ME 1110 – Engineering Practice 1

Engineering Drawing and Design - Lecture 13

Principles of Mechanical Design

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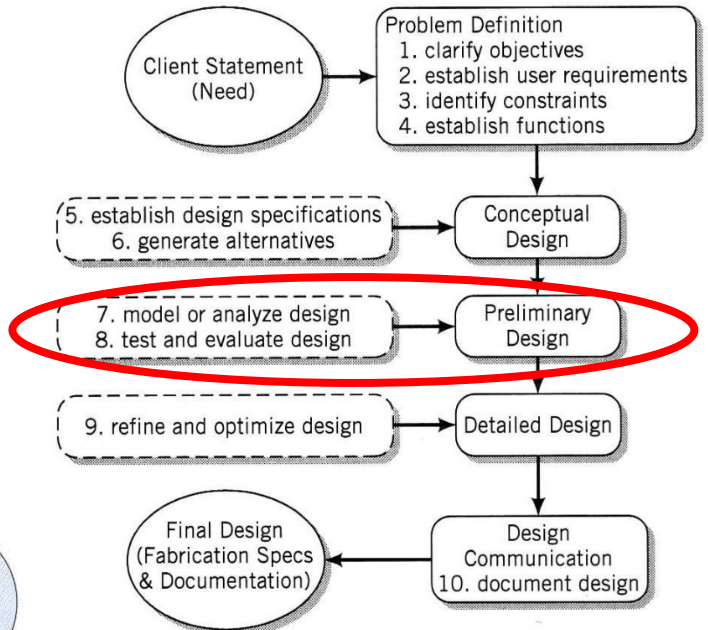
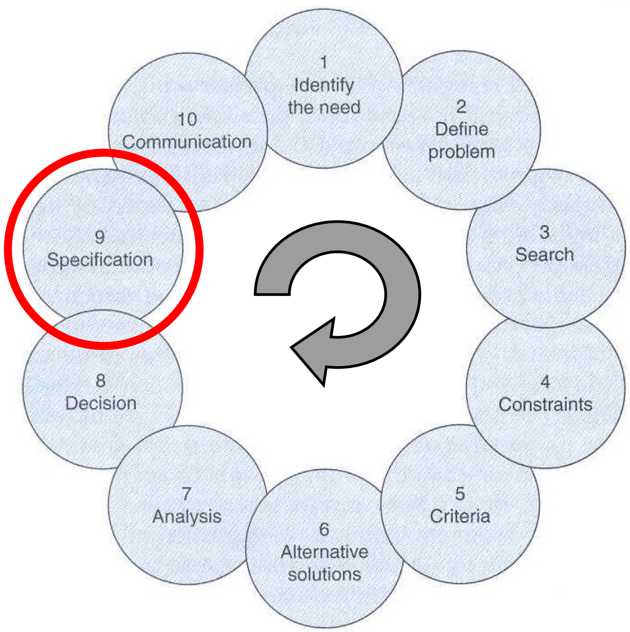
www.staff.city.ac.uk/~ra600/intro.htm

Design web

Objectives for today

- Preliminary design for mechanical systems
- Learn phases in mechanical design





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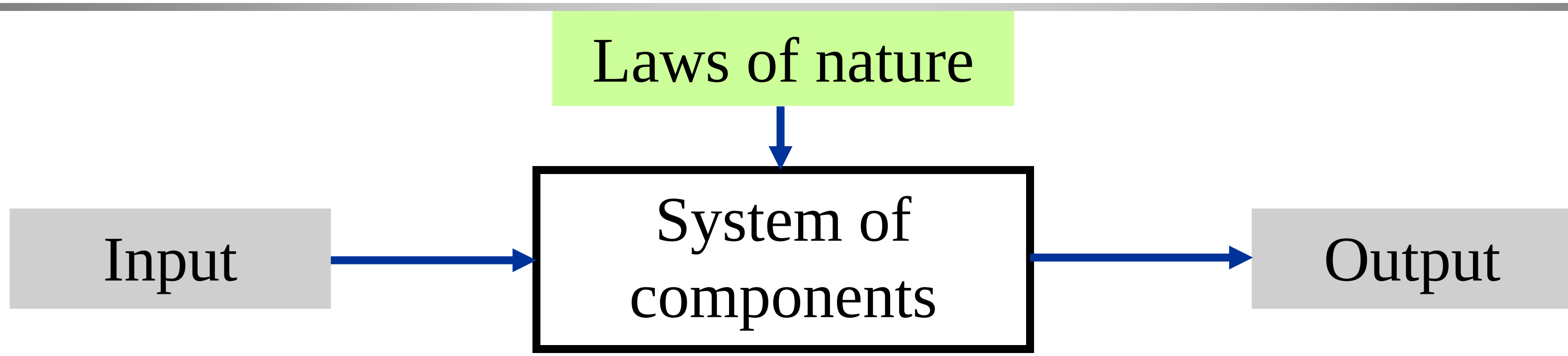
Mechanical Engineering Design



'Name of the game'	To find	Skills
Analysis	Output	Deduction
Reverse analysis	Input	Deduction
Science	Laws	Induction
Engineering	System	Analysis & Synthesis

Science explains *what is* - **Engineering** creates *what never was*

Mathematics is neither science not engineering

Physics and *Chemistry* are science but not engineering

Science - Engineering

- In 1911, a great mathematician named Theodore Von Karman wrote: ***"Scientists discover what is, engineers create what has never been."***
- In 1989, Edward B. Fiske wrote:
  *"**The scientist** seeks to understand the world and operates against an absolute standard. His findings either describe nature accurately or they do not.*

  *By contrast, **the engineer** is problem oriented. He seeks not to describe the world but to change it...*

  The engineer lives in the world where science and values meet."

Engineering -> Mechanical Design Process

Engineering design process

an *iterative decision making* activity, to produce plans by which *resources are converted*, preferably optimally with due consideration for environment *into systems and devices to meet human needs.* *(Woodson.T.T)*

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)*

Mechanical Design

- ***Mechanical design*** is a broad subject encompassing all disciplines of mechanical engineering, thermal and fluid sciences, solid mechanics, materials and processes, manufacturing sciences.
- ***Machine*** is a combination of certain general purpose and special purpose elements which can transmit power (or motion) in a controlled manner and which is capable of performing some useful work or task
- ***General-purpose elements*** are components /elements of various machines, which are identical in shape or geometry and carry out same or similar function. Example: shafts, bearings, springs, fasteners, gears brakes, clutches etc.

Textbook

» Mechanical Engineering Design, J.E. Shigley, C.R. Mischke, R.G. Budynas, McGrawHill, ISBN 0-07-252036-1

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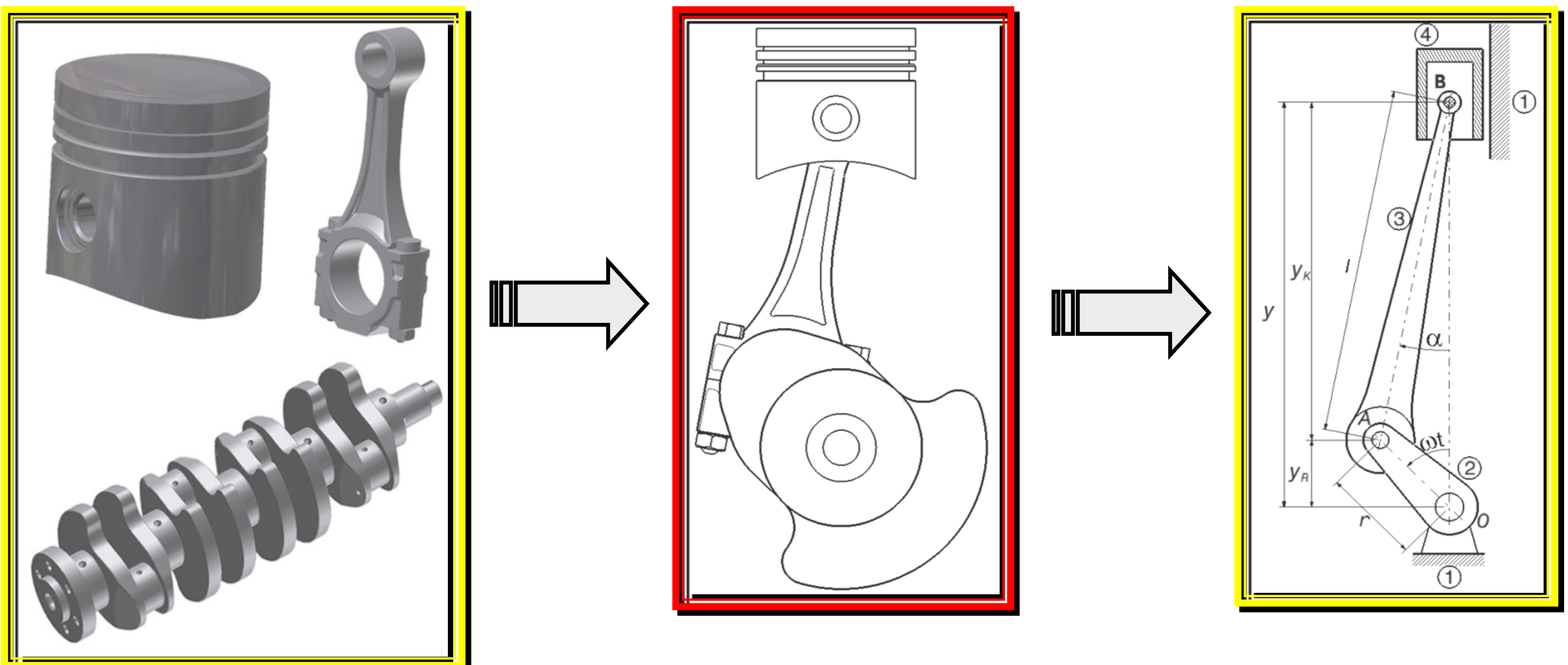
Mechanical Design Procedure

