Chapter 1

Introduction to Design

1.1 Introduction :

Machine design can be defined as an art of creation of new and better machines which are more economical and efficient in overall cost of production and operation in the form of plans and drawings and improving the existing ones. It can also be defined as an art of developing new ideas for the construction of machines and expressing those ideas in the form of plans and drawings.

The machine design is a long and the time consuming process. In this, from the study of existing ideas, a new idea has to be developed. The idea is then studied keeping in the mind of its economical success and given the shape in the form of drawings. While preparing these drawings care must be taken that availability of resources in money, in men and in materials required for the successful completion of the new idea into an actual reality.

1.2 Classification of Machine Design :

The machine design may be classified as :

1. Adaptive Design :

It is concerned with the adoption of existing design. The designer only makes minor alteration or modification in the existing designs of the product. This design does not require any special knowledge or skill.

2. Development Design :

It is concerned with the modification of existing designs into new one by adopting new ideas, new materials and methods of manufacturing. This design requires considerable scientific training and design ability.

3. **New Design :**

It is concerned with the development of new thing with new design and it needs lot of research, technical ability and creative thinking.

These can be classified into following :

a) **Rational design :** This design depends upon mathematical formulae of principle of mechanics.

b) **Empirical design :** This design depends upon empirical formulae based on the practice and past experience.

c) **Industrial design :** This design depends upon the production aspects of any machine component in the industry.

d) **Optimum design :** It is the best design for the given objective function under the specified constraints. It may be achieved by minimizing the undesirable effects.

e) **System design :** It is the design of any complex mechanical system such as motor car.

f) **Element design :** It is the design of any element of the mechanical system like piston, crank shaft, etc.

g) **Computer aided design :** This design depends upon the use of computer systems to assist in the creation, modification, analysis and optimization of a design.

1.3 General Considerations in Machine Design :

Following are the general considerations in machine design :

1. **Functional requirement :** The function of the machine element or the system that has to perform is the foremost factor considered in machine design. The links, gear drive or belt drive is correspondingly chosen to perform the particular operation.

2. **Motion of the parts :** The movement of the parts may be rotating or reciprocating with constant velocity or variable velocity. The parts of the machine should be aligned so that the relative motion should be efficient.

3. **Type of load :** The type of the load which acts on the element of a machine is to be considered to identify the stresses that set up within the element. A load may be steady, variable, shock or impact and the element should sustain the load acting on it.

4. **Frictional resistance and lubrication :** Frictional resistance is always leads to a loss of power. Therefore it is necessary to provide good lubrication between the surfaces which are in contact with the others and are with relative motion. Cooling should be provided in order to avoid the over-heating which results into the damage of the parts.

5. **Selection of materials :** Proper material is to be selected for the making of certain part. The properties such as strength, ductility, durability, flexibility, weight, resistance to heat and corrosion, ability to cast or weld, machinability are to be studied and considered.

6. **Use of standard parts :** The use of standard size of components for example bolts, nuts etc., and standard speed of prime movers are preferred to reduce the manufacturing cost and maintenance of the machine.

7. **Safety devices :** Some machines are dangerous to operate while they run at a very high speed. The design should include built-in-safety device for the protection and safety of the operator.

8. **Operational features :** The starting, controlling and stopping of levers should be within the reach of the operators. The controls are also to be located in such a way that, during their replacement due to break or wear, they can be easily dis-assembled without dis-assembling the other parts.

9. **Overall weight and space :** As far as possible efforts should be made to reduce the weight of the element or machine and be made to the size for the given available space.

10. **Number of machines to be manufactured :** The number of parts or elements or machines to be manufactured should also be considered while designing. An order of few articles may cost heavy for production if the designing procedure is same as that of mass production.

11. **Cost of construction :** The price of the product in the market justifies the cost of construction and the design is to be made economical.

1.4 Common Procedure Adopted for Machine Design :

The common procedure that can be adopted for machine design is :

1. **Recognition of need :** First of all, make a complete statement of the problem, indicating the need, aim or purpose for which the machine is to be designed.
2. **Synthesis (mechanisms) :** Select the possible mechanism or group of mechanisms which will give the desired motion.
3. **Analysis of forces :** Find the forces acting on each member of the machine and the energy transmitted by each member.
4. **Material selection :** Select the material best suited for each element of the machine.
5. **Design of elements (size and stresses) :** Find the size of each element of the machine depending upon the force acting on the member and the permissible stresses for the material used. There should not be any deformation or deflection of the member than the permissible limit.
6. **Modification :** Modify the size of the member to agree with the past experience and judgement to facilitate manufacture. The modification may also be done to reduce overall cost.
7. **Detailed drawing :** Draw the detailed drawing of each component and the assembly of the machine with complete specification for the manufacturing process suggested.
8. **Production :** The component, as per the drawing is manufactured in the workshop.

