics**, the study of biological materials, such as bone and heart tissue
x. **variational formulations and computational mechanics**, the study of the numerical (approximate) solution of the mathematical equations which arise in the various branches of solid mechanics, including the Finite Element Method
xi. **dynamical systems and chaos**, the study of mechanical systems which are highly sensitive to their initial position

xii. **experimental mechanics**

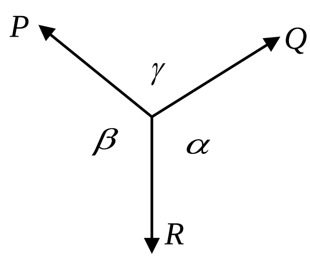
xiii. **thermo-mechanics**, the analysis of materials using a formulation based on the principles of thermodynamics

7. Expand ASTM, ASME, AISC, NASA, NACA, ASM and AASHTO.

AASHTO	American Association of State and Highway and Transportation Officials
AISC	American Institute of Steel Construction
ASM	American Society of Metals
ASME	American Society for Mechanical Engineers
ASNT	American Society for Non-destructive Testing
ASTM	American Society for Testing and Materials
ICAF	International Committee on Aeronautical Fatigue
NACA	National Advisory Committee for Aeronautics
NASA	National Aeronautics and Space Administration

8. State Lami's theorem or the Law of sines.

$$\frac{P}{\sin\alpha} = \frac{Q}{\sin\beta} = \frac{R}{\sin\gamma}$$



9. Explain how you obtain area moment of inertia.

Area × distance = first moment of area = $\int ydA$ or $\int xdA$

Area × distance× distance = moment of moment of area = second moment of area = area moment of inertia = $\int y^2 dA$ or $\int x^2 dA$

10. Explain synclastic and anticlastic curvature.

The curvature of a hyperboloid of one sheet, or of a hyperbolic paraboloid, every point of it, is said to be anticlastic to distinguish it from the curvature of an ellipsoid, or a hyperboloid of two sheets, which is said to be synclastic.

The shape of a saddle is a familiar example of anticlastic curvature. At the middle of a saddle, the surface of it curves upwards in front and behind, and downwards towards each side. Accordingly a surface with anticlastic curvature is sometimes referred to as saddle shaped. An anticlastic surface may also be illustrated by the top of a mountain pass, where the path goes down in front and behind and hills rise on either hand. On a map contour lines intersect there.

11. Units of important quantities

Moment = force × distance perpendicular to the direction of the force

Work done = force × distance moved along the direction of the force

10 millimeter = 10 mm = 1 cm	**1 cm = 10 mm** **1m = 100 cm** **1m = 1000 mm**
10 centi meter = 1 deci meter	
10 decimeter = 1 meter	Acceleration due to gravity = g = 9.80665 m/s^2 = 9.81 m/s^2,
10 meter = 1 deca meter	Density of water = 1000 kg/m^3
10 decameter = 1 hecto meter	Density of air = 1.2256 kg/m^3,
10 hecto meter = 1 kilo meter	Atmospheric pressure = 101325 Pa = 1.01325 ×10^5 N/m^2,

Length	mm, cm, m
Area	mm^2, cm^2, m^2
Volume	mm^3, cm^3, m^3
Velocity	m/s, kmph
Acceleration	m/s^2
Moment of inertia	mm^4, cm^4, m^4

Force or weight	**N = 1kg-m/s^2**
Moment	N-m
Work done	N-m = Joule
Energy = work done	Joules = N-m
Pressure or stress	MPa, N/mm^2
Power	Watt = Joule/s
Mass	kg

12. Selected prefixes used in the metric system.

Prefix	Abbreviation	Meaning
Giga	*G*	10^9
Mega	*M*	10^6
Kilo	*k*	10^3
Deci	*d*	10^{-1}
Centi	*c*	10^{-2}
Milli	*m*	10^{-3}
Micro	*μ*	10^{-6}
Nano	*n*	10^{-9}
Pico	*p*	10^{-12}
Femto	*f*	10^{-15}