A component is usually designed in the following sequence:

1. A design scheme (lay out) is drawn.
   The shape of the part is designed and the nature of 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;



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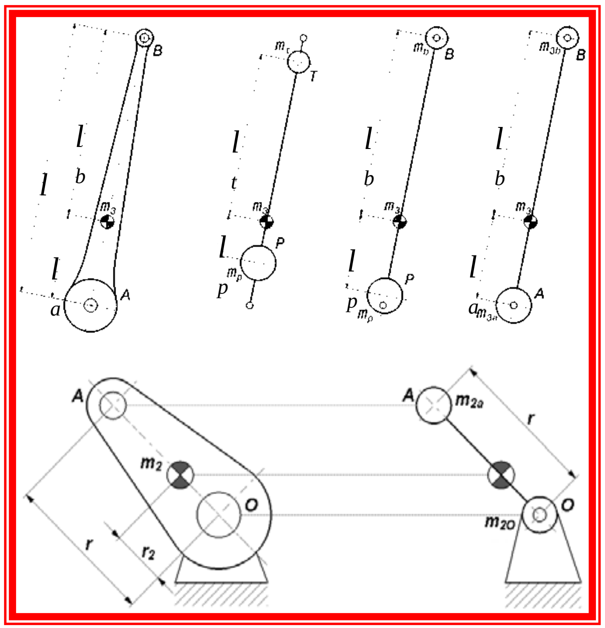
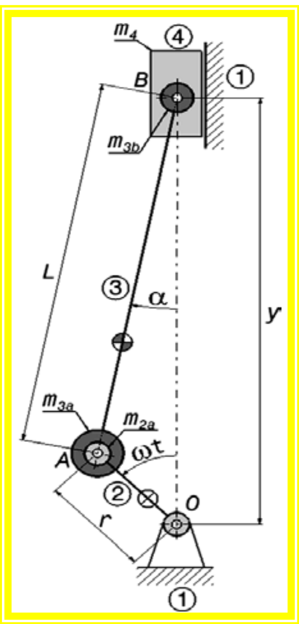
2. *Forces* acting on the part in the process of machine operation *are determined*





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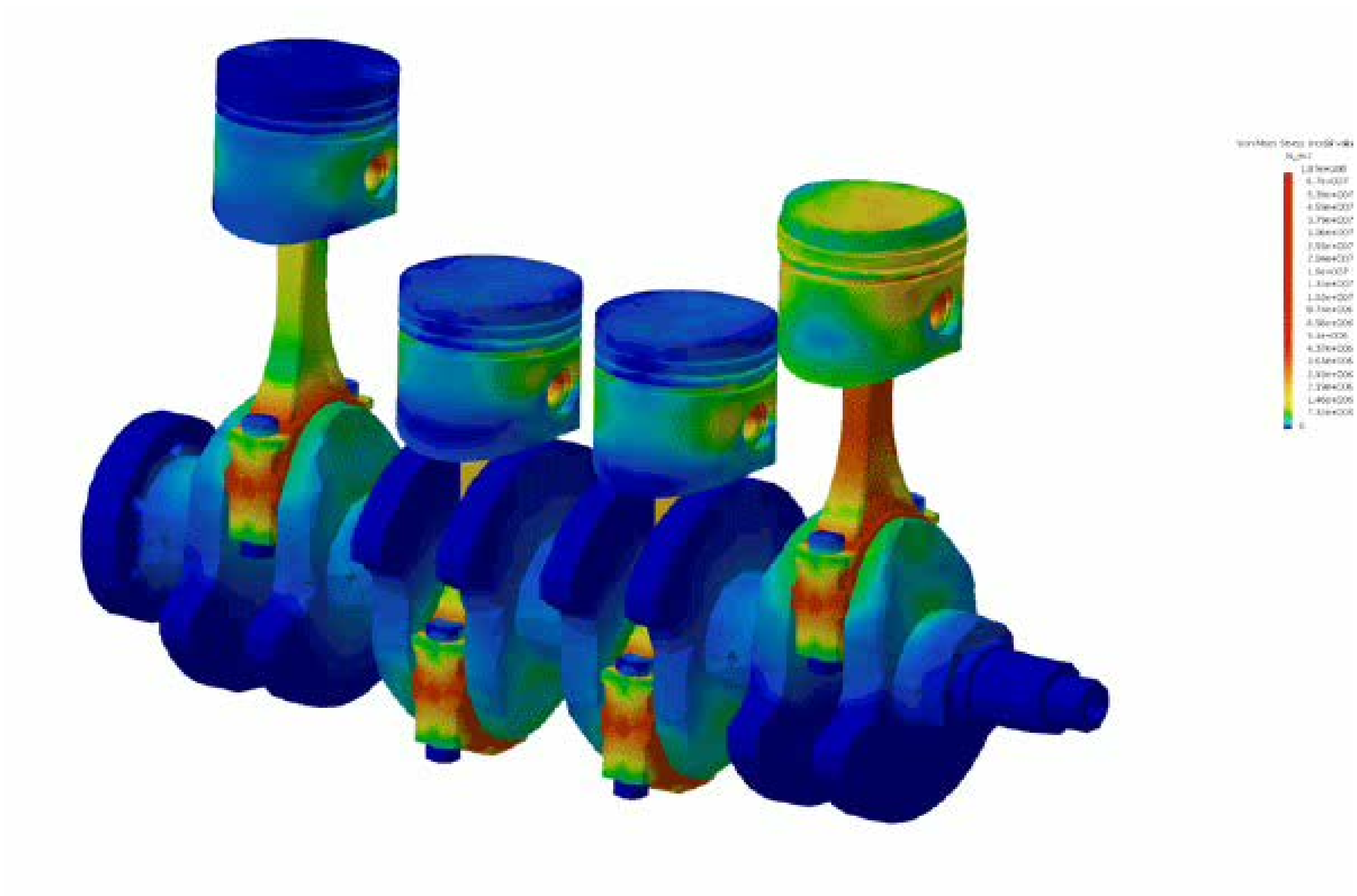
2. *Forces* acting on the part in the process of machine operation *are determined*

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.

Machine or Mechanism



System, Equilibrium and Free-Body Diagram

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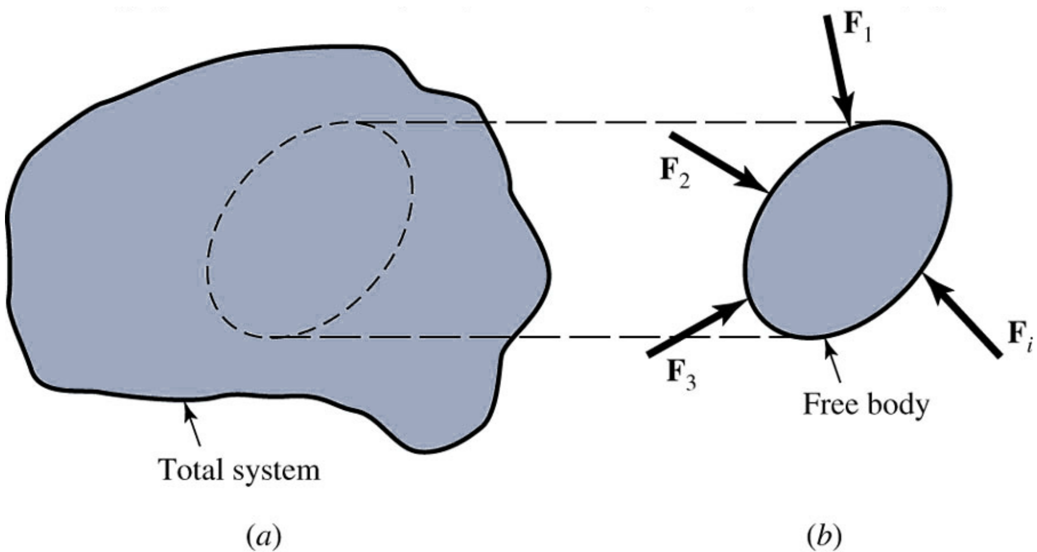
- *System* is any isolated part or portion of a machine or structure that one wants to study. If the system is motionless or has constant velocity it is said the system is in *equilibrium*.
- For such a system *all forces and moments* acting on the system *balance*:

$$\Sigma \mathbf{F}=0 \qquad \Sigma \mathbf{M}=0$$

- The isolated system together with all forces and moments due to external effects and the reactions with the main system is called *free-body diagram*.



An analysis of any structure can be greatly simplified by successively isolating each element and studying and analysing it by the use of free-body diagram.

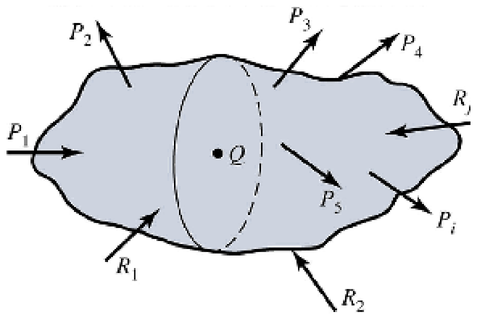
Stress and Strength

The quality of many products depends on how the designer adjusts the maximum stress to the component strength

1. **Strength** is an *inherent property of a material* built into the part because of the use of a particular material and process.

   Strength is denoted with capital letter S with subscripts to denote the kind of stress:

   S_s – shear strength
   S_y – yield strength
   S_u – ultimate strength
   S_m – mean strength



(a) Structural member

Dimension of strength is [N/m^2]

Stress and Strength

2. **Stress** is a *state property* of a body which is a function of load, geometry, temperature and manufacturing processing.

