

CIVIL ENGINEERING

Structural Analysis



Comprehensive Theory
with Solved Examples and Practice Questions





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Structural Analysis

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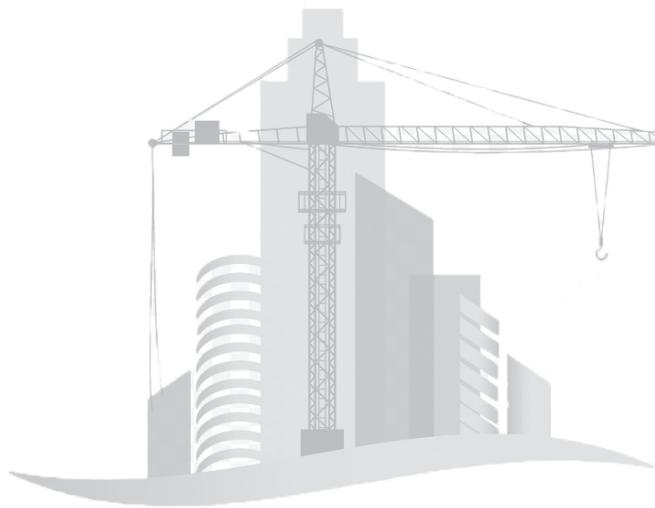
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Stability and Indeterminacy

1.1 INTRODUCTION

A structure is referred to as a system of connected parts used to support a load. Some of the examples related to Civil Engineering include buildings, bridges and towers etc. Various considerations such as safety, aesthetics and serviceability etc. of structure are taken into account while designing a structure. There are various unknown quantities in a structure such as axial forces, shear forces, bending moments, deflections and support reactions that are to be determined for purpose of analysis of a structure. These quantities are determined by using a number of independent equations which will be discussed in later part of book. In this chapter, we are going to study different types of beam, loads and supports. Stability of structure is also discussed in details. Determinacy of both type i.e., static as well as kinematic are also covered in detail in this chapter.

1.2 EQUATIONS OF STATIC EQUILIBRIUM

A structure that is initially at rest and remains at rest when subjected to a system of forces and couple is said to be in a state of static equilibrium. If a structure is in equilibrium, then all its members and parts are also in equilibrium.

(a) For 3-D

The necessary and sufficient conditions for a space structure are:

$$\begin{array}{lll} \Sigma F_x = 0 & \Sigma F_y = 0 & \Sigma F_z = 0 \\ \Sigma M_x = 0 & \Sigma M_y = 0 & \Sigma M_z = 0 \end{array}$$

These 6 conditions of static equilibrium for 3-D structure implies that net force at any section in any member of structure and net moment of all the forces in any direction both are equal to zero. First 3 conditions resist the translational movement of structure while last 3 conditions resist rotational movement of structure.



On a space structure, if loads and reactions acting are concurrent, then conditions of static equilibrium are:

$$\Sigma F_x = 0 \quad \Sigma F_y = 0 \quad \Sigma F_z = 0$$

(b) For 2-D

Although, all the structures are in 3-D in practical situations but as the principal load carrying elements of most structures are in 2-D stress condition, therefore, such elements are treated as 2-Dimensional structures also called as planar structures.

For a planar structure, conditions for static equilibrium are:

$$\Sigma F_x = 0 \qquad \Sigma F_y = 0 \qquad \Sigma M_z = 0$$

The first two equations indicate that total force on structure in two perpendicular directions i.e., x and y axis and moment due to all the force about an axis perpendicular to x - y plane is zero.



On a planar structure, if forces and reaction acting are concurrent, then conditions of static equilibrium are:

$$\Sigma F_x = 0 \qquad \Sigma F_y = 0$$

1.3 JOINTS

The various elements in a structure are connected to each other by joints and these are connected to foundations by special types of joints known as supports. Every connection whether it is joint or support is to serve two types of functions:

- Kinematic function:** Each joint should ensure that elements which are connected by the joint should have identical displacement (translation and/or rotation) to provide the required integrity of structure.
- Static function:** Each joint should transmit internal forces (axial forces, shear force, bending moment, twisting moment) from one connecting member to another.

