Course: Machine Design-I: MEC-212

Unit-I Design against Fluctuating Load

UNIT-I

Introduction: Systematic Design Process (SDP), Basic principles for mechanical design, Use of standards. Manufacturing consideration in design of casting & machining parts.
Dynamic and fluctuating stresses, fatigue failure and endurance limit, design under combined direct & varying stresses. Stress concentration, causes and remedies in design.
Factor of safety and it's affecting factors, Tolerances and fits as per BIS, Materials selection, Designation of steels.
Detailed design procedure of Spigot & Socket Cotter joint, Knuckle joint, Pipe joint. Numerical Design Problems.

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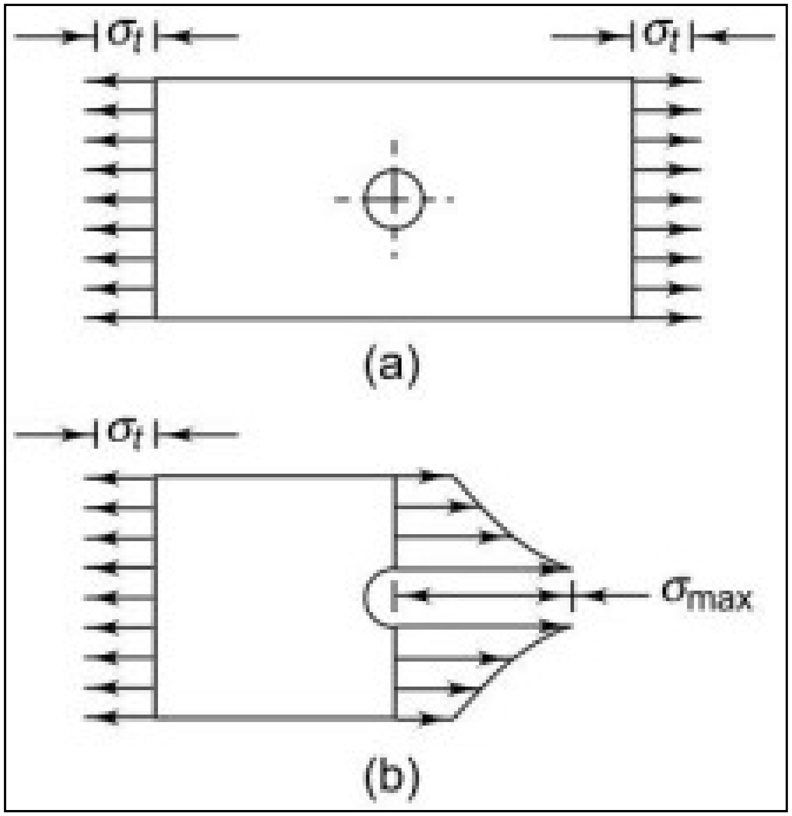
STRESS CONCENTRATION

• Basic SOM equations are based on the assumption that there are no discontinuities in the cross-section of the component

• However, in practice, discontinuities and abrupt changes in cross-section are unavoidable due to certain features of the component such as **oil holes and grooves, keyways and splines, screw threads and shoulders**.

• Therefore, it cannot be assumed that the cross-section of the machine component is uniform. Under these circumstances, the SOM equations do not give correct results.



Stress concentration is defined as the localization of high stresses due to the irregularities present in the component and abrupt changes of the cross section.

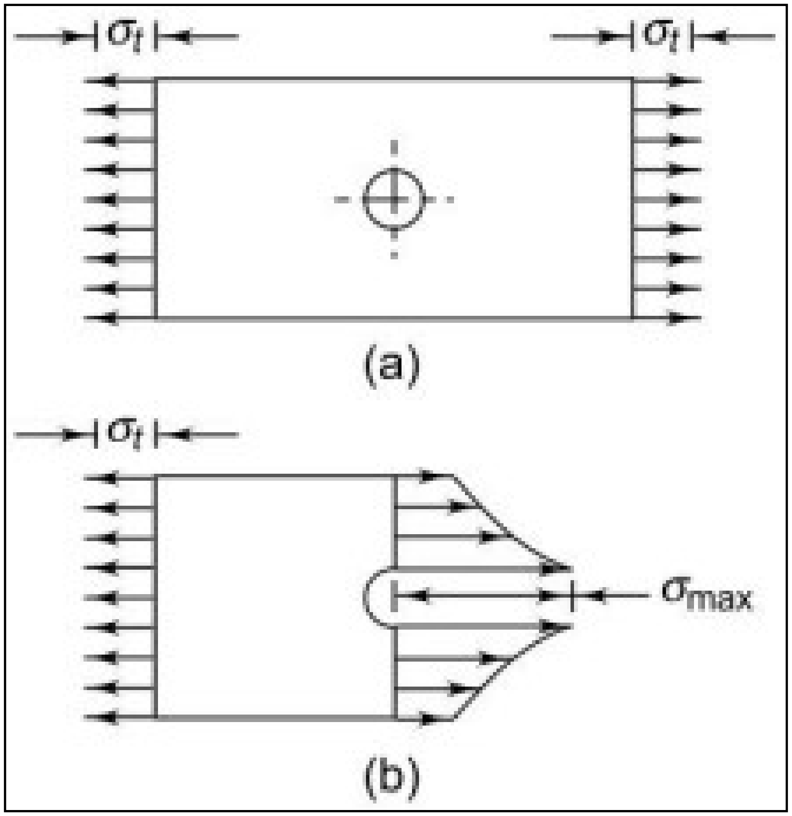
STRESS CONCENTRATION FACTOR (K_t)

- In order to consider the effect of stress concentration and find out localized stresses, a factor called stress concentration factor is used. It is denoted by K_t and defined as:

$$K_t = \frac{\text{Highest value of actual stress near discontinuity}}{\text{Nominal stress obtained by elementary equations for minimum croos} - \text{section}}$$

$$K_t = \frac{\sigma_{max.}}{\sigma_0} = \frac{\tau_{max.}}{\tau_0}$$

where σ_0 and τ_o are stresses determined by basic SOM equations and $\sigma_{max.}$ and $\tau_{max.}$ are localized stresses at the discontinuities. The subscript 't' denotes the **'theoretical'** stress concentration factor. The magnitude of stress concentration factor depends upon the geometry of the component.



CAUSES OF STRESS CONCENTRATION

1. Variation in Properties of Materials:

- Internal cracks and flaws like blow holes
- cavities in welds
- air holes in steel components
- nonmetallic or foreign inclusions.

2. Load Application

- Contact between the meshing teeth of the driving and the driven gear
- Contact between the cam and the follower
- Contact between the balls and the races of ball bearing
- Contact between the rail and the wheel
- Contact between the crane hook and the chain

3. Abrupt Changes in Section: Steps cut on the shaft and shoulders to mount gears, sprockets, pulleys and ball bearings

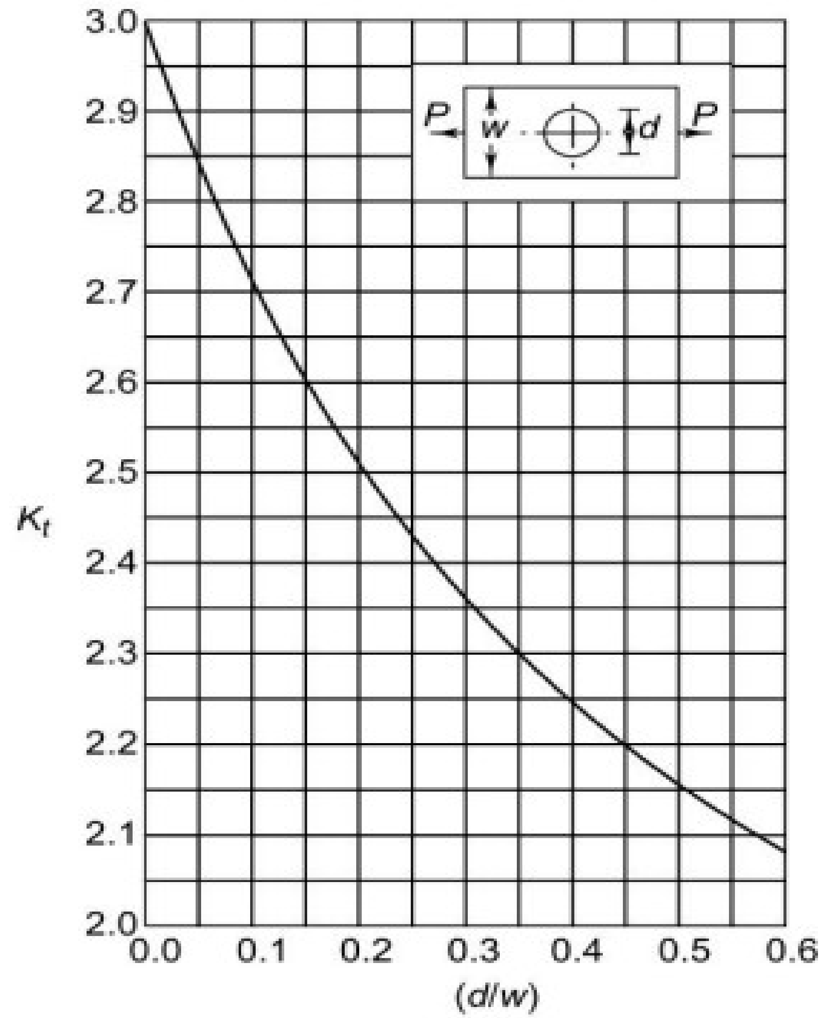
4. Discontinuities in the Component: Oil holes or oil grooves, keyways and splines, and screw threads

5. Machining Scratches: Machining scratches, stamp marks or inspection marks

STRESS CONCENTRATION FACTORS

- The stress concentration factors are determined by two methods, viz., **the mathematical method based on the theory of elasticity and experimental methods like photo-elasticity**.
- For simple geometric shapes, the stress concentration factors are determined by photoelasticity.
- The chart for the stress concentration factor for a rectangular plate with a transverse hole loaded in tension or compression is shown. The nominal stress σ_0 in this case is given by,