Stress is denoted with Greek letters:

σ – normal stress

τ – shear stress

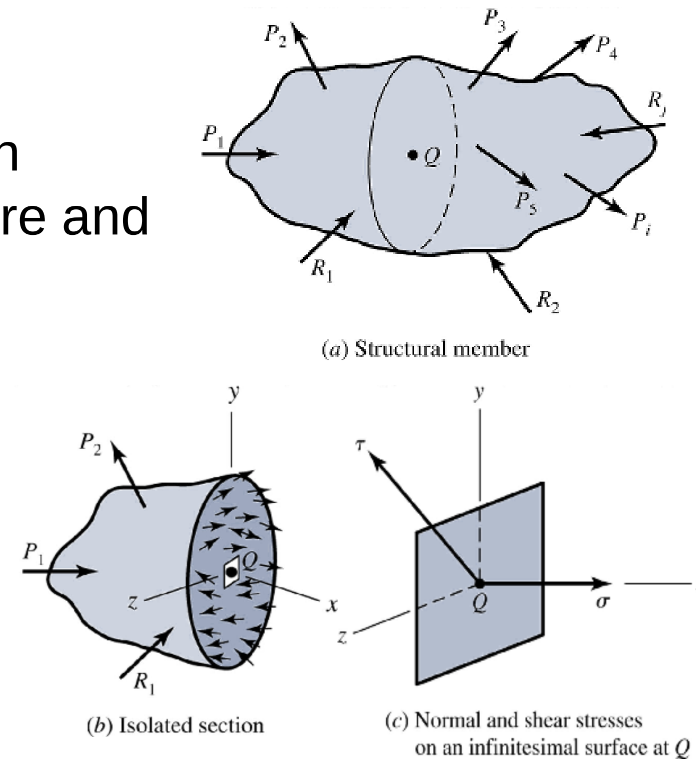
Various marks denote various types of stress:

σ_1 – principal stress

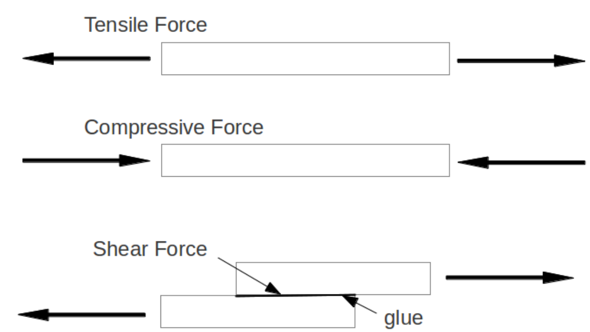
σ_y – coordinate stress component

σ_r – radial stress component

Dimension of both,
stress and strength is [N/m^2] {$\sigma = F/A$}



(a) Structural member
(b) Isolated section
(c) Normal and shear stresses on an infinitesimal surface at Q



Stress, Strain and Strength

2. **Strain** is defined as *deformation of a solid due to stress* in terms of displacement of material

Strain is denoted with Greek letters:

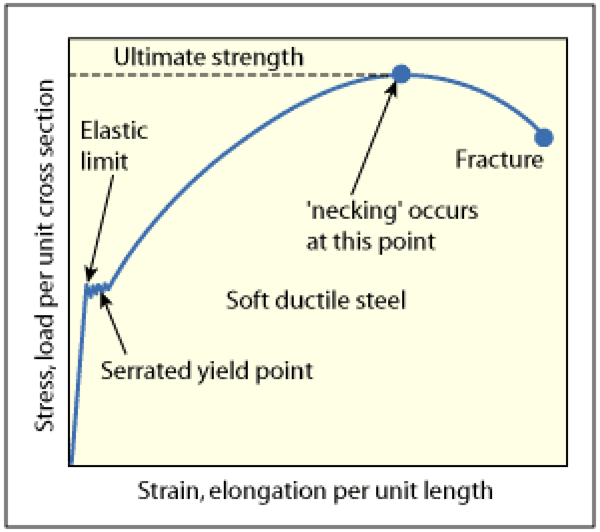
$\varepsilon = dl / l_o$ [m/m]

$\gamma = ds / s_o$ [m/m]

Elastic Moduli are ratio of stress / strain:

$E=\sigma/\varepsilon$ [N/m^2] - *Young's modulus*
Modulus of Elasticity

$G=\tau/\gamma$ [N/m^2] - *Shear modulus*
Modulus of Rigidity



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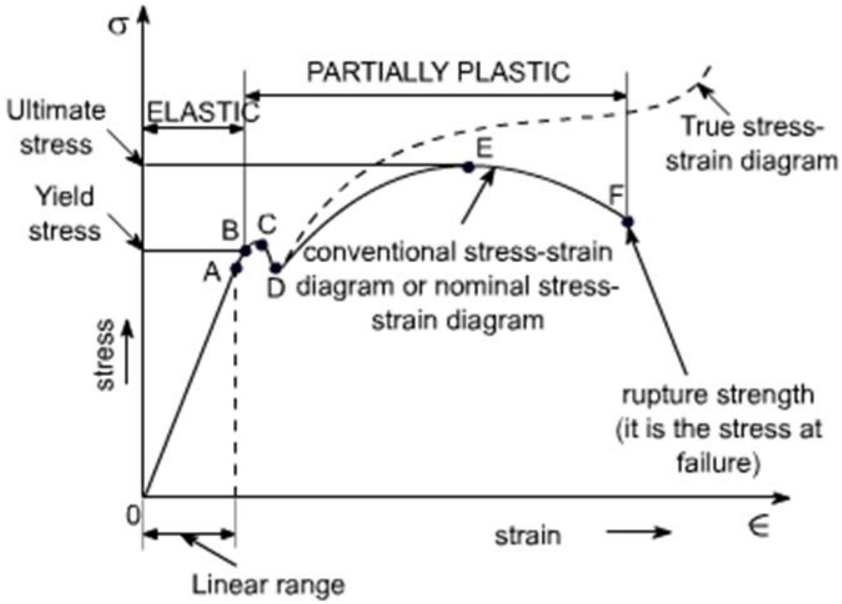
Stress and Strength

The quality of a mechanical system depends on the relationship of the maximum stress to the component strength

1. **Strength** is an *inherent property of a material* built into the part because of the use of a *particular material and process*.
   Strength is denoted with capital letter S *[N/m2]*
   S_E – Yield strength (lowest stress that produces permanent deformation)
   S_G – Shear strength (lowest shear stress that produces permanent deformation)
   S_τ – Tensile or ultimate strength
   (limit state of tensile stress)
   S_d – Fatigue strength – dynamic loading
   (in a stress range $\Delta\sigma=\sigma_{max}-\sigma_{min}$)
   S_i – Impact strength



Design Consideration or Criteria

specific characteristics which influence the design of the element or the entire system

1. **Strength**: *A component should not fail or have residual deformations* under the effect of the forces that act on it.
   This is satisfied if the *induced stress* is less then the *material strength*

   $$\sigma \leq [S]$$

   The necessary and sufficient strength of the part with a given load and a selected material is ensured by such *dimensions and shapes*, which preclude damage and residual deformations.
   A component can also fail because of damaged working surfaces induced by the very high stress or very small area.

2. **Rigidity:** is the *ability of parts to resist deformations* under the action of forces.
   Proper rigidity is necessary to ensure that the mated elements and machine as a whole operate effectively. In many cases this parameter of operating capacity proves to be most important.
   Therefore apart from the strength calculations rigidity of a number of parts is also calculated by comparing *the actual displacements* (deflections, angles of turn, angles of twist) with *allowable (rated) displacements*.

Design Consideration or Criteria (Cont.)

3. **Wear Resistance**: Wear is the principal cause of putting machine elements out of commission. Problems: frequent stops, loss of machine accuracy etc. *Calculations of wear* are usually of an arbitrary nature and carried out *together with calculations of strength*.
4. **Heat resistance**: The liberation of heat involved in the working process or some times due to friction between moving surfaces, causes the components of some machines to operate under conditions of increased temperature. An increased temperature (> 100º C) impairs the lubricating ability of oils; Continuous operations involving temperatures > 300-400º C causes slow plastic deformations called ***creep***. Thermal deformations may reduce the accuracy of a machine.
   Effective cooling and special calculations for heat to *find the working temperature* of the machine elements, *evaluate the working stresses* and *compare* them *with the creep limits* for the material of the part.
5. **Resistance to vibrations**: The term implies the ability of a machine to operate at the assigned speeds and loads without impermissible oscillations Dynamic analysis after finalizing the design to *avoid inherent unbalances*.

General Consideration in Design

1. **Type of load and stresses induced;**
   To design a machine part it is necessary to know the forces, which the part must sustain.
2. **Motion of the parts or kinematics of the machine;**
   Forces and their relations change during the motion of the part. The motion of the part may be:
   - Rectilinear motion
   - Curvilinear motion
   - Constant or variable velocity
   - Constant or variable acceleration
3. **Selection of materials;**
   Body of the component is the material. The designer should have thorough knowledge of the properties of the materials and their behaviour under working conditions.
   Important characteristics of materials are: *strength*, *stiffness/flexibility*, *durability*, *weight*, *resistance to heat*, *corrosion* and *wear*, *ability to cast*, *weld or hardened*, *machinability*, *electrical or magnetic properties* etc.
   Avoid the use of scarce materials.

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/in^3	lbf/ft^3	kN/m^3
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

General Consideration in Design

4. **Form and size of the parts;**
   The smallest practicable cross section may be used;
   Ensure that the stresses induced are reasonably safe.
   Easy to machine. Part or assembly should not involve undue stress concentrations.
   Small weight and minimum dimensions should be the criteria *(shape and material)*
5. **Production soundness;**
   The component should be designed such that its production requires the minimum expenditure of labour and time.
6. **Number to be manufactured;**
   The number of components to be manufactured affects the design in a number of ways.
7. **Cost of construction;**
   The cost of construction of a part is one of the most important considerations involved in design. The aim is to reduce the manufacturing costs in any circumstance.

General Consideration in Design

8. **Safety;**

The shape and dimensions of the part should ensure safety of the personnel responsible for not only its manufacture but during its operation in a machine also.