Things to understand

Force × distance along the direction of force is called **work done**.
Force × distance perpendicular to the direction of force is called **moment**.
Momentum = mass × velocity ($p = mv$)
In translational motion, Power = force × velocity = N-m/s = J/s = Watt
In rotary (rotational) motion, Power = Torque × angular velocity = $T\omega$
$P = T\omega = T 2\pi f = T\frac{2\pi N}{60} = \frac{2\pi NT}{60} Watts$ $P = \frac{2\pi NT}{60 \times 1000} kiloWatts$

Convert m^2 into mm^2.

$$1m^2 = 1m^2 \frac{m}{m} = 1m^2 \frac{1000mm}{1m} = 1m^2 \frac{(1000mm)^2}{(1m)^2} = \left(10^3 mm\right)^2 = 10^6 mm^2$$

Explain the major classes of engineering materials.

Materials Class		Predominant Type of Bonding		Microstructure		Advantages
Metals & Alloys	→	Metallic	→	• Crystalline • Amorphous	→	• Strong • Ductile • Conductive
Polymers	→	Mixed Covalent & Secondary	→	• Chain molecules • Networks • Amorphous	→	• Low cost • Light weight • Resist corrosion
Ceramics & Glasses	→	Ionic, Covalent or Mixed "Ionic-covalent"	→	• Crystalline • Amorphous	→	• Strong, stiff, hard • Resist creep • Resist corrosion
Intermetallics	→	Mixed Metallic with some ionic and covalent character	→	• Crystalline • Amorphous	→	• Strong, stiff, hard • Resist creep • Resist corrosion • Light weight
Composites	→	Various	→	• Matrix + fibers • Matrix + particles • etc.	→	• Strong, stiff • Light weight

Fig. 1.1 General characteristics of major classes of engineering materials

Convert GPa into N/mm².

$$1GPa = 10^9 \frac{N}{m^2} = 10^9 \frac{N}{m^2}\frac{1m}{1000mm} = 10^9 \frac{N}{m^2}\frac{(1m)^2}{(1000mm)^2} = 10^9 \frac{N}{(10^3 mm)^2} = 10^9 \frac{N}{10^6 mm^2} = 10^3 \frac{N}{mm^2} = \frac{kN}{mm^2}$$

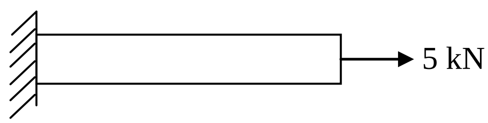
From the above equation, we can also arrive at $1MPa = 1\frac{N}{mm^2}$

Stresses in structures are always expressed in terms of *MPa*.

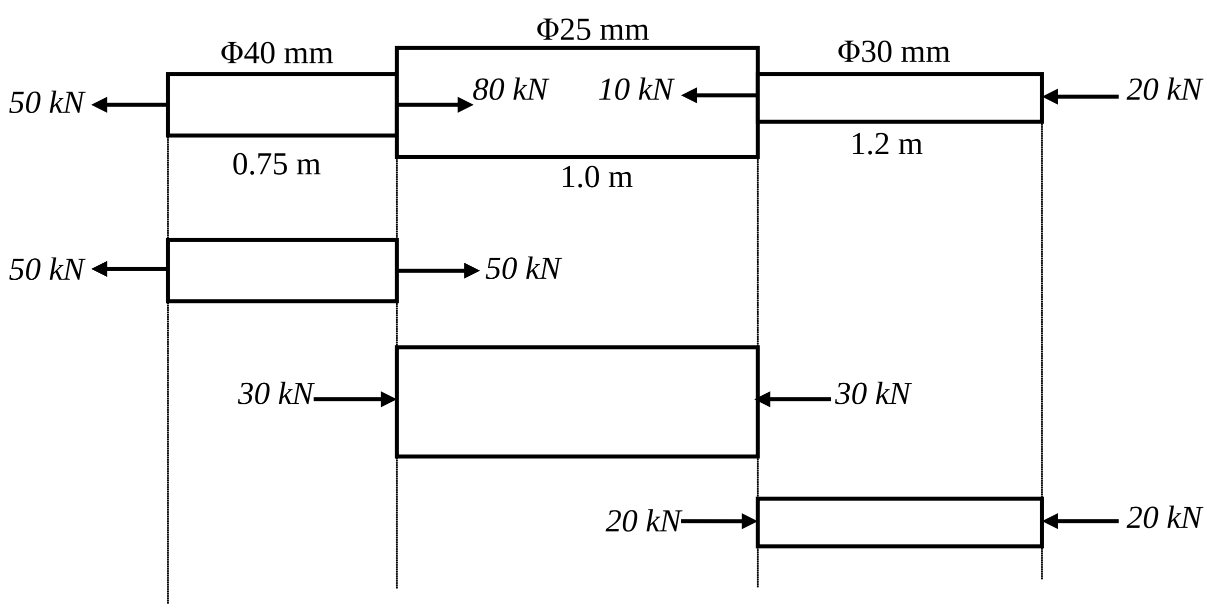
Modulus values (Young's modulus, Rigidity modulus and Bulk modulus) are always expressed in terms of *GPa*.

