CONTENTS

CHAPTER

2

LOADS

Overview: Structures are subjected to loads, and these loads have to be resisted safely. Therefore, the knowledge of the anticipated maximum loads applied on the structures is essential to design safe structures. The different kinds of loads that must be considered, along with the description of their characteristics, are presented in this chapter. For the purposes of structural analysis, loads are idealized as concentrated loads, line loads, and distributed loads. Loads are broadly classified as static and dynamic loads. Static loads do not change with time, whereas dynamic loads do change in magnitude and direction. Examples of both categories of loads are given in this chapter.

Static loads consist of dead loads, live loads, and environmental loads such as snow loads, rain loads, hydrostatic and earth pressures. Typical basic values for some of these loads are presented in the chapter to facilitate the readers to compute total loads applied on the structures. Besides, there are loads due to settlement, thermal effects, shrinkage, etc. The chapter explains the details of these loads and how these loads are induced.

Dynamic loads are of varied types. Wind, wave, earthquake, etc. are some of the dynamic loads that result due to natural phenomena. There are dynamic loads generated by man-made activities. A few examples are: traffic-induced loads, loads due to air, underground and underwater blasting.

General descriptions of wind load—both its static and dynamic effects due to galloping, flutter, and ovaling—are given in this chapter along with necessary expressions for calculating the load applied on the structure. Similarly, seismic loads have also been described. Basic values for both kinds of loads are specified by the building codes and bye-laws of a country, for which it is divided into different zones. These codes have to be invariably followed in the estimation of relevant loads.

Cyclic loads and their importance in the design of structures have been described in brief in this chapter.

As for the mode of the application of loads is concerned, loads are broadly classified as axial, shear, bending, and torsion. These are explained in this chapter with necessary sketches.

2.1 Introduction

It is of prime importance that structures must carry the loads imposed on them very safely without any problem. Therefore, a knowledge of the expected maximum loads applied on the structures is essentially required to design safe structures. A rational combination of loads that will produce maximum stresses or displacements in various parts of the structure must be determined as a prelude to the designing of structures. In designing a structure, a clear idea of the nature and magnitude of the loads acting on the structure is necessary. The various kinds of loads that must be considered along with the description of their characteristics are depicted in Fig. 2.1.

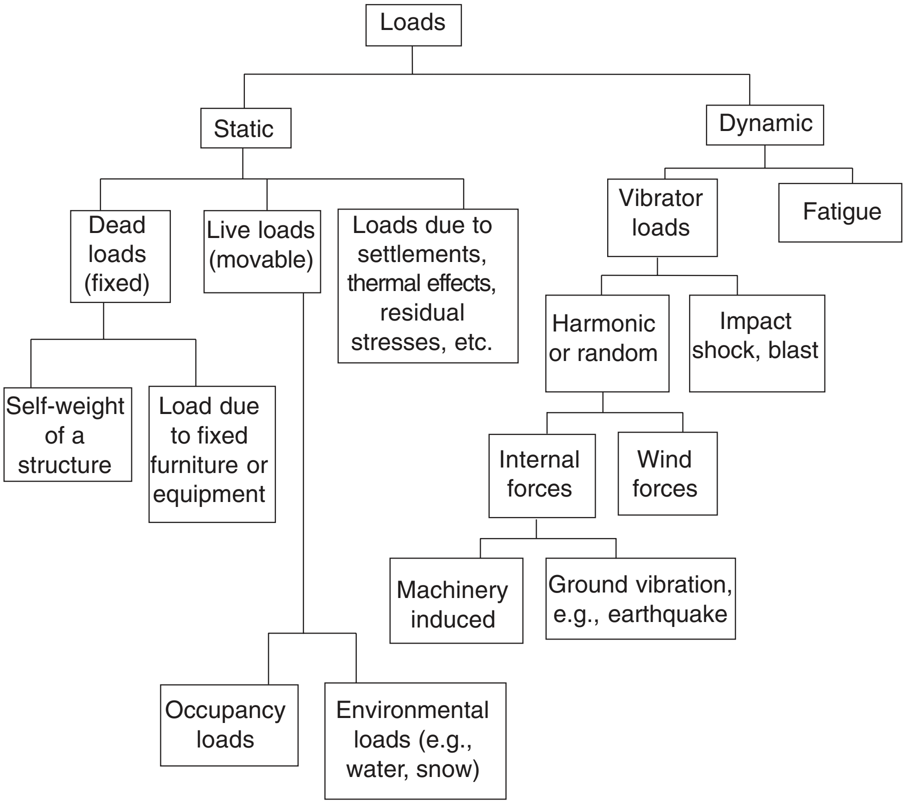


Figure 2.1 Types of loading applied on structures

2.2 Types of Loads

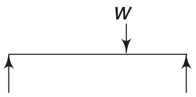
Loads acting on structures are broadly classified as *static* and *dynamic*. Static loads are applied slowly and gradually on the structure, and these are steady-state in character. They do not change with time. Deformations resulting from the application of static loads are slow and gradual, and also are of steady-state character. The peak deformations occur under maximum static loads. Examples of static loads are: water loads in a tank, load due to occupants of apartments and residential houses, weight of furniture and stored materials in office buildings, etc. Dynamic loads are characterized by their sudden application on the structures and their variation of the magnitude with time. They are not steady-state loads and vary rapidly with time. The resulting deformation also varies rapidly with time. Dynamic loads cause oscillations of structures, with the result peak deformations do not necessarily occur at maximum loads. Traffic-induced loads on bridges, wave loads on marine and offshore structures, wind forces on high-rise structures and towers, and earthquake loading on structures are some of the examples of dynamic loads exerted on structures.

Among these classifications of loads, some are man-made and some are natural. Weights of personnel, furniture, machinery, stored materials, and similar other items and blast and impact loads are man-made in character. Such loads can be controlled to some degree. Wind, wave, and seismic (earthquake) forces result from natural phenomena and, therefore, cannot be controlled.

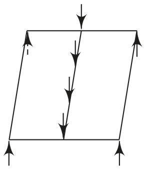
Static loads are further classified as *dead loads*, *live loads*, and *forces due to settlements or thermal effects*. Dead loads (DL) are mostly of gravity type and essentially remain constant during the life of the structure. Gravity loads always act vertically downwards. Such loads normally consist of the self-weight of the structure as well as weights of permanent building elements, such as floor finishes—tiles, marbles, granites—mechanical equipments, electrical installations and appliances, non-movable partitions, etc. Dead loads are relatively fixed in character. On the contrary, live loads (LL) vary greatly and may not be present always. Live loads are also called *imposed loads*. Occupancy loads, snow loads, vehicle loads, wind forces, earthquake loads, and wave loads are some of the examples of live loads. When live loads are applied slowly and gradually, like in the case of occupancy loads, they are of static nature. When they are applied suddenly and their magnitude varies rapidly with time, they are of dynamic nature.

For the purposes of structural analysis, loads can be, generally, idealized as one of the following three kinds.

Concentrated loads These loads act as a single load at a particular point on a structure, as shown in the sketch below. The force exerted by a beam on another perpendicular beam in a structure, column loads, and heavy machinery loads, and wheel loads of vehicles are all examples of concentrated loads. As it is very difficult to apply loads at a point, these loads occupy a relatively small area of the structural element.



Line loads These loads act along a line, as shown in the following sketch. The self-weight of a partition wall resting on a floor slab, loads exerted by a train on the track, etc. fall under this category of loading.



