MEMS1028
Mechanical Design 1

Lecture 1

Introduction and revision

Objectives

- Describe the course including the class policy, topics, learning outcomes, etc.
- Explain the elements of mechanical design, including scope, considerations, standards, uncertainties, factor of safety, ethics and responsibilities
- Revise stress & strength; strain & deformation, FBDs, loads resulting in axial, bending, shear, & torsion

Instructors’ & class information

- **Instructor:** S.C. Fok, PhD
- **Office:** Room 222 (Zone 4) Currently outside China
- **Office hours:** Monday 14:00 – 16:00
  Thursday 10:00 – 12:00
- **Email:** saicheong.fok@scupi.cn
- **TA:**
  - Yuan Ping
  - Email: 1291068322@qq.com

Lectures: in Zone 3-103 on Wednesday 8:15-11:00

Learning resources

- **Textbook:**

a) Shigley's Mechanical Engineering Design, Budynas and Nesbett, McGraw Hill, ISBN – 978-9-813-15100-0

Additional references and supplementary notes (if needed) will be posted on Blackboard

Course objective

This course provides an overview of strength of materials analysis techniques as related to the design of mechanical components. The basic topics of uniaxial tension/compression, torsion, bending and combined loading will be reviewed in the context of failure analysis. Failure theories and criterion for both static and fatigue conditions will be presented and applied to mechanical design

Skill Set
Design including analysis & communication; utilization of design standards and codes; ethics & responsibilities

Course overview

No.	Topics
1	Review of Statics and Strength of Materials
2	Mechanical Design Elements (Spring, Bars, Beam, Pressure Vessels)
3	Modes of Mechanical Failure (Failure Criteria)
4	Advanced Stress and Deformation Analysis (Combined Loading, Mohr's Circle, Buckling)
5	Stiffness Driven Design (Flexural Elements, Mechanical Hinges)
6	Stress Concentrations (Static, Fatigue)
7	Design Standards - (Application of ASME Pressure Vessel Code)
8	Static Failure Theories (Brittle Materials, Ductile Yielding, Ultimate Strength)
9	Fatigue Failure Theories (Service Life Estimates, Soderberg and Modified Goodman Methods)

Course learning outcomes

After the successful completion of this course students should be able to:

- Analyze the design of mechanical components;
- Apply failure theories and criteria for both static and fatigue conditions to mechanical design;
- Utilize established standards and codes in engineering design;
- Explain the design considerations, design uncertainties and the responsibilities of the designer

Assessments & Grading

Description	Percentage
Assignments & quizzes	20%
Project, design exercises & participation	20%
Midterm	30%
Final exam	30%

- Students must follow/satisfy the rules/requirements stated in the assessment items

Class policy

- Attendance at all scheduled class section is expected
- Students who are absent should inform the instructor in a timely manner. They are responsible to acquire class materials and assignment notes from their classmates
- All assignments must be neatly completed and submitted on time. Only in exceptional circumstances where supporting evidence is supplied and discussed with the instructor, in a timely manner, will

  (a) extensions be granted

  (b) late work be accepted without penalty (Penalty will be decided by the instructor based on the circumstances)
- Academic misconduct is not tolerated
- All disputes and appeal of grades must be filed through a written process

Class policy

Blackboard

- Important information concerning this unit of study is placed on Blackboard, accessible via https://learn.scupi.cn/
- It is your responsibility to access on a regular basis the Blackboard site for
  - Course materials,
  - Course announcements,
  - Online quizzes, assignments, projects, etc.
- You should also check your SCUPI email regularly

What is the course about?

- How to design machine elements so they won’t break under varying loads
- You will learn design philosophies and common commercial standards and “guidelines”
- Understand the engineer’s responsibilities in product design

What is Engineering Design?

Design is an iterative decision-making process to produce plans by which resources are converted (preferably optimally with due consideration for environment) into systems and devices to meet human needs. (This is a structured problem solving activity)

Mechanical Design Process is the use of scientific principles and technical information along with innovations, ingenuity or imagination **in the definition of a machine**, mechanical device or system to perform pre specified functions with **maximum economy and efficiency**.
(**Engineering Design Council, UK**)

Standards and codes

- Standard
  - A set of specifications for parts, materials, or processes
  - Intended to achieve uniformity, efficiency, and a specified
  - quality
  - Limits the multitude of variations
- Code
  - A set of specifications for the analysis, design, manufacture,
  - and construction of something
  - To achieve a specified degree of safety, efficiency, and performance or quality
  - Does not imply absolute safety
- Various organizations establish and publish standards and codes for common and/or critical industries

Engineer's responsibilities

Professional ethics defined by professional codes

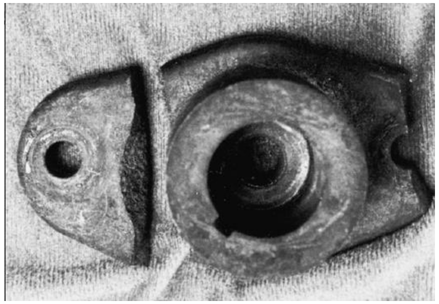
- Regulates actions and set standards for members
- Assures high standards of competence in the field
- Strengthens relationships among practitioners
- Promotes the welfare of the whole community
- Deals with members who violate the code

***Engineers shall*:**

1. Hold paramount the safety, health and wealth of the public in the performance of their professional duties
2. Perform services only in areas of their competence
3. Issue public statements only in an objective and truthful manner
4. Act in a professional manner for each employer or client as faithful agents or trustees
5. Avoid deceptive acts in the solicitation of professional employment.

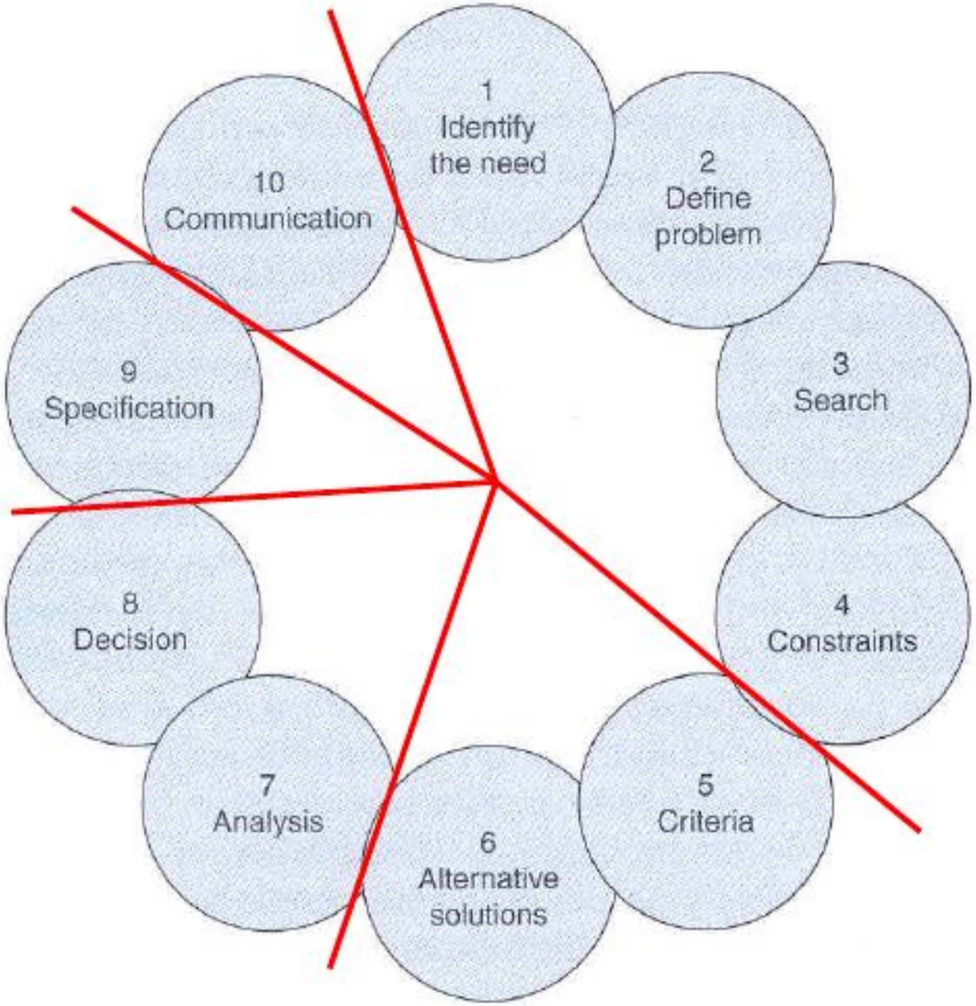
Design failures

- Break into pieces,
- Deform permanently,
- Too much elastic deformation (too flexible),
- Crack
- Wear and Surface damage



