DEPARTMENT OF MECHANICAL ENGINEERING

DESIGN OF MACHINE MEMBERS

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UNIT I Introduction, Design for Static and Dynamic loads

Mechanical Engineering Design: Design process, design considerations, codes and standards of designation of materials, selection of materials. **Design for Static Loads:** Modes of failure, design of components subjected to axial, bending, torsional and impact loads. Theories of failure for static loads. **Design for Dynamic Loads:** Endurance limit, fatigue strength under axial, bending and torsion, stress concentration, notch sensitivity. Types of fluctuating loads, fatigue design for infinite life. Soderberg, Goodman and modified Goodman criterion for fatigue failure. Fatigue design under combined stresses.

UNIT II Design of Bolted and Welded Joints

Design of Bolted Joints: Threaded fasteners, preload of bolts, various stresses induced in the bolts. Torque requirement for bolt tightening, gasketed joints and eccentrically loaded bolted joints.

Welded Joints: Strength of lap and butt welds, Joints subjected to bending and torsion. Eccentrically loaded welded joints.

UNIT III Power transmission shafts and Couplings

Power Transmission Shafts: Design of shafts subjected to bending, torsion and axial loading. Shafts subjected to fluctuating loads using shock factors.

Couplings: Design of flange and bushed pin couplings, universal coupling.

UNIT IV Design of Clutches, Brakes and Springs

Friction Clutches: Torque transmitting capacity of disc and centrifugal clutches. Uniform wear theory and uniform pressure theory.

Brakes: Different types of brakes. Concept of self-energizing and self-locking of brake. Band and block brakes, disc brakes.

Springs: Design of helical compression, tension, torsion and leaf springs.

UNITV Design of Bearings and Gears

Design of Sliding Contact Bearings: Lubrication modes, bearing modulus, McKee's equations, design of journal bearing. Bearing Failures.

Design of Rolling Contact Bearings: Static and dynamic load capacity, Stribeck's Equation, equivalent bearing load, load-life relationships, load factor, selection of bearings from manufacturer's catalogue.

Design of Gears: Spur gears, beam strength, Lewis equation, design for dynamic and wear loads.

What is Machine Design?

What is the importance of Machine Design for engineers?

Creation of new and better machines, and Improving Existing Ones so that it is economical in the cost of production and operation.

Definition of Machine Design

1) Machine design is defined as the use of scientific principles, technical information & imagination.

or

2)Machine design is defined as the use of scientific principles, technical information & imagination in the description of a machine or a mechanical system to perform specific functions with maximum economy & efficiency.

Basic Requirement of Machine Elements

Strength and Rigidity

Wear Resistance

Minimum Dimensions & Weight

Manufacturability

Safety

Conformance to standards

Reliability

Maintainability

Minimum Life-cycle Cost

Engineering Materials and their Properties

- Selection of proper material for the machine components is one of the most important steps in process of machine design
- The best material is one which will serve the desired purpose at minimum costs
- Factors Considered while selecting the material:

i) Availability: Material should be readily available in market in large enough quantities to meet the requirement.

ii) Mechanical properties

Manufacturing Considerations:

- In some applications machinability of material is an important consideration in selection
- Where the product is of complex shape, castability or ability of the molten metal to flow into intricate passages is the criterion of material selection
- In fabricated assemblies of plates & rods, weldability becomes the governing factor

Toughness: Ability to absorb energy before fracture takes place

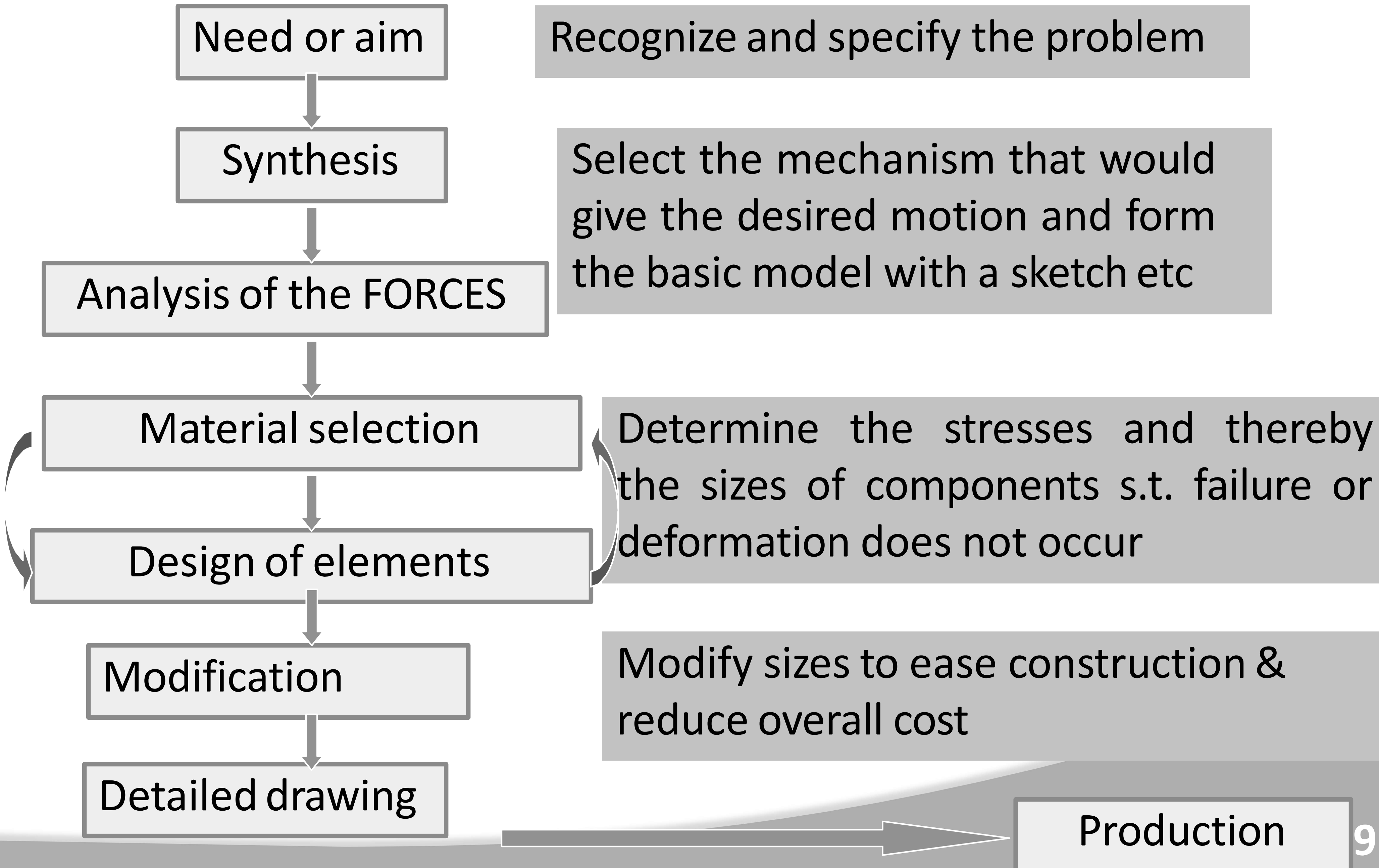
Malleability: Ability to deform to a greater extent before the sign of crack, when it is subjected to compressive force

Ductility: Ability to deform to a greater extent before the sign of crack, when subjected to tensile force

Brittleness: Property of the material which shows negligible plastic deformation fracture takes place

Hardness: Resistance to penetration or permanent deformation

General Procedure in Machine Design



DESIGN CONSIDERATIONS

- Strength
- Rigidity
- Reliability
- Safety
- Cost
- Weight
- Ergonomics
- Aesthetics
- Manufacturing considerations
- Assembly considerations
- Conformance to standards
- Friction and wear
- Life
- Vibrations
- Thermal considerations
- Lubrication
- Maintenance
- Flexibility
- Size and shape
- Stiffness
- Corrosion
- Noise
- Environmental considerations

MANUFACTURING CONSIDERATIONS IN DESIGN

- Minimum total number of parts in a product
- Minimum variety of parts
- Use standard parts
- Use modular design
- Design parts to be multifunctional
- Design parts for multiple use
- Select least costly material
- Design parts for ease of manufacture
- Shape the parts for minimizing the operations