9. **Workshop facilities;**

A design engineer should be familiar with the limitations of the available workshop. Here, the policy to manufacture or to by should be decided.

10. **Use of standard parts;**

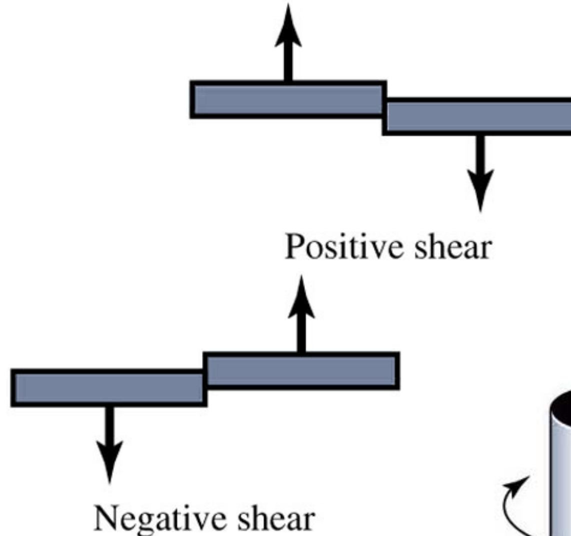
The use of standard parts is closely related to cost.
The standard or stock *parts* should be used whenever possible:
gears, pulleys, bearings and *screws, bolts, nuts, pins*.
Variety (number and size) of such parts should be as few as possible.

11. **Conformance to standards and codes;**

Any part should confirm to the standards covering the shape, grade and type of material and safety codes where applicable.

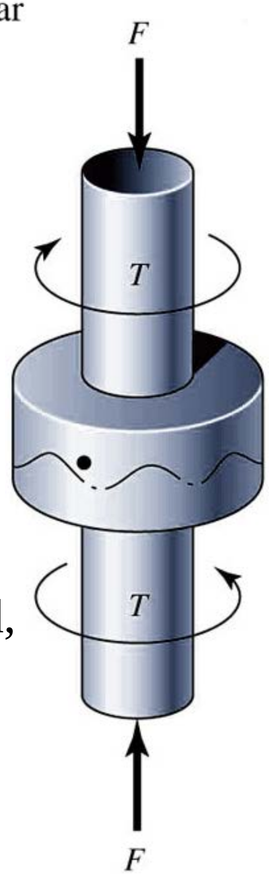
Design for Strength – Static Load

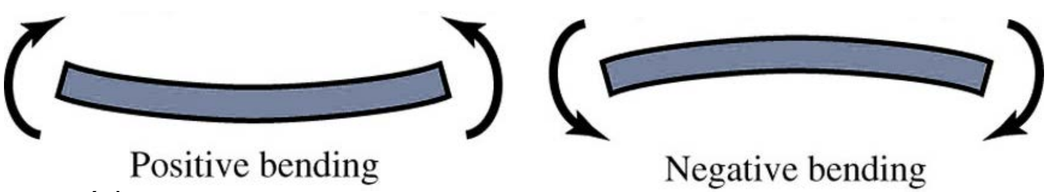
- **Basic assumptions**
  - Material of the body has continuous structure
  - Material is homogenous and isotropic
  - Material is linearly elastic or Hook's law is valid
  - There are no internal stresses prior to loading
  - Load is static



- **STATIC LOAD**

  A static load is a stationary force or moment acting on a member unchanged in magnitude, point of application and direction.
  A static load can be *axial tension*, *compression*, a *shear load*, a *bending load*, a *torsional load* or *any combination* of these.
  The load can not change in any manner if it is to be considered static.
  If the time of application of load is greater than **three times** its natural period, dynamic effects are neglected and the load can be considered static.





Design for Strength – Static Load

- **The part to be designed must be capable of**
  - » *transmitting* the necessary *forces* and performing necessary motions efficiently and economically
  - » failure must not occur in it before a predetermined span of operating life has elapsed
  - » the part must *perform* its *function* with out interfering with any other part of the machine

Strength **is the primary criteria for the design. The** ***relation between the strength*** **of the part** ***and the stress*** **induced on it due to the anticipated static loading must also be considered in order to select the optimum material and dimensions for satisfying above requirements**

- **Two distinct and separate approaches**

1. *The deterministic, or factor-of-safety approach.* In this method, the maximum stress or stresses in a part are kept below the minimum strength by a suitable design factor or margin of safety, to ensure that the part will not fail.
2. *The stochastic, or reliability approach*. This method involves the selection of materials, processing and dimensions such that the probability of failure is always less than a pre selected value

Factor of Safety Method

- **Factor of safety method,** the classical method of design, employs reduced values of strengths that are used in the design to determine the geometrical dimensions of the parts.
- A design factor of safety N_d, some times called simply design factor N, is defined by the relation

$$N = \frac{Loss\,of\ \ function\,Load}{Allowable\,Load} = \frac{Strength}{Stress} = \frac{S}{\sigma}$$

- The failure stress (strength) can be anything the designer chooses it to be. Often such strengths as minimum, mean, yield, ultimate, shear, fatigue as well as others are used; of course it must correspond in type and units to the induced stress.

Material	Load	Factor of safety value N
Exceptionally reliable	Certainly known	1.25 to 1.50
Well known	Known	1.50 to 2.00
Known	Well known	1.50 to 2.00
Less tried	Known orAverage	2.00 to 2.50

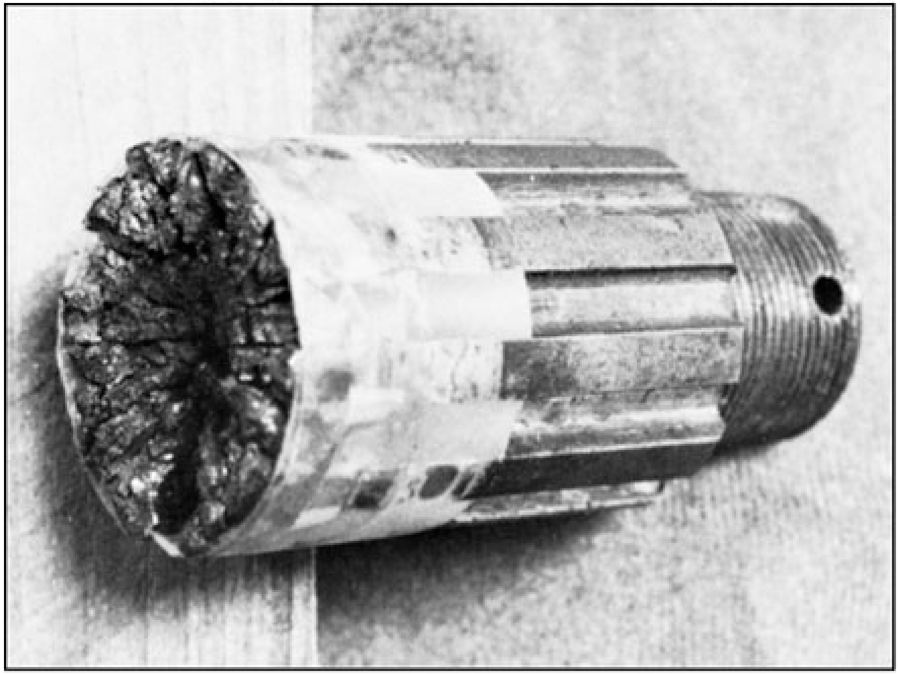
Reliability Method

- The **reliability method,** is the method in which designer obtains the distribution of stresses and the distribution of strength and than relates these two in order to achieve an acceptable success rate.
- The statistical measure of the probability that a mechanical element will not fail in use is called the *reliability* of that element. It can be quantified as:

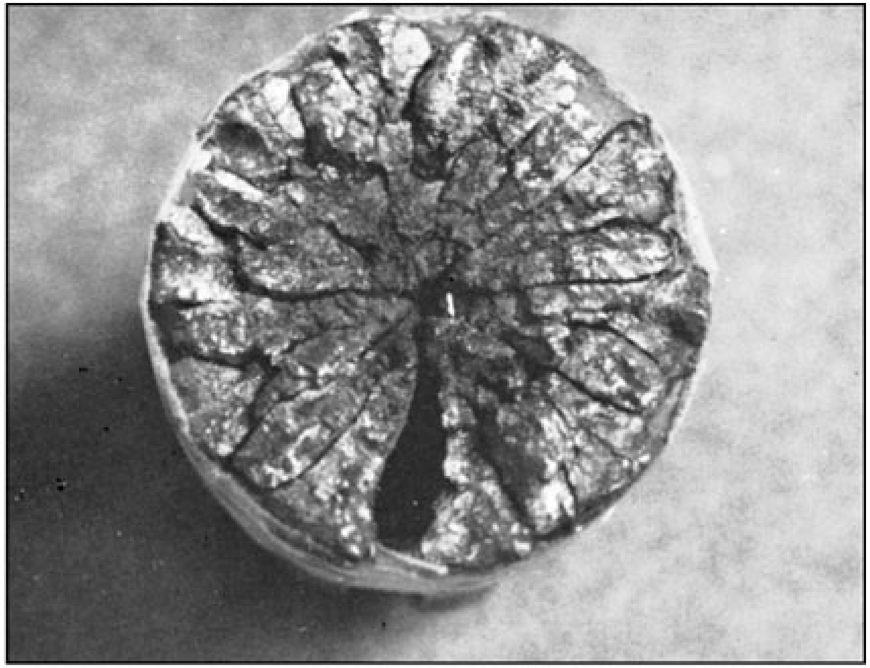
$$0 \le R \le 1$$

- If in the above equation R=0.90 that means that there is 90% chance that the part will perform its proper function without failure.
- In the reliability method, designer should select materials, processes and geometry in order to achieve a reliability goal.
- Analyses that lead to an assessment of reliability address uncertainties, or their estimates, in parameters that describe the situation. Stochastic variables such as stress, strength, load, or size are described in terms of their means, standard deviations and distributions.