- Stresses are developed in the elements due to applied loads
- Mechanical design involves ensuring that the elements can sustain the induced stresses without failure

Design Process



Traditional Considerations

1. Materials
2. Geometry
3. Operating conditions
4. Cost
5. Availability
6. Producibility
7. Component life

Modern Considerations

1. Safety
2. Ecology
3. Quality of life

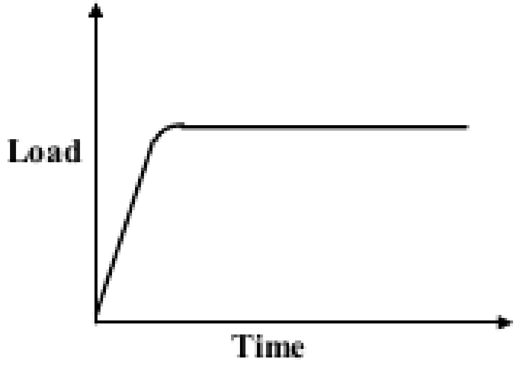
Miscellaneous Considerations

1. Reliability and maintainability
2. Ergonomics and aesthetics

Mechanical design procedure

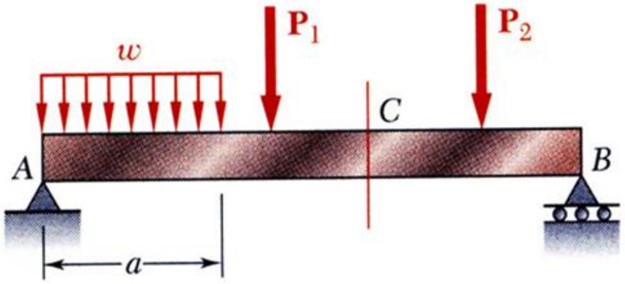
1) A design lay out is drawn. The shape of the part and its connection with other elements are presented in a simplified form while the forces acting on the part are assumed to be either concentrated or distributed in conformity with some simple law
2) Forces acting on the part during operation are analyzed
3) Material is selected; Allowable stresses are found accounting for all the factors that affect the strength of the part
4) The dimensions of the part are determined; Size of the part is found according to the design criteria (strength, rigidity, wear resistance etc.) corresponding to the accepted design scheme
5) The drawing of the part is made; Drawings should indicate all dimensions, accuracy of manufacture, surface finish and other information necessary for the manufacture of the part

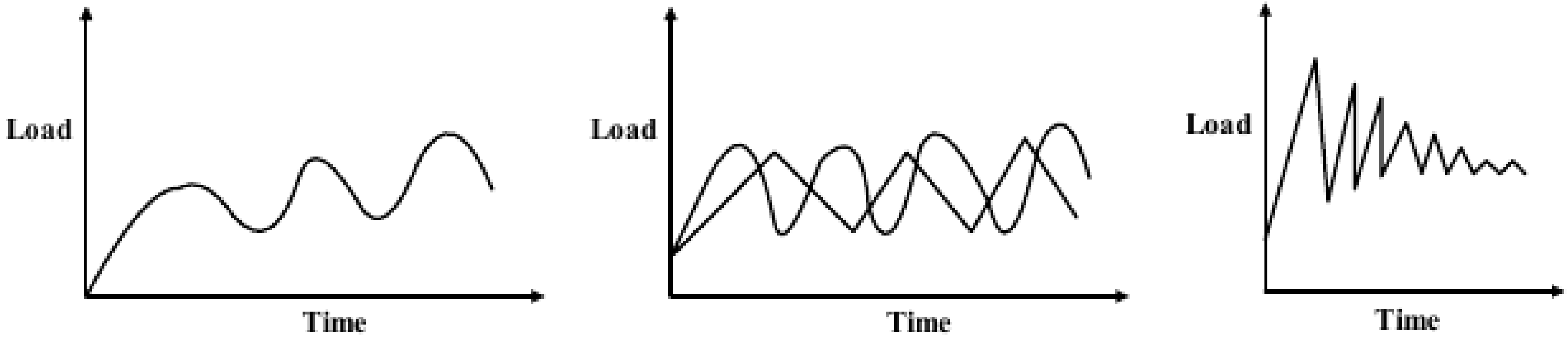
Type of loadings



Static load

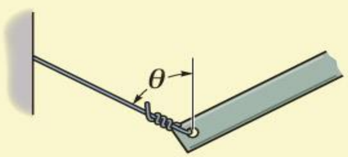
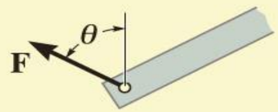
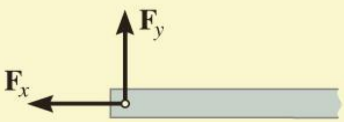
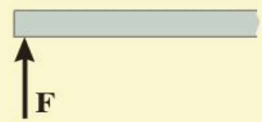
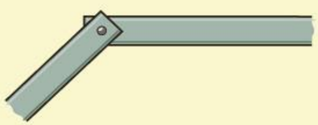
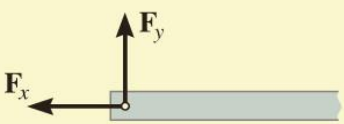
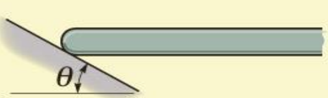
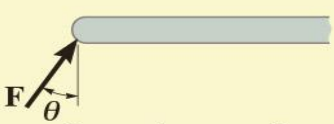
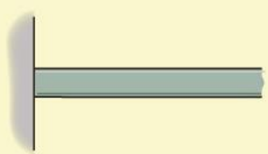
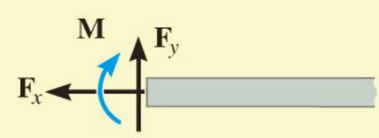
Point vs distributed loadings:





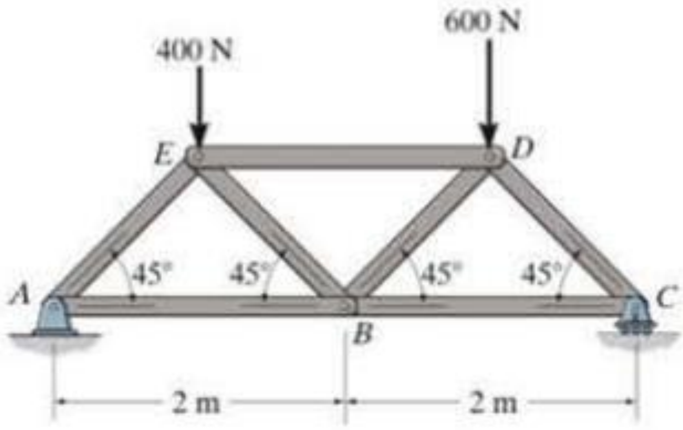
Dynamic Loading

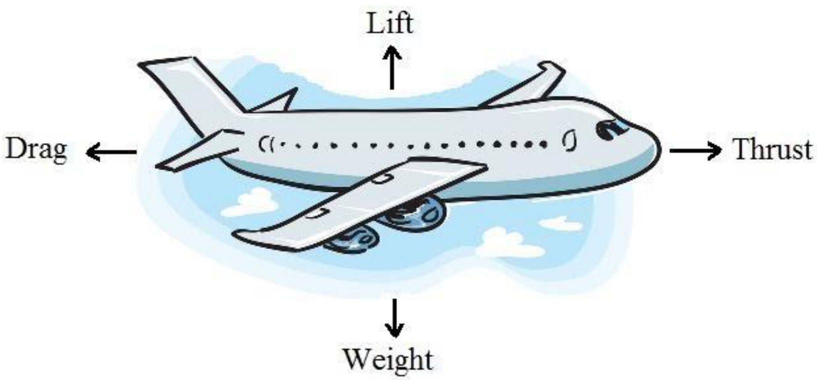
Supports & reactions

Type of connection	Reaction	Type of connection	Reaction
 Cable	 One unknown: F	 External pin	 Two unknowns: F_x, F_y
 Roller	 One unknown: F	 Internal pin	 Two unknowns: F_x, F_y
 Smooth support	 One unknown: F	 Fixed support	 Three unknowns: F_x, F_y, M

Statics

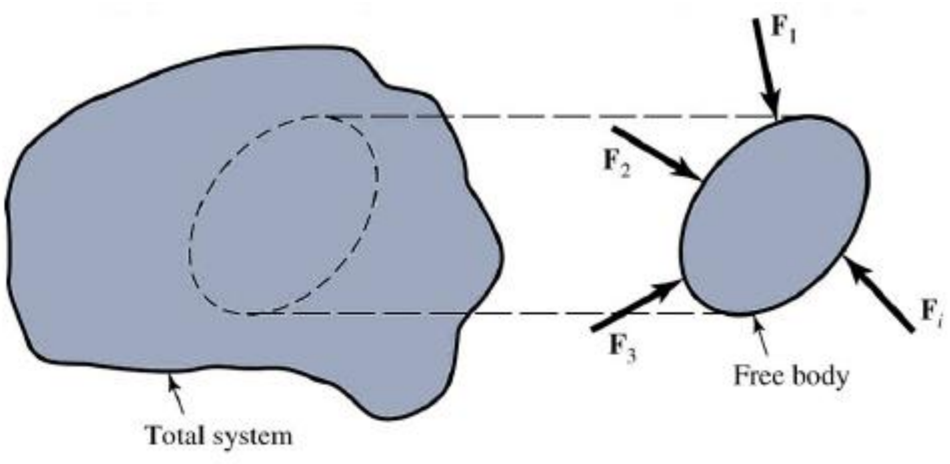
- Statics study bodies at rest or at constant velocity (thus in equilibrium)
- Equilibrium
  - Net force on the object is zero
  - Net moment on the object is zero



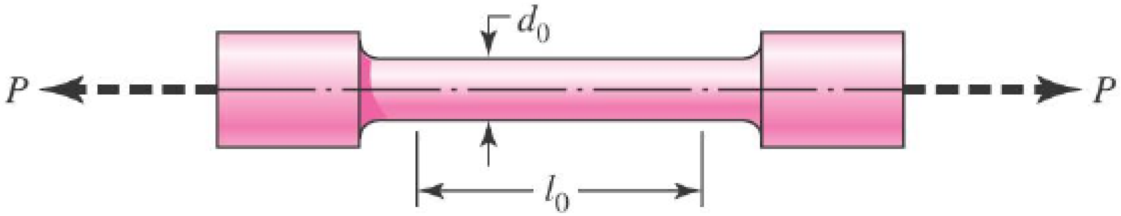


Equilibrium & FBDs

- System is any isolated part of a structure. If the system is motionless or has constant velocity it is in equilibrium
- For such a system all forces and moments acting on the system balance: $\sum F = 0$ and $\sum M = 0$
- The isolated system together with all forces and moments due to external effects and the reactions is called free-body diagram.



Normal stress & strain



Stress $\sigma = \frac{P}{A_0}$ Normal strain $\epsilon = \frac{l - l_0}{l_0}$

A_0= original cross-sectional area

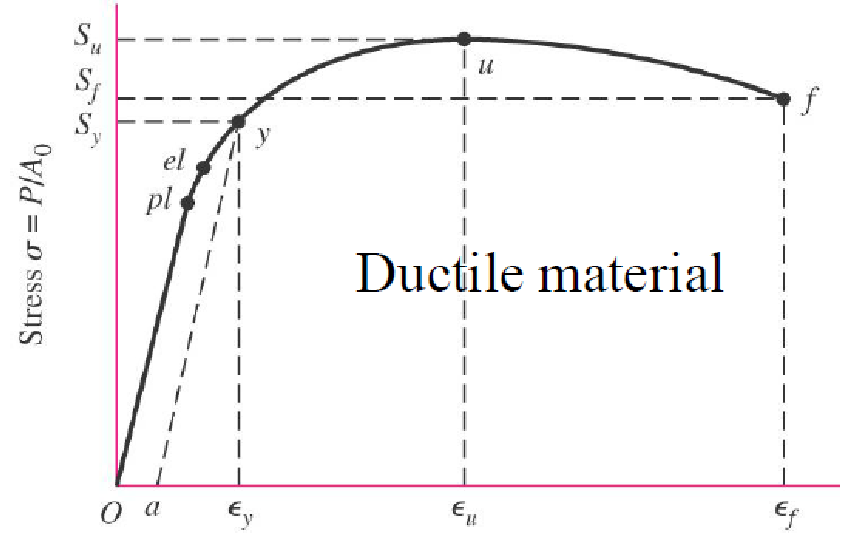
l_0 = original gauge length

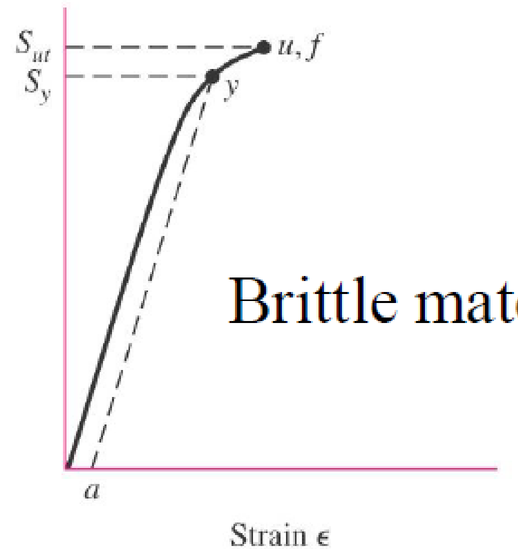
l = current length

- Stress is a state property of a body which is a function of load, geometry, temperature and manufacturing processing
- Strain is defined as deformation of a solid due to stress in terms of displacement of material

Normal stress-strain curve

- Typical linear relationship until proportional limit *pl* (Hooke's law: $\sigma = E\varepsilon$)
- No permanent deformation until elastic limit *el*
- Yield strength S_y usually defined at *y* by offset strain of 0.2%
- Plastic deformation occurs after yield point *y*
- Ultimate strength S_u defined at maximum stress
- Fracture strength S_f defined at fracture point *f*





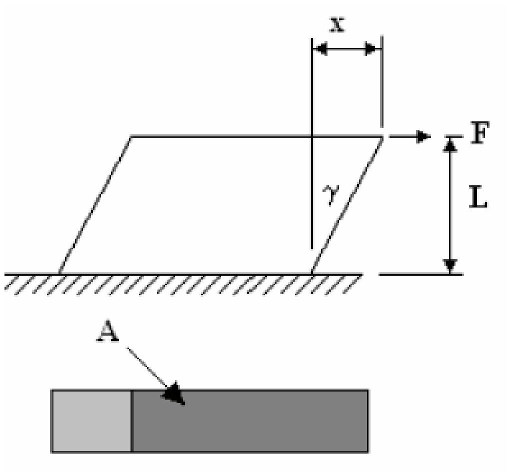
Material strength

- Strength is an inherent property of a material
- A material can have many different types of strength:
- S_y – yield strength
- S_u – ultimate strength
- S_f – fracture strength
- For compression, buckling can be problematic
- For ductile materials, compressive strengths are usually about the same as tensile strengths, $S_{uc} = S_{ut}$
- For brittle materials, compressive strengths, S_{uc}, are often greater than tensile strengths, S_{ut}