DESIGN CONSIDERATIONS FOR CASTINGS

- Design parts to be in compression then in tension
- Strengthen parts under tension by use of external devices
- Shape the casting for orderly solidification
- Avoid abrupt change in cross-section
- Provide more thickness at the boss
- Round off the corners
- Avoid concentration of metal at junctions
- Avoid thin sections
- Make provision for easy removal of pattern from the mould

DESIGN CONSIDERATIONS FOR FORGINGS

- Keep fibre lines parallel to tensile and compressive forces and perpendicular to shear forces
- Avoid deep machining cuts
- Keep vertical surfaces of forged parts tapered
- Keep the parting line in one plane
- Provide adequate fillet and corner radii
- Avoid thin sections

DESIGN CONSIDERATIONS IN WELDING

- Use the minimum possible number of welds
- Select the same thickness for the parts to be welded together
- Locate the welds at the areas in the design where stresses and/or deflections are not critical
- Effect of shrinkage and distortion should be minimized by post welding annealing and stress relief operations
- Decide proper welding sequence
- Design welding in the flat or horizontal position and not in the overhead position
- Use only the amount of weld metal that is absolutely required

STANDARDIZATION

- It is the process of establishing the set of norms to which a specified set of characteristics of a component or a product should conform
- **Example:** Standardizing the shaft consists of specifying the set of shaft diameters and material

➢ **Objectives of standardization**

- To make the interchangeability of the components possible
- To make the mass production of components easier

PREFERRED SERIES AND ITS SELECTION

- Preferred series are series of numbers obtained by geometric progression and rounded off
- The four basic preferred series are designated as:

R5 Series	$\sqrt[5]{10} = 1.58$
R10 Series	$\sqrt[10]{10} = 1.26$
R20 Series	$\sqrt[20]{10} = 1.12$
R40 Series	$\sqrt[40]{10} = 1.06$

- The other series are called derived series and are obtained by multiplying or dividing the basic sizes by 10, 100, etc.


MECHANICAL PROPERTIES OF MATERIALS
➢Strength
➢Stiffness/Rigidity
➢Elasticity
➢Plasticity
➢Ductility
➢Brittleness
➢Malleability
➢Toughness
➢Machinability
➢Resilience
➢Creep
➢Fatigue
➢Hardness

EFFECT OF ALLOYING ELEMENTS

- Chromium
- Nickel
- Manganese
- Silicon
- Molybdenum
- Vanadium
- Tungsten

STEELS DESIGNATED ON THE BASIS OF MECHANICAL PROPERTIES

- These steels are carbon and low alloy steels where the main criterion in the selection and inspection of steel is the tensile strength or yield stress.
- According to Indian standard these steels are designated by a symbol 'Fe' or 'Fe E' depending on whether the steel has been specified on the basis of minimum tensile strength or yield strength, followed by the figure indicating the minimum tensile strength or yield stress in N/mm^2
- For example 'Fe 290' means a steel having minimum tensile strength of 290 N/mm^2 and 'Fe E 220' means a steel having yield strength of 220 N/mm^2.

STEELS DESIGNATED ON THE BASIS OF CHEMICAL COMPOSITION

- According to Indian standard, steels are designated in the following order :
- (*a*) Figure indicating 100 times the average percentage of carbon content,
- (*b*) Letter 'C', and
- (*c*) Figure indicating 10 times the average percentage of manganese content. The figure after multiplying shall be rounded off to the nearest integer.
- For example 20C8 means a carbon steel containing 0.15 to 0.25 per cent (0.2 per cent on an average) carbon and 0.60 to 0.90 per cent (0.75 per cent rounded off to 0.8 per cent on an average) manganese.

INDIAN STANDARD DESIGNATION OF LOW AND MEDIUM ALLOY STEELS

- According to Indian standard, low and medium alloy steels shall be designated in the following order :

1. Figure indicating 100 times the average percentage carbon.

2. Chemical symbol for alloying elements each followed by the figure for its average percentage content multiplied by a factor as given below :

Element	*Multiplying factor*
Cr, Co, Ni, Mn, Si and W	4
Al, Be, V, Pb, Cu, Nb, Ti, Ta, Zr and Mo	10
P, S and N	100

- For example 40 Cr 4 Mo 2 means alloy steel having average 0.4% carbon, 1% chromium and 0.25% molybdenum.

INDIAN STANDARD DESIGNATION OF HIGH SPEED TOOL STEEL

- According to Indian standard, the high speed tool steels are designated in the following order :

1. Letter 'XT'.

2. Figure indicating 100 times the percentage of carbon content.

3. Chemical symbol for alloying elements each followed by the figure for its average percentage content rounded off to the nearest integer, and

4. Chemical symbol to indicate specially added element to attain the desired properties.

- For example, XT 75 W 18 Cr 4 V 1 means a tool steel with average carbon content 0.75 percent, tungsten 18 per cent, chromium 4 per cent and vanadium 1 per cent.

Preferred Numbers

- The system is based on the use geometric progression to develop a set of numbers
- There are five basic series denoted as R5, R10, R20, R40, and R80 series which increases in steps of 56%, 26%, 12%, 6% and 3% respectively
- Each series has its own series factor as shown below

R5 Series	$\sqrt[5]{10} = 1.58$
R10 Series	$\sqrt[10]{10} = 1.26$
R20 Series	$\sqrt[20]{10} = 1.12$
R40 Series	$\sqrt[40]{10} = 1.06$
R80 Series	$\sqrt[80]{10} = 1.03$

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LIMITS & FITS

CONTENTS

LIMTS FITS AND TOLERANCES

INSPECTION

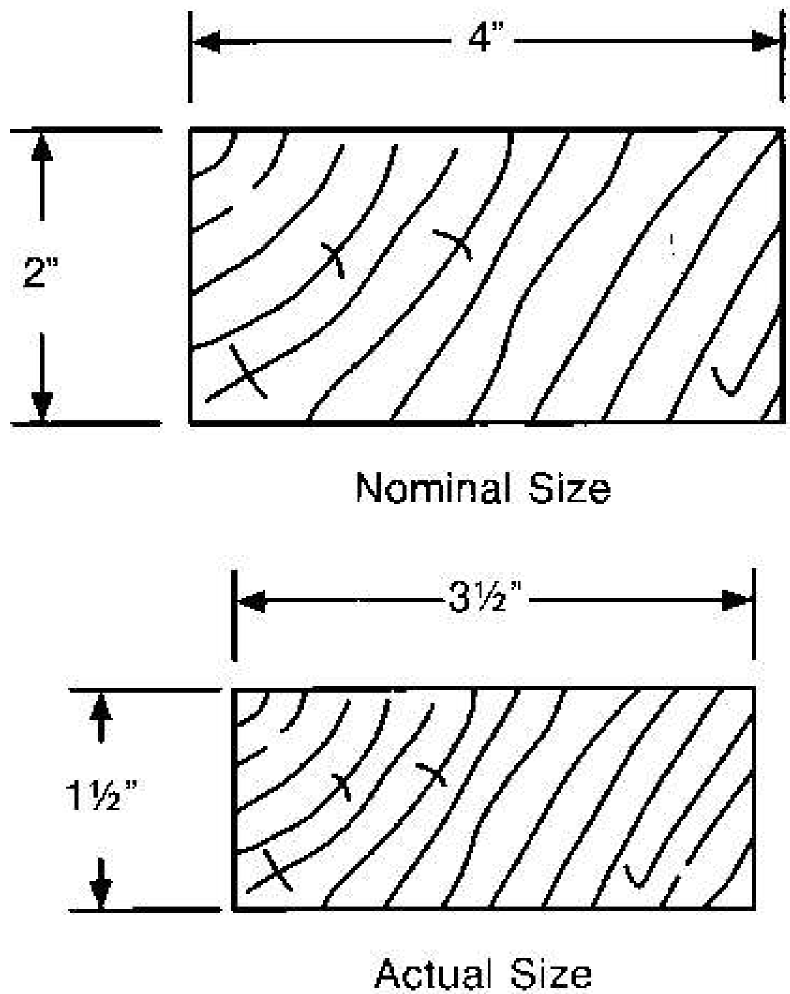
TYPES OF INSPECTION

TERMINOLOGY

NOMINAL SIZE: It is the size of a part specified in the drawing.