Distributed loads These loads act over an area of the surface. Water pressure acting on a tank wall, soil pressure acting on a foundation, the weight of floor finishes, and wind load acting on a structure are some examples of this category of loading. A typical representation of distributed loads is shown in the sketches below.

2.3 Static Loads

Structures are invariably subjected to static loads. As the name suggests, they remain constant and stationary. Some of these loads are man-made, some are imposed by environment, and some are due to other effects. Man-made loads are classified as dead and live (or imposed) loads. Environmental loads are mostly due to natural phenomena such as snow, rain, ice, etc. Subsidence of foundation, thermal variations, etc. are categorized as other effects which also impose loads on the structures. For the strength and safety of structures, these loads have to be considered in the design. The following sections describe in detail various types of static loads that structures are subjected to.

2.3.1 Dead Loads

Among various loading types, dead loads are simple to handle. These can be easily computed from the given dimensions of members of the structures and known densities of materials that have been used in their construction. Unit weights of materials are given in codes and handbooks. Table 2.1 gives typical unit weights of some of the common building materials. The tabulated information facilitates the process of obtaining dead loads for common building materials. The Indian Standard IS: 875 (part 1)-1987 gives the unit weight of materials used in construction.

TABLE 2.1 Densities of popular materials—typical values

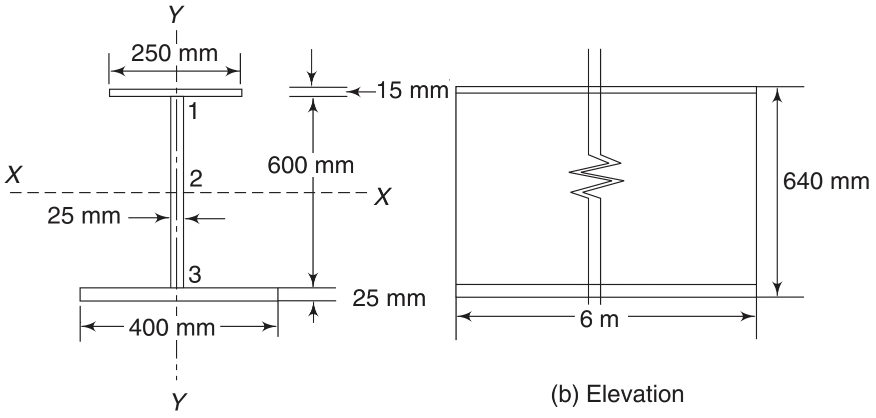
Material	Density (kg/m^3)
Aggregate, dry	1800
Brick	2500
Cement	1440
Concrete	
Plain	2400
Lightweight	1201–1762
Reinforced	2500
Cast iron	7000

(Contd)

(Contd)

Material	Density (kg/m^3)
Earth	
Clay, dry	1009
Clay, wet	1762
Sand, dry	1600
Sand, wet	2000
Gypsum mortar	2579
Lime slaked	1020
Metal	
Aluminium, cast	2643
Copper, cast	8907
Lead, cast	11,340
Steel, rolled	7850
Water	1000

Example *A steel girder of cross-sectional dimension shown in Fig. 2.2 and length 6 m weighs 78.5 kN/m^3. Determine the self-weight of the girder.*



(a) Cross section

(b) Elevation

Figure 2.2 Details of a steel girder

Solution

Unit weight of steel = 78.5 kN/m^3

Area of cross section = area1 + area2 + area3

$$= \left(\frac{250}{1000} \times \frac{15}{1000}\right) + \left(\frac{600}{1000} \times \frac{25}{1000}\right) + \left(\frac{400}{1000} \times \frac{25}{1000}\right)$$

$$= 3.75 \times 10^{-3} + 0.015 + 0.01 \text{ m}^2$$

$$= 0.02875 \text{ m}^2$$

Volume = $0.02875 \times 6 = 0.1725$ m^3

Self-weight of girder = $0.1725 \times 78.5 = 13.54$ kN

Dead load of girder = 13.54 kN

Example *A spherical steel ball of diameter 300 mm weighs 78.5 kN/m³. Find its weight.*

Solution

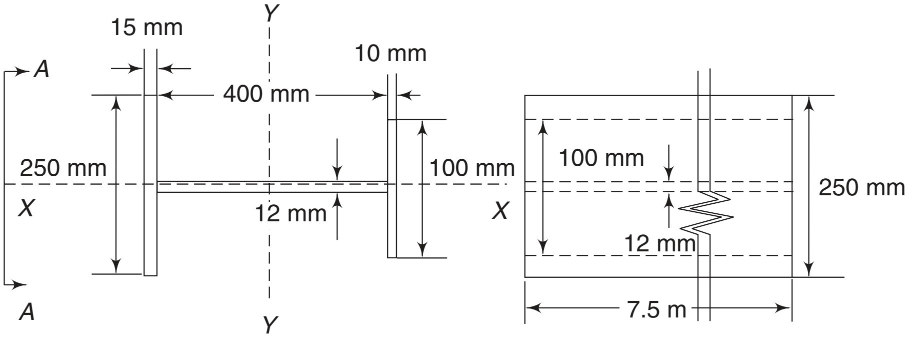
$$\text{Volume of ball} = \frac{4}{3}\pi r^3$$

$$\text{Radius of ball} = 300/2 = 150 \text{ mm}$$

$$\therefore \quad \text{Volume} = \frac{4}{3}\pi\left(\frac{150}{1000}\right)^3 = 0.01414 \text{ m}^3$$

$$\text{Weight of ball} = 0.01414 \times 78.5 = 1.11 \text{ kN}$$

Problem *A steel beam of dimensions shown in Fig. 2.3 weighs 78.5 kN/m³. Find its self-weight.*



(a) Cross section (b) Elevation on *AA*

Figure 2.3 Dimensions of steel beam

Ans. 5.62 kN

Problem *A circular disc of diameter 400 mm and thickness 100 mm weighs 78.5 kN/m³. What is the weight of the disc?*

Ans. 0.986 kN

2.3.2 Live Loads

These loads are also called superimposed loads or occupancy loads. These loads are directly caused by humans, machines, or movable objects. Although movable, live loads are still applied slowly on a structure. They may or may not be present and acting upon a structure at any given point in time. Though these loads usually act only during a fraction of the life of the structure, it is necessary to design for conservatively high values.

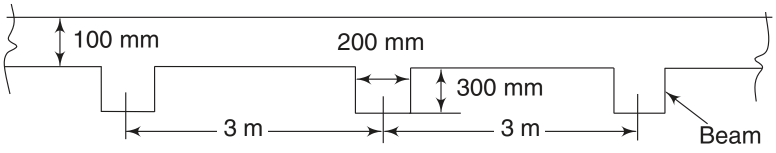
Live loads mostly act vertically downward, but occasionally can act horizontally as well. The live loads tend to be conservative. Normally structures are designed to withstand live loads specified in various codes and handbooks. Typical values of live loads, recommended for several different occupancy types, are given in Table 2.2.