Shear stress & shear strain

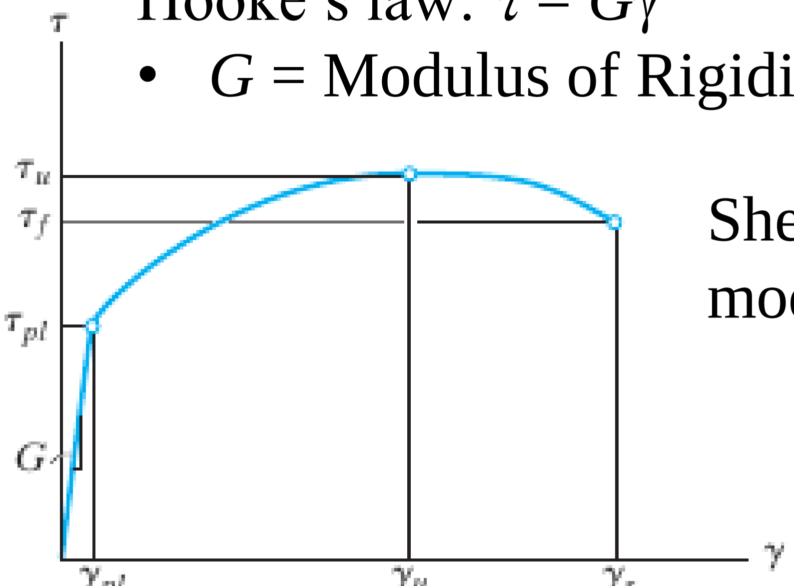
Shear stress $\tau = \frac{F}{A}$

Shear strain $\gamma = \frac{x}{L}$



Hooke's law: $\tau = G\gamma$

- G = Modulus of Rigidity or shear modulus of elasticity



Shear modulus (G) is related to Young's modulus (E) by Poisson's ratio (ν):

$$G = \frac{E}{2(1 + \nu)}$$

Some material properties

$$\sigma = E\varepsilon \qquad \tau = G\gamma \qquad \nu = -\frac{\text{lateral strain}}{\text{axial strain}} \qquad E = 2G(1+\nu)$$

Material	Modulus of Elasticity E		Modulus of Rigidity G		Poisson's Ratio ν	Unit Weight w		
	Mpsi	GPa	Mpsi	GPa		lbf/in³	lbf/ft³	kN/m³
Aluminum (all alloys)	10.4	71.7	3.9	26.9	0.333	0.098	169	26.6
Beryllium copper	18.0	124.0	7.0	48.3	0.285	0.297	513	80.6
Brass	15.4	106.0	5.82	40.1	0.324	0.309	534	83.8
Carbon steel	30.0	207.0	11.5	79.3	0.292	0.282	487	76.5
Cast iron (gray)	14.5	100.0	6.0	41.4	0.211	0.260	450	70.6
Copper	17.2	119.0	6.49	44.7	0.326	0.322	556	87.3
Douglas fir	1.6	11.0	0.6	4.1	0.33	0.016	28	4.3
Glass	6.7	46.2	2.7	18.6	0.245	0.094	162	25.4
Inconel	31.0	214.0	11.0	75.8	0.290	0.307	530	83.3
Lead	5.3	36.5	1.9	13.1	0.425	0.411	710	111.5
Magnesium	6.5	44.8	2.4	16.5	0.350	0.065	112	17.6
Molybdenum	48.0	331.0	17.0	117.0	0.307	0.368	636	100.0
Monel metal	26.0	179.0	9.5	65.5	0.320	0.319	551	86.6
Nickel silver	18.5	127.0	7.0	48.3	0.322	0.316	546	85.8
Nickel steel	30.0	207.0	11.5	79.3	0.291	0.280	484	76.0
Phosphor bronze	16.1	111.0	6.0	41.4	0.349	0.295	510	80.1
Stainless steel (18-8)	27.6	190.0	10.6	73.1	0.305	0.280	484	76.0
Titanium alloys	16.5	114.0	6.2	42.4	0.340	0.160	276	43.4

Some material properties

APPENDIX 9 TYPICAL PROPERTIES OF ALUMINUM

Alloy and temper	Tensile strength (ksi)	Tensile strength (MPa)	Yield strength (ksi)	Yield strength (MPa)	Ductility (percent elongation in 2 inches)	Shearing strength (ksi)	Shearing strength (MPa)	Endurance strength (ksi)	Endurance strength (MPa)
1060-O	10	69	4	28	43	7	48	3	21
1060-H14	14	97	11	76	12	9	62	5	34
1060-H18	19	131	18	124	6	11	121	6	41
1350-O	12	83	4	28	28	8	55		
1350-H14	16	110	14	97		10	69		
1350-H19	27	186	24	165		15	103	7	48
2014-O	27	186	14	97	18	18	124	13	90
2014-T4	62	427	42	290	20	38	262	20	138
2014-T6	70	483	60	414	13	42	290	18	124
2024-O	27	186	11	76	22	18	124	13	90
2024-T4	68	469	47	324	19	41	283	20	138
2024-T361	72	496	57	393	12	42	290	18	124
2219-O	25	172	11	76	18				
2219-T62	60	414	42	290	10			15	103
2219-T87	69	476	57	393	10			15	103
3003-O	16	110	6	41	40	11	121	7	48
3003-H14	22	152	21	145	16	14	97	9	62
3003-H18	29	200	27	186	10	16	110	10	69
5052-O	28	193	13	90	30	18	124	16	110
5052-H34	38	262	31	214	14	21	145	18	124
5052-H38	42	290	37	255	8	24	165	20	138
6061-O	18	124	8	55	30	12	83	9	62
6061-T4	35	241	21	145	25	24	165	14	97
6061-T6	45	310	40	276	17	30	207	14	97
6063-O	13	90	7	48		10	69	8	55
6063-T4	25	172	13	90	22				
6063-T6	35	241	31	214	12	22	152	10	69
7001-O	37	255	22	152	14				
7001-T6	98	676	91	627	9			22	152
7075-O	33	228	15	103	16	22	152		
7075-T6	83	572	73	503	11	48	331	23	159

Note: Common properties:

Density: 0.095 to 0.102 lb/in^3 (2635 to 2829 kg/m^3)

Modulus of elasticity: 10 to 10.6 $\times$ 10^6 psi (69 to 73 GPa)

Endurance strength at 5 $\times$ 10^8 cycles

Uncertainties in Design

A **design factor** is use to:

- Account for uncertainty (e.g. material properties, load variability, validity of mathematical models, etc.)
- Ensure safety

Design factor is a ratio of two quantities that have the same units; e.g.

- Critical load/Allowable applied load;
- Failure load/Expected allowable service load;
- Maximum failure cycles/Allowable applied cycles;
- Maximum safe speed/Allowable operating speed

Design Factor & Factor of Safety

Design factor based on stress is: $n_d = \left(\frac{strength}{stress} \right)$

The **Factor of Safety** has the same definition as the design factor, but is numerically different due to rounding (usually up) by using standard sizes

- The failure stress (strength) can be anything the designer chooses it to be. Often such strengths as yield, ultimate, shear, fatigue as well as others are used
- The value of the factor of safety depends on many factors including brittle vs ductile materials, seriousness of the consequences, types of loadings, accuracy of the parameters, etc.