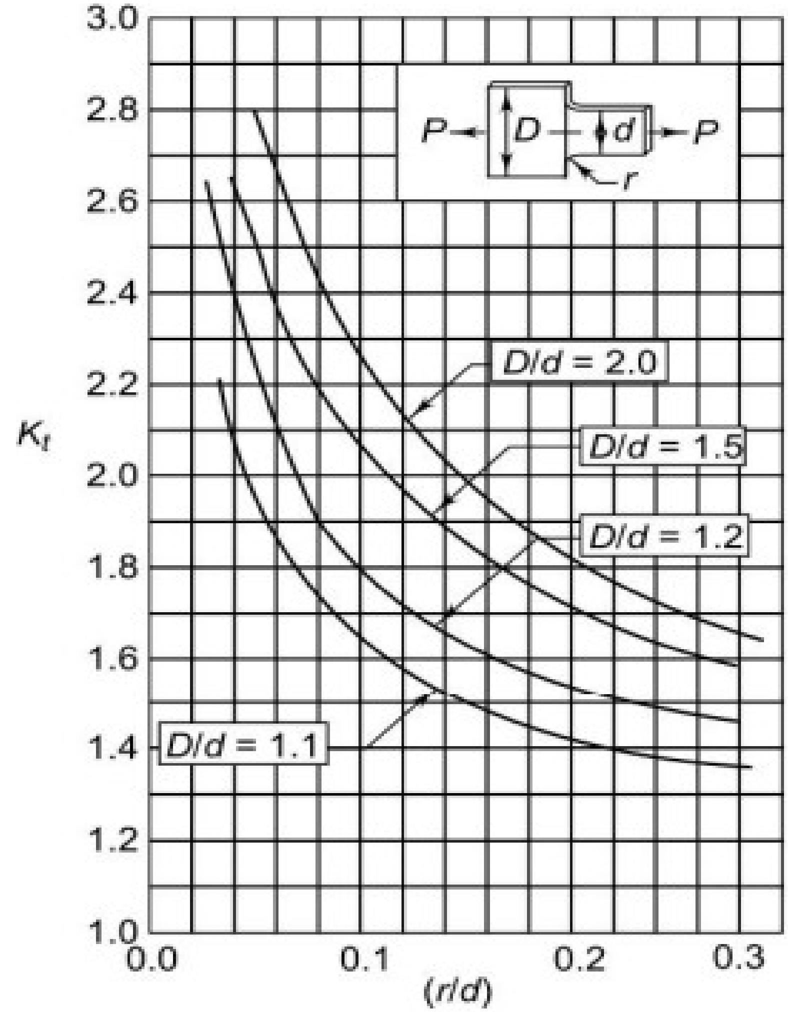
$$\sigma_o = \frac{P}{(w-d)t}$$



STRESS CONCENTRATION FACTORS

• The values of stress concentration factor for a flat plate with a shoulder fillet subjected to tensile or compressive force are determined. The nominal stress σ_0 for this case is given by

$$\sigma_o = \frac{P}{dt}$$



SCF for a round Shaft With Shoulder Fillet subjected To Tensile Force, Bending, And Torsion

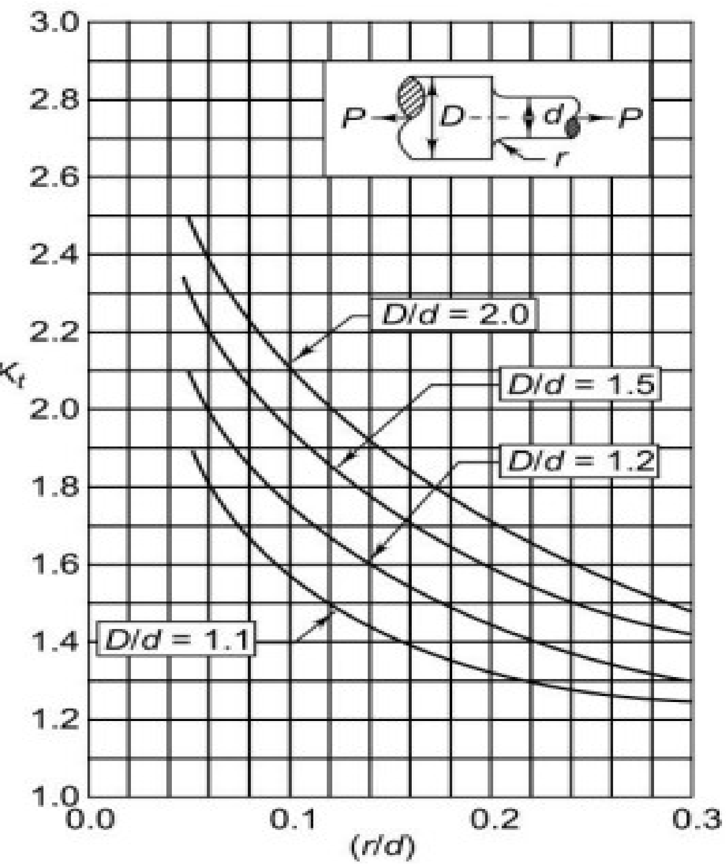
$$\sigma_o = \frac{P}{\left(\frac{\pi}{4} d^2\right)}$$

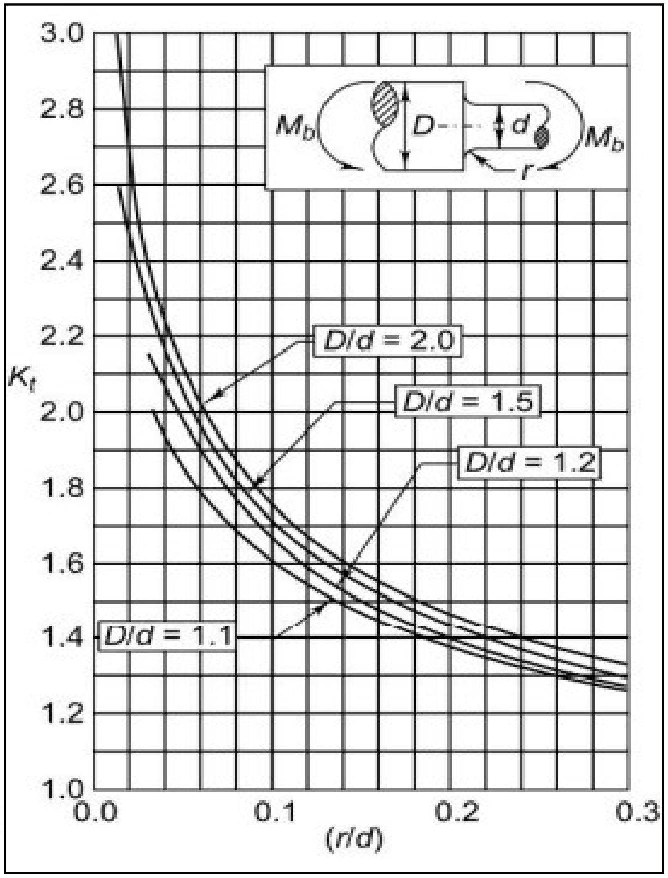
$$\sigma_o = \frac{M_b\, y}{I}$$

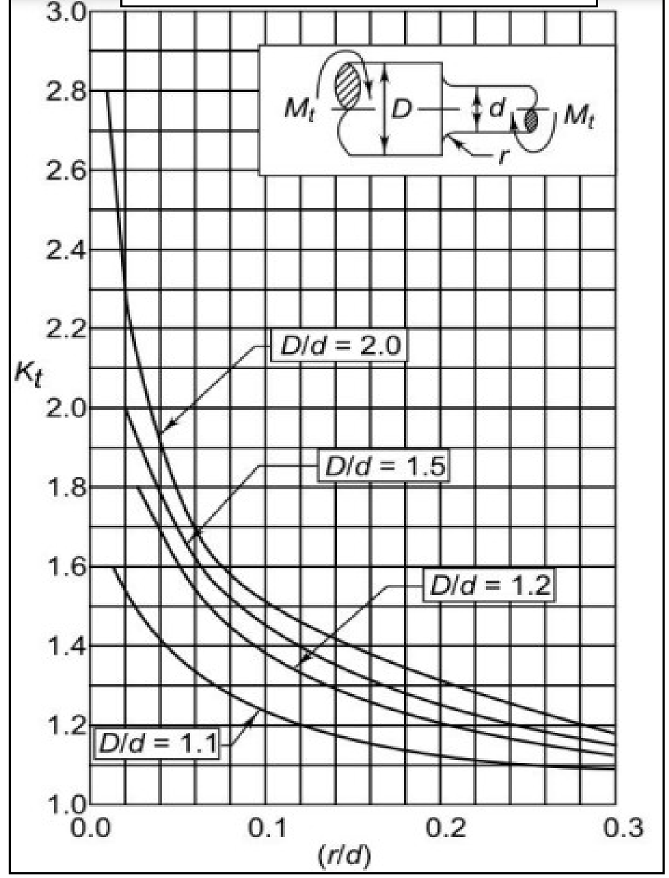
where $I = \frac{\pi d^4}{64}$ and $y = \frac{d}{2}$

$$\tau_o = \frac{M_t\, r}{J}$$

where, $J = \frac{\pi d^4}{32}$ and $r = \frac{d}{2}$







Theoretical Stress Concentration Factor (K_t)

- The stress concentration charts are based on either the **photo-elastic analysis of the epoxy models using a circular polariscope or theoretical** or finite element analysis of the mathematical model. That is why the factor is called theoretical stress concentration factor.
- The model is made of a different material than the actual material of the component. The ductility or brittleness of the material has a pronounced effect on its response to stress concentration. Also, **the type of load**— whether **static or cyclic—**affects the severity of stress concentration.
- Therefore, there is a difference between the **stress concentration indicated by the theoretical stress concentration factor** and **the actual stress concentration in the component.**

Stress Concentration in case of Brittle materials

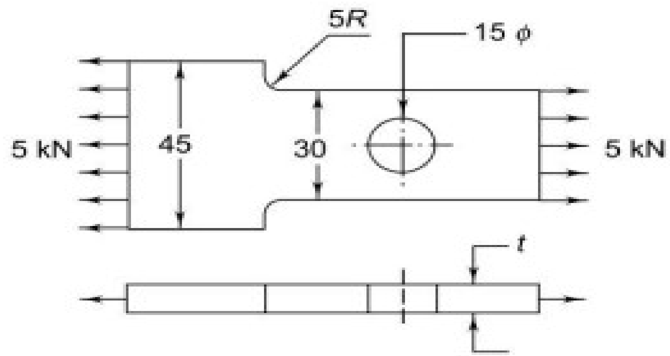
- The effect of stress concentration is more severe in case of brittle materials, due to their inability of plastic deformation.
- Brittle materials do not yield locally and there is no readjustment of stresses at the discontinuities. Once the local stress at the discontinuity reaches the fracture strength, a crack is formed. This reduces the material available to resist external load and also increases the stress concentration at the crack. The part then quickly fails.
- Therefore, SCFs are used for components made of **brittle materials subjected to both static load as well as fluctuating load.**

Stress Concentration in case of ductile material

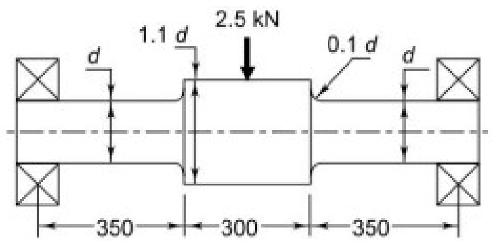
1. **Under a static load**, ductile materials are not much affected by the stress concentration. When the stress in the vicinity of the discontinuity reaches the yield point, there is plastic deformation, resulting in a **redistribution of stresses**. This plastic deformation or yielding is local and restricted to a very small area in the component. There is no perceptible damage to the part as a whole. Therefore, it is common practice to **ignore the theoretical SCF** for components that are made of **ductile materials and subjected to static load**.
2. **When the load is fluctuating**, the stress at the discontinuities may exceed the **endurance limit** and in that case, the component may fail by **fatigue**. Therefore, endurance limit of the components made of ductile material is greatly reduced due to stress concentration. This accounts for the use of SCFs for ductile components. However, some materials are more sensitive than others to stress raising notches under a fluctuating load. To account for this effect, a parameter called **notch sensitivity factor** is found for each material. The notch sensitivity factor is used to modify the theoretical SCF.