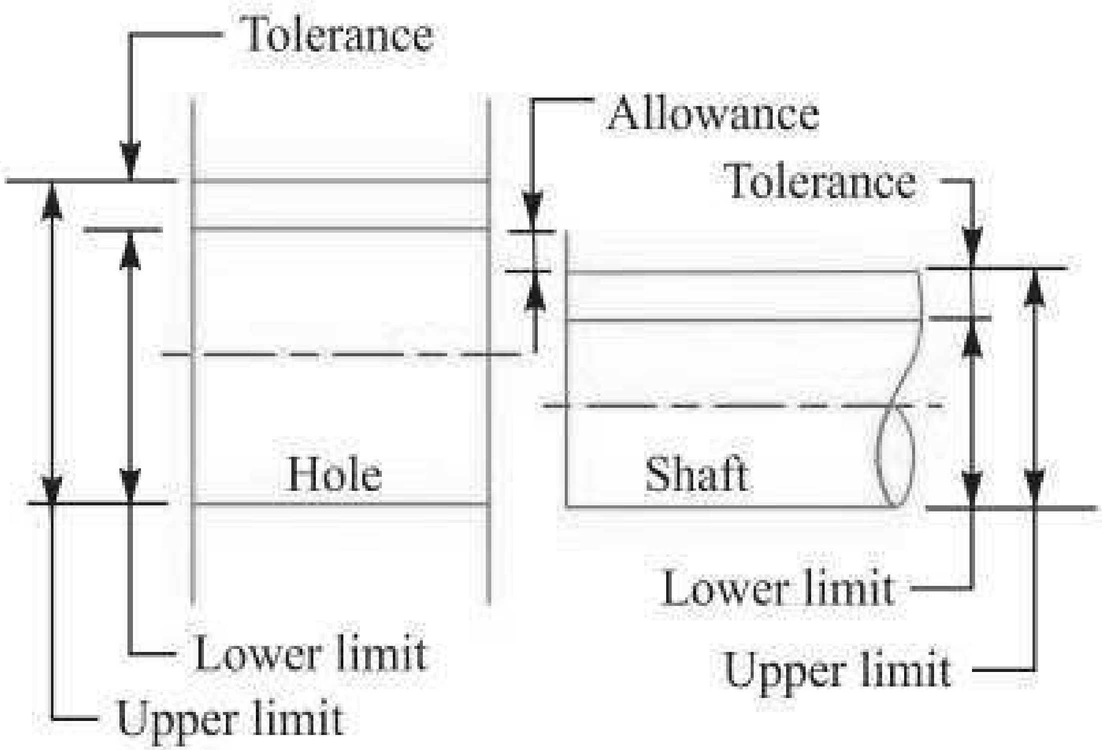
BASIC SIZE: It is the size of a part to which all limits of variation are determined.

ACTUAL SIZE: It is the actual measured dimension of a part. Nominal and basic size are often the same



LIMIT OF SIZES

There are two extreme possible sizes of a component. The largest permissible size for a component is called upper limit and smallest size is called lower limit.



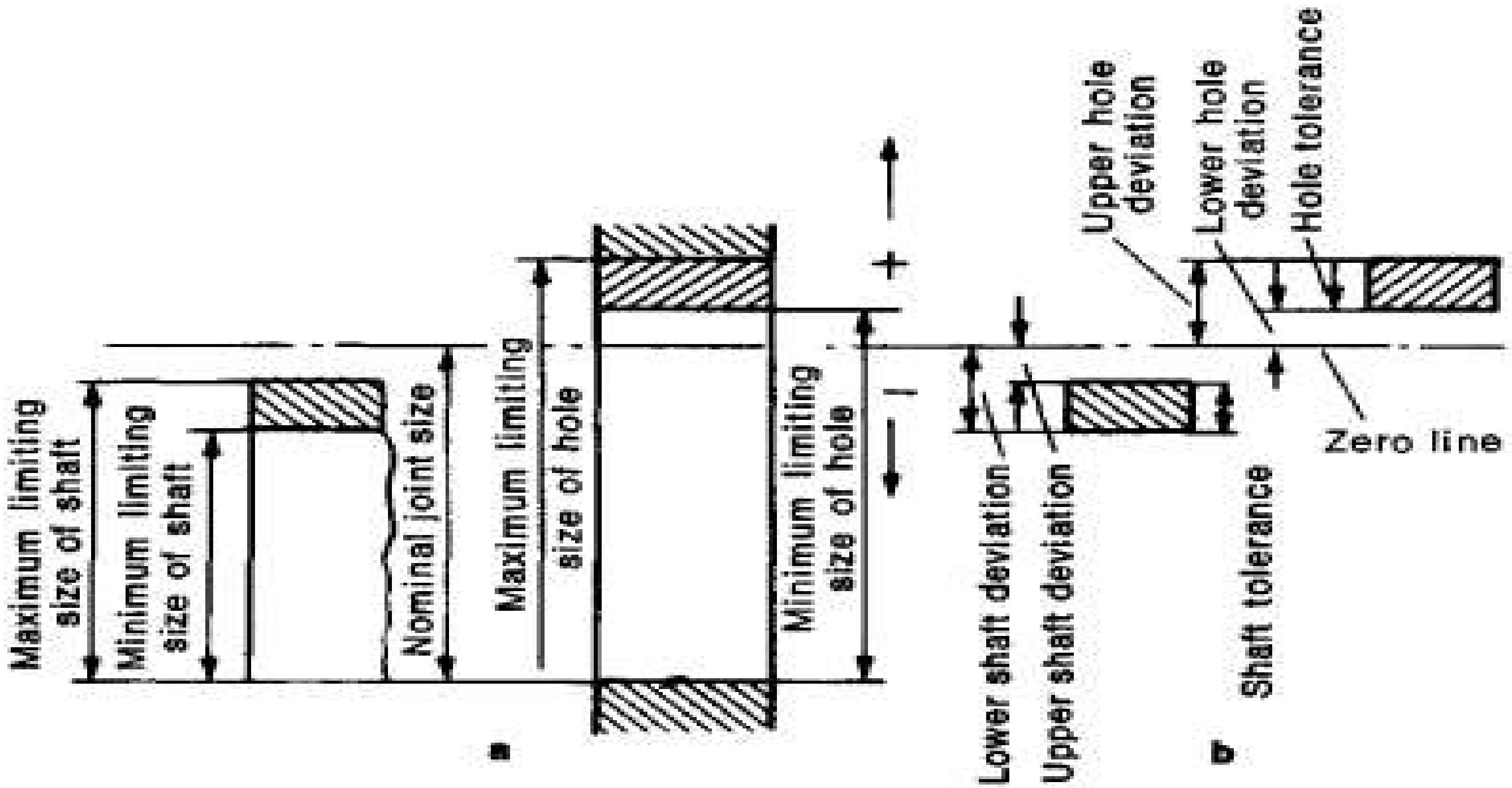
DEVIATION

LOWER DEVIATION: It is the algebraic difference between the minimum limit of size and the basic size.

UPPER DEVIATION: It is the algebraic difference between the maximum limit and the basic size.

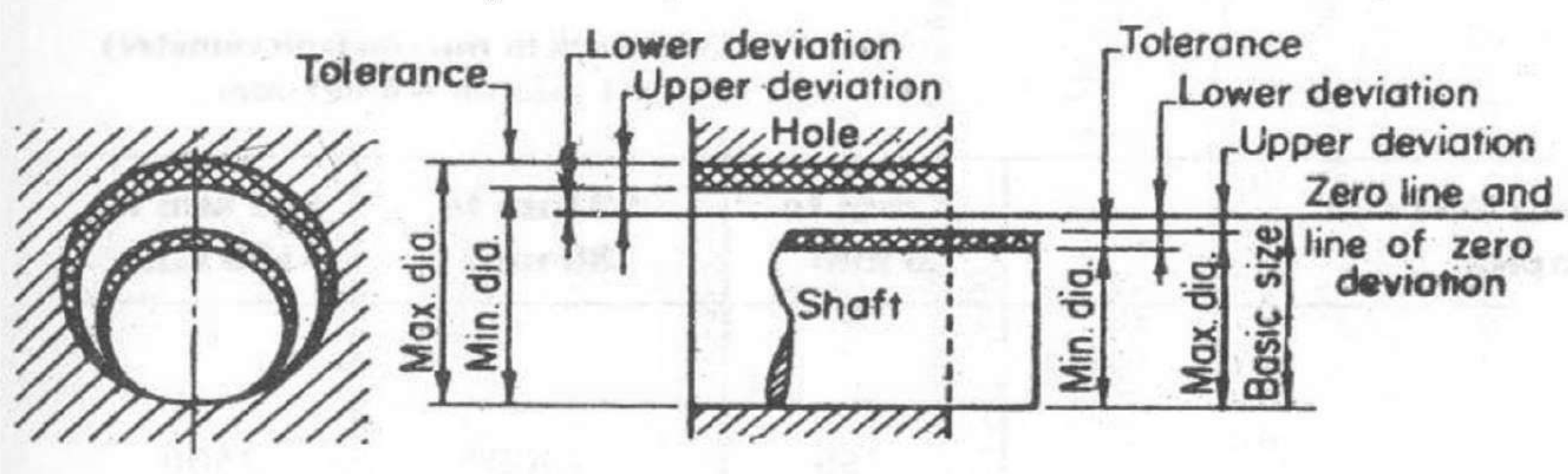
ZERO LINE

It is the straight line corresponding to the basic size. The deviations are measured from this line.