Reliability

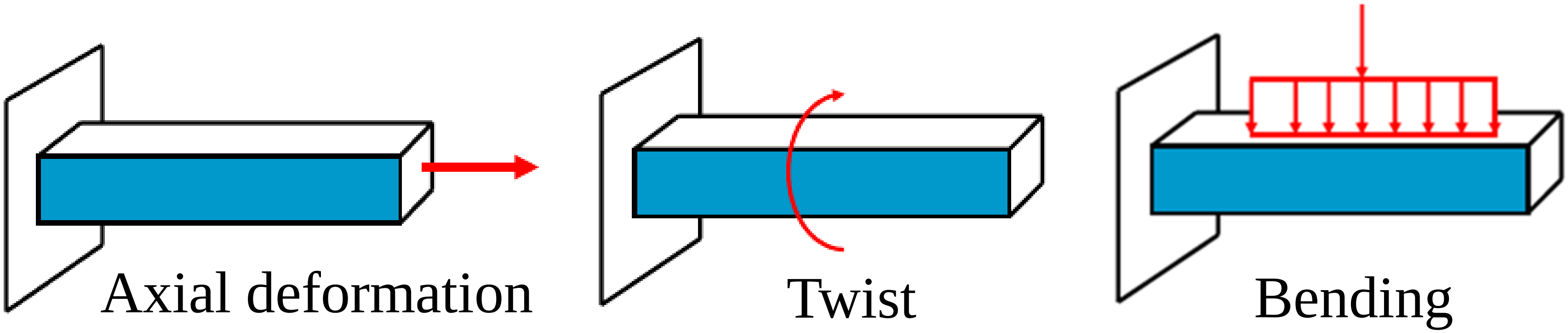
Factor of Safety is deterministic. For statistical data, there is a need to use Probabilistic approach.

Reliability is the probability that the component will not fail during use, i.e. it has range $0 \leq \boldsymbol{R} \leq 1$

- If $\boldsymbol{R} = 0.8$, it means there is a chance of 80% that the component will perform its function without failure

What is the reliability if 10 parts fail out of 100?

Loads and stresses - review

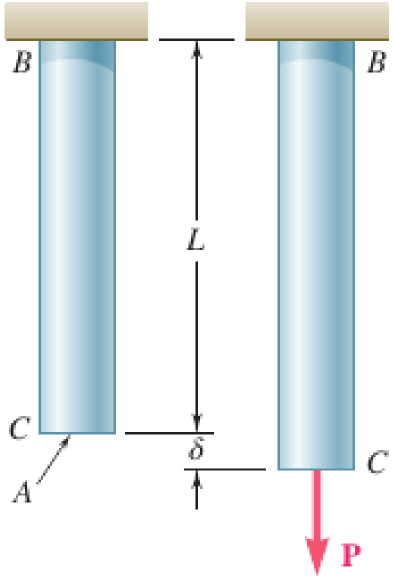


- Axial loading (tension +ve/compression -ve)

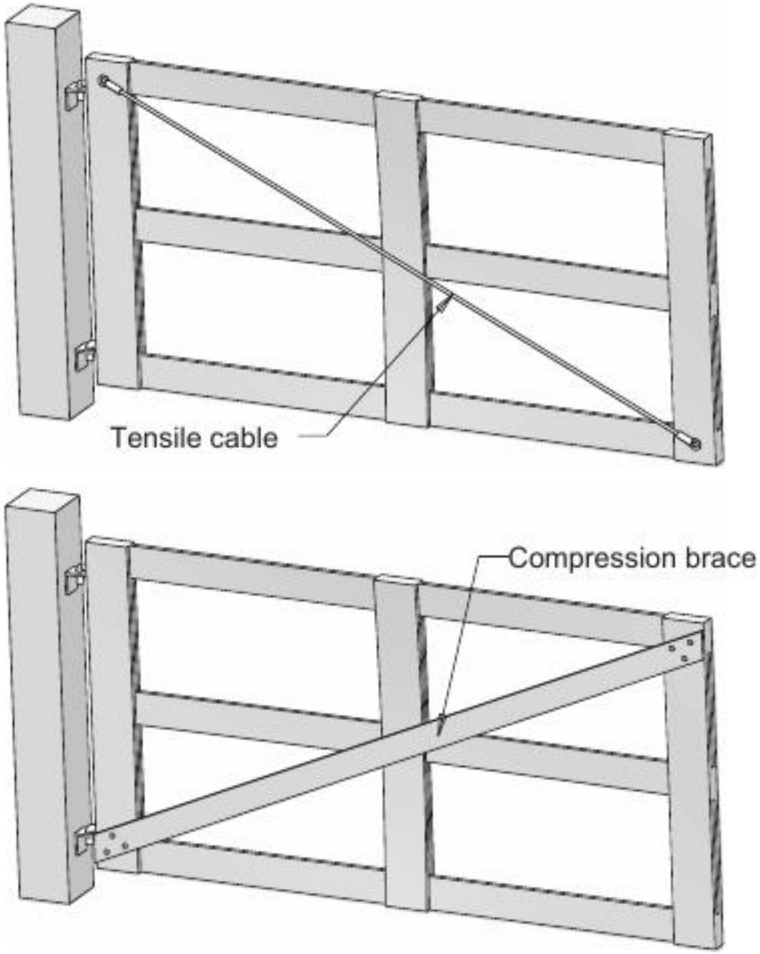
Stress $\sigma = \frac{F}{A}$

Strain $\varepsilon = \frac{\delta}{L}$

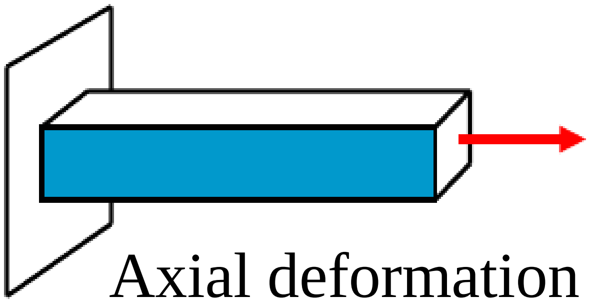
Deformation $\delta = \frac{PL}{AE}$

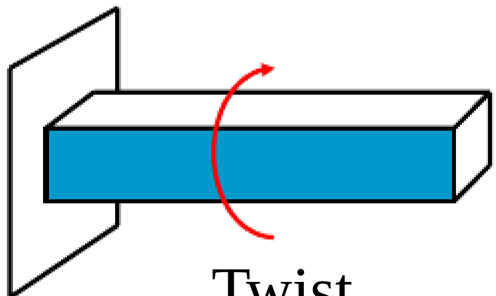


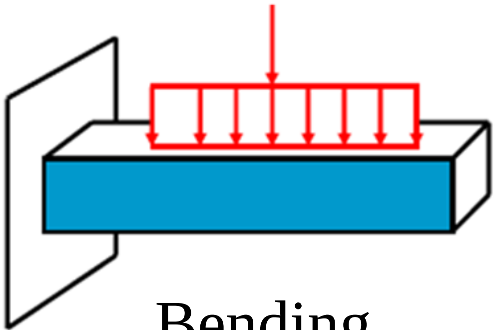
Loads and stresses - review

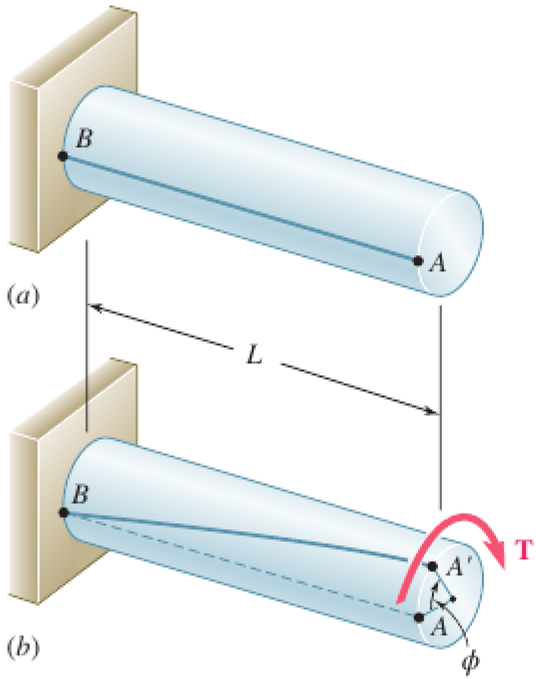


Loads and stresses - review









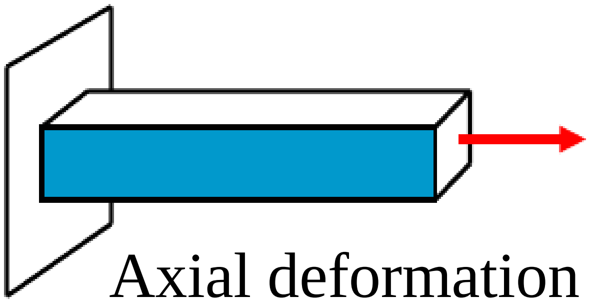
- Torque (torsion)