Numericals

A flat plate subjected to a tensile force of 5 kN is shown. The plate material is grey cast iron FG 200 and the factor of safety is 2.5. Determine the thickness of the plate.

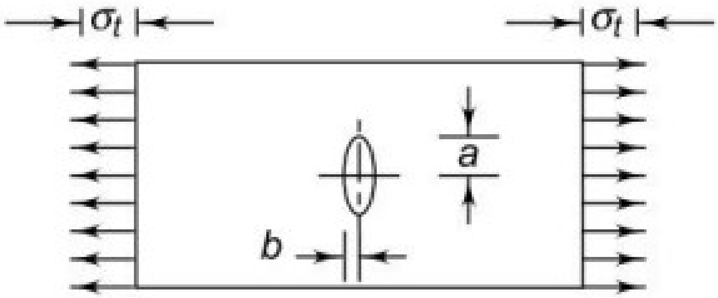


A non-rotating shaft supporting a load of 2.5 kN is shown in Fig. 5.14. The shaft is made of brittle material, with an ultimate tensile strength of 300 N/mm2. The factor of safety is 3. Determine the dimensions of the shaft.



Stress Concentration due to Elliptical Hole

$$K_t = 1 + 2\left(\frac{a}{b}\right)$$



where, a = half width (or semi-major axis) of the ellipse perpendicular to the direction of the load

b = half width (or semi-minor axis) of the ellipse in the direction of the load

- As b approaches zero, the ellipse becomes sharper and sharper. A very sharp crack is indicated and the stress at the edge of the crack becomes very large.

$K_t = \infty$ when b=0

- Theoretical stress concentration factor due to a small circular hole in a flat plate, which is subjected to tensile force, is 3.

$$K_t = 1 + 2\left(\frac{a}{b}\right) = 1 + 2 = 3$$

Fatigue Stress Concentration Factor (K_f)

- K_t is the theoretical stress concentration factor is applicable to ideal materials that are homogeneous, isotropic and elastic.
- Experiments have shown that the actual stress concentration factor in fatigue, K_f is less than K_t.
- It depends on the size of the stress concentration and the material.
- K_f is applicable to actual materials and depends upon the grain size of the material. It is observed that there is a greater reduction in the endurance limit of fine-grained materials as compared to coarse-grained materials, due to stress concentration.
- K_f is calculated by using K_t and notch sensitivity factor (q).

Notch Sensitivity Factor (q)

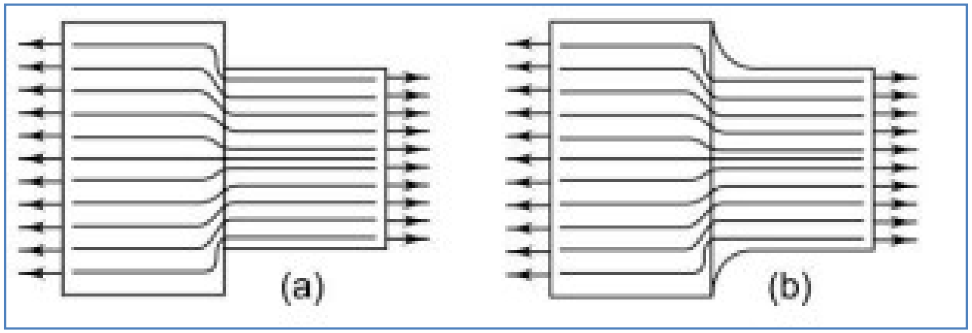
- The notch sensitivity of a material is a measure of how sensitive a material is to notches or geometric discontinuities.
- It is defined as the ratio of increase of actual stress over nominal stress and increase of theoretical stress over nominal stress.

$$K_f = 1 + q(K_t - 1)$$

- When the material has no sensitivity to notches, $q = 0$ and $K_f = 1$
- When the material is fully sensitive to notches, $q = 1$ and $K_f = K_t$
- The magnitude of the notch sensitivity factor q varies from 0 to 1.

Reduction of Stress Concentration

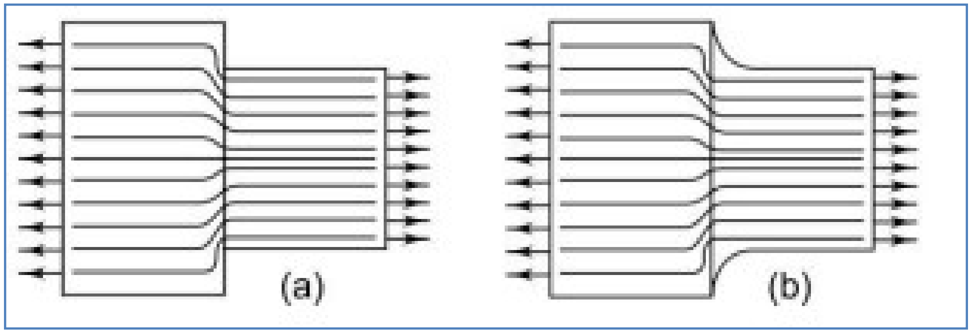
- In order to know what happens at the abrupt change of cross-section or at the discontinuity and to reduce the stress concentration, understanding of **Flow Analogy** is useful.
- There is a similarity between **velocity distribution in fluid flow in a channel** and the **stress distribution in an axially loaded plate** as shown.
- When the cross-section of a channel has uniform dimensions throughout, the velocities are uniform and the streamlines are equally spaced. On the other hand, when the cross-section of the plate has the same dimensions throughout, the stresses are uniform and stress lines are equally spaced.



Force Flow Analogy: (a) Force Flow around Sharp Corner (b) Force Flow around Rounded Corner

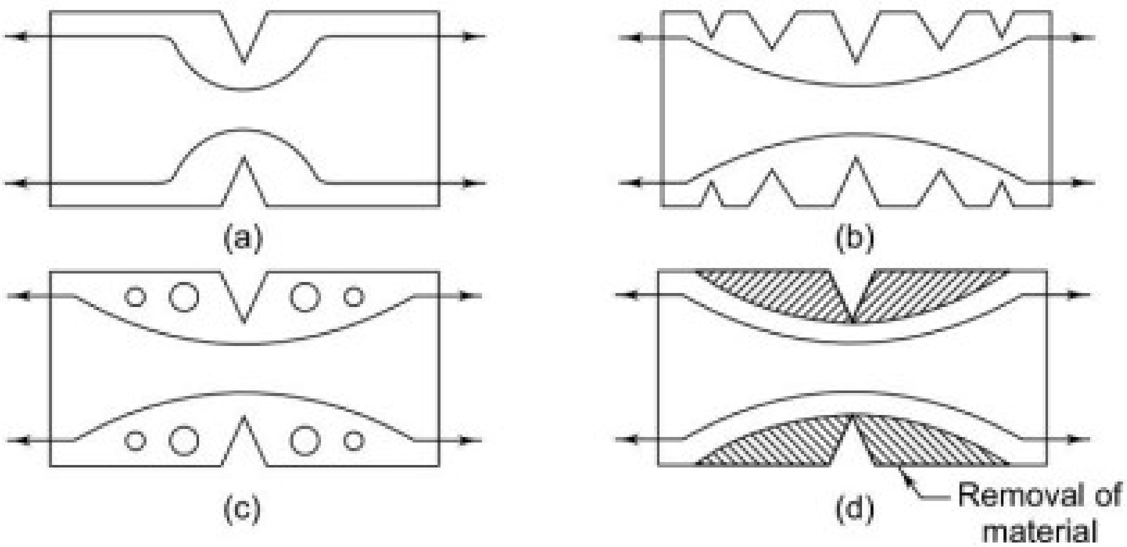
Reduction of Stress Concentration

- When the cross-section of the channel is suddenly reduced, the velocity increases in order to maintain the same flow and the streamlines become narrower and narrower and crowd together.
- A similar phenomenon is observed in a stressed plate. When there is sudden change in cross-section, bending of stress lines is very sharp and severe resulting in stress concentration.
- Therefore, stress concentration can be greatly reduced by **reducing the bending by rounding the corners.**
- Streamlining, or rounding the corners of mechanical components, has similar beneficial effects in reducing stress concentration.



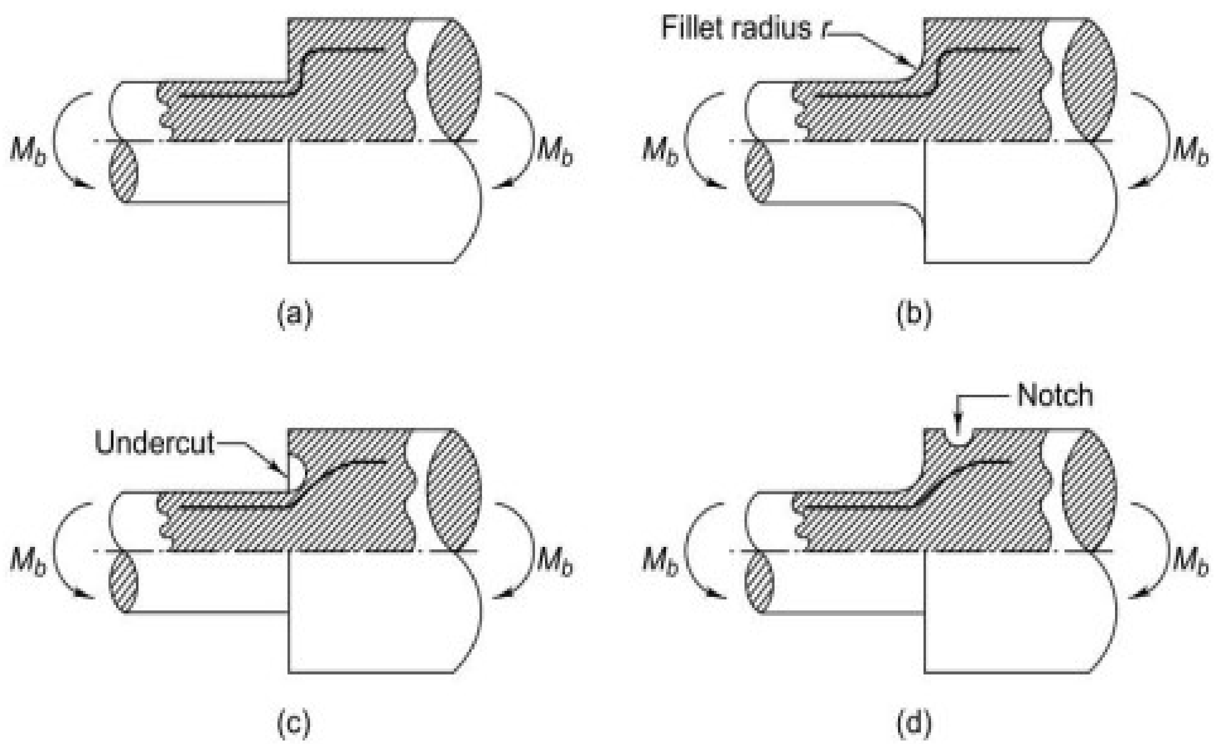
Force Flow Analogy: (a) Force Flow around Sharp Corner (b) Force Flow around Rounded Corner