Examples of failure

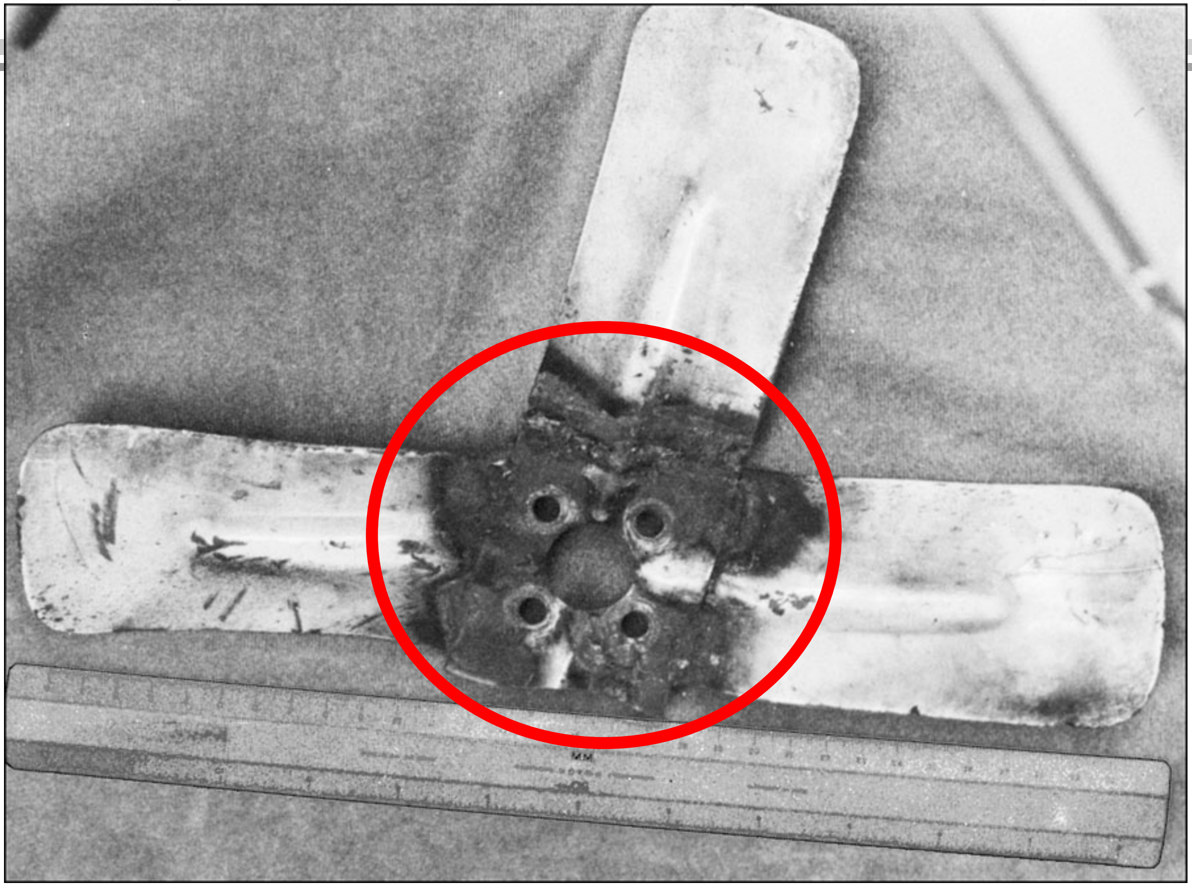


(a)

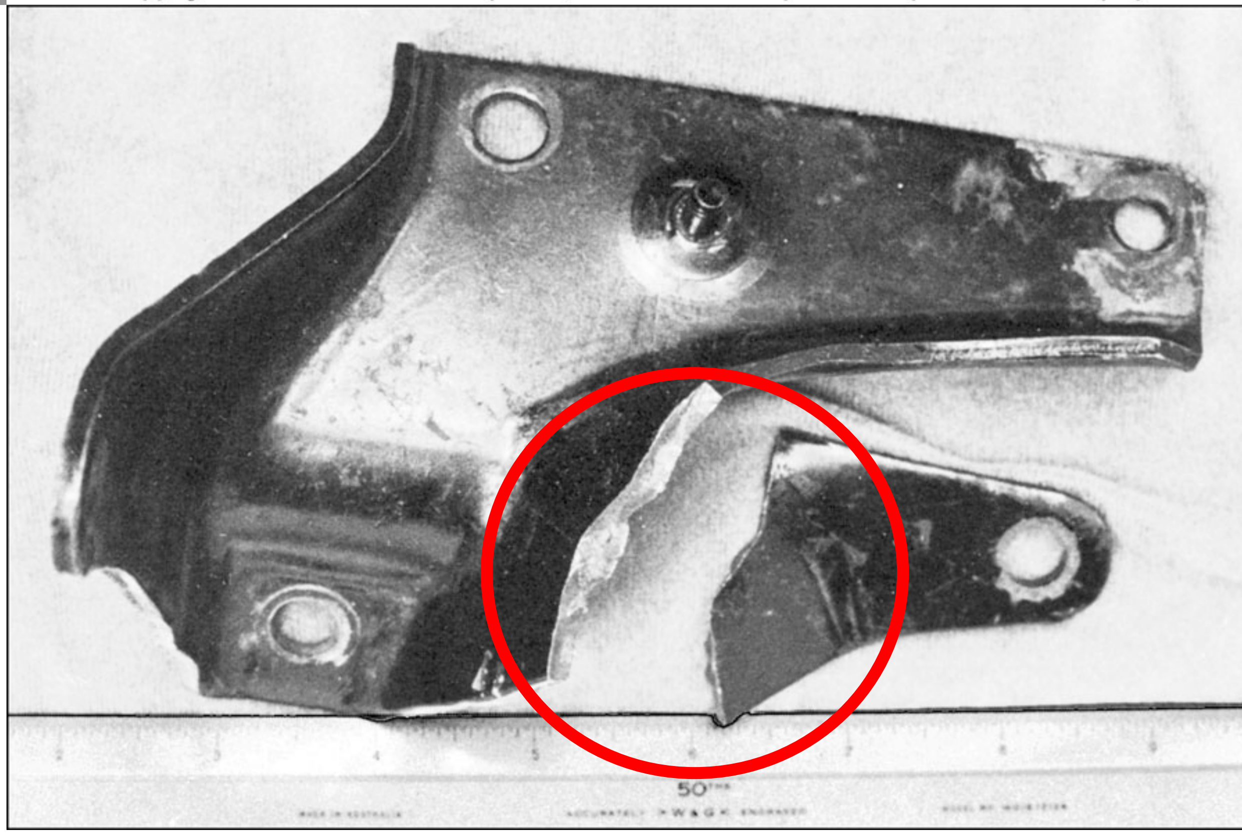


(b)

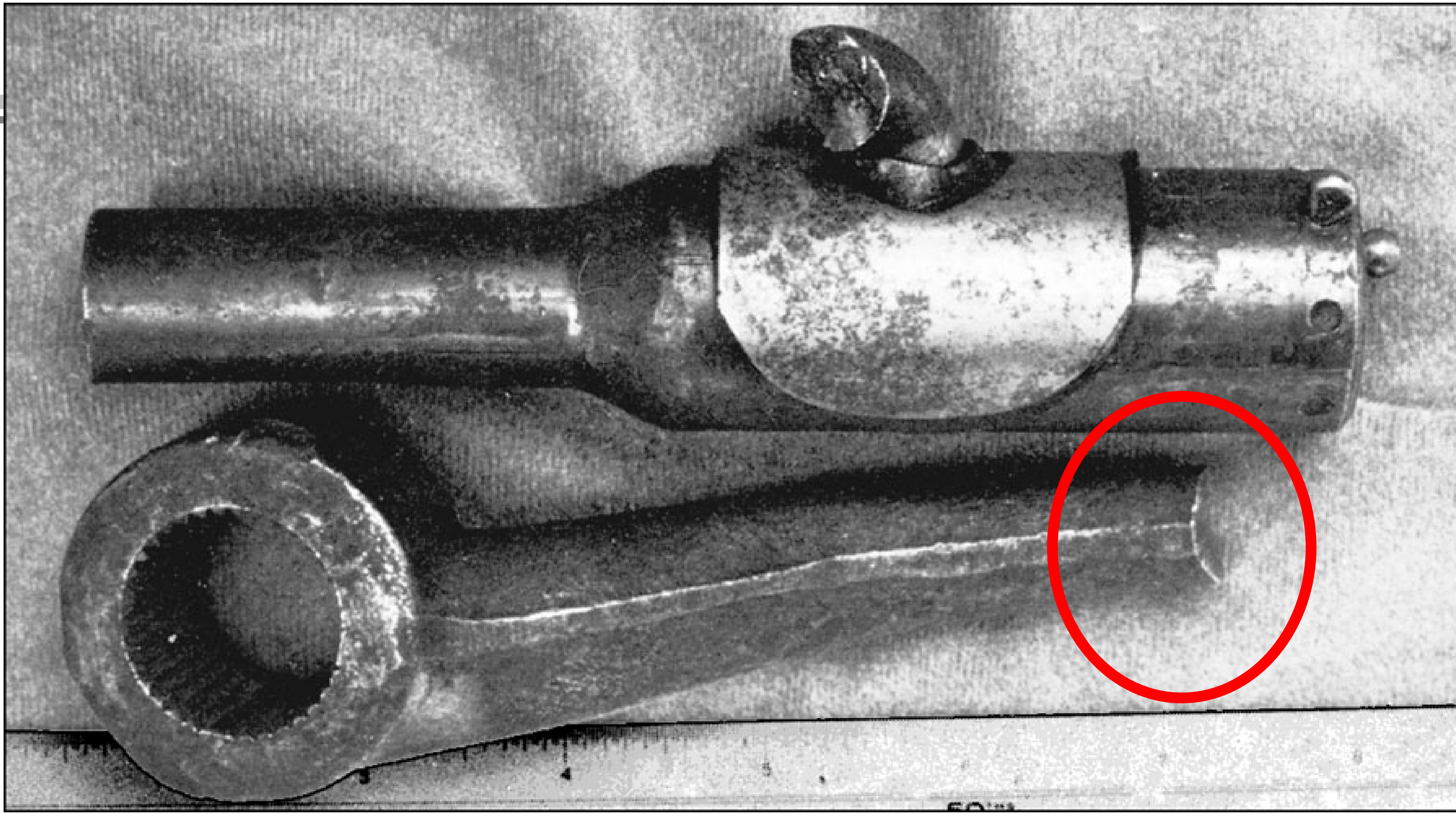
Corrosion Failure of a truck drive shaft