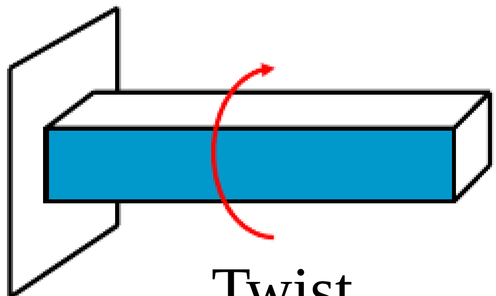
Shear stress $\tau = \frac{T\rho}{J}$

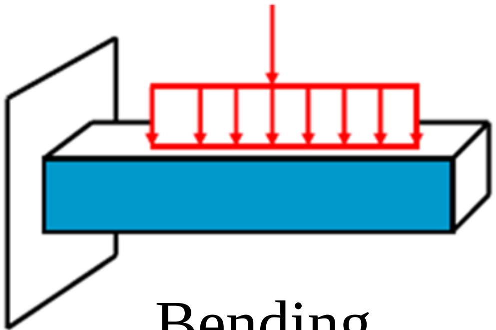
Shear strain $\gamma = \frac{\rho\phi}{J}$

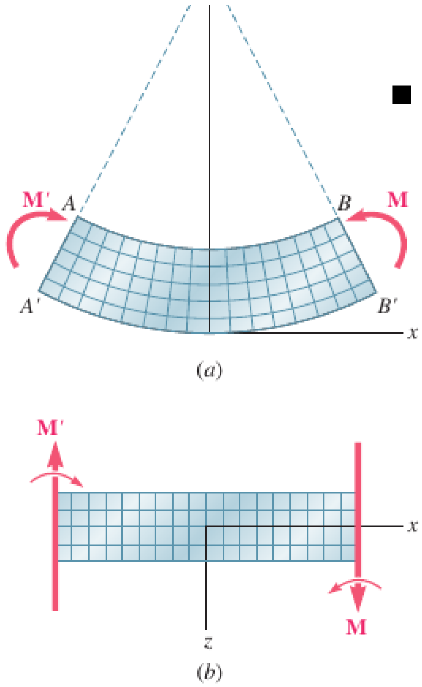
Angle of twist $\phi = \frac{TL}{JG}$

Loads and stresses - review





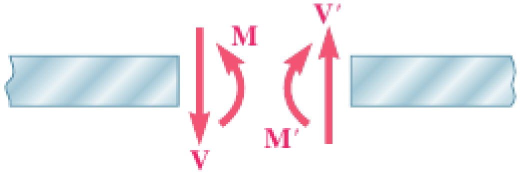




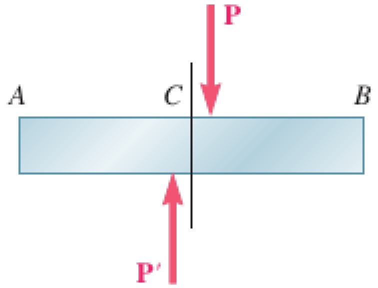
- Normal stress and shearing stress due to bending

$$\text{Normal stress } \sigma = -\frac{My}{I}$$

$$\text{Shear stress } \tau_{\text{ave}} = \frac{VQ}{It}$$

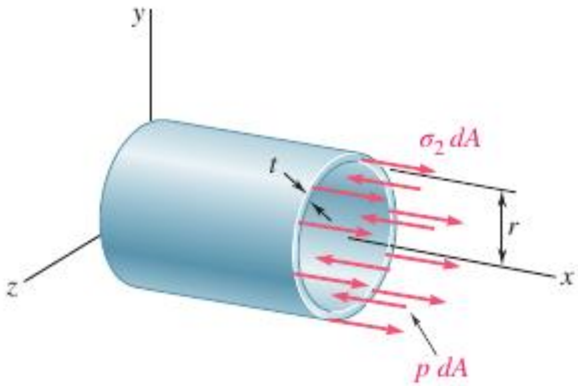


(a) Internal forces
(positive shear and positive bending moment)

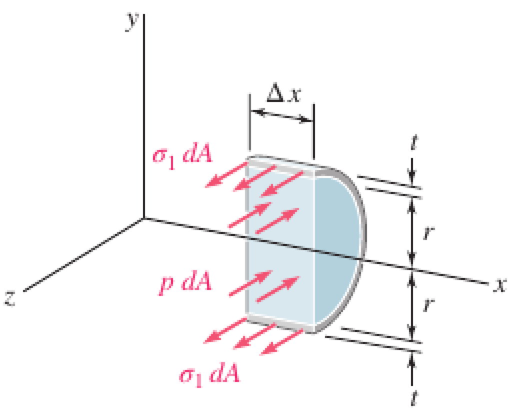


Loads and stresses - review

- Cylindrical pressure vessels



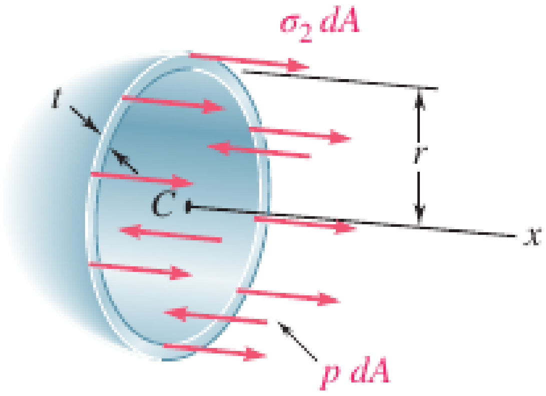
Longitudinal stress $\sigma = \frac{pr}{2t}$



