Production & Industrial Engineering

General Engineering

Vol. III : Machine Design

Comprehensive Theory

with **Solved Examples** and **Practice Questions**

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Corporate Office: 44-A/4, Kalu Sarai (Near Hauz Khas Metro Station), New Delhi-110016
E-mail: infomep@madeeasy.in
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General Engineering : Vol. III – Machine Design

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Contents

Machine Design

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VOLUME III

Machine Design

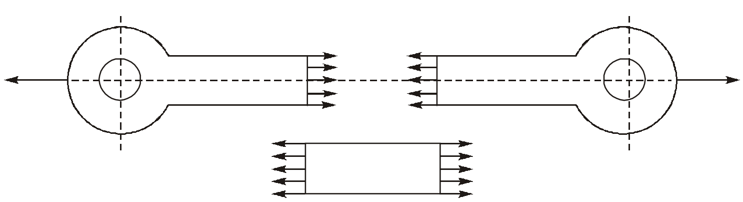
INTRODUCTION

Machine Design or mechanical design is primarily concerned with the systems by which the energy is converted into useful mechanical forms and of mechanisms required to convert the output of the machine to the desired form. The design may lead to an entirely new machine or an improvement on an existing one.

Thus machine design is the production or creation of the right combination of correctly proportioned moving and stationary components so constructed and joined as to enable the liberation, transformation, and utilization of energy.

3.1 Loading of Machine Elements

Machine parts fail when the stresses induced by external forces exceed their strength. The external loads cause internal stresses in the elements and the component size depends on the stresses developed. Stresses developed in a link subjected to uniaxial loading is shown in figure. Loading may be due to: (a) The energy transmitted by a machine element; (b) Dead weight; (c) Inertial forces; (d) Thermal loading; (e) Frictional forces.

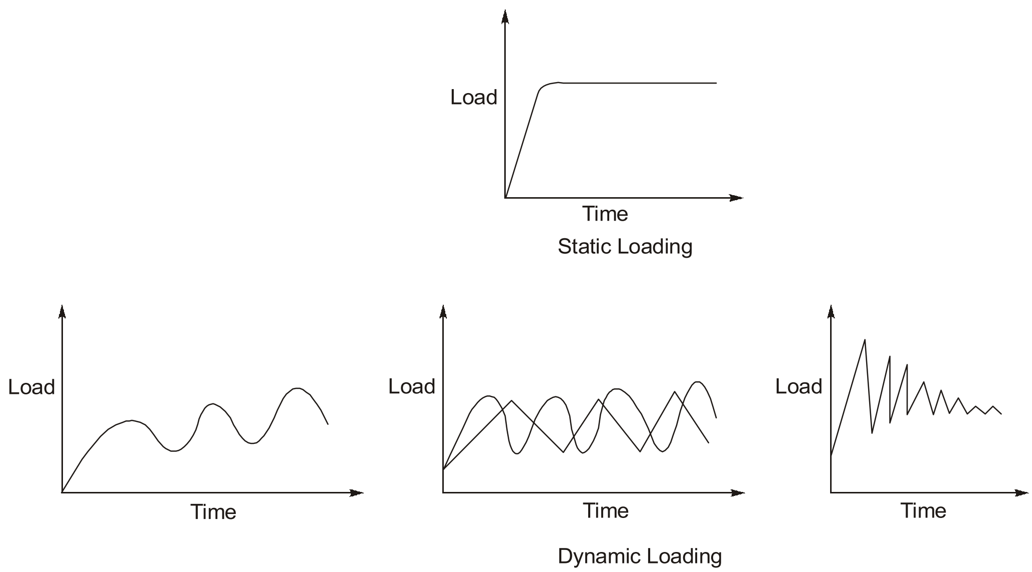


Stresses developed in a link subjected to uniaxial loading

In another way, load may be classified as:

(a) **Static load :** Load does not change in magnitude and direction and normally increases gradually to a steady value.

(b) **Dynamic load :** Load may change in magnitude for example, traffic of varying weight passing a bridge. Load may change in direction, for example, load on piston rod of a double acting cylinder. Vibration and shock are types of dynamic loading. Figure shows load vs time characteristics for both static and dynamic loading of machine elements.