1.5 Design Considerations :

1. **Load :** The main object of the machine is to transmit the motion through its various links to some particular part, where the work is to be done. While doing its work various parts of the machine elements are subjected to different forces and these forces are known as loads.

   These loads are classified as :

   i) **Static load :** It is the load whose magnitude or direction or point of application will not change with respect to time.

ii) **Dynamic load or live load :** It is the load whose magnitude or direction or both changes with respect to time. Cyclic load and impact or shock load are the types of dynamic load.

2. **Stress :** When a body is subjected to an external force, the resisting forces are set up within the body against the deformation and it is measured in terms of force exerted per unit area is known as stress. It is expressed as:

$$\sigma = \frac{F}{A} \text{ N/mm}^2$$

where, σ = unit stress

F = force acting on a body in N

A = Area of cross-section of a body in mm^2.

Note : 1 N/mm^2 = 1 MPa.

3. **Strain :** Whenever a force or a system of forces acts on a body, it undergoes some deformation. This deformation per unit length is known as strain. It is expressed as :

$$\varepsilon = \frac{\text{deformation}}{\text{original length}}$$

$$= \frac{\delta}{l}$$

4. **Poisson's ratio :** When a body is stressed within the elastic limit, the ratio of lateral strain to linear strain is known as poisson's ratio and it is constant for a particular material. It is denoted by 1/m.

$$\text{Poisson's ratio, } \quad {}^{1}\!/_{m} = \frac{\text{Lateral strain}}{\text{Linear strain}}$$

5. **Modulus of rigidity :** It is the ratio of shear stress to shear strain is known as modulus of rigidity. It is denoted by C or G.

$$\text{Modulus of rigidity, } \quad G = \frac{\text{Shear stress}}{\text{Shear strain}}$$

$$= \frac{\tau_s}{\phi}$$

6. **Bulk modulus :** It is the ratio of direct stress to the corresponding volumetric strain, and it is denoted by 'K'.

$$\text{Bulk modulus, } K = \frac{\text{Stress}}{\text{Volumetric strain}}$$

$$= \frac{\left(P/A\right)}{\left(\delta V/V\right)}$$

1.6 Stress-Strain Diagram for Mild Steel :

The mechanical properties of the metals are commonly determined from a tensile test by using universal testing machine (UTM). The test consists of gradually loading a standard specimen of a material and noting the corresponding values of load and elongation until the specimen fractures. The load is applied and measured by a testing machine. The stress is determined by dividing the load values by the original cross-sectional area of specimen. The strain is determined by dividing the elongation values by the gauge length (original length).

The values of stress and corresponding strain are used to draw the stress-strain diagram of the material tested. The fig. 1.1 shows the stress-strain diagram for mild steel. The various properties of the material are discussed below :

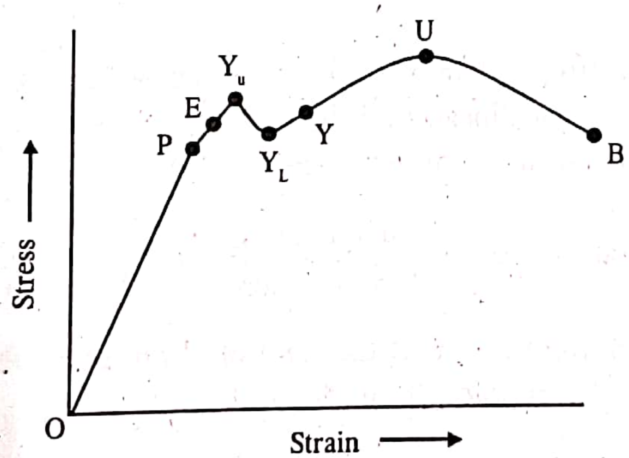

Fig. 1.1 : Stress-strain curve

☞ **Limit of Proportionality (P) :** From O to P the curve is straight line i.e, stress is directly proportional to the strain and Hooke's law holds good up to point P and this point is known as limit of *proportionality*.