TABLE 2.2 Typical values of uniformly distributed live loads

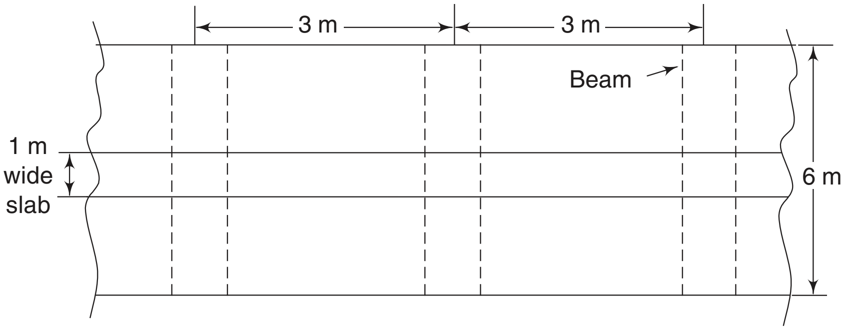
Type of occupancy	N/m^2
Apartments	
Corridors	3830
Rooms in flats	1915
Public rooms	4788
Assembly halls	2873
Fixed seats	4788
Movable seats	4788
Dance halls	11,970
Driveways, side walks (public)	4788
Gymnasiums	4788
Hotels	
Corridors	4788
Guest rooms	1915
Public rooms	4788
Libraries	
Reading rooms	2873
Stacks	7182
Manufacturing	5985
Office buildings	
Offices	2873
Lobbies	4788
Recreational areas	3591
Residential dwellings	
First floor	1915
Second floor	1436
Restaurants	4788
Schools	
Classrooms	1915
Corridors	3830
Skating rings	4788
Stairs	4788
Stores (retail)	
First floor	4788
Upper floors	3591
Theatres	
Aisles, corridors	4788
Balconies	2873
Floors	2873
Stage	7182
Warehouses	
Light storage	5985
Heavy storage	11,970

For design purposes, values of live loads recommended by local building codes should be used. IS: 875 (part 2)-1987 prescribes live loads for different types of buildings and occupancy. These values are prescribed as uniformly distributed. The actual live loads on a structure at any particular point in time are typically less than those for which the structures have been designed. However, at some point of time, there is a high probability that the structure will indeed have to carry the designed loads. A change in the type of occupancy may also affect the design of structures. A structure originally designed to carry loads specified for apartment houses would be inadequate if the building is used for office purposes or for storage of materials, e.g., a warehouse. Provisions in building regulations typically require that structures be designed according to loadings recommended for the appropriate type of occupancy or use.

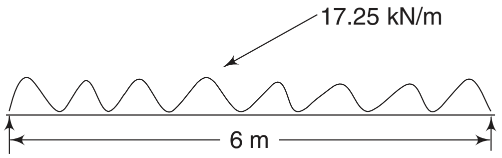
Example *A reinforced concrete (RC) slab of thickness 10 cm is supported on beams. The spacing of beams is at 3 m centre to centre. The unit weight of RC is 25 kN/m^3. The live load on the slab is 2500 N/m^2. The unit weight of the floor finish is 750 N/m^2. Calculate the dead and live loads transferred from the slab to the supporting beams. If the beams of the size shown in Fig. 2.4(a) are supported on columns spaced at 6 m centre to centre, determine the load transferred to the columns.*



(a) Cross section



(b) Plan



(c) Load on the beam

Figure 2.4 Beam–slab system

Solution

Let us consider the slab of 1 m width [Fig. 2.4(b)]. Calculations are made for the transfer of load to the central beam.

Span of the slab is 3 m.

Dead load

$$
\begin{aligned}
\text{Self-weight of the slab} &= 3\text{ m} \times 1\text{ m} \times (10/100)\text{ m} \times 25\text{ kN} = 7.5\text{ kN/m}\\
\text{Floor finish} &= 3\text{ m} \times 1\text{m} \times (750/1000)\text{ kN} \qquad\qquad = \underline{2.25\text{ kN/m}}\\
&\qquad\qquad\qquad\qquad\qquad\qquad\qquad\quad \underline{9.75\text{ kN/m}}
\end{aligned}
$$

$$\text{Live load on the slab} = 3\text{ m} \times 1\text{ m} \times (2500/1000)\text{ kN} = 7.5\text{ kN/m}$$

$$\text{DL} + \text{LL} = 9.75\text{ kN}+ 7.5\text{ kN} = 17.25\text{ kN/m}$$

Therefore, 17.25 kN load is applied on the beam by the slab for 1 m run of the beam.

$$\text{Self-weight of the beam} = 6\text{ m} \times \frac{200}{1000}\text{m} \times \frac{300}{1000}\text{m} \times 25\text{ kN} = 9\text{ kN}$$

$$\text{Load transferred from slab} = 17.25 \times 6 = 103.5\text{ kN}$$

$$\therefore \quad \text{Total load} = 103.5\text{ kN} + 9\text{ kN} = 112.5\text{ kN}$$

This is the load transferred by the beam to two columns.

$$\therefore \quad \text{Load/column} = 112.5/2 = 56.25\text{ kN}$$

Problem *A slab–beam–column system consists of an RC slab 12 cm thick with a span of 4 m and a beam length of 6.5 m. The beam size is 350 mm in depth below the slab and 225 mm in width. Calculate the load transferred to the column, assuming the unit weight of RC to be 25 kN/m^3 and floor finish 600 N/m^2.*

Ans. 85.7 kN (assuming live load of 2.5 kN/m^2)

2.3.3 Environmental Loads

Examples of these loads are snow, rain, water, earth pressure, and ice. Snow, rain, and ice loads affect the design of roofs.

2.3.3.1 Snow loads

Snow loads are often significant, especially in the design of roofs. Snow is a movable load, because it will not necessarily cover the entire roof, and some members supporting the roof may receive the maximum stress, with the snow covering only a portion of the roof. The design snow load can be considered as uniformly distributed load. The minimum design snow load on a roof area, or any other area above ground which is subjected to snow accumulation, is obtained by multiplying the snow load on ground, P_0, by the shape coefficient β, as applicable to the particular roof area considered:

$$P = \beta P_0 \tag{2.1}$$

where P is the design snow load in Pa on the plan area of roof, β is the shape coefficient, and P_0 is the ground snow load in Pa. The nominal values of the shape coefficient β are given in the IS: 875(part 4)-1987 code for the snow loads.

Snow loads on roofs vary very widely and depend on such factors as elevation, latitude, wind frequency, duration of snow fall, site exposure, roof size, geometry, and inclination. Typical values of downloads are given in Table 2.3 for the American states. These figures vary widely, however, depending on snow density. Most design snow loads for typical urban areas range from 958 to 2873 N/m^2. Local experience should always be checked, however, since in particular areas, loads can be much higher than the indicated figures. This is particularly true for mountainous regions. Snow and wind loads do not act simultaneously because wind is likely to remove much of the snow.

TABLE 2.3 Typical snow loads in USA

Region	N/m^2
Southern states	0–718
Central states	1197–1676
Northern states	1436–2394
Great Lakes, New England, and mountain areas	1436–3830

2.3.3.2 Ice loads

Ice forms on surfaces, so this should be considered in the design of slender members such as cables or towers (built of relatively small members that have proportionately large areas on which ice may accumulate). Ice having a density approximately equal to that of water may build up to a thickness of 50 mm or more on such members. The mass density of ice may be assumed to be equal to 0.9 g/cm^3. Formation of ice results in an increase in the weight and the surface area on which the wind pressure acts. Therefore, this should be considered in computing wind loads acting on members covered with ice. A very difficult type of ice loading is encountered on bridge piers where river ice may occur. The force on a bridge pier caused by a mass of ice floating down a river can be formidable; its magnitude is often estimated to be equal to the area of the ice in contact with the pier multiplied by the compressive strength of the ice. This force may be reduced by shaping the upstream face of the pier to reduce the exposed area or to force the flowing ice to rise up on a ramp like edge that breaks the ice.