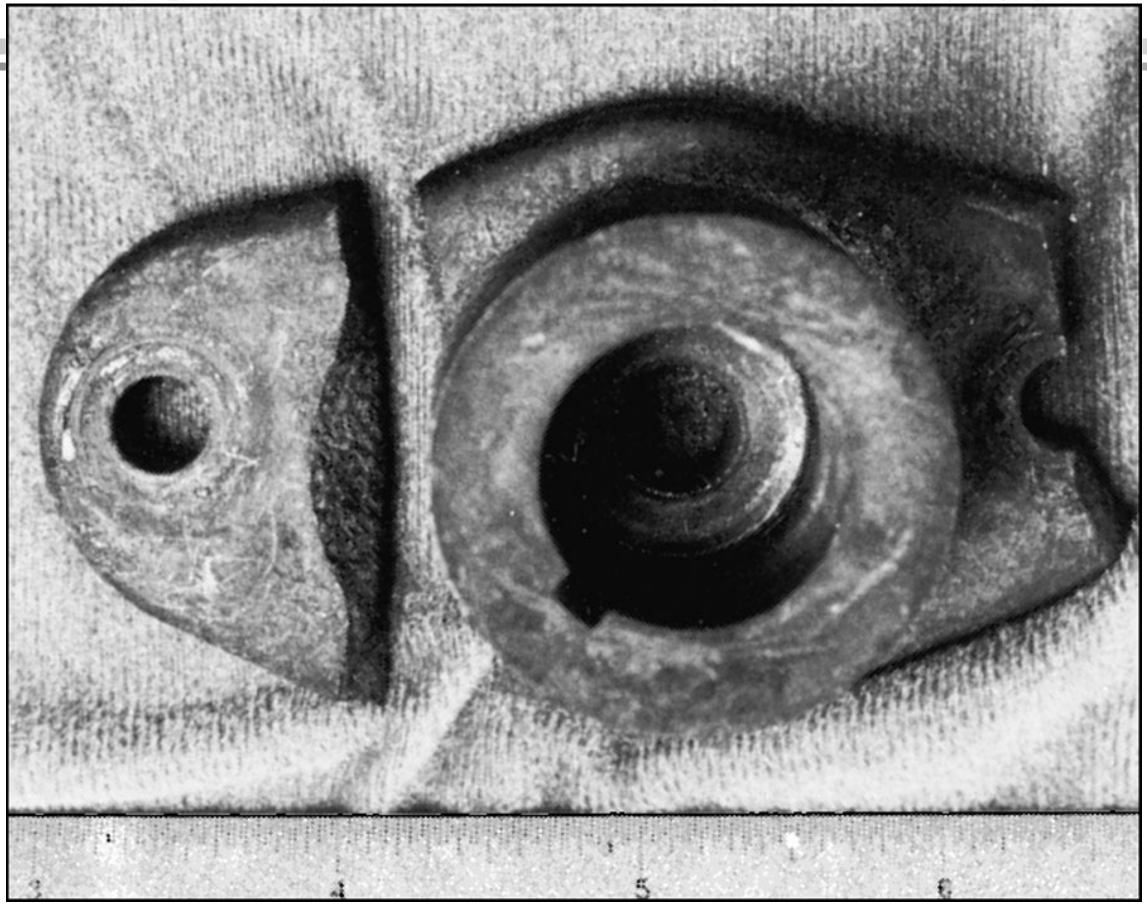
Fatigue failure of an automotive cooling fan due to vibration caused by faulty water pump



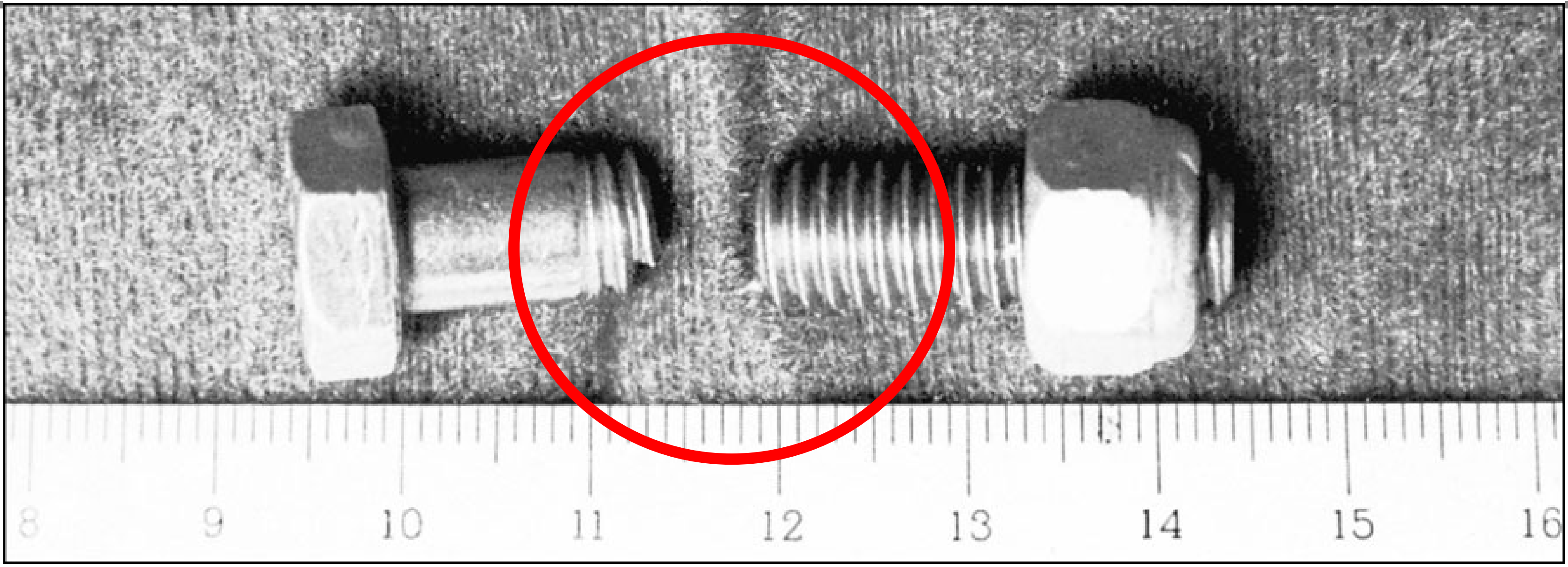
Fatigue failure of an alternator bracket after about 40000km due to residual stress after cold-forming process (stamping)



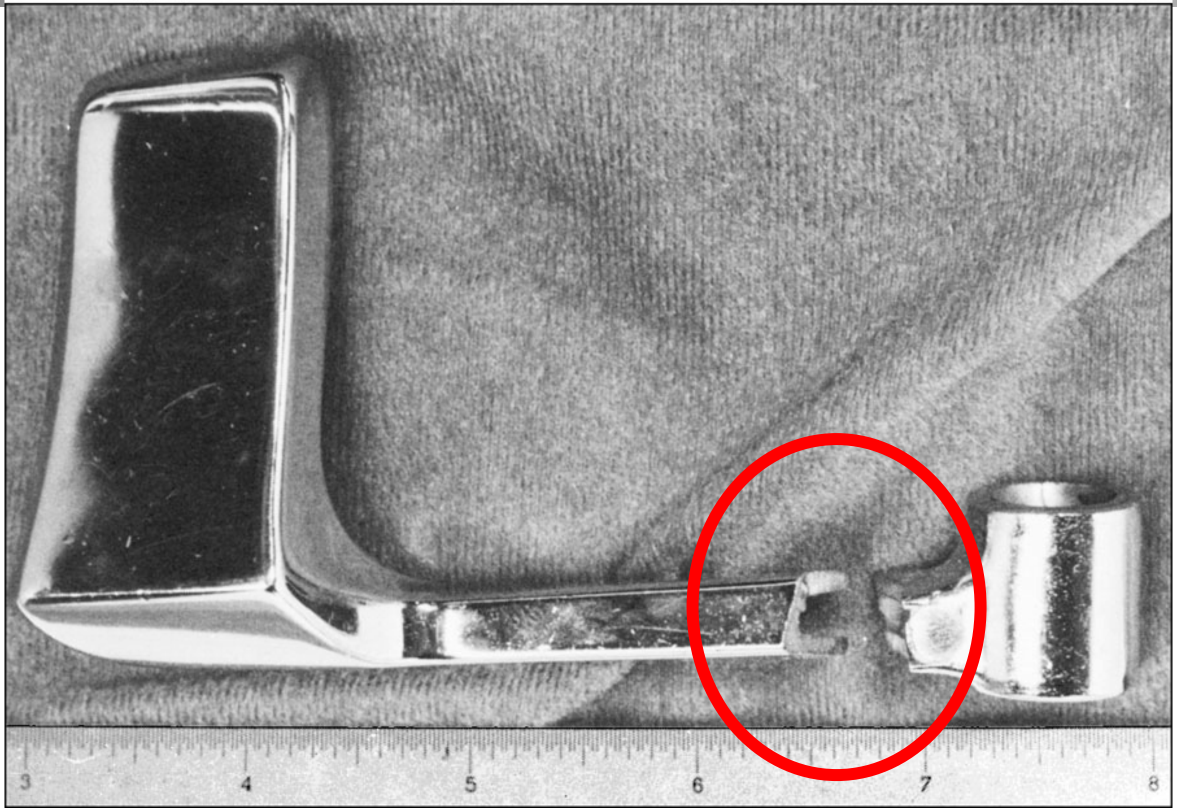
Fatigue of an automotive drag link (that results in total disconnect of the steering wheel from the steering mechanism; this one failed after 225000km driving