Tolerance

- A tolerance is the total permissible variation from the specified basic size of the part.



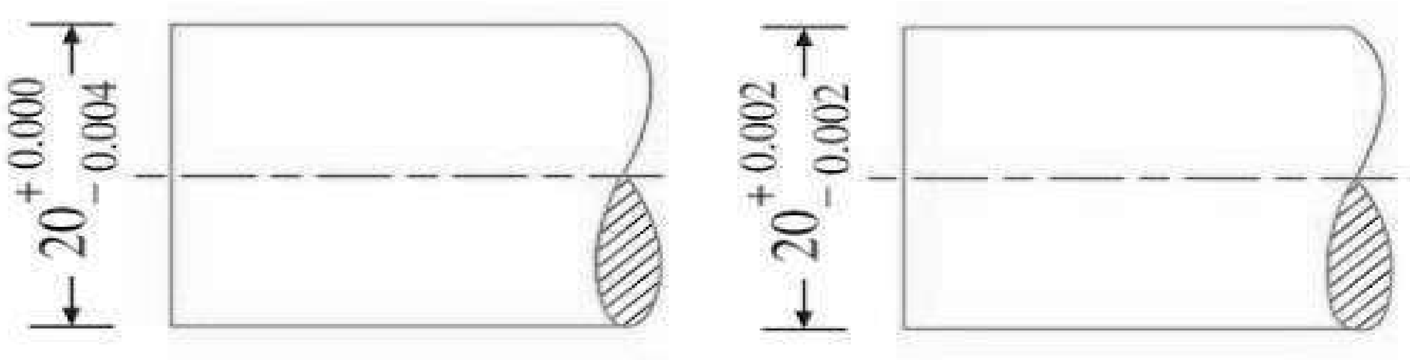
POSITIONAL TOLERANCES

Two types of positional tolerances are used:

Unilateral tolerances

Bilateral tolerances

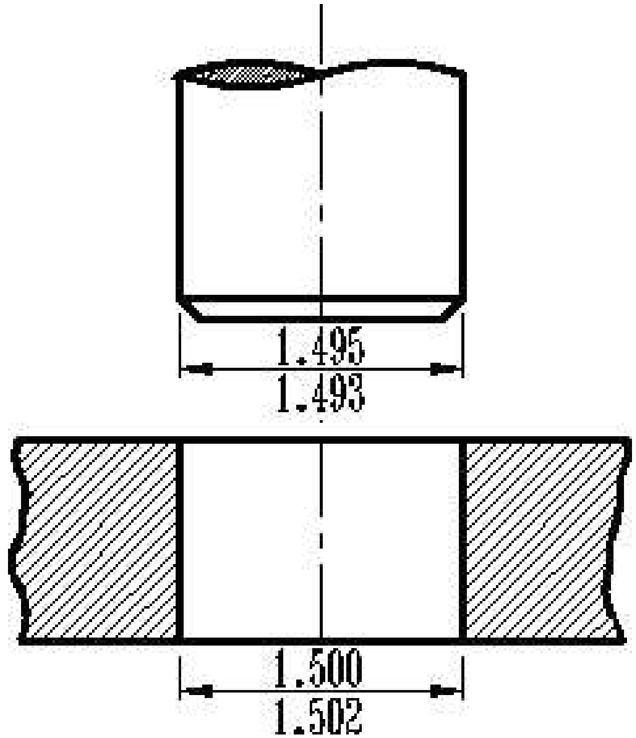
When tolerance is on one side of basic size, it is called unilateral and if it is both in plus and minus then it is known as bilateral tolerance.



(*a*) Unilateral tolerance (*b*) Bilateral tolerance.

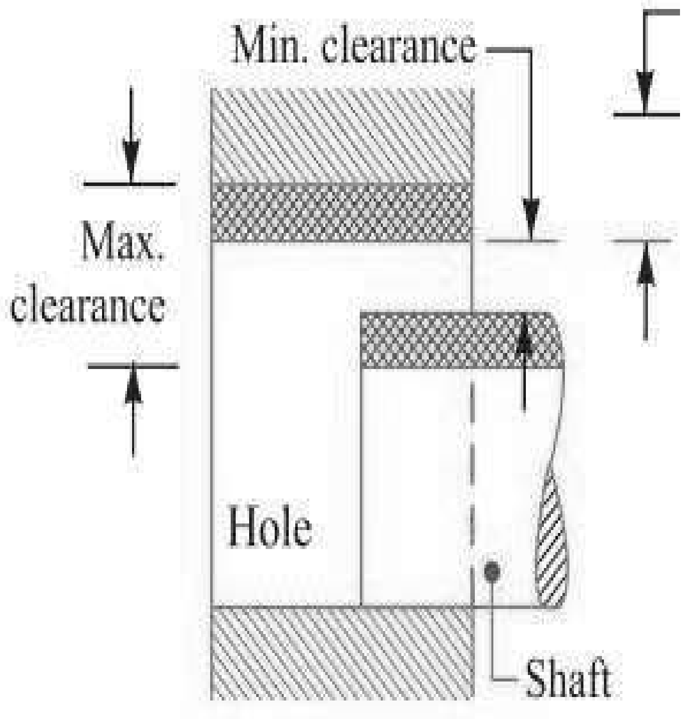
FITS

The degree of tightness or looseness between two mating parts is called a fit.



TYPES OF FITS

CLEARANCE FIT: There is a clearance or looseness in this type of fits. These fits maybe slide fit, easy sliding fit, running fit etc**.**

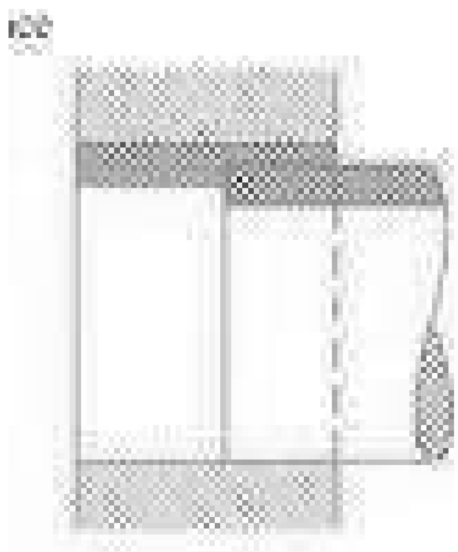


(*a*) Clearance fit.

TYPES OF FITS

INTERFERENCE FIT: There is an interference or tightness in these type of fits. E.g. shrink fit, heavy drive fit etc.