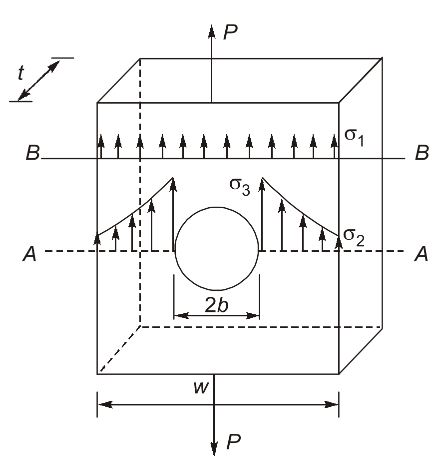


Types of loading on machine elements

3.2 Concept of Stress Concentration

In developing a machine it is impossible to avoid changes in cross-section, holes, notches, shoulders etc. Any such discontinuity in a member affects the stress distribution in the neighbourhood and the discontinuity acts as a stress raiser. Consider a plate with a centrally located hole and the plate is subjected to uniform tensile load at the ends. Stress distribution at a section A-A passing through the hole and another section BB away from the hole are shown in figure below.

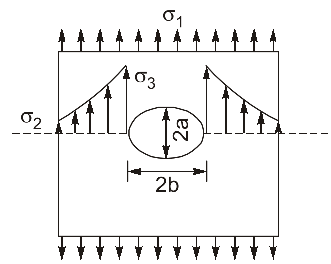
Stress distribution away from the hole is uniform but at AA there is a sharp rise in stress in the vicinity of the hole. Stress concentration factor k_1 is defined as $k_1 = \frac{\sigma_3}{\sigma_{av}}$, where σ_{av} at section AA is simply $\frac{P}{t(w-2b)}$ and $\sigma_1 = \frac{P}{tw}$. This is the theoretical or geometric stress concentration factor and the factor is not affected by the material properties.



Stress concentration due to a central hole in a plate subjected to an uni-axial loading.

It is possible to predict the stress concentration factors for certain geometric shapes using theory of elasticity approach. For example, for an elliptical hole in an infinite plate, subjected to a uniform tensile stress σ_1 as shown in figure, stress distribution around the discontinuity is disturbed and at points remote from the discontinuity the effect is insignificant. According to such an analysis

$$\sigma_3 = \sigma_1\left(1+\frac{2b}{a}\right)$$



Stress concentration due to a central elliptical hole in a plate subjected to a uni-axial loading

If $a = b$ the hole reduces to a circular one and therefore $\sigma_3 = 3\sigma$ which gives $k_t = 3$. If, however 'b' is large compared to 'a' then the stress at the edge of transverse crack is very large and consequently k is also very large. If 'b' is small compared to a then the stress at the edge of a longitudinal crack does not rise and $k_t = 1$.

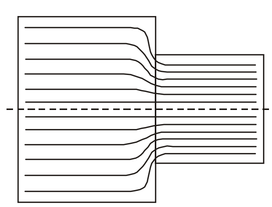
Stress concentration factors may also be obtained using any one of the following experimental techniques:

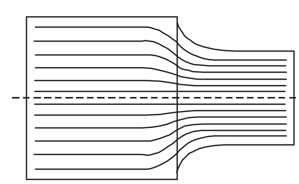
1. Strain gage method
2. Photoelasticity method
3. Brittle coating technique
4. Grid method

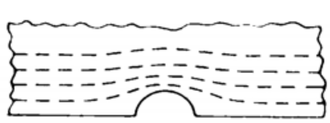
3.2.1 Methods to Reduce Stress Concentration

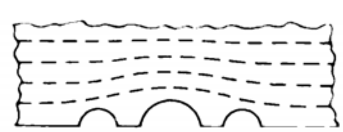
A number of methods are available to reduce stress concentration in machine parts. Some of them are as follows :

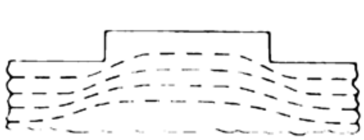
1. Provide a fillet radius so that the cross-section may change gradually.
2. Sometimes an elliptical fillet is also used.
3. If a notch is unavoidable it is better to provide a number of small notches rather than a long one. This reduces the stress concentration to a large extent.
4. If a projection is unavoidable from design considerations it is preferable to provide a narrow notch than a wide notch.
5. Stress relieving groove are sometimes provided. These are demonstrated in figure.