2.3.3.3 Rain loads

Rain load is usually less than snow load. So it is not considered separately. Moreover, drains on the roof do not permit accumulation of rainwater. Therefore, under normal circumstances, the necessity of considering the rain load in the design does not arise. However, because of the design or construction errors or clogged drains, failures have occurred when rain caused local deflections due to the ponding effect. When rainwater collects, it may, under certain conditions, cause additional deflection, which causes more water to accumulate. This progressive deflection and accumulation may continue and lead to failure. Such a ponding failure occurs when the flexural stiffness of the roof system is small relative to the span. The American Institute of Steel Construction (AISC) specifications contain provisions on ponding which specify the minimum stiffness for primary and secondary roof beams.

2.3.3.4 Water/hydrostatic pressure

Dams, water tanks, irrigation structures, etc. are subjected to water pressure, which acts normal to the surface of the structure. The magnitude of water pressure is given by

$$p = \gamma h \tag{2.2}$$

where γ is the unit weight of water and h is the water head, which is the difference in the elevation between the water surface and the point at which the pressure acts. This water pressure varies linearly with the depth of water (Fig. 2.5). Walls of tanks, vessels, and underwater structures are subjected to this linear water pressure. The floors of all these structures are subjected to the weight of water contained in these structures.

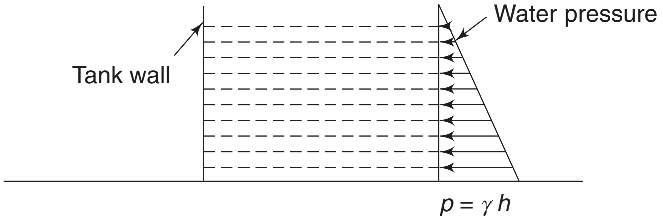


Figure 2.5 Water pressure acting on a wall

Example *An RC water tank of inner dimensions 10 m × 8 m × 5 m is filled with water up to 4 m height above the bottom slab. If the unit weight of the water is 10 kN/m^3, calculate the pressure on side walls and also the weight of water in the tank.*

Solution

As water is up to 4 m deep,

$$\begin{aligned}\text{Weight of water} &= \text{volume of water} \times \text{unit weight}\\ &= 10\text{ m} \times 8\text{ m} \times 4\text{ m} \times 10\text{ kN}\\ &= 3200\text{ kN}\end{aligned}$$

This is the dead load acting on the bottom slab of the tank. The water pressure on the wall is calculated from Eq. (2.2):

$$\begin{aligned}p &= \gamma h\\ &= 10 \times 4 = 40\text{ kN/m}^2\\ &= 40 \times 10^3\text{ N/m}^2\\ &= 0.04 \times 10^6\text{ Pa} = 0.04\text{ MPa}\end{aligned}$$

Problem *A water tank of outer dimensions 8 m × 4 m × 3 m has a uniform wall thickness of 100 mm all around. Water is filled in the tank. Calculate the weight of water on the bottom slab as well as the water pressure on the walls, assuming the unit weight of water to be 10 kN/m^3.*

Ans. 889.2 kN, 0.03 MPa

2.3.3.5 Earth/soil pressure

Underground structures such as foundation walls, retaining walls, and tunnels are subjected to earth pressure, which acts laterally on the structure. This pressure depends on many variables, such as the cohesion and friction in the soil, the possibility of swelling, a characteristic exhibited by clays, and the rigidity of the structure. Earth pressure varies linearly with depth (Fig. 2.6).

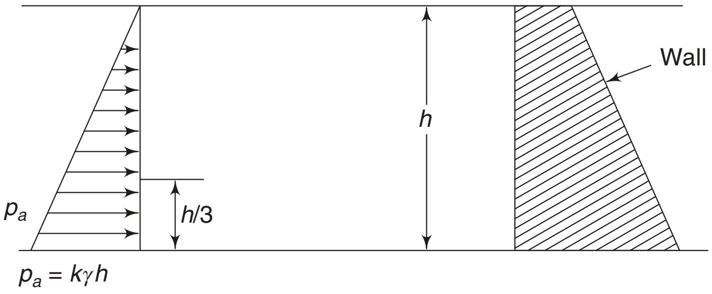


Figure 2.6 Earth pressure on wall

The earth pressure on a wall is given by

$$p_a = k\gamma h \tag{2.3}$$

where γ is the unit weight of soil, h is the height of the wall, and k is the coefficient of earth pressure given by

$$k = \cot^2\left(45^\circ + \frac{\phi}{2}\right) = \frac{1 - \sin\phi}{1 + \sin\phi} \tag{2.4}$$

where ϕ is the angle of internal friction of soil, details of which are available in any book on soil mechanics.

2.3.4 Load due to Other Effects

2.3.4.1 Settlements

Differential settlement of buildings and structures occurs due to the consolidation of soil or transmission of vibration generated by construction activities such as pile driving, hydraulic compaction, traffic-induced movements, etc. Due to this differential settlement, additional loads are applied on the structure, which in all likelihood are not considered at the design stage. In the past, many structures got damaged or collapsed due to the differential settlement. While designing the structures, it is advisable to take into account the load due to settlement. With the help of a foundation engineer, it may be possible to obtain bounds on the differential settlements of the foundations. When the differential settlements are large, the internal stresses will also be large. The load due to settlements is considered non-directional.

2.3.4.2 Thermal loads

When a structure is restrained so that movements between various points in the structure do not occur freely, forces may be generated due to a change in temperature. The forces set up in a structure as a result of temperature changes are often called *thermal forces*. In addition to considering the forces set up by changes in temperature, it is important to take into consideration the expansion and contraction of a structure, particularly in connection with support details. As an illustration of this, a steel bar with both ends fixed is considered. The bar is heated uniformly and a temperature of 30 °C is reached over the entire length of the bar. The strain (defined in Chapter 3) in the bar is given as

$$\varepsilon = \alpha \Delta T \tag{2.5}$$

where α is the coefficient of thermal expansion, the values of which for different materials are available in standard reference books on engineering. The stress (defined in Chapter 3) induced in the bar is

$$f = E\varepsilon \tag{2.6}$$

where E is Young's modulus (defined in Chapter 3) of steel. It is worth noting that the stress induced in the bar due to the change in temperature is independent of the length and cross-sectional area of the bar. Temperature stresses also develop if materials with significant thermal coefficients, e.g., mild steel and stainless steel, are joined. The coefficients of the thermal expansion of steel and concrete are nearly equal. Therefore, it has been made possible to use steel as reinforcement in concrete members. Thermal loadings that produce large forces and stresses occur in nuclear reactor structures and in other types of industrial facilities. Expansion joints between rails, between two parts of large structures, are some of the classic examples that allow different parts of the structure to expand freely without inducing any strain or crack in the structure.

2.3.4.3 Fabrication errors

Stresses may also result from a lack of fit. This type of situation arises when a member of improper size is forced into place during fabrication. The difference in dimensions of a structure is called *actual fabrication error*. Fabrication errors, either actual or induced, are non-directional loads that cause a structural response. By careful detailing of joints and connections, this problem can be avoided.

2.3.4.4 Shrinkage

Among the popular and widely used construction materials, concrete is most susceptible to shrinkage. A fixed length L of freshly poured concrete shortens by an amount δL as it sets. The coefficient δ is called *shrinkage ratio*. Most specifications prescribe a constant value for δ. For concrete, on an average, $\delta = 0.0003$. During the shrinkage, if a structural resistance occurs, internal stresses will develop.