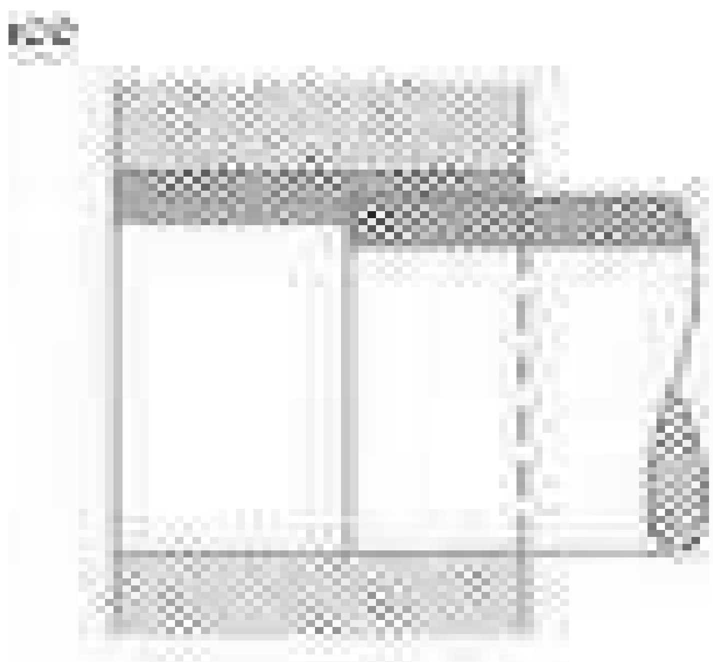
TRANSITION FIT: In this type of fit, the limits for the mating parts are so selected that either a clearance or interference may occur depending upon the actual size of the mating parts.



(c) Transition fit.

TYPES OF FITS

TRANSITION FIT: In this type of fit, the limits for the mating parts are so selected that either a clearance or interference may occur depending upon the actual size of the mating parts.



(c) Transition fit.

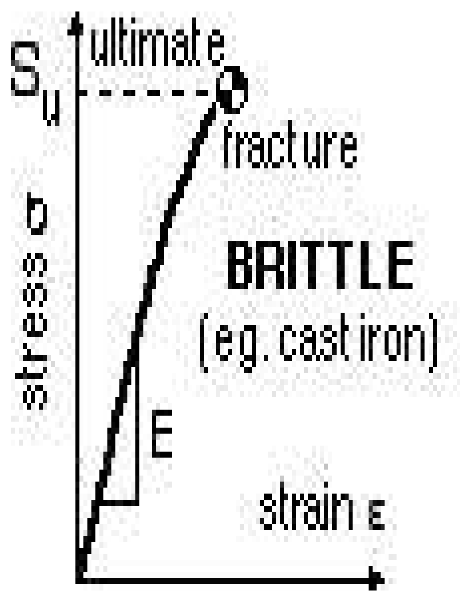
Factor of Safety (Safety Factor)

Eg: If a component needs to withstand a load of 100 N and a FoS of 3 is selected then it is designed with strength to support 300 N.

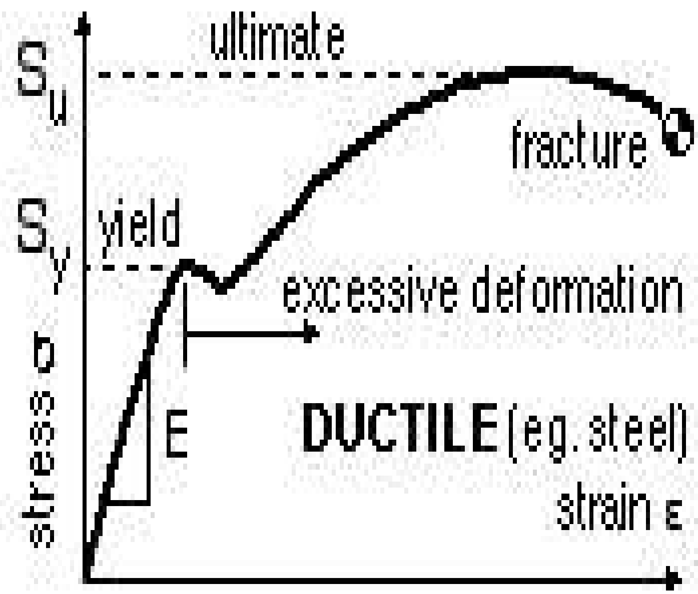
$$\text{FoS} = \frac{\text{Strength of the component (Max load)}}{\text{Load on the component (Actual load)}}$$

Factor of Safety (Safety Factor)

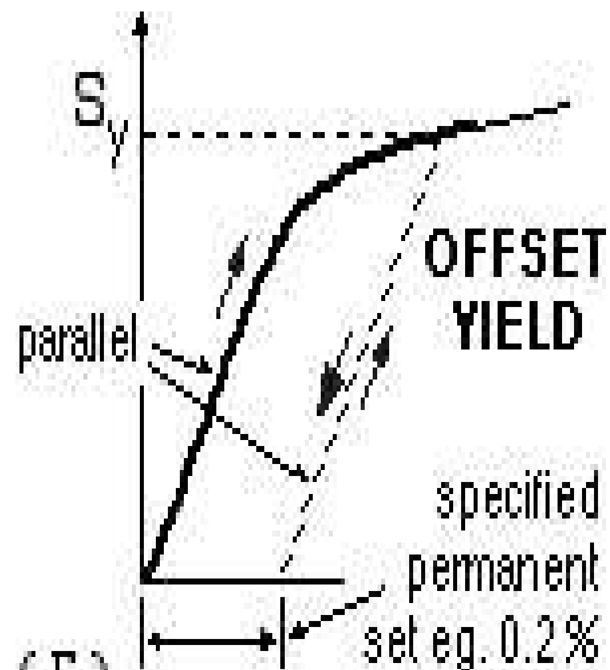
FoS (*Based on yeild strength*)	Application
1.25 - 1.5	Material properties known in detail Operating conditions known in detail Load and the resulting stresses and strains are known to a high degree of accuracy Low weight is important
2 - 3	For less tried materials or Brittle materials under average conditions of environment, load and stress
3 - 4	For untried materials under average conditions of environment, load and stress Better known materials under uncertain environment or uncertain stresses


S
u
ultimate
fracture
stress σ
BRITTLE
(eg. cast iron)
E
strain ε

(D)


S
u
ultimate
fracture
S
y
yield
excessive deformation
stress σ
E
DUCTILE (eg. steel)
strain ε

(E)


S
y
OFFSET
YIELD
parallel
specified
permanent
set eg. 0.2%

(F)

$$\text{FoS} = \frac{\text{Strength of the component } (S_u, S_y)}{\text{Stress in the component due to the actual load}}$$

- The cost factor (cost of material, manufacture)
- Whether failure could cause serious injury or death (a steam boiler or pressure vessel would use 8 – 10 FoS)
- Unknown stresses in the manufacturing process (casting would use 10 – 14 FoS)
- Environmental conditions (used in harsh environment or not)
- Knowledge of the environment
- Knowledge of the properties of the material used
- Knowledge of the loads (tension, compressive, shear, bending, cyclic loads, impact loads etc)
- Weight factor (aerospace 1.5 – 3 to reduce weight but strict quality control)
- Quality control, maintenance

Genesis of BIS

Government of India resolution on 3 September 1946 for establishment of Indian Standards Institution.

Indian Standards Institution (predecessor of Bureau of Indian Standards)set up on 6 January 1947.

Objectives : Promoting standardization ,quality control and simplification in industry & commerce.

Bureau of Indian Standards (BIS)Established on 1 April 1987 under BIS act, 1986 as statutory body

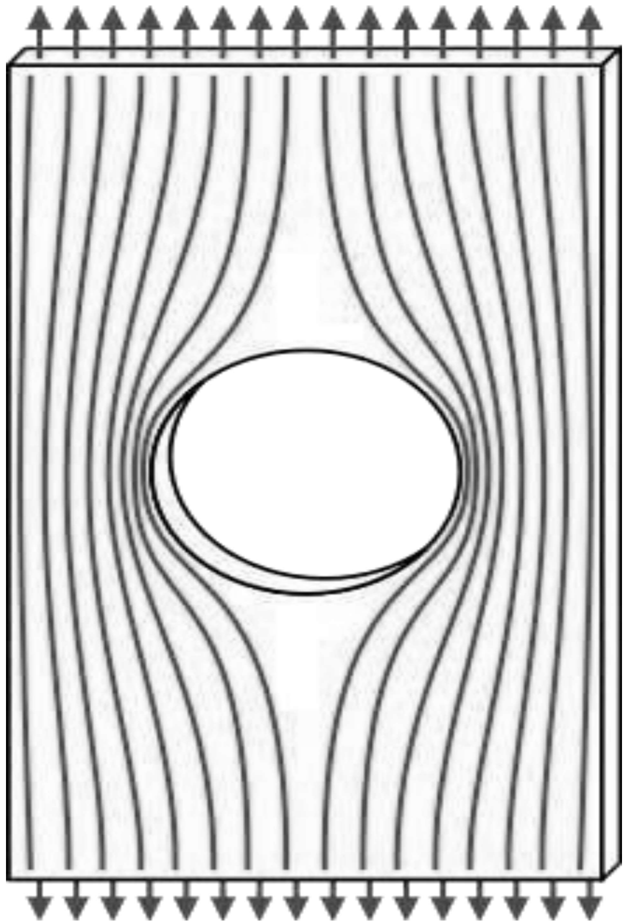
Bureau of Indian Standards

- Bureau of Indian Standards (BIS) took over work of ISI through enactment of ***BIS Act (1986)*** by the Indian Parliament.
- Formulates National standards and carried out conformity assessment by operating the Product and Management System Certification Scheme.
- Formulated over 18000 National Standards and also operating more than 22000 Certification licenses.
- Project India’s view in various committees of International Organization for Standardization (ISO) and International Electro technical Commission (IEC)