13. A rod is subjected to two equal and opposite tensile forces of 5 kN applied at each end. What is the total force acting on the rod?

Answer 1: 10 kN – wrong answer. Because both the forces are acting in the opposite directions.
Answer 2: zero kN – wrong answer. Because if zero force were acting on the rod, the rod will not undergo deformation, i.e., the rod will not elongate. Actually, if you apply the above said forces, the rod will elongate.
Answer 3: 5 kN – correct answer. For every action force, there is an equal and opposite force. The same problem can be represented as



14. Draw the free body diagram for the bar structure shown.



UNIT 0.2 - DESTRUCTIVE TESTING AND MATERIAL PROPERTIES

15. Classify materials.

Metals: iron, aluminum, copper, zinc, lead, etc.

Non-metals: leather, rubber, asbestos, plastics, carbon, concrete, wood, glass

16. What are destructive and non-destructive tests?

a. Destructive testing – test specimen either breaks or yields so that it cannot be used further.
b. Non-destructive testing – test specimen do not break or yield and hence it can be further used.

17. What are the types of mechanical testing in destructive testing methods?

a. Tensile test
b. Torsion test
c. Impact test (Charpy test, Izod test)
d. Hardness test (Brinell hardness, Rockwell hardness and Vickers hardness)
e. Fatigue test
f. Creep test

18. What is a static test and what is a dynamic test?

Destructive tests in which the load is applied at the rate of 10 N/minute are called static tests.

Destructive tests in which the load is applied at the rate of 100 N/second are called dynamic tests.

19. Explain static testing.

In most mechanical testing of materials to find properties that relate to the stress-strain diagram, the load is applied gradually, to give sufficient time for the strain to fully develop. Furthermore, the specimen is tested to destruction, and so the stresses are applied only once. Testing of this kind is called static testing. Such testing closely approximates the actual conditions to which many structural and machine members are subjected.

20. What is a ramp load?

A gradually changing (increasing or decreasing) load is called a ramp load.

Ramp – the slanting path in hospitals for moving patients in wheel chairs, retractable slanting plate-like structures in the nose and/or tail portions of large military airplanes to load and unload tanks, jeeps, etc.

21. Differentiate between ductile materials and brittle materials.

Materials which show large deformation before failure are termed ductile materials.

Materials which show very little deformation or no deformation before failure are termed brittle materials. (Materials which fail at relatively low values of strain or without strain are termed brittle materials.)

22. Give examples of metals.

Iron, Aluminum, copper, bronze, brass, etc.

23. Give examples of non-metals.

Leather, rubber, asbestos, plastics, wood, concrete, etc.