2.3.4.5 Centrifugal forces

Vehicles negotiating curved tracks or roadways exert *centrifugal forces*. These forces are of considerable magnitude and must be considered in the design of structures, especially bridges. Such centrifugal forces are lateral loads and should be considered as moving loads.

2.3.4.6 Longitudinal forces

Whenever vehicles crossing a structure, especially bridges, increase or decrease their speed, horizontal forces are induced in the direction of the longitudinal axis of the structure. These forces are called *longitudinal forces*. Since they are inertia forces resulting from acceleration or deceleration of vehicles, they act through the centres of gravity of vehicles. The magnitude of such forces is limited by frictional forces that can be developed between the contact surface of the wheels of the vehicles applying these forces to the roadway or track and the surface of the roadway or track.

2.4 Dynamic Loads

Machine foundations, turbo-generator foundations, offshore platforms, wind energy towers, crushers, bridges, structures excited by ground vibration are some examples of the structures subjected to dynamic loads. The following categories of loads are of dynamic nature:

1. Wind loads
2. Wave loads
3. Earthquake loads
4. Traffic-induced loads
5. Load induced by air blasting
6. Load due to underground blasting
7. Underwater blasting load
8. Impact loads
9. Construction activities induced loads
10. Forces caused by rotating machinery, and
11. Cyclic loads

The above categories of loads are special forms of live loads typically considered in this section because of their dynamic aspects.

A structure possesses both *mass* and an elastic property called *stiffness*. These parameters are combined to give an important property of the structure called *natural frequency* or *period of vibration*, details of which will be presented in Chapter 10. The above listed dynamic loads also possess some frequencies with which these excite structures. This process sets the structure into vibration. The frequency of the dynamic load is called excitation or driving frequency. When the natural frequency of the structure and the excitation frequency coincide, a phenomenon, called *resonance*, occurs. Because of this resonance effect, large deformations and stresses may build up in the structure. This is similar to the effect when one jumps rhythmically on a flat diving board to excite it or when troops march in step on a suspension bridge.

Certain types of live loads of dynamic nature produce large dynamic stresses even though their magnitudes may be small. In most instances the effects of possible vibrations are minimized by single measures. Overhead moving cranes in industrial establishments and elevators are some examples involving dynamic live loads in buildings. In order to account for the dynamic effects of cranes, the static vertical lift-loads are increased by about 25% and to account for the deceleration on the runway, a horizontal force equal to about 20% of the load is applied along the runway. The effective weight of elevators is usually increased by about 100% to include the dynamic effects produced by acceleration or braking.

In certain dynamic situations, complex dynamic analyses are necessary to calculate the dynamic response of the structure. For example, aircraft, suspension bridges, machine foundations, towers, etc. are often analysed for vibration effects. The methods of evaluation of the response of structures under dynamic loads are covered in Chapter 10.

2.4.1 Wind Loads

The analysis of civil engineering structures subjected to wind load is very complex. This must be taken into account while designing safe and serviceable structures. Some of the examples of wind engineering problems that require special attention include the dynamic response of tall structures, oscillations and flutter of suspension bridges, action of tornadoes on nuclear power plants, etc. Wind engineering is a new and rapidly developing field, and hence current procedures for estimating wind effects and the information on which they are based should, therefore, not be regarded as definitive. However, considerable progress has been made in the past decade towards understanding some of the questions relating to wind effects on structures. As a result, procedures and techniques have been developed that have improved the designer's ability to estimate the effects of wind from the standpoint of both strength and serviceability.

2.4.1.1 Static effects

When wind strikes a structure in its path, it is deflected or, in some cases, stopped by the structure. This results in the kinetic energy of the wind being transformed into potential energy of pressure or suction, the magnitude of which depends on the velocity of the wind, nature of the surface on which it acts, mass density of the air, geometrical shape, dimensions and orientation of the structure, and its overall stiffness as well as the exact location of the point on the structure at which the wind acts.

Wind forces acting on a structure are based primarily on the velocity of wind 10 m above the ground level at a particular location. Design wind velocities for different geographical locations are determined from data gathered from weather stations. Wind velocities range from 96 km/hr in some inland regions to 161 km/hr in other inland regions. During cyclones wind velocities in coastal areas go up to 200 km/hr. Design velocities are usually based on a 50-year mean recurrence interval. Wind velocities increase with the height above the ground level in a parabolic manner. So also the design values increase accordingly. Suitable allowances are made in velocity depending upon whether the structure is in an urban or a rural area. Local building codes should be consulted for exact design loadings or velocities.

Once the design wind velocity is known, it is possible to determine the dynamic pressure arising from wind action and express it as an equivalent static force, using a pressure coefficient C_D that depends on the geometry of the body on which the wind impinges. The reactive force F_D exerted by the structure in opposing the motion of the wind is given by

$$F_D = C_D q_h A \tag{2.7}$$

where C_D is the pressure coefficient for the shape involved, q_h is the velocity/wind pressure at height h (expressed in N/m^2), and A is the exposed area of the building surface normal to the wind. The velocity pressure is related to the design wind velocity, also called basic wind velocity, and is given by

$$q_h = 0.6 V_h^2 \tag{2.8}$$

where V_h is the design wind velocity in m/s at height h. The coefficient 0.6 in Eq. (2.8) is in SI units. It depends on a number of factors and mainly on the atmospheric pressure and air temperature. The value chosen corresponds to the average appropriate Indian atmospheric conditions. Variation in the dynamic wind pressure due to wind gust may also have to be factored into a design wind-load analysis. The wind gust is represented as a gust factor G_F. A more exact expression involving the gust factor is given by

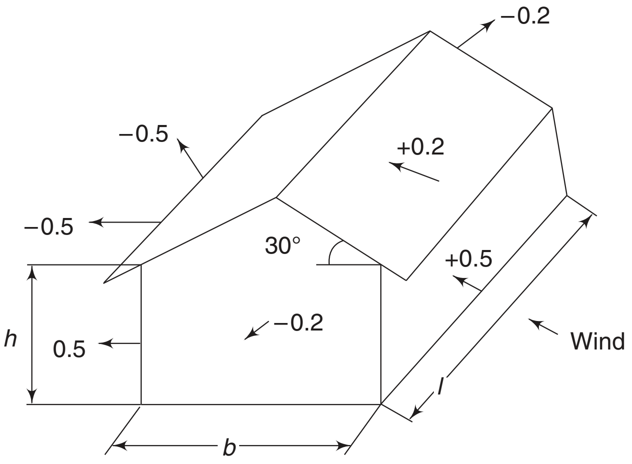
$$F_D = C_D q_h A G_F \tag{2.9}$$

Using the simpler expression in Eq. (2.7), the *average static pressure* p is given by

$$p = F_D/A \quad \text{or} \quad p = C_D q_h \tag{2.10}$$

Equation (2.10) is frequently used.

The *pressure coefficient* C_D, also called shape coefficient, depends on the shape of the building and is different for different shapes. Generally, it denotes the relative amount of obstruction caused by the shape of the building to an impinging air flow. The pressure coefficient C_D is equal to unity when the air flow is completely stopped by the shape of the structure. However, in the case of actual building shapes, there is no stoppage of air, but air is diverted or deflected along the boundaries. The pressure coefficients for a number of different building shapes and configurations have been developed and tabulated. On any given building, the wind produces both pressure and suction, depending on the location of the point under consideration. Suction means pressure below atmospheric or static pressure and is considered to act away from the surface. The pressure coefficients specifically for different locations on the buildings have been tabulated and are available in the relevant codes of practice. For example, the Indian Standard IS: 875 (part 3)-1987 gives the average values of the coefficients for some building shapes for different angles of incidence of the wind. Typical coefficients are shown in Fig. 2.7. The wind load acting normal to a surface is obtained by multiplying the area of that surface or its appropriate position by the pressure coefficient C_D and the design velocity/wind pressure at the height of the surface from the ground.