Reduction of Stress Concentration: By providing additional Notches and Holes in Tension Member



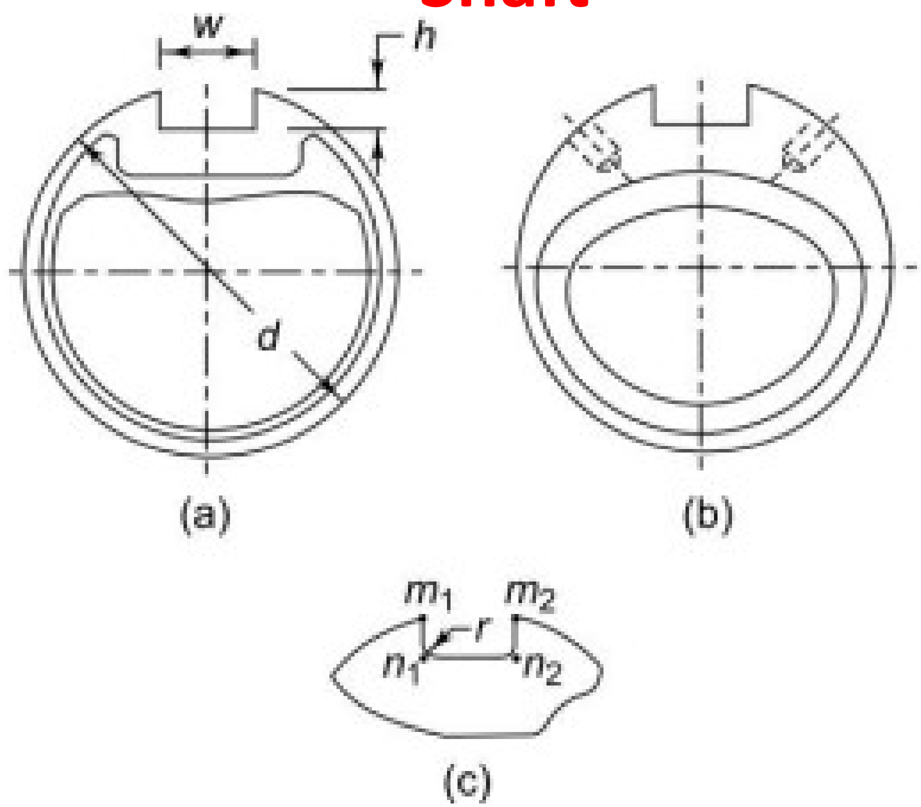
Reduction of Stress Concentration due to V-notch: (a) Original Notch (b) Multiple Notches (c) Drilled Holes (d) Removal of Undesirable Material

Reduction of Stress Concentration: Fillet Radius, Undercutting and Notch for Member in Bending



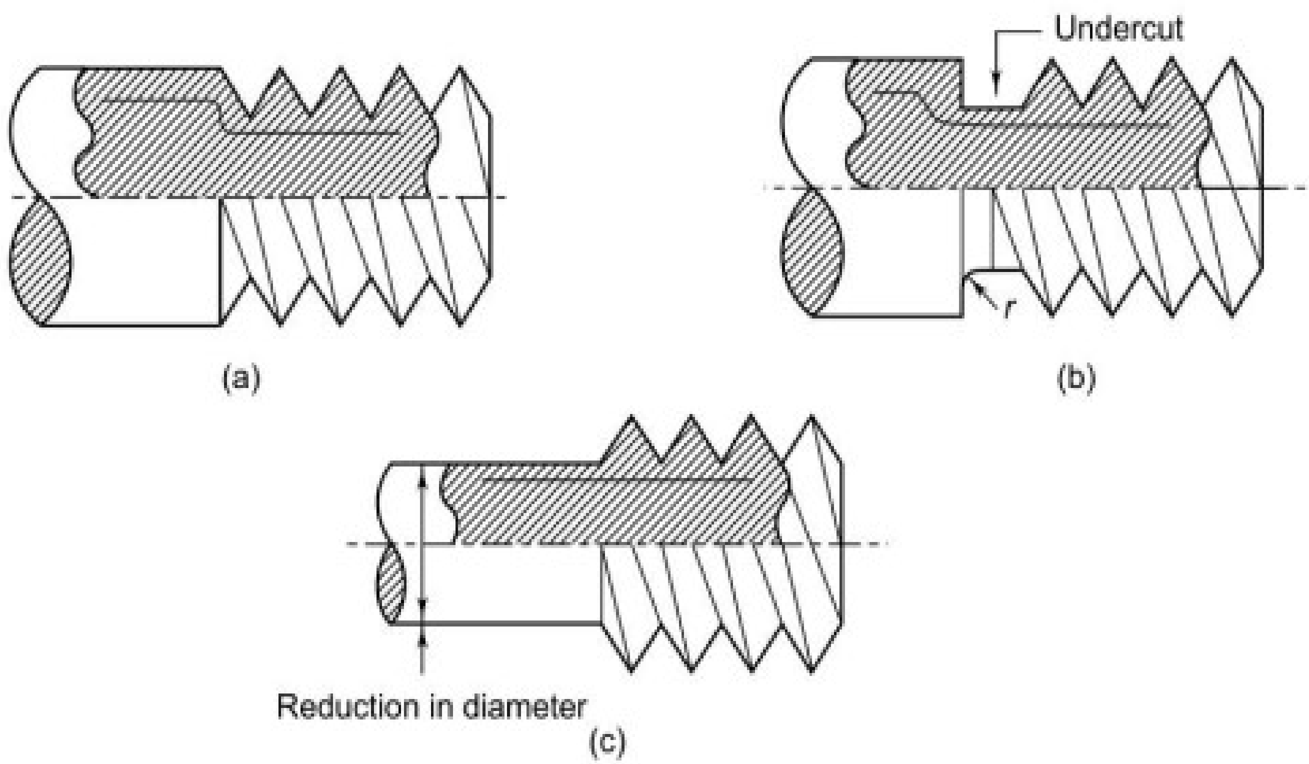
Reduction of Stress Concentration due to Abrupt Change in Cross-section: (a) Original Component (b) Fillet Radius (c) Undercutting (d) Addition of Notch

Reduction of Stress Concentration: Drilling Additional Holes for Shaft



Reduction of Stress Concentration in Shaft with Keyway: (a) Original Shaft (b) Drilled Holes (c) Fillet Radius

Reduction of Stress Concentration in Threaded Members

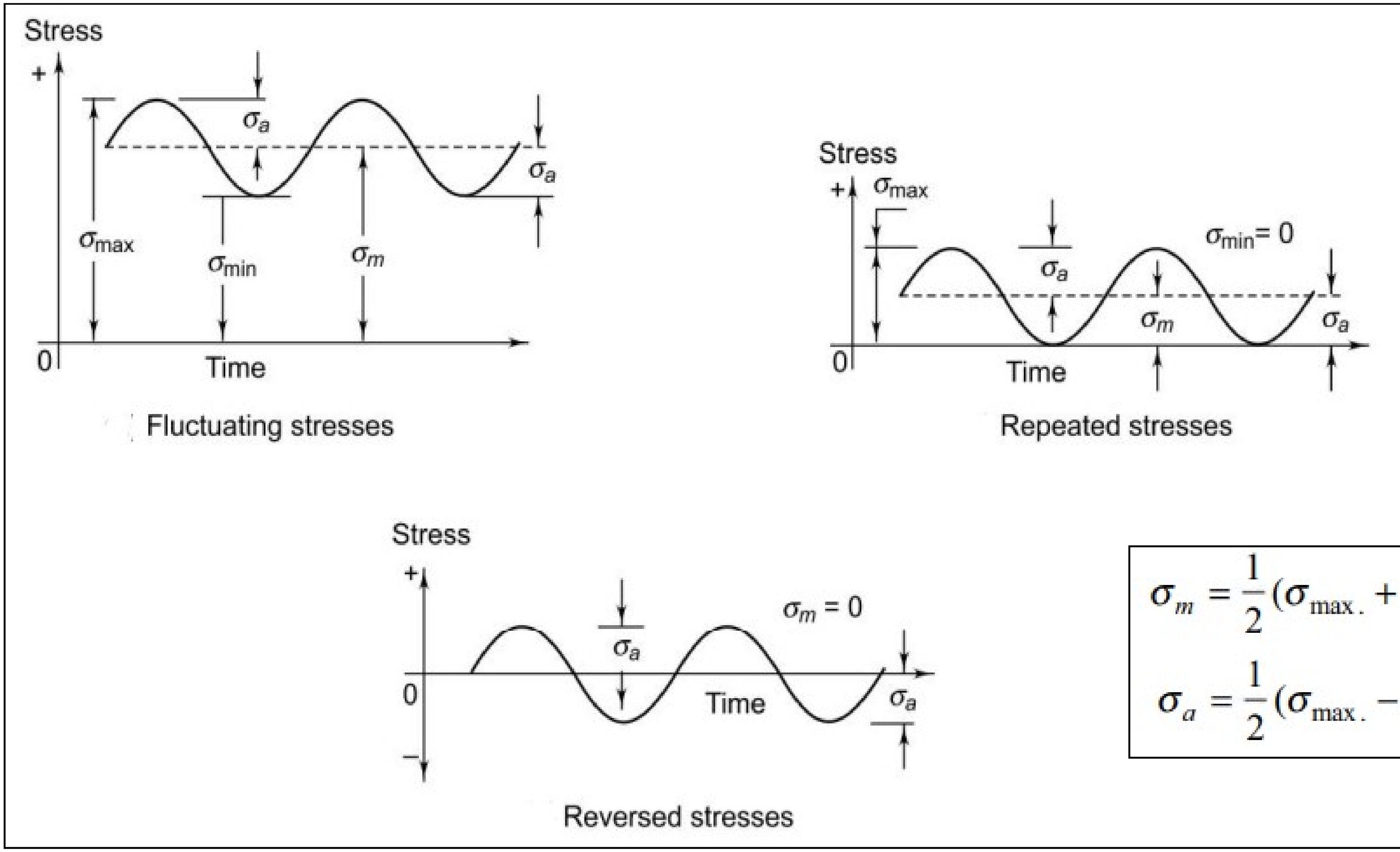


Reduction of Stress Concentration in Threaded Components: (a) Original Component (b) Undercutting (c) Reduction in Shank Diameter

Fluctuating stresses

- In many applications, the components are subjected to forces, which are not static, but vary in magnitude with respect to time. The stresses induced due to such forces are called **fluctuating stresses**.
- About 80% of failures of mechanical components are due to **‘fatigue failure’** resulting from fluctuating stresses.
- For the purpose of design analysis, simple models for stress–time relationships are used. The most popular model for stress–time relationship is the **sine curve.**