☞ **Elastic Limit (E) :** Up to point E the material will regain its size and shape, when the load is removed, i.e., the material has the elastic properties up to the point E. This point is known as *elastic limit.*

☞ **Upper Yield Point (Y_u) :** If the material is stressed beyond the point E, the plastic stage will reach, i.e., on the removal of load, the material will not be able to recover its original size and shape. This point is known as *upper yield point* 'Y_u'.

☞ **Lower Yield Point (Y_L) :** At point Y_u, there is an increase in strain without appreciable increase in load. Thus the curve drops down to the point Y_L called as lower yield point. Then again with the increase in load, the strain increases and is constant upto point 'Y'. This phenomenon of increase in strain without appreciable increase in load in called *yielding*.

☞ **Ultimate Stress (U) :** On further loading, the ductile extension takes place. During the extension the cross-sectional area decreases uniformly over the length and at a point U, the stress attains its maximum value known as ultimate point. The stress at this point is known as *ultimate stress*.

☞ **Breaking Point (B) :** On further loading, the load reaches its maximum value i.e., local yielding takes place and a neck is formed. At point B the specimen breaks called as breaking point. The stress corresponding to this point is known as *breaking stress*.

1.7 Bending and Torsion Stress Equations :

1.7.1 Bending Stress Equation :

Whenever a machine part or a beam is subjected to a static or dynamic loads causes a bending moment at a section tends to bend or deflect the beam, at the same time the internal stresses tends to resist its bending. The resistance offered by the internal stresses to the bending is known as bending stress.

In order to derive the bending equation, following assumptions have been made :

1. The beam is initially straight and unstressed.
2. The beam material is perfectly homogeneous and isotropic.
3. The beam material is stressed within the elastic limit and thus obey's the Hook's law.

4. Plane cross-sections remain plane before and after bending.
5. Each layer of the beam is free to expand or contract independently, of the layer, above or below it.
6. The value of E is same in tension and compression.
7. The section is symmetrical about the plane of bending.

When the beam or machine part is bent, its outer layer is under tension and inner layer is under compression. There is an intermediate layer where there is no stress is known as neutral layer. The magnitude of stress induced in a layer due to bending moment is proportional to its distance from the neutral axis.

The bending stress at any distance y from the neutral axis is given by

$$\sigma_b = \frac{My}{I} \quad \text{or} \quad \frac{\sigma_b}{y} = \frac{M}{I}$$

where σ_b = Bending stress

M = Bending moment acting on a section

y = Distance from the neutral axis

I = Moment of inertial about the neutral axis.

The strain induced is given by

$$\varepsilon = \frac{y}{R}$$

where R = radius of curvature of a beam

We know that,

$$\sigma_b = \varepsilon_c \times E$$

$$= \frac{y}{R} \times E$$

$$\frac{\sigma_b}{y} = \frac{E}{R}$$

Therefore the bending equation is given by

$$\boxed{\frac{E}{R} = \frac{\sigma_b}{y} = \frac{M}{I}}$$

1.7.2 Torsion Stress Equation :

When a shaft is subjected to the action of two equal and opposite couples acting in a parallel plane, then the shaft is under twisting moment called torsion and the stresses induced are known as *Torsional Stresses*. Its value varies from zero at the centroidal axis to the maximum at the outer layer. The torsional shear stress in a circular shaft is given by the equation :

$$\tau = \frac{T \times y}{J}$$

where τ = Shear stress at any distance y from centroidal axis

T = Torque applied

J = Polar moment of inertia.

The angular twist of the shaft over a length l is given by the equation :

$$\theta = \frac{Tl}{CJ}$$ where T = applied torque

C = Modulus of rigidity

$$\therefore \quad \frac{T}{J} = \frac{C.\theta}{l}$$

The intensity of shear stress on any layer at a distance y from the centroidal axis is also given by the equation :

$$\frac{\tau}{y} = \frac{C.\theta}{l}$$

Therefore, the maximum shear stress which occures at the outer layer of a shaft of radius R is given by

$$\boxed{\frac{T}{J} = \frac{\tau}{R} = \frac{C.\theta}{l}}$$

In design, for a solid shaft of diameter d when subjected to a twisting moment, then the maximum shear stress is given by :

$$\boxed{\tau = \frac{16T}{\pi d^3}}$$

1.8 Factor of Safety :

Generally, it is defined as the ratio of the maximum stress to the working stress. Therefore,

$$\text{F.O.S.} = \frac{\text{Maximum stress}}{\text{Working or design stress}}$$