24. How do you classify metals?

a. Ferrous metals – cast iron, wrought iron, steel
b. Nonferrous metals – copper, Aluminum, Zinc, lead

25. Give examples of brittle materials and ductile materials.

Brittle materials – cast iron, glass

Ductile materials – structural steel, copper

26. List the mechanical properties of metals.

i. Strength
ii. Elasticity
iii. Plasticity
iv. Ductility
v. Malleability
vi. Toughness
vii. Brittleness
viii. hardness

27. What mechanical properties can be obtained from a tension test in a UTM?

i. Young's modulus
ii. Proportional limit stress
iii. Yield stress
iv. Ultimate stress
v. Fracture stress
vi. Percentage elongation

28. Sketch the tensile test specimen.

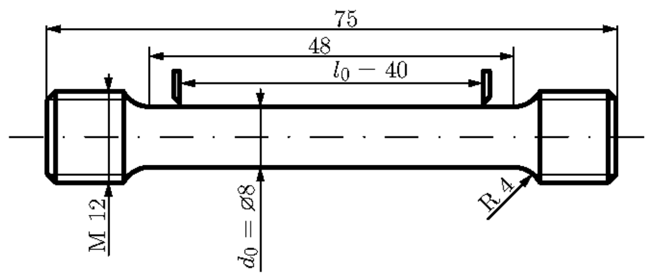
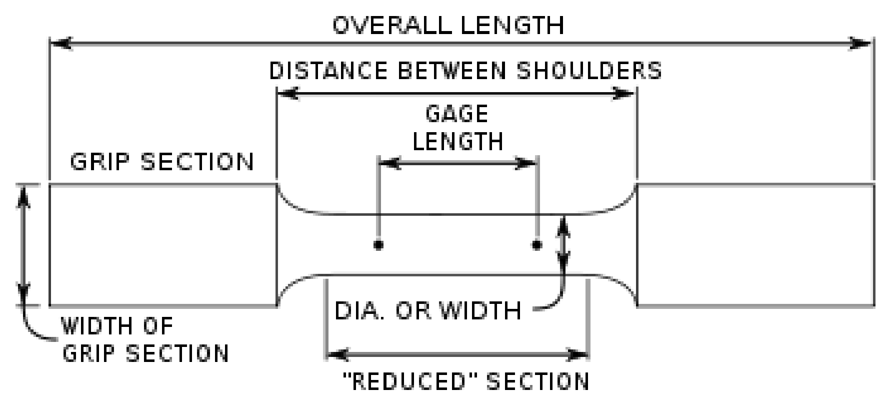


Fig. 3.4. Tensile test specimen (type B) with circular cross section with nominal diameter $d_0 = 8\,\text{mm}$ and original gauge length $L_0 = 40\,\text{mm}$ (designation: Tensile test piece DIN 50 125-B 8×40)



29. Define gage length.

Gage length is the distance between two displacement sensing points in the test specimen.

30. What are the other names of structural steel?

Mild steel or low carbon steel.

31. Define yielding.

Continuous deformation of the test specimen without any increase in stress is called yielding.

32. Define creep.

Some materials develop additional strains over long periods of time under constant loading (constant stress) and are said to creep. Other name is stress relaxation.

33. Define fatigue.

The process of progressive, localized, permanent structural change occurring in a material subjected to conditions which produce fluctuating stresses and strains at some point or points and which may culminate in cracks or complete fracture after a sufficient number of fluctuations is called fatigue.

34. What is strain hardening?

During strain hardening, the material undergoes changes in its atomic and crystalline structure resulting in increased resistance of the material to further deformation.

35. How do you find the Young's modulus from the stress-strain curve?

The slope of the stress-strain diagram in the linear elastic region is Young's modulus.

36. What is an extensometer?

The device used to find the elongation or shortening in test specimens (loaded in a universal testing machine) is called an extensometer. See double dial-gage extensometer.

37. Define failure.

Failure can mean the fracture or complete collapse of a structure, or it can mean that the deformations have exceeded some limiting value so that the structure is no longer able to perform its intended functions.