Types of cyclic stresses

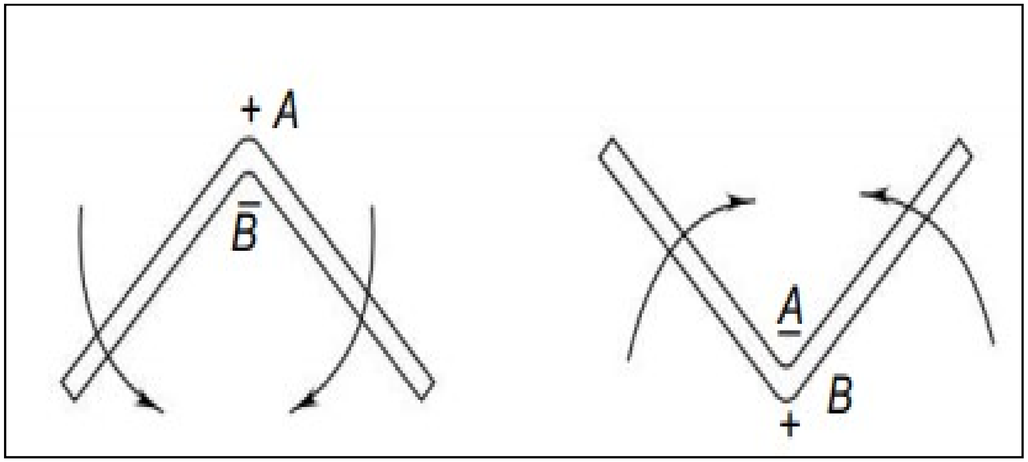


$$\sigma_m = \frac{1}{2}(\sigma_{max.} + \sigma_{min})$$

$$\sigma_a = \frac{1}{2}(\sigma_{max.} - \sigma_{min.})$$

Fatigue Failure

- It has been observed that materials fail under fluctuating stresses at a stress magnitude which is lower than the ultimate tensile strength of the material. Sometimes, the magnitude is even lower than the yield strength.
- Further, it has been found that the magnitude of the stress causing **fatigue failure** decreases as the **number of stress cycles** increase. This phenomenon of decreased resistance of the materials to **fluctuating stresses** is the **main characteristic of fatigue failure**.
- Examples of parts in which fatigue failures are common are **transmission shafts, connecting rods, gears, vehicle suspension springs and ball bearings**.



Fatigue Failure

- Fatigue failure begins with a **crack** at some point in the material. The crack is more likely to occur in the **regions of discontinuity** (oil holes, keyways, screw threads, etc.), **regions of irregularities** in machining operations (scratches on the surface, stamp mark, inspection marks, etc.) and **internal cracks** due to defects in materials like blow holes.
- Fatigue failure depends on:
    - No. of cycles
    - Stress Amplitude
    - Mean Stress
    - Stress Concentration
    - Residual stress
    - Corrosion & Creep
- Therefore design of components subjected to fluctuating stresses become more complex.

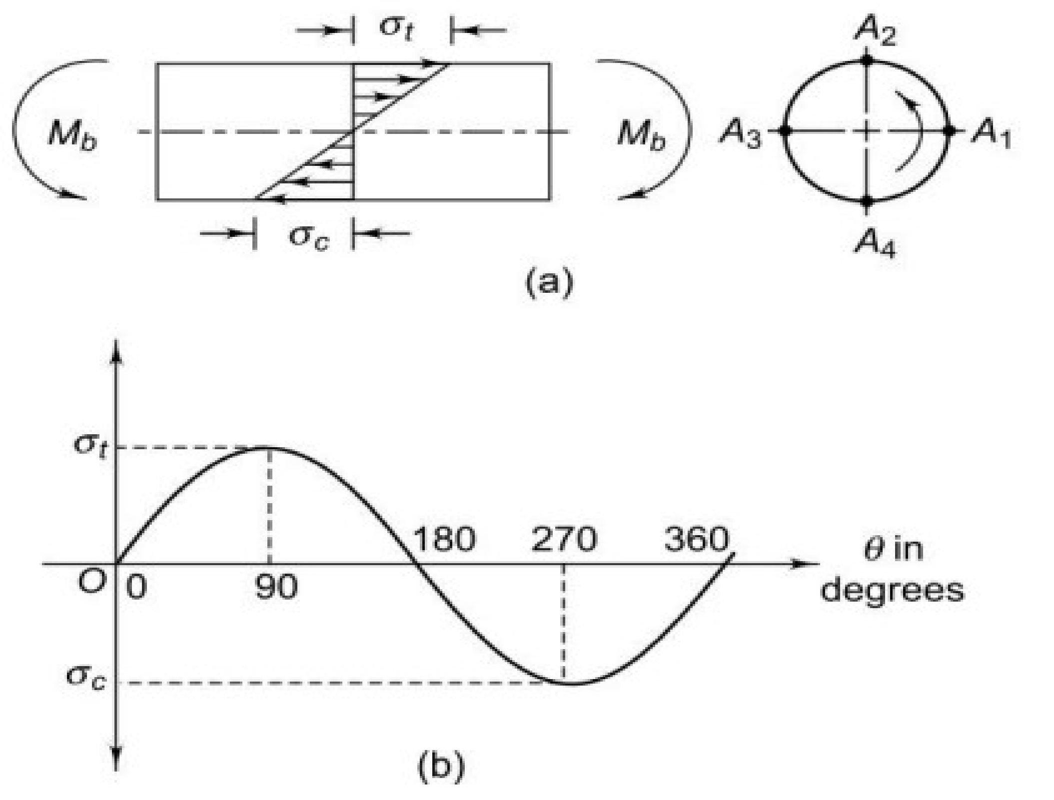
Endurance limit

- The **fatigue or endurance limit** of a material is defined as the **maximum amplitude** of **completely reversed stress** that the standard specimen can sustain for an **unlimited** number of cycles without fatigue failure.
- **10^6 cycles** is considered as a sufficient number of cycles to define the endurance limit.
- The **fatigue life** is defined as the **number of stress cycles** that the standard specimen can complete during the test before the appearance of the first fatigue crack

Determination of Endurance limit

- The endurance limit is determined by means of a **rotating beam machine** developed by **R R Moore**.
- Beam is subjected to completely reversed stresses.
- The distribution is sinusoidal and one stress cycle is completed in one revolution.

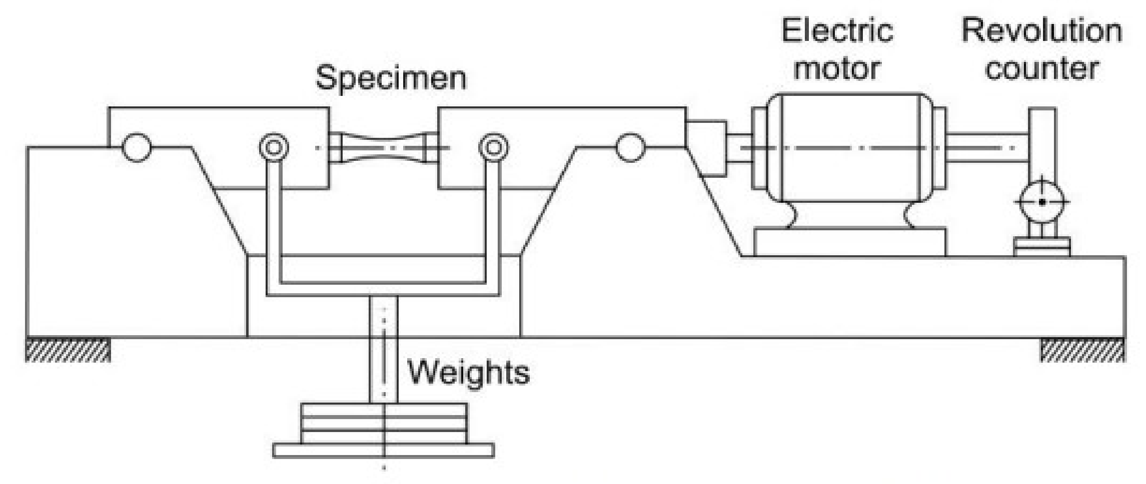
$$\sigma_t \text{ or } \sigma_c = \frac{M_b y}{I}$$



Rotating Beam Subjected to Bending Moment: (a) Beam, (b) Stress Cycle at Point A

Determination of Endurance limit

- The specimen acts as a **'rotating beam'** subjected to a bending moment. Therefore, it is subjected to a **completely reversed stress cycle**.
- Changing the bending moment by addition or deletion of weights can vary the stress amplitude. The specimen is rotated by an electric motor. The **number of revolutions before the appearance of the first fatigue crack is recorded on a revolution counter**.
- In each test, two readings are taken, viz., **stress amplitude (S_f) and number of stress cycles (N).** These readings are used as two coordinates for plotting a point on **the S–N diagram**.



Rotaing Beam Fatigue Testing Machine

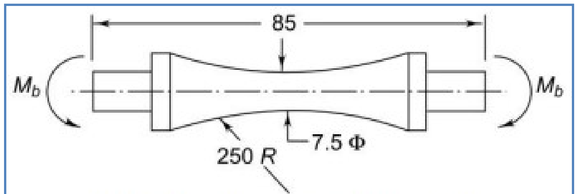
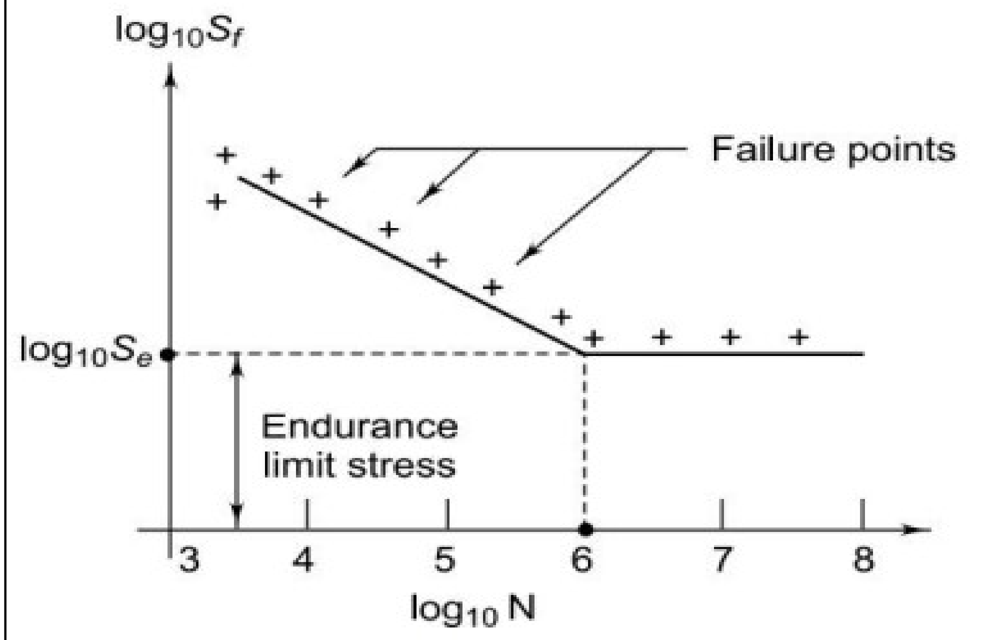