Wind force = $C_D q_h A$

For h/b between 1/2 and 3/2 and roof angle 30°

Figure 2.7 Typical pressure coefficients for a building with gable roof

2.4.1.2 Dynamic effects

So far the discussions were focused on the static nature of wind. However, the dynamic nature of the wind forces is also important. A structure immersed in a given flow field is subjected to aerodynamic forces, which include drag forces, i.e., along-wind forces, which act in the direction of mean flow, and lift forces, i.e., across-wind forces, which act perpendicular to the direction of wind. Aerodynamic forces are dependent on time. So the methods of structural dynamics have to be employed to determine the response of the structures. The random nature of the dependency of the aerodynamic forces on time essentially requires the application of the theory of the random vibrations in the analysis of the structures subjected to wind to evaluate the response.

Structures and structural elements which are flexible and slender shall be investigated to ascertain the importance of wind-induced oscillations or excitations along and across the direction of the wind. The dynamic effects of wind on high-rise structures, which are more flexible, can be problematic due to undesirable swaying caused by the wind. There can also be the phenomenon of resonance described in Chapter 10.

The following three forms of wind-induced motion are very important and every designer must be aware of these. These motions are characterized by an increase in the amplitude of the vibration with an increase in the wind speed.

Galloping This is the transverse vibration of some structures due to development of aerodynamic forces which are in phase with the motion. The characteristics of galloping are the progressive increase in the transverse vibration with an increase in the wind speed. All structures that are not circular in cross section, namely, triangles, squares, polygons, angles, crosses, T-sections, twisted cables, and cables covered with ice are prone to this type of excitation.

Flutter It is an unstable oscillatory motion of a structure. This is caused by the coupling between aerodynamic force and elastic deformation of the structure. The application of combined bending and torsion may result in this form of oscillatory motion. Though oscillatory motions in each degree of freedom may be damped, instability can set in due to energy transfer from one vibration to another, and the structure apparently executes sustained or divergent oscillations with a type of motion which is a combination of the individual modes of vibration. Terms such as damping, degrees of freedom, modes of vibration, etc. are defined in Chapter 10. Flutter can set in at wind speeds much less than those required for exciting the individual modes of vibration. Long-span suspension bridge decks or members of a structure with a large ratio of its depth along the wind stream and its least lateral dimension are prone to low-speed flutter.

Ovaling This type of motion occurs in thin-walled structures with open ends at one or both ends, such as oil storage tanks, and natural draught cooling towers in which the ratio of the diameter of minimum lateral dimension to the wall thickness is of the order of 100 or more. These oscillations are characterized by the periodic radial deformation of the hollow structure.

In addressing the wind loads due to dynamic phenomena such as galloping, flutter, and ovaling, many publications and references are available for assistance. If the required information is not available in these publications, specialist advice should be sought, including experiments on models in wind tunnels. Buildings and structures that may be excited seriously by wind require careful investigation. It is to be borne in mind that wind-induced vibrations may occur at wind speeds lower than the static design wind speed for a given location.

2.4.2 Earthquake or Seismic Loads

In areas of great seismic activity, earthquake loads are very important in the design of structures. Besides other types of loads, seismic loads are also taken into consideration in the design. However, wind and earthquake do not occur simultaneously. So while designing for earthquake loads, wind loads need not be considered.

Earthquakes are essentially a vibratory phenomenon. They are associated with shock loading on the earth's crust as a result of a number of causes. But the primary reason is the abrupt slippage between adjacent crust plates which the surface of the earth is made up of. Places where such slippage occurs are called *fault zones*. The shock resulting from the slippage is propagated in the form of waves in the ground. The highly irregular or random shaking of the ground transmits acceleration to structures through the foundation and the mass of the structure resists the motion due to the inertia effects. Therefore, the forces developed are consequently inertial in character.

The ground motion generated by an earthquake is three-dimensional in nature. However, the transmitted accelerations are largely horizontal and are usually most important from the consideration of the design of structures. Vertical components of acceleration are normally not considered. In active earthquake regions, the maximum rate of horizontal acceleration of the foundations may reach values having a magnitude between 0.5 and 1.0 times g, the acceleration due to gravity, i.e., between 4.9 and 9.8 $\mathrm{m/s^2}$. If the structure is assumed to act as a rigid body, it will accelerate horizontally at the same rate as its foundations. Hence each part of the structure will be acted upon by a horizontal force equal to its mass multiplied by its horizontal acceleration:

$$\text{Lateral force} = \frac{\text{weight } (w)}{g} \times 0.5g = 0.5\ \text{W}$$

The response of structures to earthquakes depends on a number of factors: characteristics of ground vibration, the stiffness and mass of the structure, the subsoil conditions, and the presence of damping mecrhanisms in the structure. A complex dynamic analysis for a specific ground vibration is possible with the help of commercially available software packages. This kind of exercise is required in the design of special or unusual structures. However, for the design of majority of common types of structures, simple methods have been developed.

An expression in a common building code for determining the equivalent static forces corresponding to the given earthquake load is of the form

$$V = ZIKCSW \tag{2.11}$$

In this expression, V is the total static shear at the base of the structure; W is the total dead load of the structure; C is a coefficient that depends on the fundamental period of vibration (T) of the structure; Z is a factor depending on the geographical location of the structure and the probable seismic activity and intensity of the location; K is a factor depending on the type of structure and construction, used especially with respect to stiffness and ductility; I is an importance factor depending on the importance of the structure, e.g., hospitals; and S is a coefficient depending on the relation between the natural period of the structure and that of the soil on which the structure is founded.

The natural or fundamental period of vibration T of the structure is the time interval necessary for the structure to complete one vibration when released from a deflected position corresponding to the fundamental mode shape. It depends on mass and stiffness properties of the structure and on the soil condition. These aspects are discussed in detail in Chapter 10. The fundamental period of vibration can be determined from

$$T = \frac{0.05H}{\sqrt{D}} \tag{2.12}$$

where H is the height of the structure and D is the dimension of the structure in a direction parallel to the applied forces. In the light of Eq. (2.12), the coefficient C is given by

$$C = \frac{15}{\sqrt{T}} \leq 0.12 \tag{2.13}$$

All the above factors and expressions are largely empirical. The base shear V obtained through the evaluation of these factors is then distributed at various storey levels through prescribed methods to act as applied lateral loads. Rigid elements, such as masonry walls, tend to attract higher forces. Extreme care must be taken to avoid brittle failures. It is highly important to ensure that all structural as well as non-structural elements have adequate deformation—called *ductility*. In the case of unusual structures, such as very tall buildings and nuclear reactor facilities, complex analyses must be performed. Dynamic rather than static analysis is now common due to the availability of commercial software packages.

2.4.3 Blast Loads

Explosion is a very fast chemical reaction producing transient air pressure waves called blast waves. For a ground-level explosive device, such as a bomb in a vehicle, the pressure wave will travel away from the surface in the form of a hemispherical wavefront if there are no obstructions in the path. The blast wave consists of a pressure phase followed by a suction phase as shown in Fig. 2.8. The peak over pressure and its duration vary with the distance from the device.