Impact failure of a lawn mower blade drive shaft after hitting a surveying pipe marker



Failure of an overhead pulley retaining bolt on a weightlifting machine; the bolt took the unexpected entire moment load when manufacturing error created a gap



Fatigue failure of an interior die-cast car-door handle; failure occurred about every 72000km

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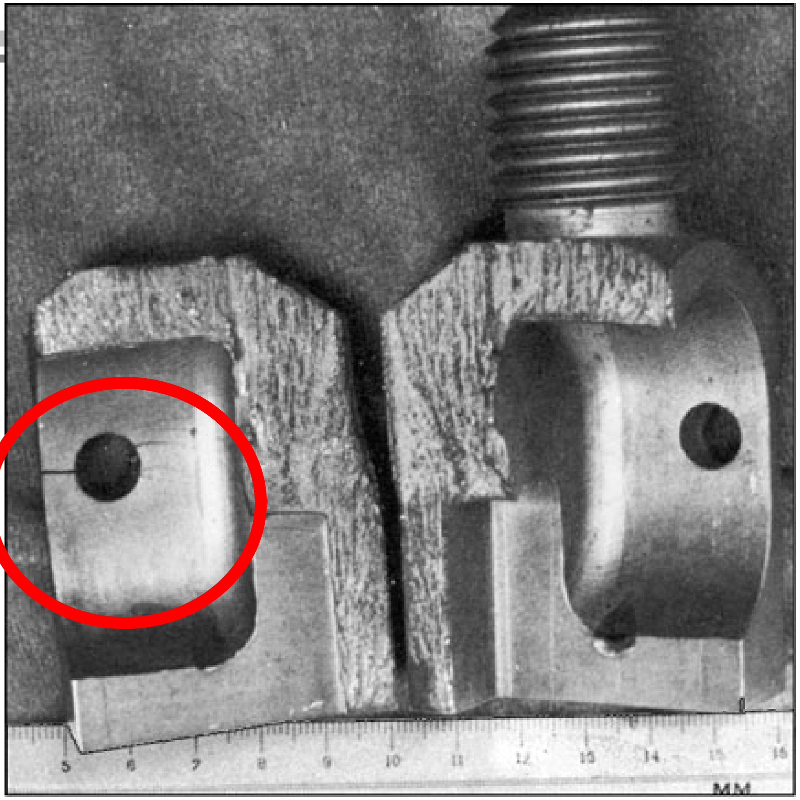
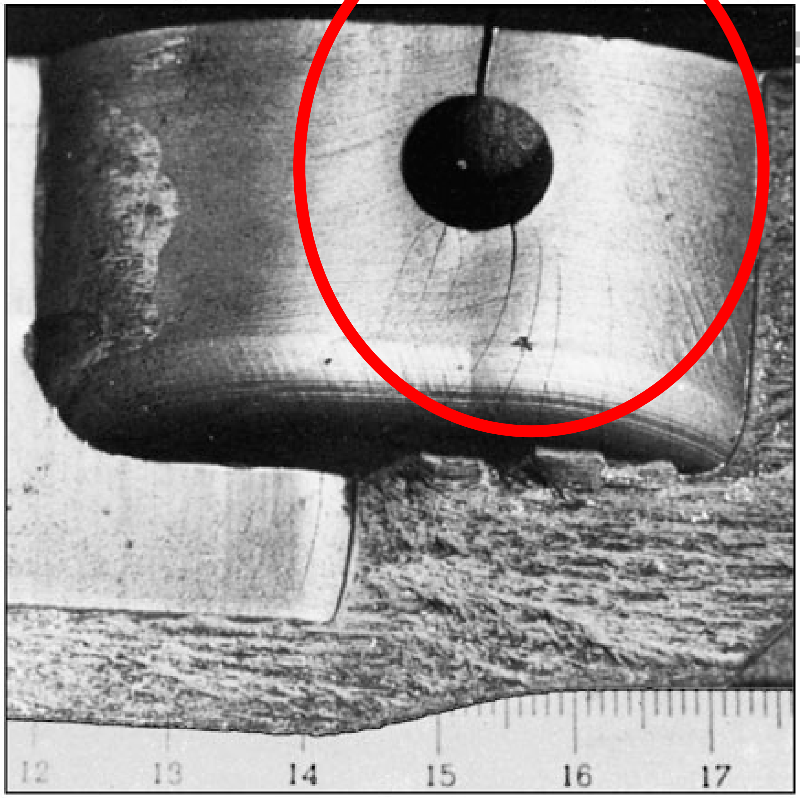
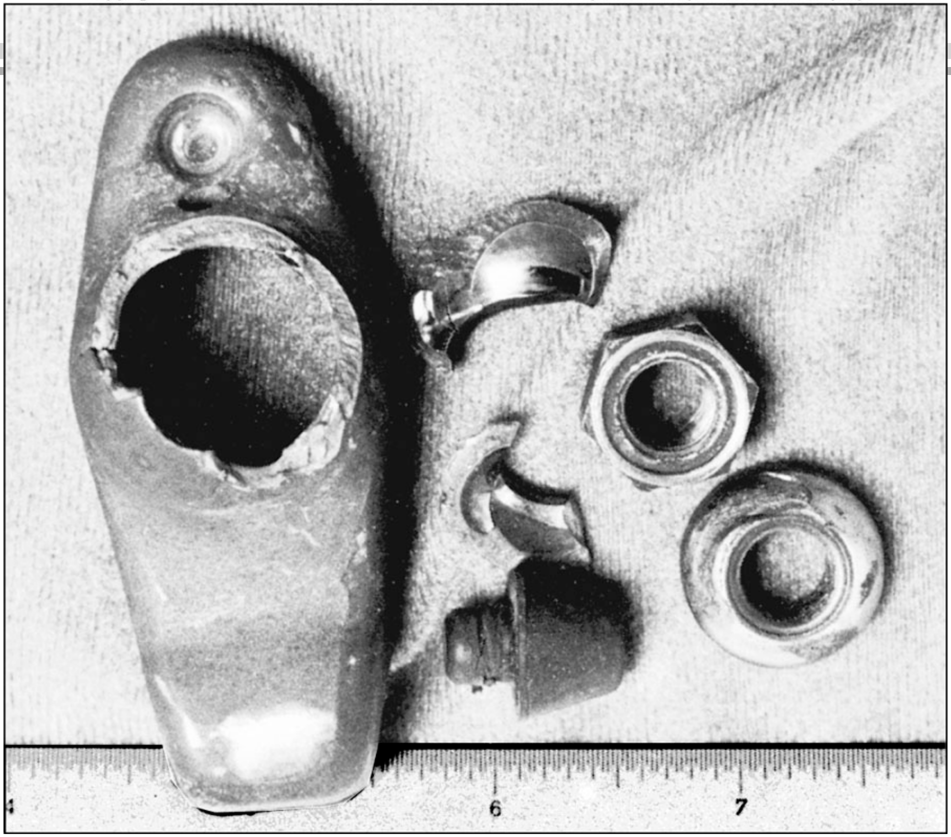


(*a*)

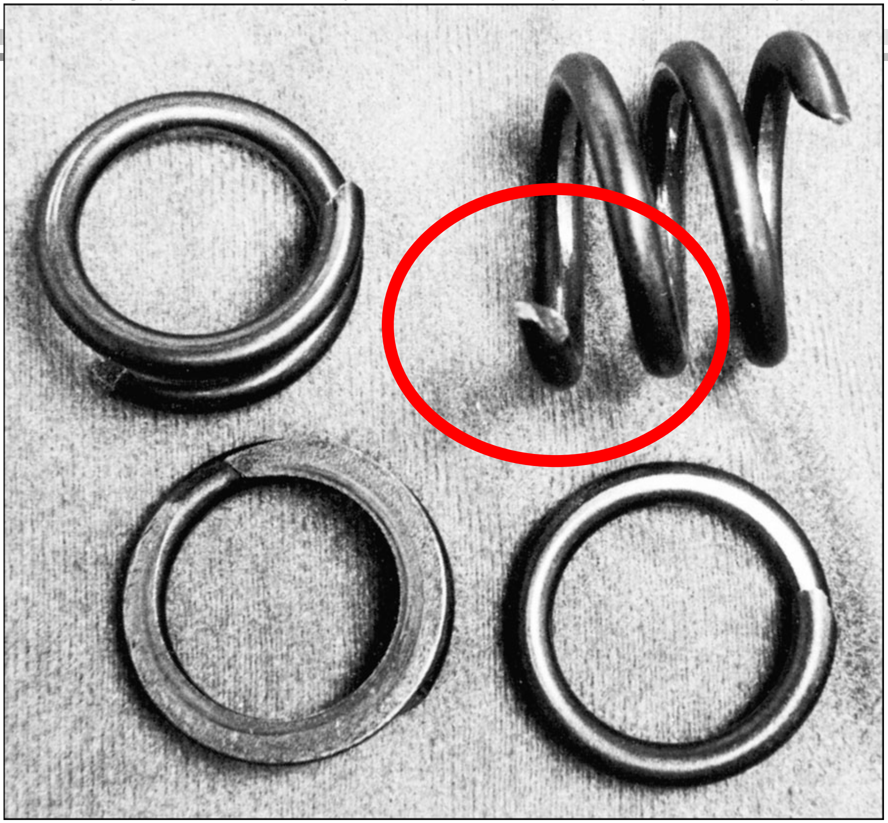


(*b*)