Hoop stress $\sigma = \frac{pr}{t}$

❖ Note: p = internal gage pressure

Loads and stresses - review



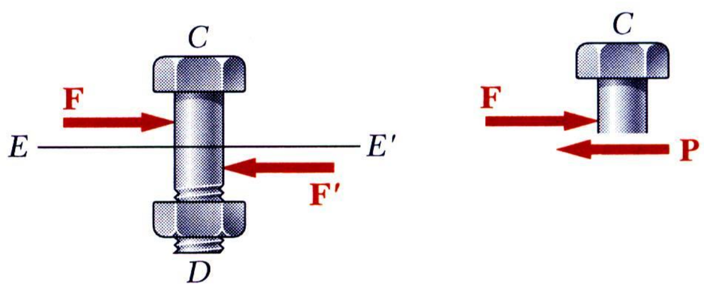
- Spherical pressure vessels

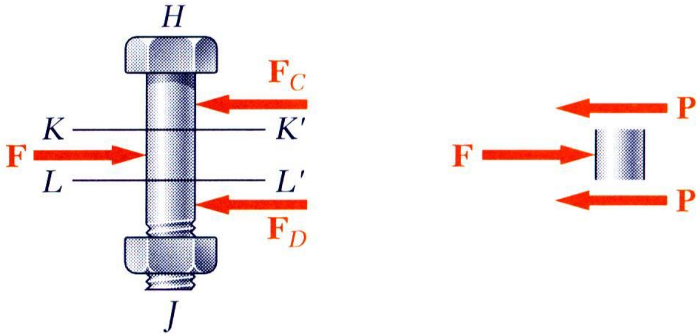
Stress $\sigma = \frac{pr}{2t}$

- Direct shearing

Direct Shear stress $\tau = \frac{F}{A}$

Shear stress $\tau = \frac{F}{2A}$



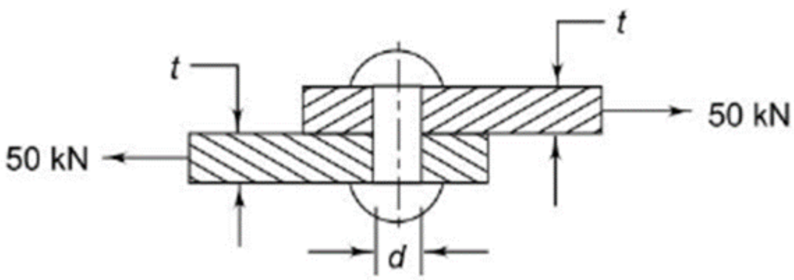


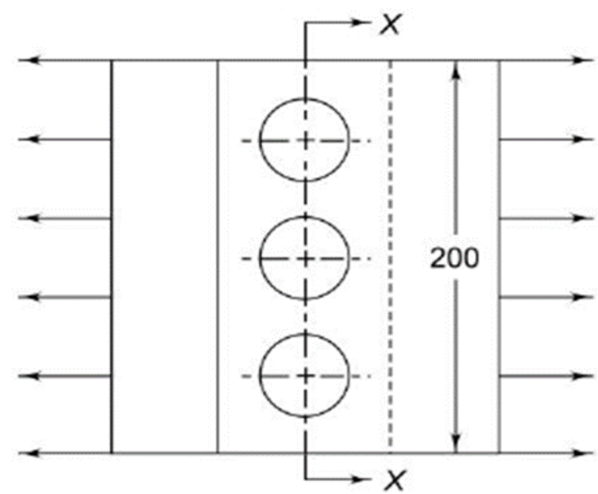
Example 1

Two plates, subjected to a tensile force of 50kN, are fixed together by means of three rivets as shown. The plates and rivets are made of plain carbon steel 10C4 with a tensile yield strength of 250N/mm^2. The yield strength in shear is 50% of the tensile yield strength, and the factor of safety is 2.5. Determine

(i) the diameter of the rivets; and

(ii) the thickness of the plates.



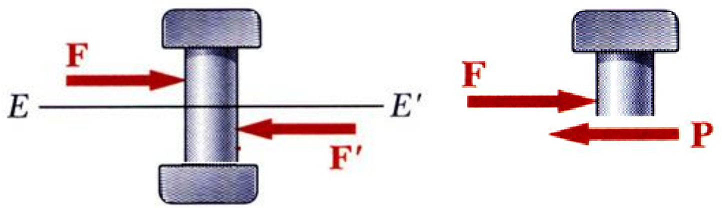


Example 1

Given P = 50kN, (fs) = 2.5, S_{yt} = 250 N/mm^2;

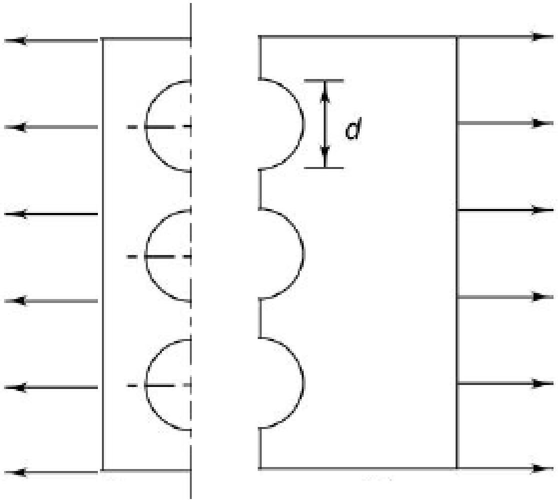
Permissible shear stress for rivets:

$$\tau = \frac{S_{sy}}{(fs)} = \frac{0.5 S_{yt}}{(fs)} = 50\text{N/mm}^2;$$



For three rivets: $3\left[\frac{\pi}{4} d^2\right] \tau = P$

$$d = 20.6\text{mm}$$



Permissible tensile stress for plates:

$$\sigma = \frac{S_{yt}}{(fs)} = 100\text{N/mm}^2;$$

Thickness of plates:

$$\sigma(200 - 3d)t = P$$

$$t = 3.73\text{mm}$$

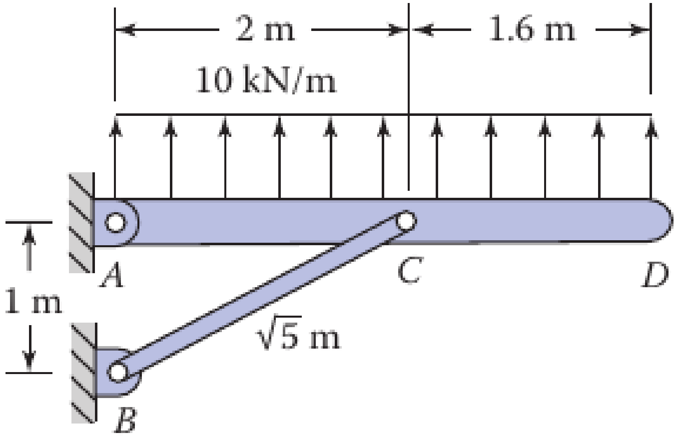
Example 2

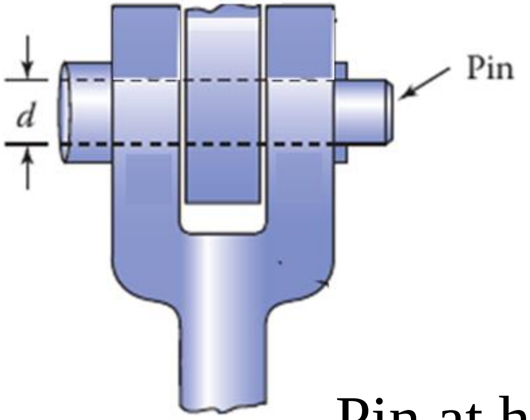
The wing of a monoplane is approximated by a pin-connected structure of beam AD and bar BC, as shown. Determine