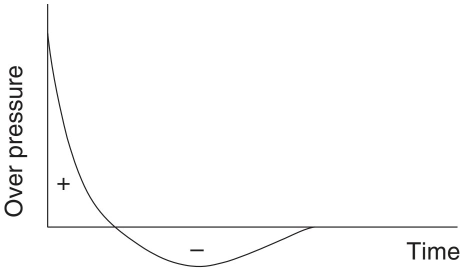


Figure 2.8 A typical blast wave

The magnitudes of these parameters also depend on the explosive material of which the bomb is made and the packing method. Usually the size of the bomb is given in terms of a weight of TNT.

When a blast wave impinges directly onto the face of a building, it is reflected from the building. The effective pressure applied to that face of the building is magnified when this occurs. Stand-off distance is a fundamental parameter in determining the blast pressures experienced by a building. As the stand-off distance increases, blast pressure drops significantly. However, it is not always a controllable parameter. For a device placed inside a building, greater damage and more injuries would be caused than if the same size device were deployed outside.

The blast load may be idealized to a triangular pressure–time function with zero rise time, as shown in Fig. 2.9. The duration of the blast wave is t_d. When the duration t_d of the blast wave is short in relation to the response time t_m of the element, such that $t_m/t_d \geq 3$, the load is assumed to be uniformly distributed.

The prime objective in the blast-resistant design of structures is to provide sufficient ductility to enable the element to deflect by an amount consistent with the degree of damage permitted. Loads from blasts are transient. Therefore, ductility and natural period of vibration of the structure govern its response to a given

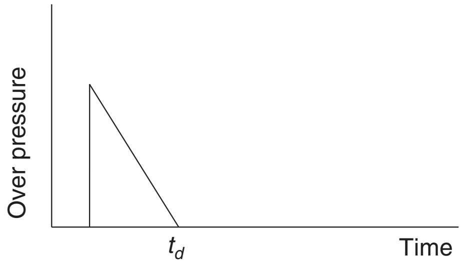


Figure 2.9 Idealized blast wave

explosion. In general, a tall building will have a low natural frequency and thus a long response time in relation to the duration of the load. Individual elements, e.g., columns and beams, will have natural response times that may approach the loading duration. Ductile elements made of steel can absorb a lot of energy, while elements made of brittle materials such as glass, brick, timber, and cast iron fail abruptly with little prior deformation.

2.4.4 Impact Loads

Impact loads result when a moving object collides with a stationary structure. Collisions of a train against the stopper at stations and an overhead crane against the stopper at the end of the gantry girder are popular examples of the application of impact load on structures. Under impact loads, structures undergo larger deformation than that induced by gradual and slow application of load. Because the deformation is greater, the induced stresses in the structure are higher. The increase in stress due to impact load over and above the value induced by the load applied gradually is known as *impact stress***.** For the purposes of structural design, impact stresses are usually obtained by multiplying the live load stresses by a fraction/factor called *impact fraction/factor,* which is rather empirical. Pile driving is possibly the most common controlled form of impact loadings in civil engineering. This technique installs a pile on the ground as part of a foundation system. A hammer of known weight is allowed to fall through a given height on the head of the pile and the pile is driven into the ground. The impact stress generated in the pile at the instant of the impact is greater than that induced in a static case where the hammer simply rests on the pile head (Fig. 2.10).

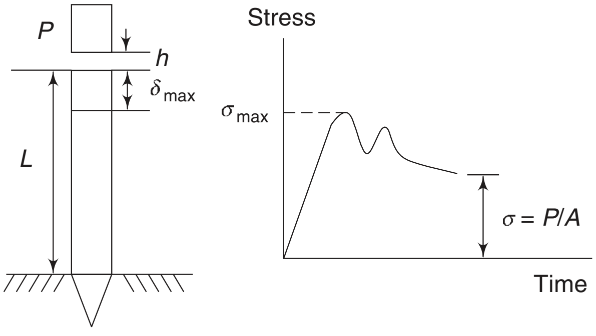


Figure 2.10 Pile driving induced stresses

2.4.5 Traffic-induced Loads

Moving vehicles such as cars, buses, trucks, and railway trains apply live loads on bridge structures. In the case of highway bridges, the live load consists of the weight of moving vehicles and pedestrians. In fact, the traffic over a highway bridge consists of a multitude of different types of vehicles. However, the design of the bridge is carried out using a train of standard trucks selected in such a manner that the bridge is safe and economical during its design service life. For each lane of the roadway, the live load consists of a train of heavy trucks following each other closely. The weight and weight distribution of each truck vary with the specification with which the design is made. Typical examples of the specifications for various categories of trucks and loading are prescribed in relevant codes, e.g., Indian Road Congress (IRC) code in the Indian context and American Association of State Highway and Transportation Officials (AASHTO) in the American context.

The maximum stress in the members of a bridge depends not only on the weight of a moving vehicle but also on its position on the bridge. Therefore, the critical positions of the moving vehicles that produce maximum forces at various points along the bridge have to be determined while designing bridges. This is achieved with the help of *influence lines,* the description of which is given in Chapter 5.

Because of the movement of vehicles on a bridge, vibrations are caused because of the surface irregularities, motion of the load, and spring mass stresses interaction of the vehicle with the bridge. This results in an increase in live load stresses. It has been customary to account this dynamic effect by the *impact factor*. This depends on speed, surface roughness of the pavement, characteristics of the vehicle, and span.

It is judicious to design bridges with some extra safety margins in anticipation of increasing traffic and heavier loads. Besides the vertical force resulting from the impact, codes also prescribe two horizontal forces: one to account for the centrifugal effect on curved bridges and the other to approximate braking force of a stopping truck, which is usually taken as 20% of the weight. The live load on a rail road bridge consists of locomotives and cars crossing it. The live load for each truck is normally prescribed as wheel loads. For details of the design loading, reference can be made to the American Railway Engineering Association (AREA) specifications.

2.4.6 Cyclic Loading

Bridges, offshore platforms, machine foundations, etc. are a special class of concrete structures that are subjected to time-dependent cyclic loads such as waves, seismic loads, repeated blasts, etc. These time-varying loads induce time-varying stresses in the material. The ability of a material to withstand these stresses decreases with the accumulation of the number of load fluctuations. When these numbers become very large, the material fails due to fatigue; such a mode of failure is not prescribed in the currently available code of practice. Therefore, fatigue is a process of progressive, permanent internal structural change in a material subjected to repetitive stress. These changes may be damaging and may result in progressive growth of cracks and complete fractures if the stress repetitions are sufficiently large. Fatigue is often described by a parameter termed *fatigue life,* which essentially represents the number of cycles required for the material to fail under a given repetitive stress. Fatigue loading consists of a sequence of load repetitions that may cause fatigue failure in a fixed number of cycles.

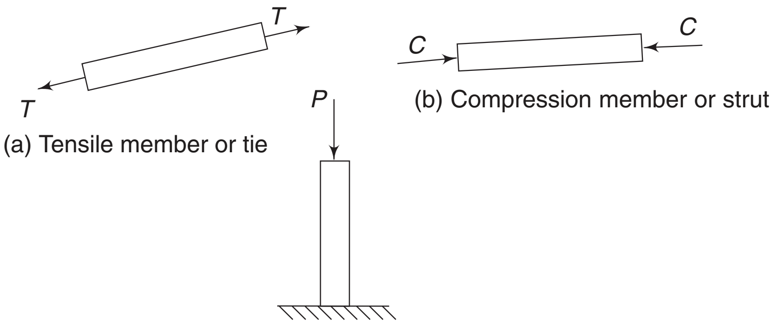
Cyclic loadings are divided into two general categories. The first category is the so-called low-cycle loading or a load history containing a few cycles, but having large stress ranges. Low-cycle loadings commonly arise in seismic and high-wind stress loadings. This loading is also referred to as low-cycle, high-stress loading. The second category is the so-called high-cycle or fatigue loading, which is a load history containing many cycles (typically thousands or millions), but at a low stress range. Bridge members, offshore structures, and members supporting vibrating machinery are often subjected to high-cycle or fatigue loading.