Stress Concentration

- Whenever a machine component changes the shape of its cross-section, the simple stress distribution no longer holds good and the neighborhood of the discontinuity is different. This irregularity in the stress distribution caused by abrupt changes of form is called ***stress concentration.***
- A **stress concentration (stress raisers** or **stress risers)** is a location in an object where stress is concentrated. An object is strongest when force is evenly distributed over its area, so a reduction in area, e.g., caused by a crack, results in a localized increase in stress.
- A material can fail, via a propagating crack, when a concentrated stress exceeds the material's theoretical cohesive strength. The real fracture strength of a material is always lower than the theoretical value because most materials contain small cracks or contaminants (especially foreign particles) that concentrate stress.
- It occurs for all kinds of stresses in the presence of fillets, notches, holes, keyways, splines, surface roughness or scratches etc.

Internal Force lines are denser near the hole



Theoretical or Form Stress Concentration Factor

- The theoretical or form stress concentration factor is defined as the ratio of the maximum stress in a member (at a notch or a fillet) to the nominal stress at the same section based upon net area.
- Mathematically, theoretical or form stress concentration factor,
- The value of *Kt* depends upon the material and geometry of the part.

$$K_t = \frac{\text{Maximum stress}}{\text{Nominal stress}}$$

Fatigue Stress Concentration Factor

- When a machine member is subjected to cyclic or fatigue loading, the value of fatigue stress concentration factor shall be applied instead of theoretical stress concentration factor.
- Mathematically, fatigue stress concentration factor,

$$K_f = \frac{\text{Endurance limit without stress concentration}}{\text{Endurance limit with stress concentration}}$$

Notch Sensitivity

- **Notch Sensitivity:** It may be defined as the degree to which the theoretical effect of stress concentration is actually reached.
- **Notch Sensitivity Factor "q":** Notch sensitivity factor is defined as the ratio of increase in the actual stress to the increase in the nominal stress near the discontinuity in the specimen.

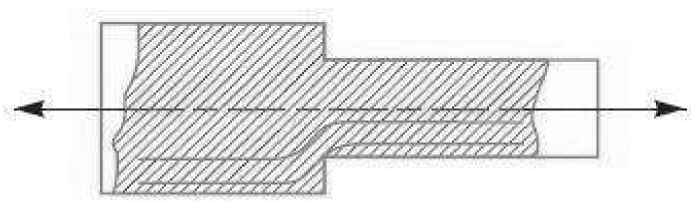
  Where, Kf and Kt are the fatigue stress concentration factor and theoretical stress concentration factor.
- The stress gradient depends mainly on the radius of the notch, hole or fillet and on the grain size of the material.

$$q = \frac{K_f - 1}{K_t - 1}$$

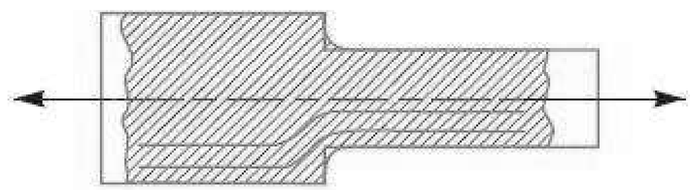
Methods to reduce stress concentration

- The presence of stress concentration can not be totally eliminated but it may be reduced to some extent.
- A device or concept that is useful in assisting a design engineer to visualize the presence of stress concentration and how it may be mitigated is that of stress flow lines.
- The mitigation of stress concentration means that the stress flow lines shall maintain their spacing as far as possible.

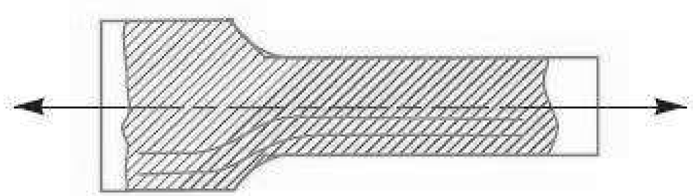
- In Fig. (a), we see that stress lines tend to bunch up and cut very close to the sharp re-entrant corner. In order to improve the situation, fillets may be provided, as shown in Fig. (*b*) and (*c*) to give more equally spaced flow lines.
- It may be noted that it is not practicable to use large radius fillets as in case of ball and roller bearing mountings. In such cases, notches may be cut as shown in Fig. (*d*).



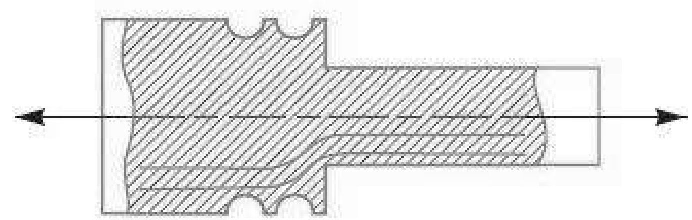
(*a*) Poor



(*b*) Good

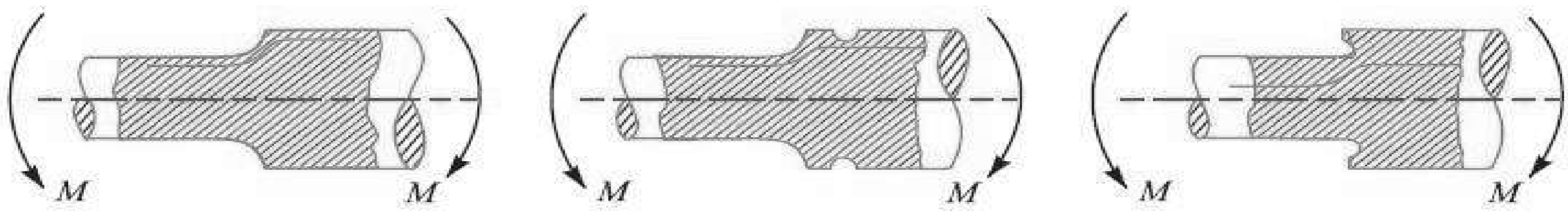


(*c*) Preferred



(*d*) Preferred

Following figures show the several ways of reducing the stress concentration in shafts and other cylindrical members with shoulders

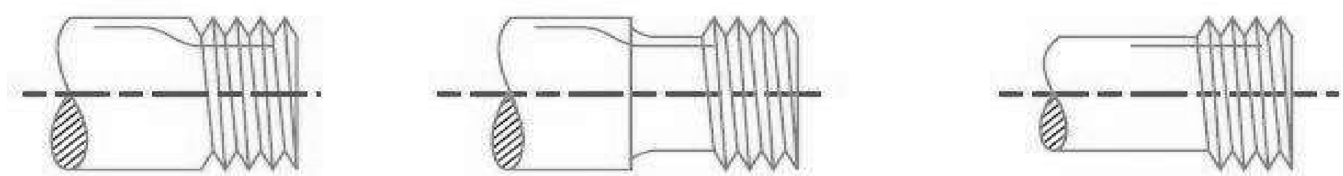


(*a*) Poor (*b*) Good (*c*) Preferred

Fig. 6.9. Methods of reducing stress concentration in cylindrical members with shoulders.

(*a*) Poor (*b*) Preferred

Fig. 6.10. Methods of reducing stress concentration in cylindrical members with holes.



(*a*) Poor (*b*) Good (*c*) Preferred

Fig. 6.11. Methods of reducing stress concentration in cylindrical members with holes.