(i) The shear stress in the pin at hinge C and Factor of Safety

(ii) The diameter of the rod BC

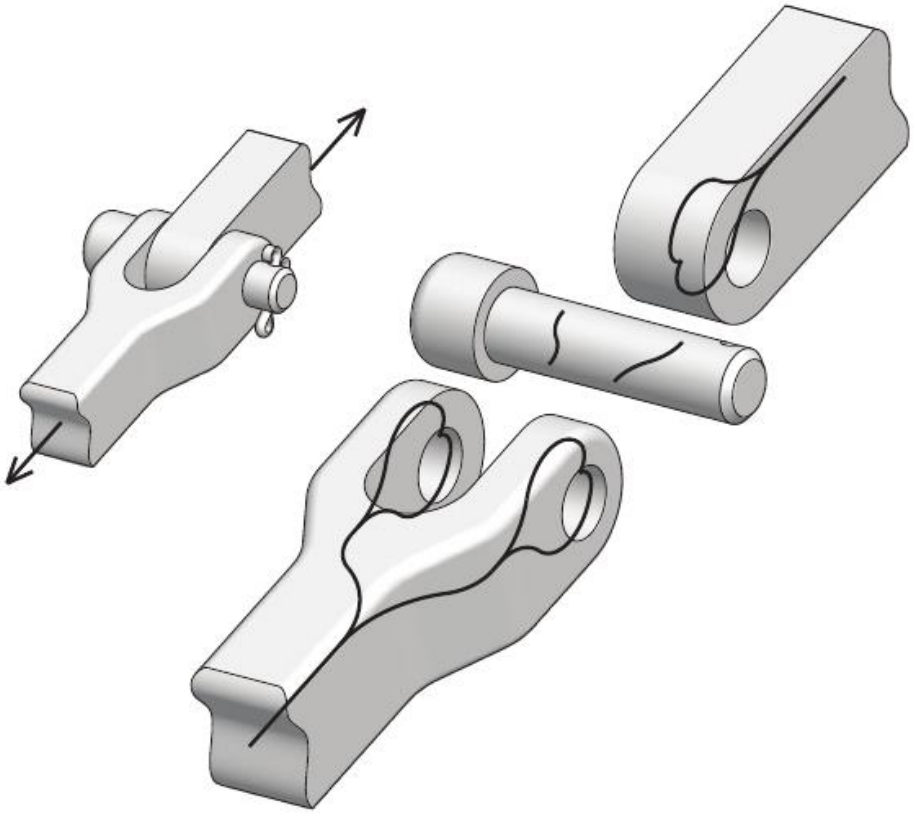
Allowable axial and shear stress is 210 MPa



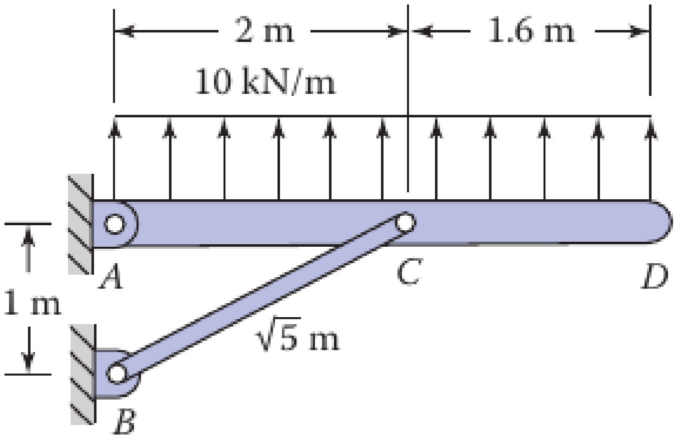


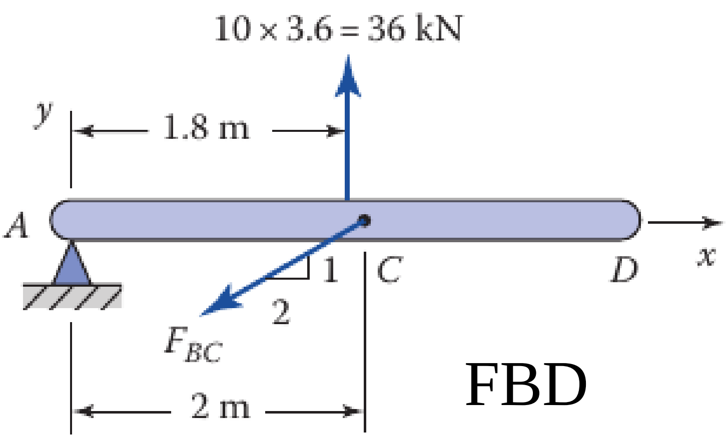
Pin at hinge C

Example 2



Example 2





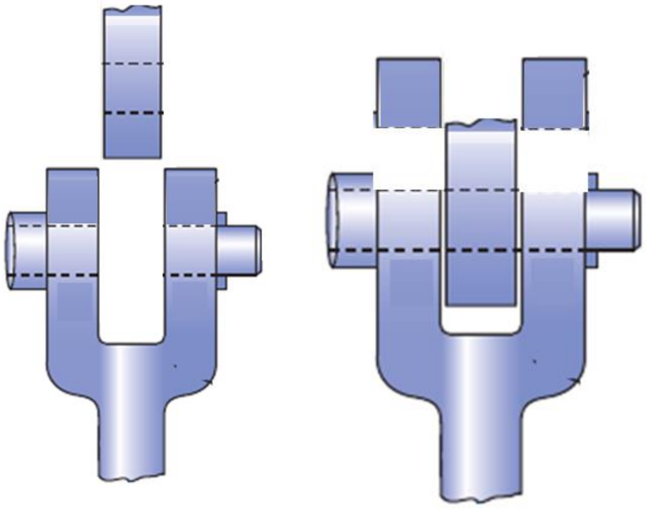
Sum moment about A: $\sum M_A = 0$

$F_{BC} = 72.45\text{kN}$

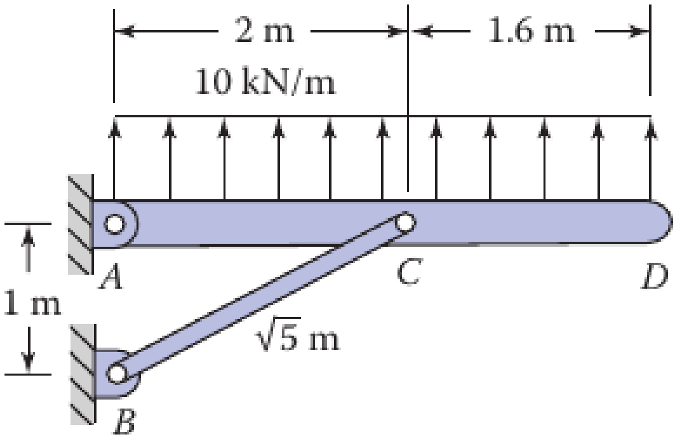
Note double shear of pin at C

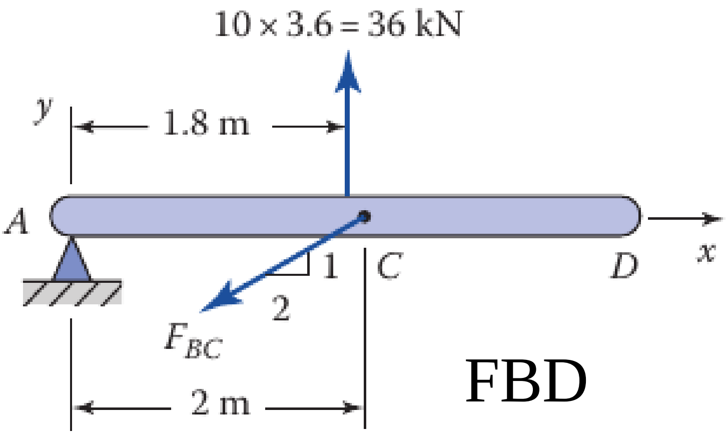
$\tau_{\text{Ave}} = \frac{F_{BC}}{2A}$ =205MPa

(FS)=210/205=1.02



Example 2





FBD

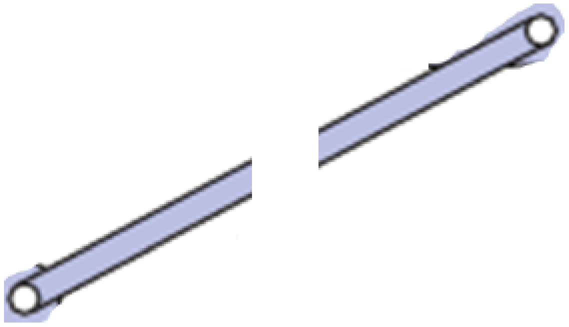
$F_{BC} = 72.45\text{kN}$

For the rod BC:

$\sigma_{BC} = \frac{F_{BC}}{A_{BC}} = 210\text{MPa}$

$A_{BC} = 345\text{mm}^2$

Diameter of rod BC = 20.96mm



Announcements

- Bring along your calculator in future classes for in-class exercises
- Read textbook chapter 3 for your next class