38. List the mechanical failure modes of metals.

a. Excess deformation – elastic, yielding or onset of plasticity
b. Ductile fracture
c. Brittle fracture
d. Impact or dynamic loading
e. Creep
f. Relaxation
g. Thermal shock
h. wear
i. Buckling – axial compressive buckling and lateral torsional buckling
j. Corrosion
k. Fatigue

39. Differentiate between stress values and strength values.

From a stress-strain diagram, we can observe that a material specimen can exist at different stress levels. But the important stress levels, like proportional stress, yield stress ultimate stress and fracture stress, are important stress values. These important stress values are called strength values, i.e., proportional strength, yield strength, ultimate strength and fracture strength.

40. Is it possible to change the Young's modulus by heat treatment process or otherwise?

The modulus of elasticity is determined by the binding forces between atoms. Because these forces cannot be changed without changing the basic nature of the material, the modulus of elasticity is one of the most structure-insensitive of the mechanical properties. Generally, Young's modulus is only slightly affected by alloying conditions, heat treatment or cold work. However, increasing the temperature decreases the modulus of elasticity.

41. What is Nd-YAG laser?

Nd:YAG = Neodymium-doped Yttrium Aluminum Garnet

42. Tabulate the important mechanical properties of few commonly used materials in aircraft industry.

Material	**Mass density, ρ kg/m^3**	**Modulus of elasticity, E GPa**	**Poisson's ratio, ν**	**Yield stress σ_y, MPa**	**Ultimate stress σ_{ult}, MPa**	**Percent elongation**	**Coefficient of thermal expansion $\alpha, 10^{-6}\ \frac{mm}{mm^oC}$**
Aluminum & aluminum alloys	2710	70	0.33	20	70	15	23
Brass	8500	100	0.34	70-550	200-620	20	20
Cast iron	7200	83-170	0.2-0.3	120-290	70-480	---	10.5
Copper	8900	115	0.33-0.36	300	360	30	17
Steel	7850	200	0.27-0.30	200-700	340-830	30	12
Titanium	4500	110	0.33	400	500	25	9
Wood	600	12	--	40	55	----	--

43. What is offset yield strength.

When a material such as aluminum does not have an obvious yield point and yet undergoes large strains after the proportional limit is exceeded, an arbitrary yield stress may be determined by the **offset method**. A line is drawn on the stress-strain diagram parallel to the initial linear part of the curve but is offset by some standard amount of strain, such as 0.002 (or 0.2%). The intersection of the offset line and the stress-strain curve defines the yield stress.