Factors to be Considered while Designing Machine Parts to Avoid Fatigue Failure

- The following factors should be considered while designing machine parts to avoid fatigue failure:

1. The variation in the size of the component should be as gradual as possible.
2. The holes, notches and other stress raisers should be avoided.
3. The proper stress de-concentrators such as fillets and notches should be provided wherever necessary.
4. The parts should be protected from corrosive atmosphere.
5. A smooth finish of outer surface of the component increases the fatigue life.
6. The material with high fatigue strength should be selected.
7. The residual compressive stresses over the parts surface increases its fatigue strength.

Endurance limit and Fatigue failure

- It has been found experimentally that when a material is subjected to repeated stresses, it fails at stresses below the yield point stresses. Such type of failure of a material is known as **fatigue.**
- The failure is caused by means of a progressive crack formation which are usually fine and of microscopic size. The failure may occur even without any prior indication.
- The fatigue of material is effected by the size of the component, relative magnitude of static and fluctuating loads and the number of load reversals.

Factors affecting endurance limit

1) SIZE EFFECT:

- The strength of large members is lower than that of small specimens.
  This may be due to two reasons.
- The larger member will have a larger distribution of weak points than the smaller one and on an average, fails at a lower stress.
- Larger members have larger surface Ares. This is important because the imperfections that cause fatigue failure are usually at the surface.

2) SURFACE ROUGHNESS:

- Almost all fatigue cracks nucleate at the surface of the members.
- The conditions of the surface roughness and surface oxidation or corrosion are very important.
- Experiments have shown that different surface finishes of the same material will show different fatigue strength.
- Methods which Improve the surface finish and those which introduce compressive stresses on the surface will improve the fatigue strength.
- Smoothly polished specimens have higher fatigue strength.
- Surface treatments. Fatigue cracks initiate at free surface, treatments can be significant
- Plating, thermal or mechanical means to induce residual stress

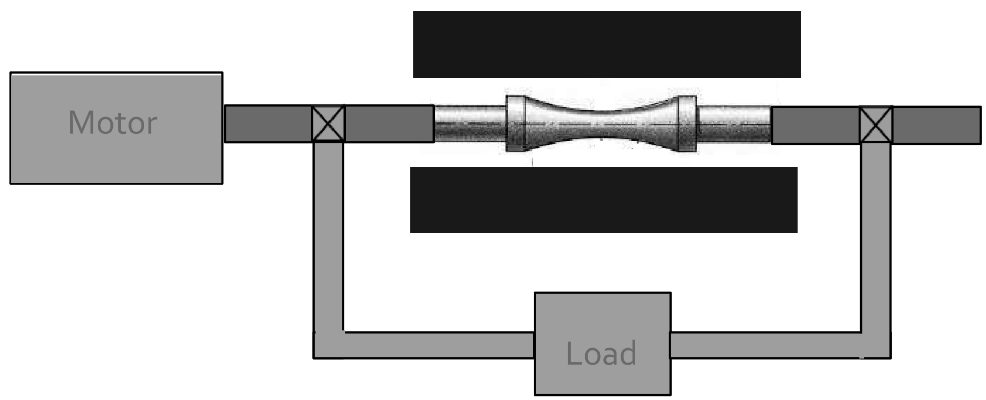
S-N Diagram

Fatigue strength of material is determined by R.R. Moore rotating beam machine. The surface is polished in the axial direction.

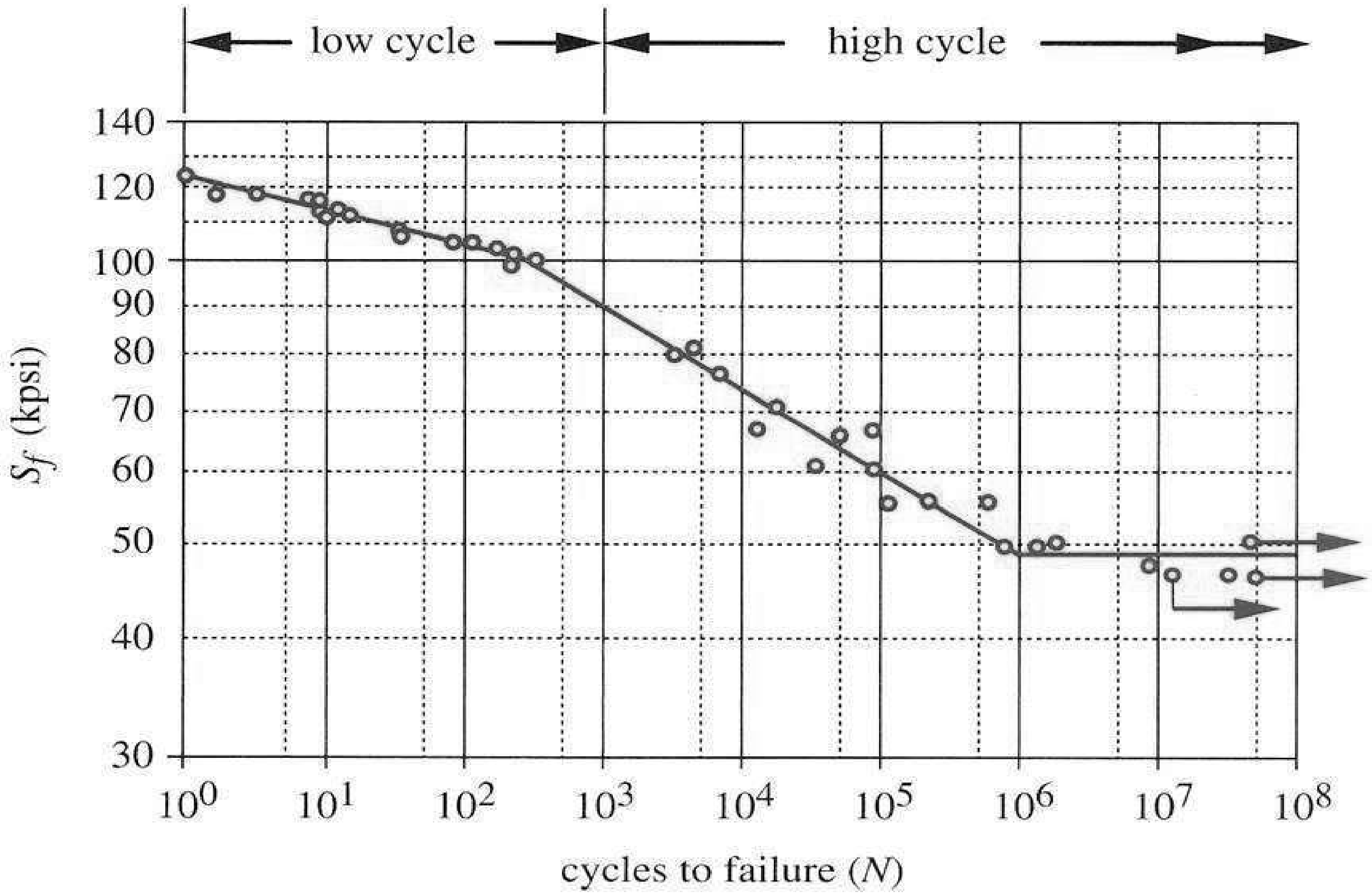
A constant bending load is applied.

The surface is polished in the axial direction. A constant bending load is applied.