Fig. 5.17 *Specimen for Fatigue Test*

S-N curve

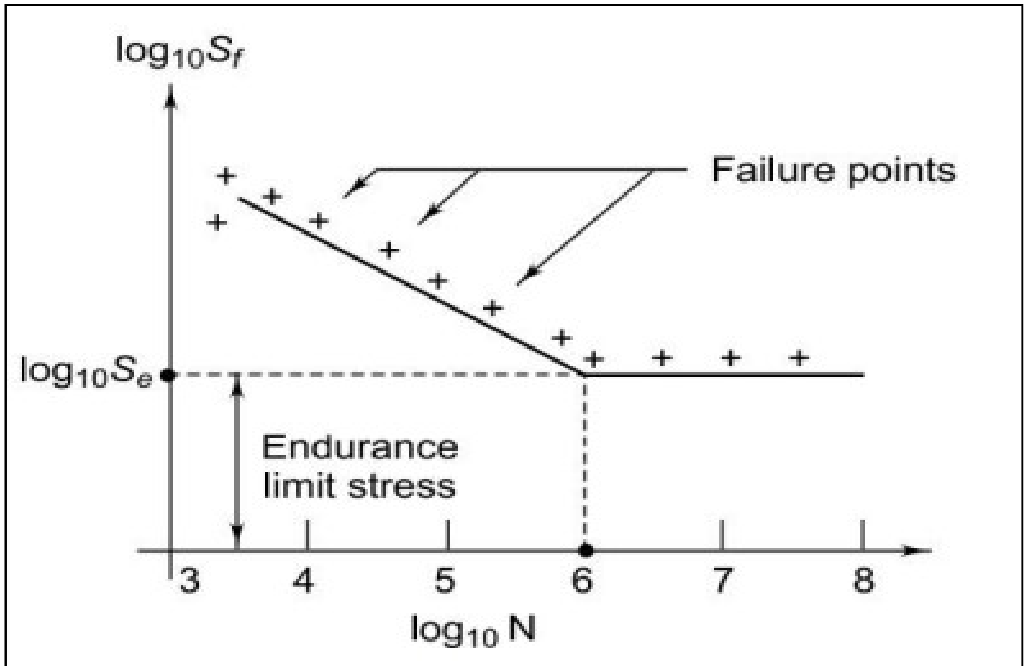
- The S–N curve is the graphical representation of stress amplitude (S_f) versus the number of stress cycles (N) before the fatigue failure.
- For ferrous materials like steels, the S–N curve becomes **asymptotic at 10^6 cycles**, and corresponding stress amplitude represents the endurance limit of the material.
- The endurance limit, in a true sense, is not exactly a property of material like ultimate tensile strength. It is affected by factors such as the **size of the component, shape of component, the surface finish, temperature and the notch sensitivity of the material**.



S-N Curve for Steels

S-N curve

- There are two regions of this curve namely, **low-cycle fatigue (<10^3 cycles) and high-cycle fatigue (> 10^3 cycles)**.
- Failure of studs on truck wheels, failure of setscrews for locating gears on shafts or failures of short-lived devices such as missiles are the examples of low-cycle fatigue.
- The failure of machine components such as springs, ball bearings or gears that are subjected to fluctuating stresses, are the examples of high-cycle fatigue.
- Components subjected to high-cycle fatigue are designed on the basis of **endurance limit, S–N curve, Soderberg lines, Gerber lines or Goodman diagrams.**



S-N Curve for Steels

Endurance limit: Approximate Estimation

- The laboratory method for determining the endurance limit of materials, although more precise, is laborious and time consuming. A number of tests are required to prepare one S–N curve and each test takes considerable time. It is, therefore, not possible to get the experimental data of each and every material.
  - S'_e = endurance limit stress of a rotating beam specimen subjected to reversed bending stress (MPa)

For steels,

$$S'_e = 0.5\ S_{ut}$$

For cast iron and cast steels,

$$S'_e = 0.4\ S_{ut}$$

For wrought aluminium alloys

$$S'_e = 0.4\ S_{ut}$$

For cast aluminium alloys,

$$S'_e = 0.3\ S_{ut}$$

Corrected Endurance limit(S_e)

- The endurance limit of a component is different from the endurance limit of a rotating beam specimen due to a number of factors.
- The difference arises due to the fact that there are standard specifications and working conditions for the rotating beam specimen, while the actual components have different specifications and work under different conditions.
- Different modifying factors are used in practice to account for this difference.

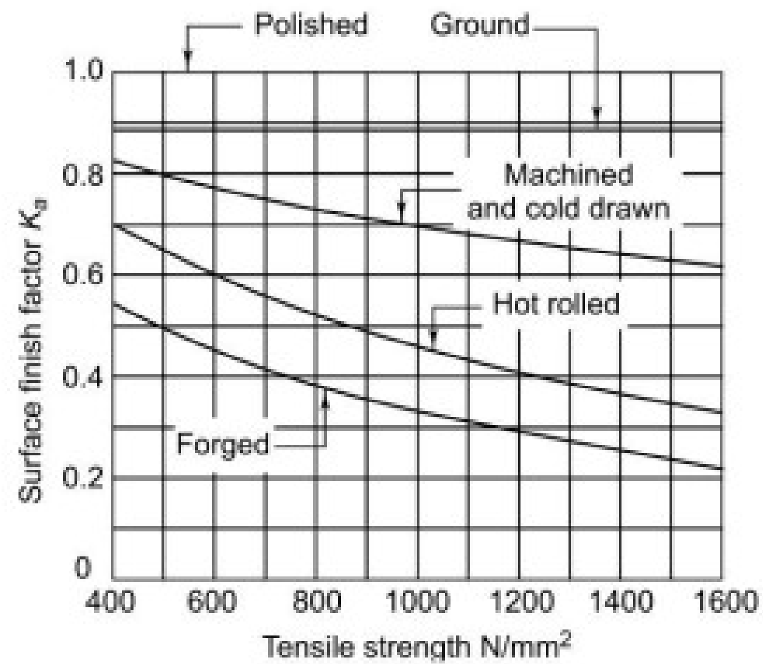
$$S_e = K_a K_b K_c K_d S_e'$$

where,

K_a = surface finish factor
K_b = size factor
K_c = reliability factor
K_d = modifying factor to account for stress concentration.

Corrected Endurance limit (S'_e): Surface finish factor (K_a)

- The surface of the rotating beam specimen is polished to mirror finish.
- The actual component may not even require such a surface finish. When the surface finish is poor, there are scratches and geometric irregularities on the surface. These surface scratches serve as stress raisers and result in stress concentration.
- The endurance limit is reduced due to introduction of stress concentration at these scratches.
- The surface finish factor takes into account the reduction in endurance limit due to the variation in the surface finish between the specimen and the actual component.
- As the ultimate tensile strength increases, the surface finish factor decreases.
- The surface finish factor **for ordinary grey cast iron components is taken as 1,** irrespective of their surface finish



Corrected Endurance limit (S'_e): Size Factor (K_b)

- The size of the rotating beam specimen is very small (7.55 diameter).
- As the size of the actual component increases, the probability of presence of defects increases.
- As the cracks are initiated at the defects, hence the endurance strength decreases with size.
- K_b takes into account the reduction in endurance limit due to increase in the size of the component

Diameter (d) (mm)	K_b
$d \le 7.5$	1.00
$7.5 < d \le 50$	0.85
$d > 50$	0.75

Corrected Endurance limit (S'_e): Reliability factor (K_c)

- The endurance strength determined by rotating beam experiment or the approximated relation is only 50% reliable, means 50% components will survive with this endurance strength.
- To ensure that more than 50% components survive, the component must be designed with lower endurance strength.
- As the reliability (% of components that survive) increases, reliability factor (K_c) decreases.

Reliability R (%)	K_c
50	1.000
90	0.897
95	0.868
99	0.814
99.9	0.753
99.99	0.702
99.999	0.659

Corrected Endurance limit (S'_e): Modifying factor to account for stress concentration. (K_d)

- To apply the effect of stress concentration, the designer can either reduce the endurance limit by (K_d) or increase the stress amplitude by (K_f).
- The modifying factor K_d to account for the effect of stress concentration is defined as,

$$K_d = \frac{1}{K_f}$$

Endurance strength under Torsion (S_{se})

- The endurance limit (S_{se}) of a component subjected to fluctuating torsional shear stresses is obtained from the endurance limit in reversed bending (S_e) using theories of failures.
  - According to the Maximum Shear Stress Theory (MSST),

$$S_{se} = 0.5Se$$

  - According to the Maximum Distortion Energy Theory (MDET),

$$S_{se} = 0.577Se$$

Endurance strength under Axial Loading (S_{ae})

- Endurance limit in axial loading is lower than the rotating beam test.
  - For axial loading,

$$S_{ae} = 0.8\ S_e$$

Types of problems in fatigue design

- **Components subjected to completely reversed stresses**
  - Design for infinite life ($N \geq 10^6$ cycles)
  - Design for finite life ($N < 10^6$ cycles)

- **Components subjected to fluctuating stresses**
  - Design for infinite life ($N \geq 10^6$ cycles)
  - Design for finite life($N < 10^6$ cycles)

Completely reversed stresses: Design for infinite life

- Endurance limit becomes the failure criteria.

$$\sigma_a = \frac{S_e}{(fs)}$$

$$\tau_a = \frac{S_{se}}{(fs)}$$

where, (σ_a) and (τ_a) are stress amplitudes in the component

and S_e and S_{se} are corrected endurance limits in reversed bending and torsion respectively.