44. Distinguish between brittle failure and ductile failure with the help of stress-strain diagram.

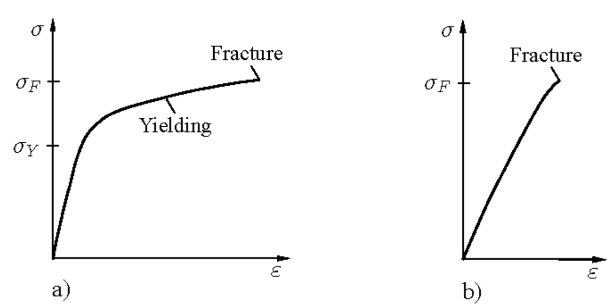
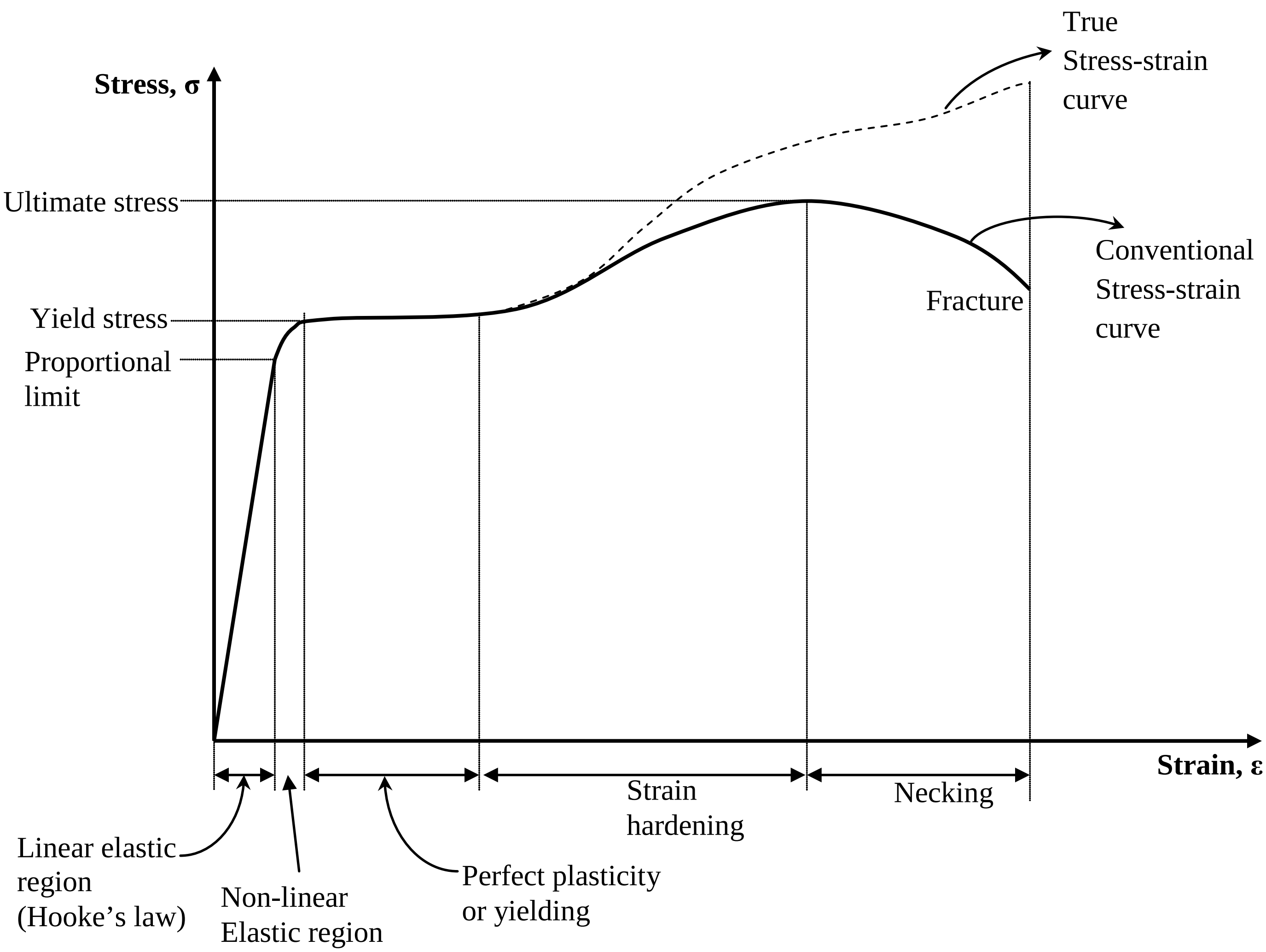


Fig. 2.1 Material behavior: a) ductile, b) brittle

45. Draw the stress-strain diagram for a typical structural steel in tension and mark the salient points and regions.



True stress-strain curve is obtained by considering the instantaneous cross-sectional area of the test specimen. That is, the cross-sectional area of the test specimen is measured at every instant during the test and that data is used for finding the stress at that instant.

Conventional stress-strain curve is obtained by the initial cross-sectional area of the test specimen.