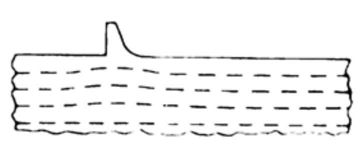

(a) Force flow around a sharp corner

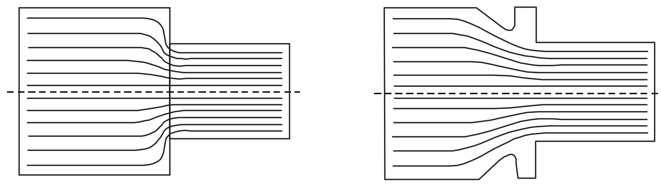

Force flow around a corner with fillet: Low stress concentration.


(b) Force flow around a large notch


Force flow around a number of small notches: Low stress concentration.


(c) Force flow around a wide projection


Force flow around a narrow projection: Low stress concentration.



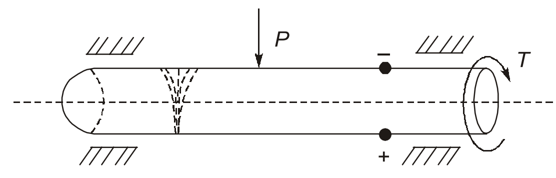
(d) Force flow around a sudden change in diameter in a shaft

Force flow around a stress relieving groove

Illustrations of different methods to reduce stress concentration

3.3 Dynamic Loading

Conditions often arise in machines and mechanisms when stresses fluctuate between a upper and a lower limit. For example in figure, the fiber on the surface of a rotating shaft subjected to a bending load, undergoes both tension and compression for each revolution of the shaft.



Stresses developed in a rotating shaft subjected to a bending load

Any fiber on the shaft is therefore subjected to fluctuating stresses. Machine elements subjected to fluctuating stresses usually fail at stress levels much below their ultimate strength and in many cases below the yield point of the material too. These failures occur due to very large number of stress cycle and are known as fatigue failure. These failures usually begin with a small crack which may develop at the points of discontinuity, an existing subsurface crack or surface faults. Once a crack is developed it propagates with the increase in stress cycle finally leading to failure of the component by fracture. There are mainly two characteristics of this kind of failures:

(a) Progressive development of crack.

(b) Sudden fracture without any warning since yielding is practically absent.

Fatigue failures are influenced by :

(i) Nature and magnitude of the stress cycle.

(ii) Endurance limit.

(iii) Stress concentration.

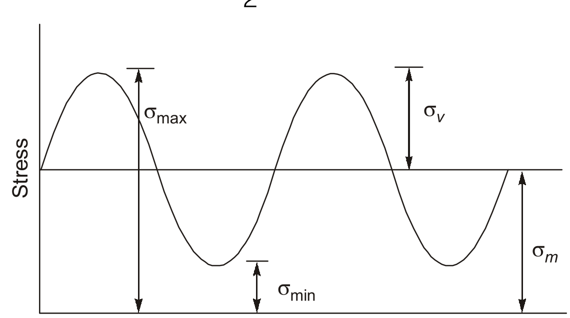
(iv) Surface characteristics

3.3.1 Stress Cycle

A typical stress cycle is shown in figure where the maximum, minimum, mean and variable stresses are indicated. The mean and variable stresses are given by

$$\sigma_{mean} = \frac{\sigma_{max} + \sigma_{min}}{2}$$

$$\sigma_{variable} = \frac{\sigma_{max} - \sigma_{min}}{2}$$

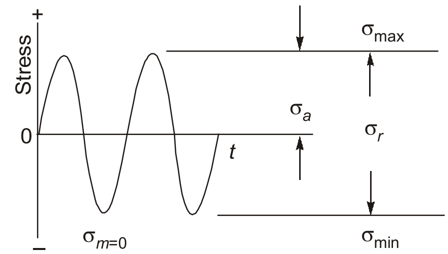


A typical stress cycle showing maximum, mean and variable stresses

3.3.2 Types of Load Variation

(a) (Completely) Reversible Stressing :

Stress variation is such that the mean stress is zero; same magnitude of maximum and minimum stress, one in tension and the other in compression. Now for completely reversible loading $\sigma_m = \sigma_{max} = \sigma_{min}$; $R = -1$ and $A = 0$.