Brittle fracture initiated by stress concentration; a chain test fixture failed in one cycle

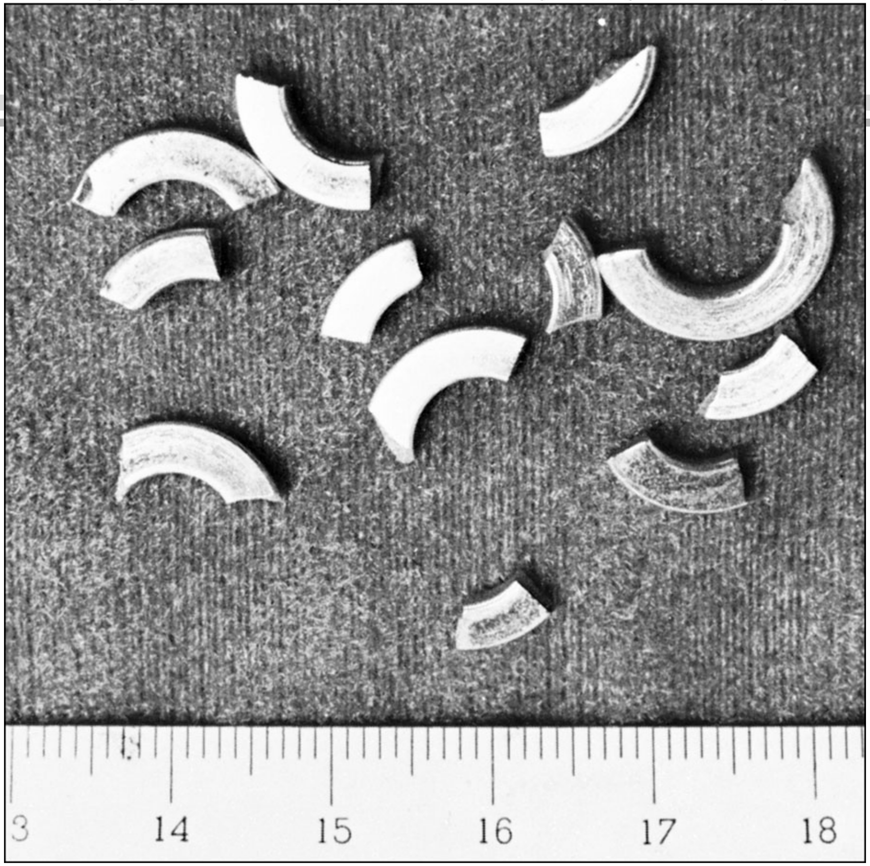


Fatigue failure; automotive rocker-arm articulation-joint fatigue failure

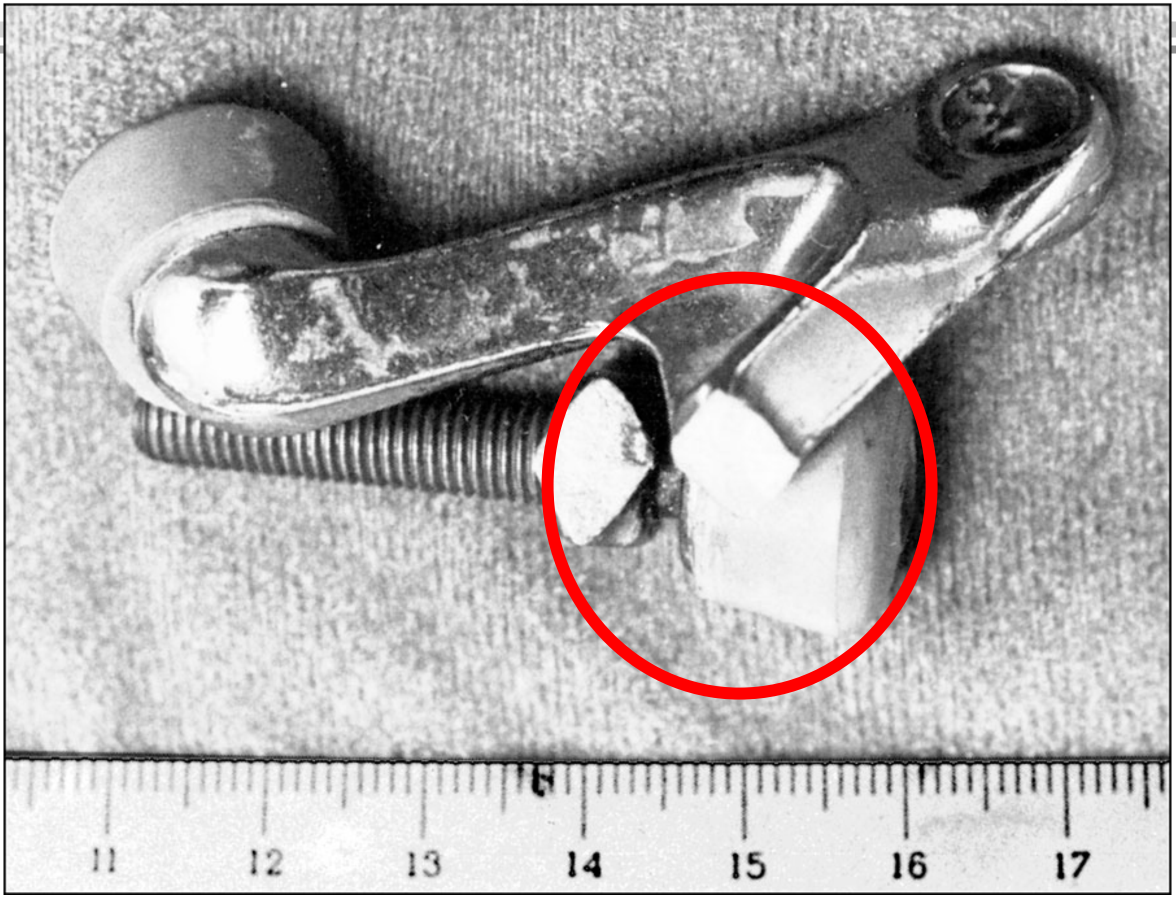


Notice 45^0 shear failure

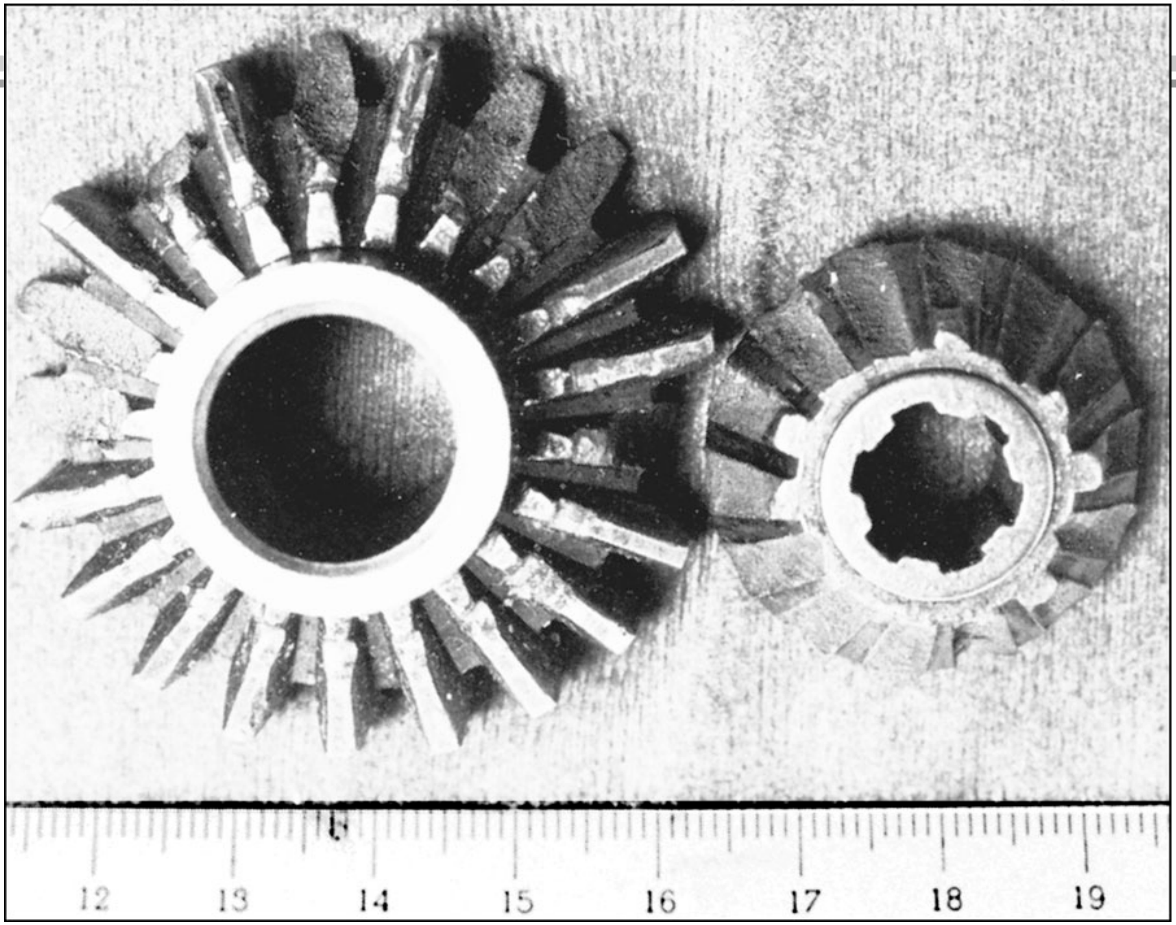
Spring surge; valve spring failure due to engine over-speed



Brittle failure of a lock washer in one-half cycle during it was installed



Fatigue failure of a die-cast residence door-bumper



An outdoor motor; failure occurred when the propeller struck a steel auger placed in the lake bottom as an anchorage