46. Draw the stress-strain diagram of a typical brittle material and show the salient features.

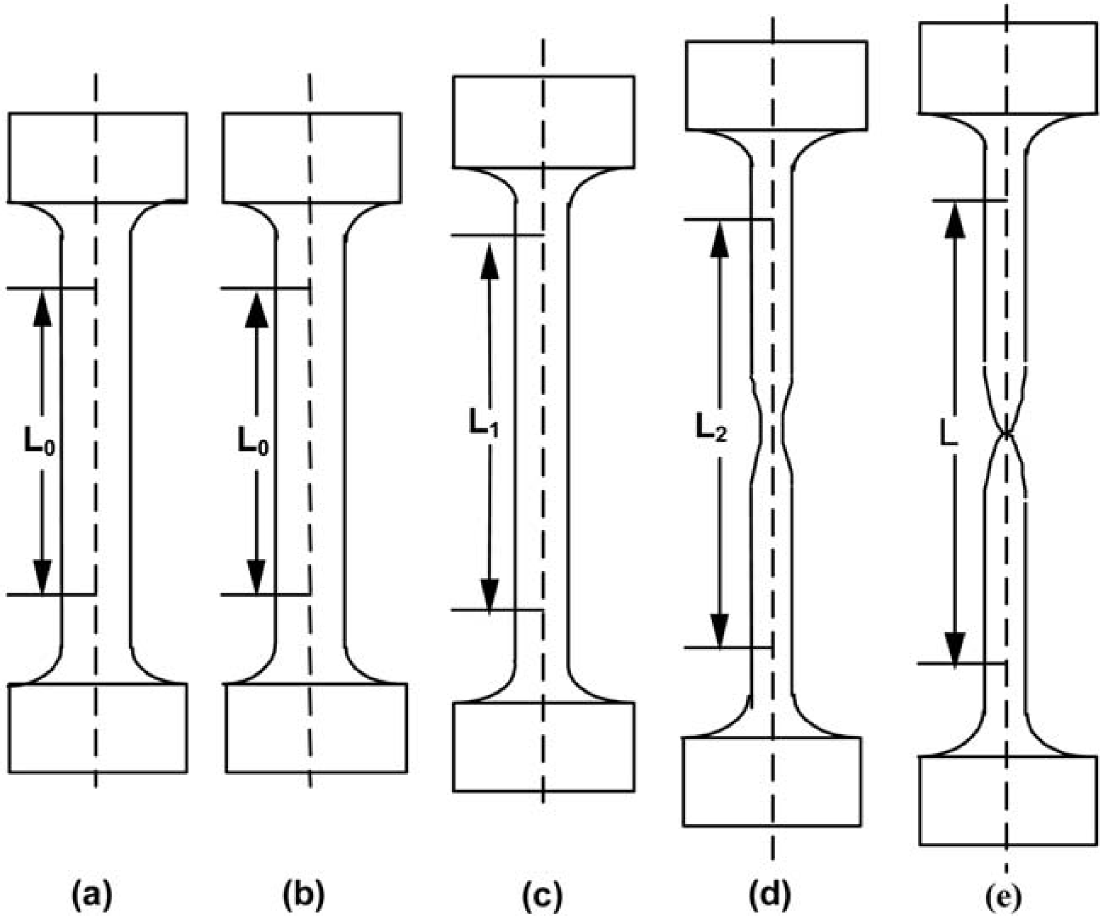


Figure 4.8 Schematics illustrating the change in shape of a tensile specimen after removing the applied load during the course of tension test. (a) Initial specimen shape. (b) Shape of specimen after removing the load within the elastic range. (c) Shape of specimen after removing the load within the uniform plastic range. (d) Shape of specimen after removing the load within the non-uniform plastic range. (e) Shape of specimen after fracture.

UNIT 0.3 CENTER OF GRAVITY AND MOMENT OF INERTIA

47. Define radius of gyration.

$I = Ar^2$ or $r = \sqrt{\dfrac{I}{A}}$

48. State parallel axis theorem.

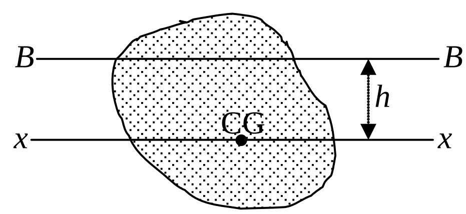
The moment of inertia of an area around any axis in its plane is equal to the moment of inertia of the same area around a parallel axis passing through the area's centroid, plus the product of the same area and the square of the distance between the two axes. $I = I_G + Ah^2$ $I_{xx} = I_{CG} + Ah^2$

49. State perpendicular axis theorem.

If I_{xx} is the area moment of inertia of a lamina about *x*-*x* axis in the plane of the lamina and I_{yy} is the area moment of inertia of a lamina about *y*-*y* axis (perpendicular to the *x*-*x* axis) in the plane of the lamina, then I_{zz}, the polar area moment of inertia of the lamina about an axis perpendicular to the plane of the lamina (and perpendicular to the *x*-*x* axis and *y*-*y* axis) is given by $I_{zz} = I_{xx} + I_{yy}$.