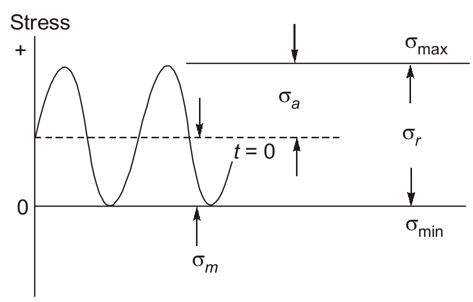


(a) Fully reversed

(b) Repeated Stressing :

Stress variation is such that the minimum stress is zero. Mean and amplitude stress have the same value for repeated loading

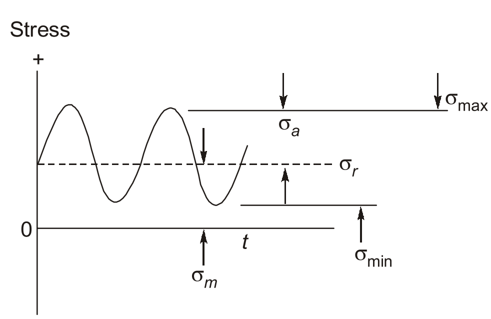
$$\sigma_{min} = 0$$
$$\sigma = \sigma_a = \sigma_{max}/2$$



(b) Repeated

(c) Fluctuating Stressing :

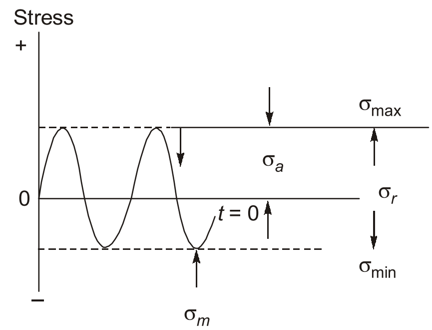
Both minimum and maximum stresses are positive and mean stress also being positive (tensile)



(c) Fluctuating

(d) Alternating Stressing :

Positive maximum stress and negative minimum stress: mean stress is generally positive but can also be negative.



3.3.3 Endurance or Fatigue Limit

In the case of the steels, a knee (flattening or saturation) occurs in the graph, and beyond this knee failure will not occur, no matter how large the numbers of cycles are. The strength (stress amplitude value) corresponding to the knee is called the endurance limit (S_e) or the fatigue limit. However the graph never does become horizontal for non-ferrous metals and alloys, hence these materials do not have an endurance limit.

Endurance or fatigue limit can be defined as the magnitude of stress amplitude value at or below which no fatigue failure will occur, no matter how large the number of stress reversals are, in other words leading to an infinite life to the component or part being stressed. For most ferrous materials Endurance limit (S_c) is set as the cyclic stress level that the material can sustain for 10 million cycles.

In general, steel alloys which are subjected to a cyclic stress level below the EL (properly-adjusted for the specifies of the application) will not fail in fatigue. That property is commonly known as "infinite life". Most steel alloys exhibit the infinite life property, but it is interesting to note that most aluminum alloys as well as steels which have been casehardened by carburizing, do not exhibit an infinite-life cyclic stress level (Endurance Limit).

Factors Influencing Fatigue :

(i) **Loading :** Nature and type of loading : Axial tension, bending, torsion and combined loading. Mean and Variable components in ease of Repeated, Fluctuating and Alternating loading and Frequency of loading and rest periods.

(ii) **Geometry :** Size effects and stress concentration

(iii) **Material :** Composition, structure, directional properties and notch sensitivity

(iv) **Manufacturing :** Surface finish, heat treatment, residual stresses

(v) **Environment :** Corrosion, high temperature, radiation

3.3.4 Endurance Limit Multiplying Factor

$S_e = k_a \times k_b \times k_c \times k_d \times k_e \times S'_e$ $S_e \equiv$ Endurance limit of part $S'_e \equiv$ Endurance limit of test specimen $k_a \equiv$ Surface factor $k_b \equiv$ Size factor $k_c \equiv$ Load factor $k_d \equiv$ Temperature factor $k_e \equiv$ Miscellaneous – effects factor	There are several factors that are known to result in differences between the endurance limits in test specimens and those found in machine elements.

3.3.5 Fatigue stress concentration factor(k_f)

It is found that some materials are not very sensitive to the existence of notches or discontinuity. In such cases it is not necessary to use the full value of k_t and instead a reduced value is needed. This is given by a factor known as fatigue strength reduction factor k_f and this is defined as,