2.5 Types of Application of Loads

Structures, in practice, are subjected to complex loading systems consisting of different types of loads, details of which are presented in preceding sections. But the application of loads can be basically grouped into four modes: axial, shear, bending moment, and torsion.

2.5.1 Axial Load

When load is applied along the longitudinal axis of a member, it is called axial load. If the action of the axial load is to cause elongation of the member, it is called a *tensile load* [Fig. 2.11(a)]. When an axial load causes shortening of the member, it is called *compressive load* [Fig. 2.11(b)]. Testing of a steel bar in the UTM shown in Fig. 3.1 is a typical case of a tensile loading. Similarly, testing of a concrete cube in CTM, described in Section 3.1.2, is a typical case of compressive loading. A vertical member with an axially applied compressive load is called a *column*, as shown in Fig. 2.11(c). In a normal building, consisting of slab–beam–column members, the live and dead loads transferred from the slab to the beam and then axially to the column which supports the beam is a typical case of the practical application of an axially loaded column member.



(a) Tensile member or tie

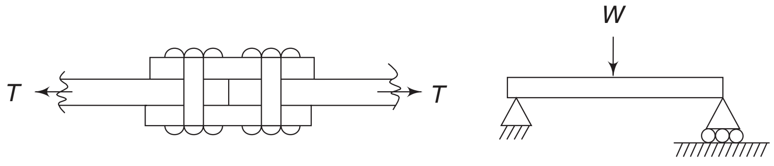
(b) Compression member or strut

(c) Column member

Figure 2.11 Axially loaded members

2.5.2 Shear Load

Shear load is applied perpendicular to the axis of a member. A bolted/riveted connection or a beam, a member supported on its edges, with a transverse load, i.e., load applied perpendicular to the axis of the member, are typical examples of shear loads (Fig. 2.12).

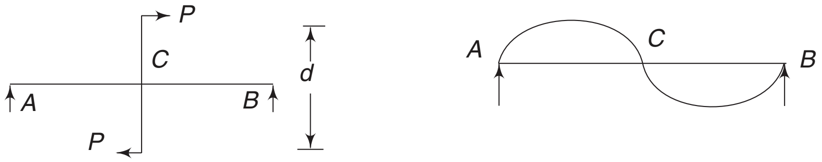


(a) Bolted connection (b) Beam

Figure 2.12 Application of shear load

2.5.3 Bending Moment

A moment is a couple of equal and opposite forces separated by a distance. When this is applied transversely on a beam [Fig. 2.13(a)], it bends the beam [Fig. 2.13(b)] and hence is called *bending moment*. While bending, the beam rotates about the lateral axis. In this case, beam *AB* is subjected to a moment of *Pd*. This bending moment *Pd* deforms the beam as shown in Fig. 2.13(b).



(a) Beam with a couple (b) Deformed shape of beam

Figure 2.13 Bending moment

2.5.4 Torsion

A pure torque is a couple applied to a member in the plane of its cross section. When a torque is applied, the member is twisted. This is called torsion (Fig. 2.14). The cross section of the member rotates about its longitudinal axis.

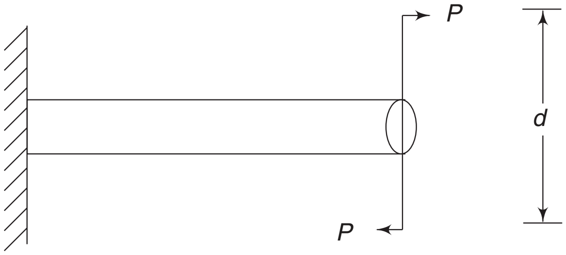


Figure 2.14 Member under torsion

In this example the torque is *Pd*. It is not possible to apply a pure torque on a member. The torque can be applied only through some other members.

Points to Remember

Concepts

- Loads are induced either by natural phenomena or by human activities.
- Static loads are time-invariant and applied gradually and slowly.
- Dynamic loads change with time and are applied rapidly and suddenly.
- Loads are idealized as concentrated loads, line loads, and distributed loads.
- Snow, ice, rain, water pressure, earth pressure, etc. are environmental loads.
- Settlement, thermal effects, shrinkage, etc. are loads due to other effects.
- Ice load is effective in slender members, such as cables and towers.
- Ponding effect of rain needs to be considered in the design of structures.
- Water and earth pressures act normal to the surface and vary linearly with depth.
- Differential settlement of a structure causes additional loads.
- The mass and stiffness of a structure give natural or fundamental frequency or period.
- The frequency of dynamic load is called excitation frequency.
- Resonance occurs when excitation and fundamental frequencies coincide.
- Wind velocity increases with height.
- Drag force is an along-wind force and acts in the direction of mean wind flow.
- Lift force is an across-wind force and acts perpendicular to the direction of wind.
- Earthquake and wind do not occur simultaneously.
- An explosion produces transient air pressure waves called blast waves.
- Blast-resistant design needs adequate ductility of members.
- Impact loads arise due to collision of objects.
- Cyclic loading causes fatigue in a structure.
- Fatigue is the progressive, permanent internal structural change in a material .
- Four modes of loading are: axial, shear, bending, and torsion.

Definitions

- Loads are categorized as static and dynamic.
- Wind forces are based on the velocity of wind at 10 m above the ground level.
- The positive phase of a blast wave is called pressure and the negative phase suction.
- Blast wave is idealized as a triangle with zero rise time.
- Stresses and deformations are quite large due to impact loads.
- Waves, earthquakes, and repeated blasting impart cyclic loads to structures.

Formulae

- Static vertical lift-load is increased by 25% for moving overhead cranes.
- Horizontal force equal to 20% is applied along the runway deceleration.
- The effective weight of elevators is increased by 100%.
- IS: 875 (part 1)-1987 gives the unit weight of material for the calculation of dead load.
- IS: 875 (part 2)-1987 gives live loads or imposed loads for different occupancies.

Exercises

1. Name the different kinds of loads that are to be considered in the design of structures.
2. What are static loads? Give some examples.
3. Give the densities of brick, reinforced concrete, and steel.
4. The size of a rectangular reinforced concrete beam is 3000 mm × 150 mm × 450 mm. Find its weight.

   Ans. 5.0625 kN
5. A steel cylinder of height 450 mm weighs 10 kN. Find its diameter.

   Ans. 600.36 mm.
6. The length of a reading room in a library is 10 m and its breadth is 8 m. Compute the distributed live load, assuming the basic value of the load to be 2873 N/m^2.

   Ans. 229.84 kN
7. The height of the wall of a water tank is 6 m. Find the water pressure on the wall.

   Ans. 60 kN/m^2
8. What is shrinkage? In which material does it occur commonly?
9. List the different categories of dynamic loads.
10. Define galloping, flutter, and ovaling.
11. Which mode of vibration is important in earthquake loading as for the design of structures is concerned?
12. How is the pressure–time history of an air blast idealized?
13. What are impact loads? Define impact factor.
14. What are cyclic loads? How have they been categorized in general?
15. What is bending moment? In which category of a structural member does it occur?