Completely reversed stresses: Design for finite life

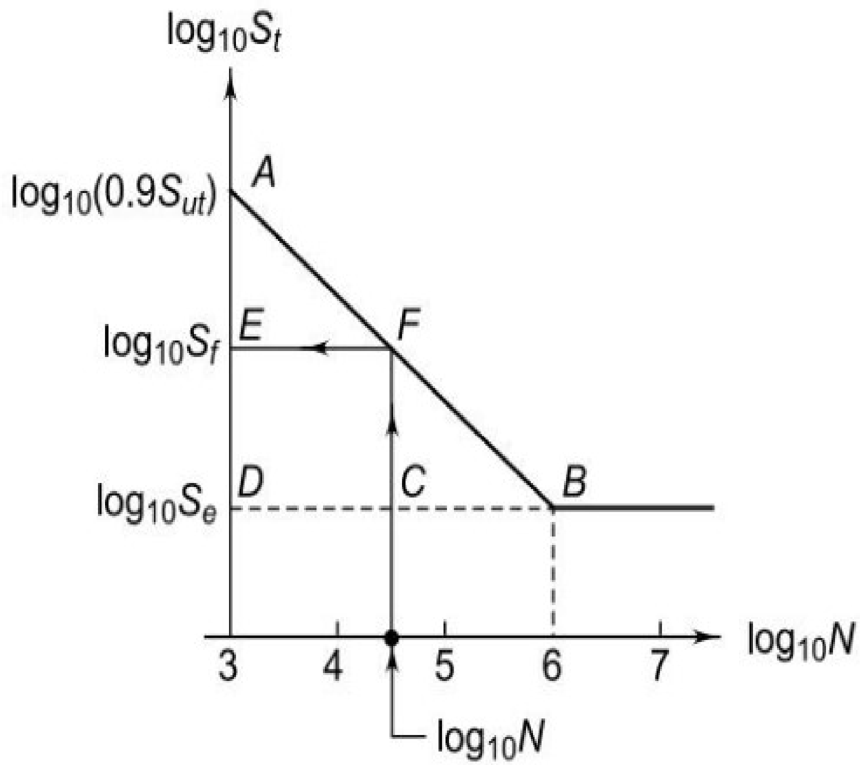
- **Fatigue Strength (S_f):** The **fatigue strength** of a material is defined as the **maximum amplitude** of **completely reversed stress** that the standard specimen can sustain for **finite** number of cycles without fatigue failure.
  - To avoid failure for N no. of cycles

$\sigma_{max} \leq S_f$ at N no. of cycles

$$\sigma_{max} = \sigma_a = \frac{S_f}{FOS}$$

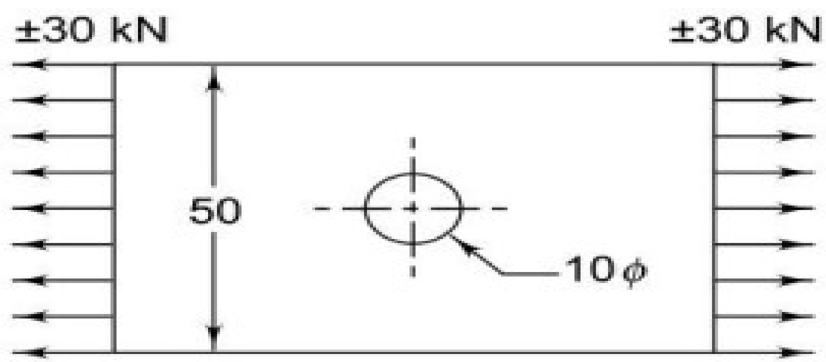
- Fatigue Strength (S_f) for a given no. of cycles can be calculated with the help of Equation of straight line AB.

$$\frac{\log_{10} S_f - \log_{10} 0.9S_{ut}}{\log_{10} S_e - \log_{10} 0.9S_{ut}} = \frac{\log_{10} N - 3}{6-3}$$



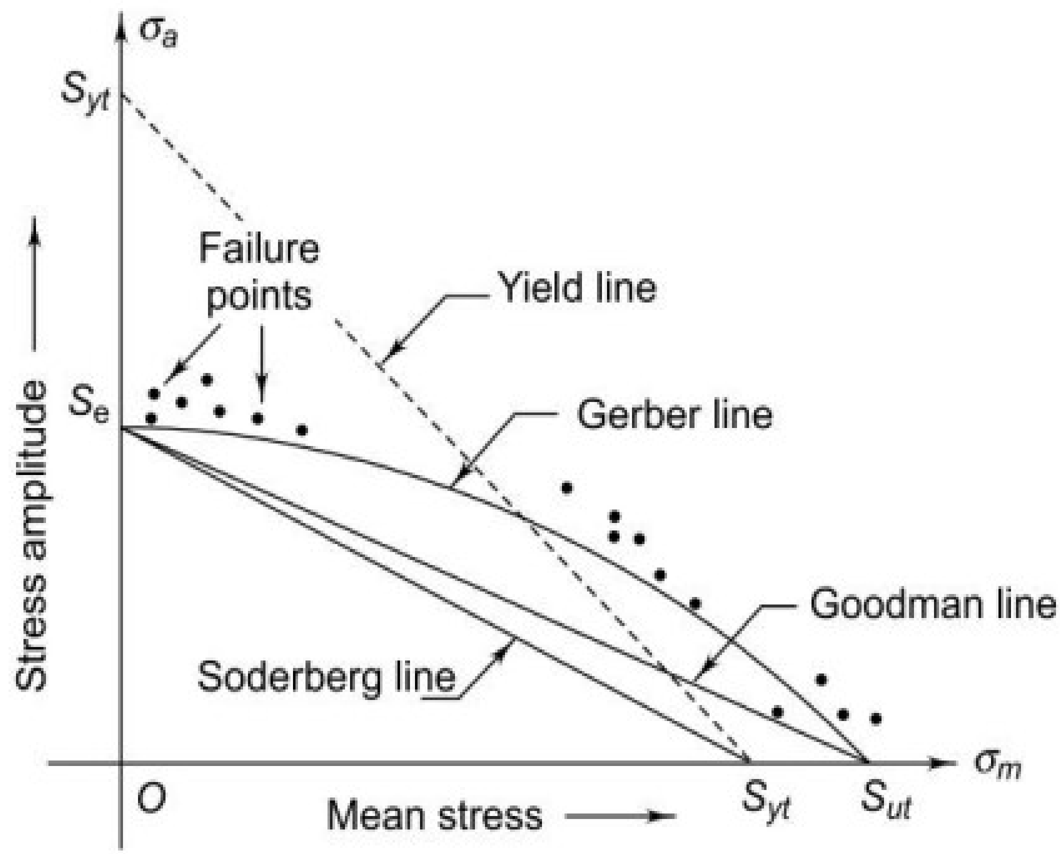
Q A cylindrical shaft is subjected to an alternating stress of 100 MPa. Fatigue strength to sustain 1000 cycle is 490 MPa. If the corrected endurance strength is 70 MPa, estimated shaft life will be

Example 5.3 *A plate made of steel 20C8 (S_{ut} = 440 N/mm^2) in hot rolled and normalised condition is shown in Fig. 5.28. It is subjected to a completely reversed axial load of 30 kN. The notch sensitivity factor q can be taken as 0.8 and the expected reliability is 90%. The size factor is 0.85. The factor of safety is 2. Determine the plate thickness for infinite life.*



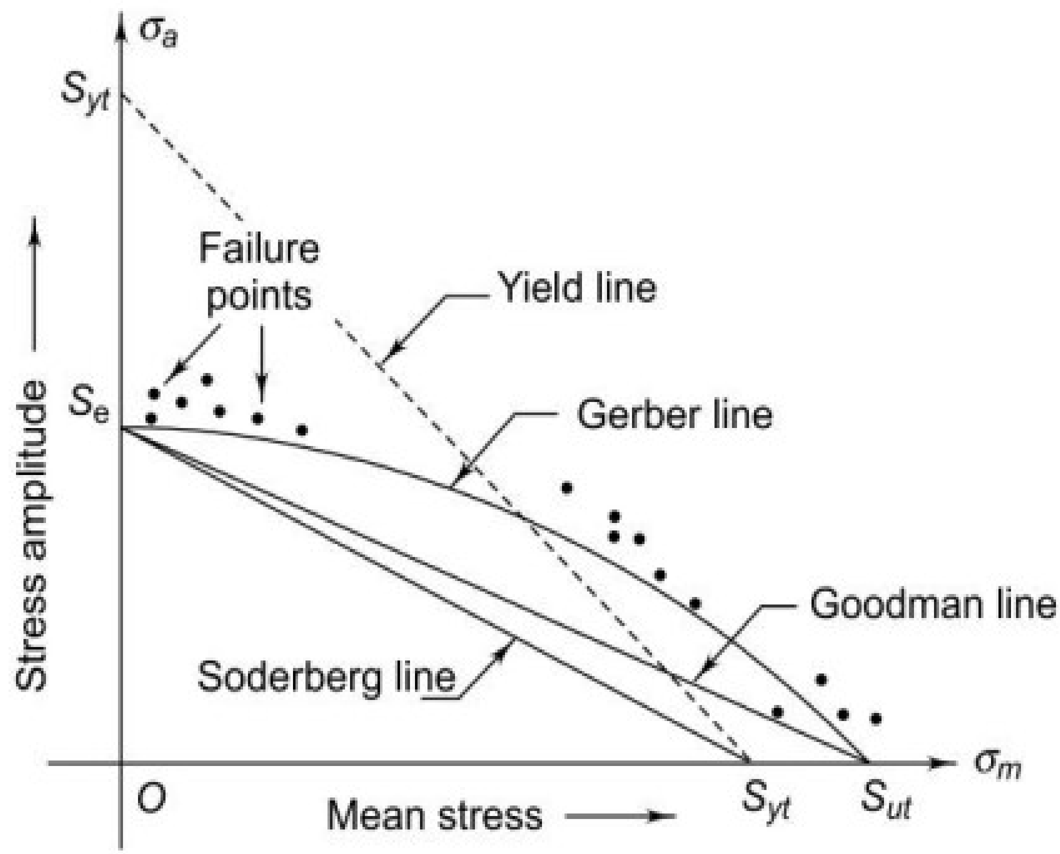
Soderberg, Goodman, Gerber Criteria

- When a component is subjected to fluctuating stresses, there is **mean stress (σ_m) as well as stress amplitude (σ_a).**
- When **σ_a** is zero, the load is **purely static** and the criterion of failure is **S_{ut} or S_{yt}.**
- When the **σ_m** is zero, the loading is **completely reversed** and the criterion of failure is the **endurance limit S_e**.
- When the component is subjected to both **σ_m** and **σ_a** , the actual failure occurs at different scattered points as shown.
- **Gerber curve, Soderberg line and Goodman line** criteria's divides safe region and unsafe region for various combinations of **σ_m** and **σ_a**



Soderberg, Goodman, Gerber Criteria

- **Soderberg line** is a more conservative failure criterion and there is no need to consider even yielding in this case.
- **Gerber parabola** fits the failure points of test data in the best possible way. Therefore, more accurate in predicting the fatigue failure.
- **Goodman line** is widely used as the criterion of fatigue failure when the component is subjected to both $\boldsymbol{\sigma_m}$ and $\boldsymbol{\sigma_a}$ because:
  - completely inside the failure points of test data.
  - straight line equation is simple compared with the curve.