50. Write the general equations for finding area moments of inertia.

$I_{xx} = \int y^2 dA$ $I_{yy} = \int x^2 dA$



A is the cross-sectional area.

51. Write the general equations for finding polar moments of inertia.

$J = \int r^2 dA$ where r is the radius from the center of the circle

52. What is the structural meaning of area moment of inertia?

The measure of ability of a beam to resist bending.

53. What is the structural meaning of Polar moment of inertia?

The measure of ability of a shaft to resist torsion.

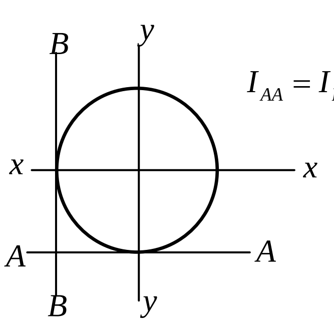
54. What is centroidal area moment of inertia?

The area moment of inertia about an axis passing through the centroid is called centroidal area moment of inertia.

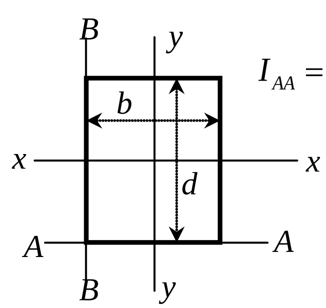
55. Write the centroidal area moment of inertia (*I*) and centroidal polar moment of inertia (*J*) of a circle and a rectangle.

for a solid circle $I_{xx} = I_{yy} = \dfrac{\pi d^4}{64}$ *J* for a solid circle = $\dfrac{\pi d^4}{32}$

for a rectangle $I_{xx} = \dfrac{bd^3}{12}$ $I_{yy} = \dfrac{db^3}{12}$ *J* for a rectangle = $\dfrac{bd^3}{12} + \dfrac{db^3}{12}$



$$I_{AA} = I_{BB} = I_{Gxx} + \left(\frac{\pi d^2}{4}\right)\left(\frac{d}{2}\right)^2$$



$$I_{AA} = I_{Gxx} + Ah^2 = \frac{bd^3}{12} + (bd)\left(\frac{d}{2}\right)^2$$

56. Define product of inertia.

$$I_{xy} = \int xydA$$

57. Write the expressions for product of inertia of a circle and a rectangle.

Product of inertia for symmetrical sections (having at least one plane of geometric symmetry) is zero.

Example: circle, rectangle, symmetrical T-section.

Product of inertia for anti-symmetrical sections and unsymmetrical sections is not zero.

Example: Z-section, general quadrilateral.

58. Differentiate between Area moment of inertia, Polar moment of inertia, Product moment of inertia and mass moment of inertia.

Area moment of inertia, Polar moment of inertia and Product moment of inertia are properties of cross-sectional area.

Mass moment of inertia is based on mass of the body (inertia) when the body is in motion.

59. Define principal centroidal area moments of inertia. (compare it with principal stresses)

The plane in which the product of inertia is zero is called principal plane.

The area moments of inertia (passing through the centroid of the area) in the principal plane are called principal centroidal area moments of inertia.

60. What are symmetrical sections?

Sections which have at least one plane of symmetry are called symmetrical sections.

When the symmetry plane is viewed from the side, it will look like an axis.

Some sections have multiple planes of symmetry.

A rectangle has two planes of geometric symmetry.

A circle has infinite planes of geometric symmetry.

Symmetry should exist in geometry, material properties and loadings.