Typical testing apparatus, pure bending



- A record is kept of the number of cycles required to produce failure at a given stress, and the results are plotted in stress-cycle curve as shown in figure.
- A little consideration will show that if the stress is kept below a certain value the material will not fail whatever may be the number of cycles.
- This stress, as represented by dotted line, is known as ***endurance*** or ***fatigue limit*** (σe).
- It is defined as maximum value of the completely reversed bending stress which a polished standard specimen can withstand without failure, for infinite number of cycles (usually 107 cycles).


low cycle
high cycle
140
120
100
90
80
70
60
50
40
30
S_f (kpsi)
10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^7
10^8
cycles to failure (N)

Correction Factors for Specimen's Endurance Limit

$S_e = k_a k_b k_c k_d k_e k_f S_e'$

Where S_e = endurance limit of component

S_e' = endurance limit experimental

k_a = surface finish factor (machined parts have different finish)

k_b = size factor (larger parts greater probability of finding defects)

k_c = reliability / statistical scatter factor (accounts for random variation)

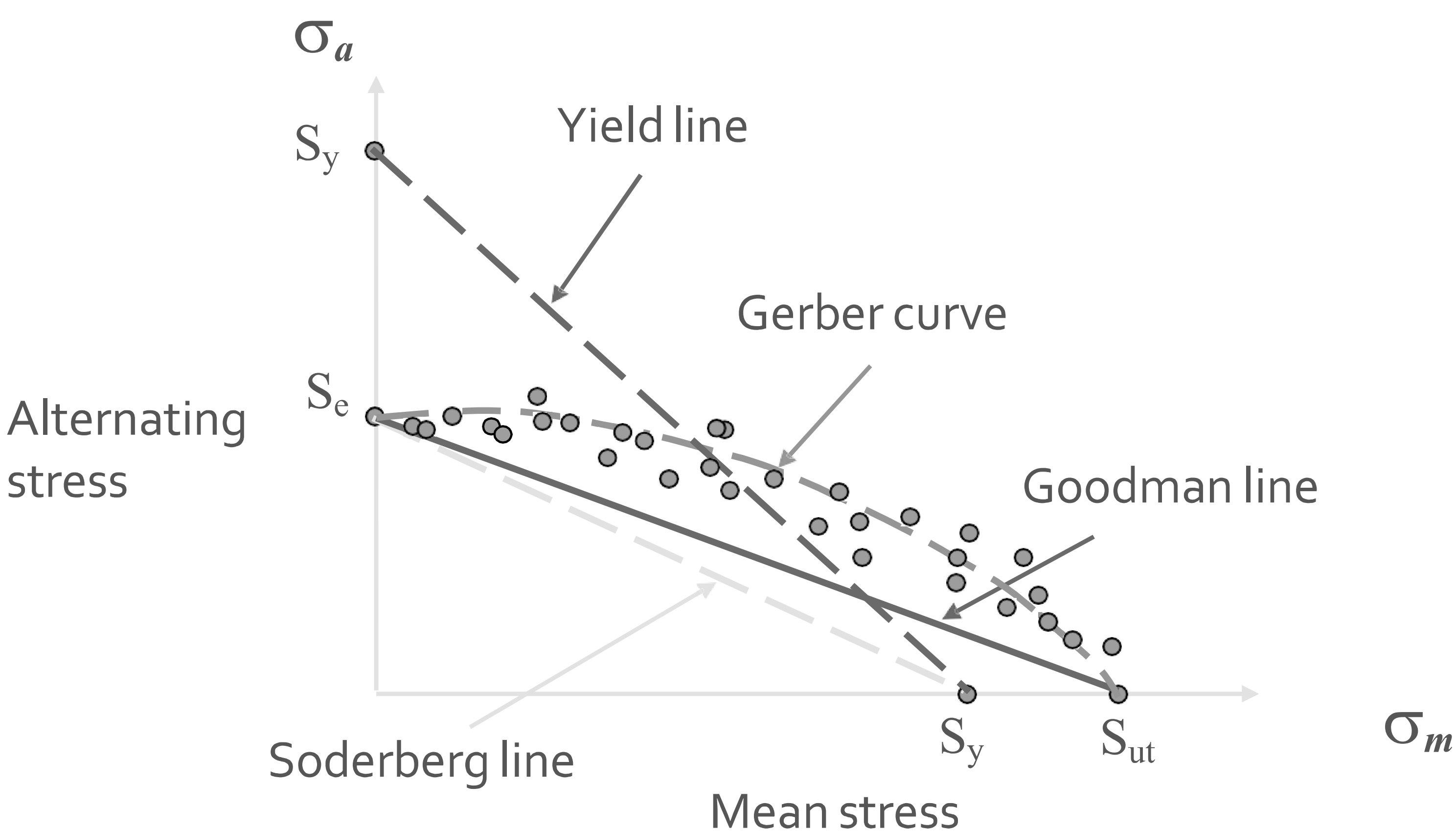
k_d = loading factor (differences in loading types)

k_e = operating T factor (accounts for diff. in working T & room T)

k_f = stress concentration factor

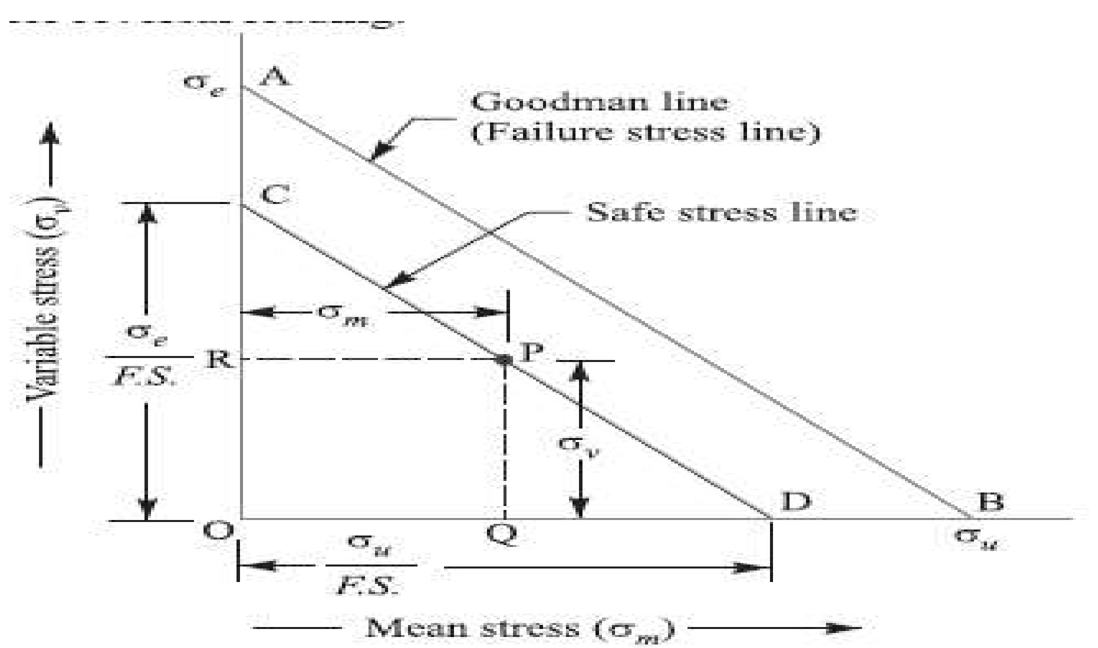
Fluctuating stresses

- The failure points from fatigue tests made with different steels and combinations of mean and variable stresses are plotted in figure as functions of stress amplitude(σa) and mean stress (σm).
- The most significant observation is that, in general, the failure point is little related to the mean stress when it is compressive but is very much a function of the mean stress when it is tensile.
- In practice, this means that fatigue failures are rare when the mean stress is compressive (or negative). Therefore, the greater emphasis must be given to the combination of a variable stress and a steady (or mean) tensile stress.


σa
Sy
Yield line
Gerber curve
Se
Alternating
stress
Goodman line
Sy
Sut
σm
Soderberg line
Mean stress

Goodman Method for Combination of Stresses:

A straight line connecting the endurance limit (σ*e*) and the ultimate strength (σ*u*), as shown by line *AB* in figure given below follows the suggestion of Goodman.
A Goodman line is used when the design is based on ultimate strength and may be used for ductile or brittle materials.



Now from similar triangles COD and PQD,

$$\frac{PQ}{CO} = \frac{QD}{OD} = \frac{OD - OQ}{OD} = 1 - \frac{OQ}{OD} \qquad \ldots(\because\ QD = OD - OQ)$$

$$\therefore \qquad \frac{\sigma_v}{\sigma_e / F.S.} = 1 - \frac{\sigma_m}{\sigma_u / F.S.}$$

$$\sigma_v = \frac{\sigma_e}{F.S.}\left[1 - \frac{\sigma_m}{\sigma_u / F.S.}\right] = \sigma_e\left[\frac{1}{F.S.} - \frac{\sigma_m}{\sigma_u}\right]$$

or

$$\frac{1}{F.S.} = \frac{\sigma_m}{\sigma_u} + \frac{\sigma_v}{\sigma_e} \qquad \ldots(i)$$

Soderberg Method for Combination of Stresses

- A straight line connecting the endurance limit (σe) and the yield strength (σy), as shown by the line *AB* in following figure, follows the suggestion of Soderberg line.
- This line is used when the design is based on yield strength. the line *AB* connecting σe and σy, as shown in following figure, is called ***Soderberg's failure stress line***.