Soderberg, Goodman, Gerber Criteria

- **Equation of Soderberg line**

$$\frac{\sigma_m}{S_{yt}} + \frac{\sigma_a}{S_e} = \frac{1}{FOS}$$

- **Equation of Gerber parabola**

$$\left(\frac{\sigma_m}{S_{ut}} FOS\right)^2 + \left(\frac{\sigma_a}{S_e} FOS\right) = 1$$

- **Equation of Goodman line**

$$\frac{\sigma_m}{S_{ut}} + \frac{\sigma_a}{S_e} = \frac{1}{FOS}$$

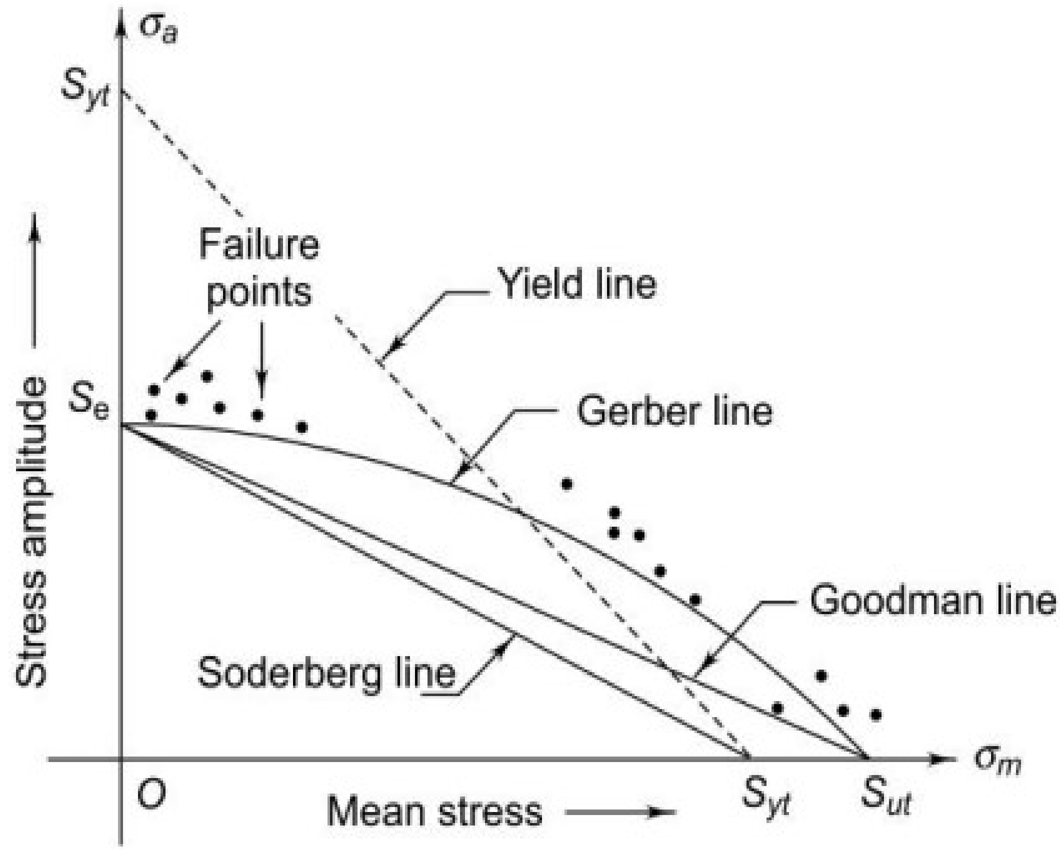
$S_e \rightarrow \textit{Corrected Endurance Limit}$

$\sigma_m \rightarrow \textit{Mean Stress}$

$\sigma_a \rightarrow \textit{Stress Amplitude}$

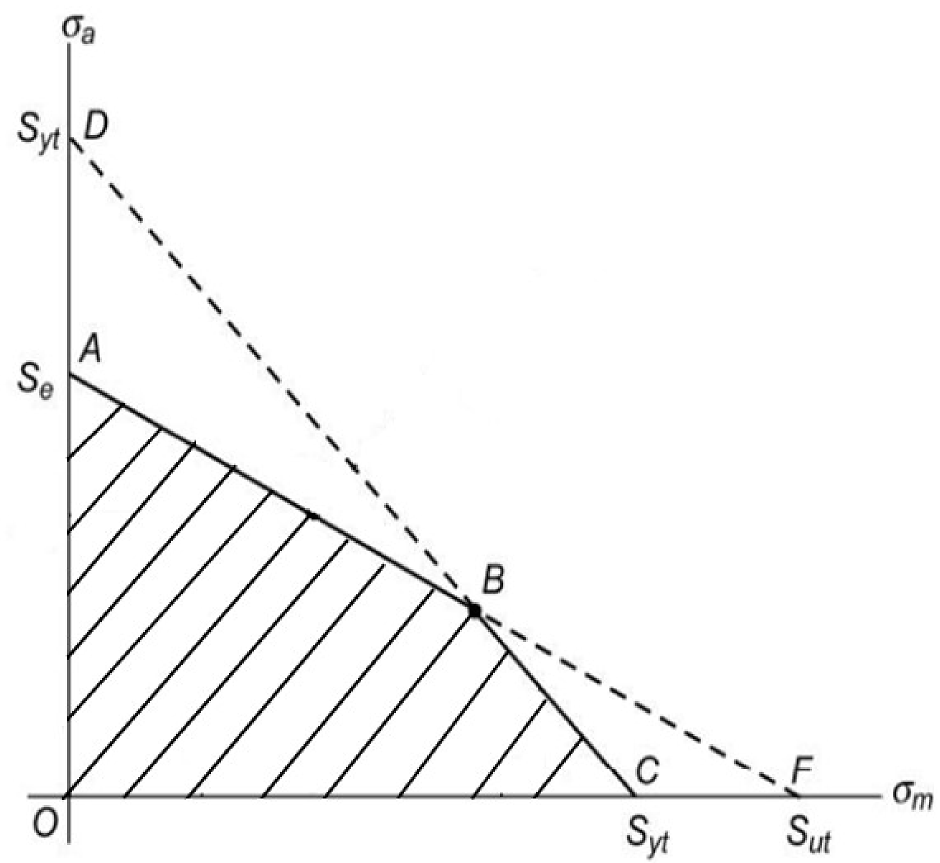
$S_{yt} \rightarrow \textit{Yield Strength}$

$S_{ut} \rightarrow \textit{Ultimate Strength}$



Modified Goodman Criteria

- **Goodman line is 'modified'** by combining fatigue and yielding failure.
- **Line CD→ Yield Line or Langer's Line**
- **Line AF→ Goodman Line**
- The point of intersection of these two lines is **B.** The area **OABC** represents the region of safety for components subjected to fluctuating stresses.
- **Region OABC → Modified Goodman Diagram**. All the points within it should cause neither fatigue failure nor yielding.
- Modified Goodman diagram combines fatigue criteria as represented by the Goodman line (portion AB) and yield criteria as represented by yield line (portion BC).



Modified Goodman Criteria

- **Equation of Yield line**

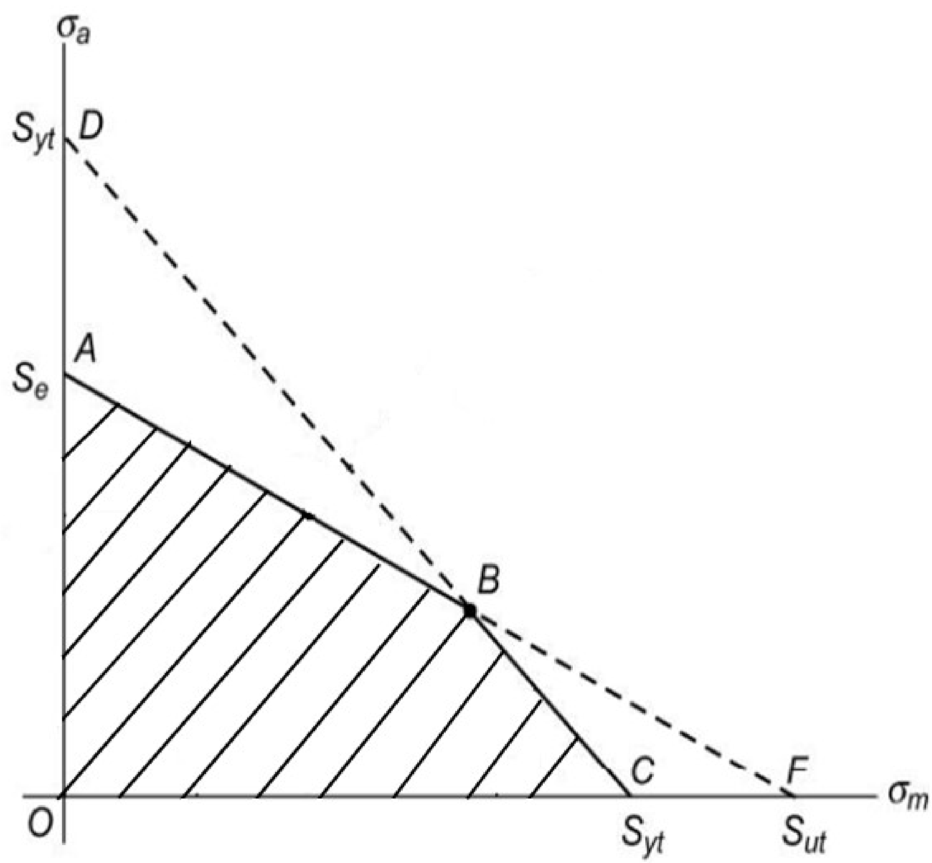
$$\sigma_m + \sigma_a = \frac{S_{yt}}{FOS}$$

- **Equation of Goodman line**

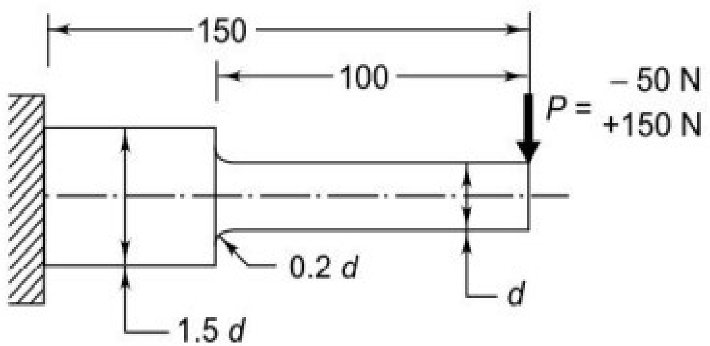
$$\frac{\sigma_m}{S_{ut}} + \frac{\sigma_a}{S_e} = \frac{1}{FOS}$$

On solving above two equations, equation which give **minimum FOS or maximum Dimension** will be considered for designing the components subjected to fluctuating load.

- At point B, FOS will be equal in both cases



Example 5.12 *A cantilever beam made of cold drawn steel 4OC8 (S_{ut} = 600 N/mm^2 and S_{yt} = 380 N/mm^2) is shown in Fig. 5.42. The force P acting at the free end varies from –50 N to +150 N. The expected reliability is 90% and the factor of safety is 2. The notch sensitivity factor at the fillet is 0.9. Determine the diameter 'd' of the beam at the fillet cross-section.*



Example 5.13 *A transmission shaft of cold drawn steel 27Mn2 (S_{ut} = 500 N/mm^2 and S_{yt} = 300 N/mm^2) is subjected to a fluctuating torque which varies from –100 N-m to + 400 N-m. The factor of safety is 2 and the expected reliability is 90%. Neglecting the effect of stress concentration, determine the diameter of the shaft.*

Assume the distortion energy theory of failure.