For ductile materials, the factor of safety is defined as the ratio of yield point stress (σ_y) to the working stress (σ). Therefore, (for simple tension or compression)

$$\text{F.O.S.} = \frac{\text{Yield point stress } (\sigma_y) \text{ (tension or compression)}}{\text{Working stress } (\sigma)}$$

For pure shear, the factor of safety is defined as the ratio of yield point stress in shear (τ_y) to the maximum or allowable shear stress (τ_{max}). Therefore,

$$\text{F.O.S.} = \frac{\text{Yield point stress in shear}}{\text{Maximum or allowable shear stress}}$$

For brittle material, the FOS is defined as the ratio of ultimate stress in tension or compression to the working stress in tension or compression.

For tension :

$$\text{F.O.S.} = \frac{\text{Ultimate stress in tension } (\sigma_{ut})}{\text{Working stress in tension } (\sigma_t)}$$

For compression :

$$\text{F.O.S.} = \frac{\text{Ultimate stress in compression } (\sigma_{uc})}{\text{Working stress in compression } (\sigma_c)}$$

1.8.1 Factors to be considered in selection of appropriate value of FOS :

1. Type of loading and stress.
2. Variation in material properties.
3. Mode of manufacture.
4. Effect of time and environment in which the device is expected to operate.
5. Effect of size in material strength.
6. Effect of wear.

7. Life and reliability.
8. Effect of heat treatment.
9. Human safety.

1.8.2 Significance or Importance of Factor of Safety :

While designing machine parts, it is desirable to keep the stress lower than the maximum or ultimate stress at which failure of the material takes place. Therefore, it is necessary to calculate the working stress which is less than the maximum or ultimate stress by using safety factor i.e.,

$$\text{Working stress} = \frac{\text{Maximum or ultimate stress}}{\text{Factor of safety}}$$

The selection of a proper factor of safety depends upon the properties of material, type of stress, mode of manufacture, reliability of applied load, general service conditions and shape of the parts.

Each of the above factor must be carefully considered and evaluated. The high factor of safety results in unnecessary risk of failure.

1.9 Concept of Theories of Failure :

The strength of machine members is based upon the mechanical properties of the materials used. Since these properties are usually determined from simple tension or compression tests, therefore, predicting the failure stresses in members subjected to uniaxial stress is very simple and straight forward. But the problem of predicting the failure stresses for the members subjected to bi-axial and tri-axial stresses is very complicated.

Infact, the problem of predicting the failure stresses for members subjected to bi-axial and tri-axial stresses is so complicated that a large number of different theories have been formulated.

Types of Theories of Failure :

1. Maximum principal stress theory (known as Rankine theory)
2. Maximum shear stress theory (known as Guest's theory)
3. Maximum principal strain theory (known as Saint Venant theory).
4. Maximum strain energy theory (known as Haigh's theory)
5. Maximum distortion energy theory (known as Hencky and Von-Mises theory).

Since ductile materials usually fail by yielding i.e. when permanent deformation occur in the material and brittle materials fail by fracture, therefore the limiting strength for these two classes of materials is normally measured by different mechanical properties. For ductile materials, the limiting strength is the stress at yield point as determined from simple tension test and it is assumed to be equal in tension or compression. For brittle materials, the limiting strength is the ultimate stress in tension or compression.

EXERCISES

I] Question Bank Questions from DTE :

Remember :

1. Define Machine Design.
2. List out the classification of machine design.
3. State general considerations in machine design.
4. Define the following terms : a) Load, b) Stress, c) Strain.
5. Define factor of safety.
6. State the equation for bending.
7. State the equation for Torsion.
8. List the various factors to be considered in deciding the factor of safety.
9. Discuss stress-strain diagram for mild steel.

II] Answer the following questions :

1. What is machine design ? Explain the types of machine design. (Dec. 2013)
2. Explain the common procedure adopted for machine design.
3. Explain the design procedure adopted for machine elements. (May 2014)
4. What are the factors to be considered in machine design ? (May 2012)
5. Explain stress-strain diagram for mild steel with sketch. (Nov. 2011, May 2013)
6. Draw the stress-strain curve for mild steel. Name the salient points. (Dec. 2012)
7. Draw and explain stress-strain diagram for mild steel. (May 2014)
8. Explain the importance of factor of safety.
9. List the factors influencing the selection of appropriate value of FOS.
10. Explain the significance of factor of safety. (May 2014)