1.3.1 Type of Joint

- Rigid joint:** At a rigid joints, two (or more) members are so rigidly connected to each other such that there is no relative displacement (translation or rotation) of connecting members at the joint. This condition is required at a rigid joint to have complete transmissibility of internal forces from one member to another.

To have better understanding of rigid joint, consider a plane frame ABC as shown in figure (a) which is subjected to a horizontal load P .

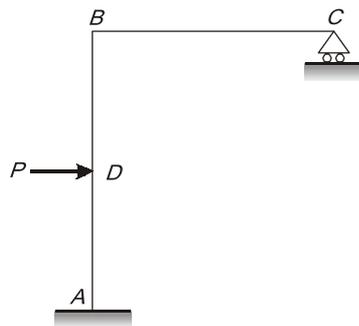


Fig. (a) Frame subjected to load

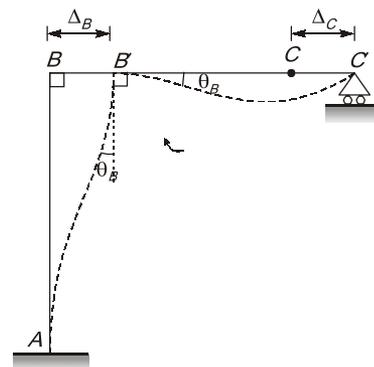


Fig. (b) Deflection of frame

Under the action of loading, displacement will occur in the frame as shown in figure (b).

Let the joint B rotate clockwise by θ_B due to load. As the joint B is rigid, the angle included between AB and BC will remain 90° as it was without the load. Hence, member AB and BC both will rotate by same angle θ_B .



Rigid joint does not mean that there will be, no deformation in structure. Rigid joint can translate and rotate but it ensures compatibility of displacement of ends of connecting elements at joints.

(b) **Pinned joint:** As discussed in previous section, rigid joints resist rotation as well as translation, but pinned joint can resist translation only and is incapable of resisting rotation between the members.

Unlike rigid joint which can transmit bending moment from one member to another, pinned joint releases bending moment and hence bending moment is zero at pinned end. However, at pinned joint, transmission of axial and shear force is similar to that of rigid joint. In trusses, member are connected to each other by pinned joints.

To have a better understanding of pinned joint, consider a plane frame ABC with B as a pinned joint and subjected to a horizontal load P as shown in figure (a).

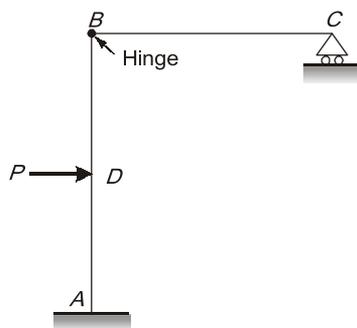


Fig. (a) Frame with pin joint subjected to horizontal load

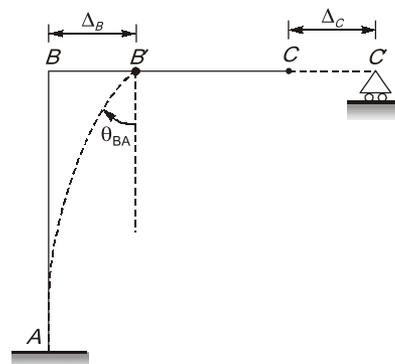


Fig. (b) Deflected shape of frame

Under the action of load, displacement will occur in frame as shown in figure (b).

Now, as the joint B is pinned, therefore relative angle between AB and BC will not remain 90° as it was before without load. It is to be noted that member BC won't have any force in it hence AB will behave as a cantilever. Portion between B and C will remain straight.



Pinned joint when encountered in a beam is known as internal hinge (except at support). Consider a propped cantilever beam of length L in which an internal hinge is provided at centre of span subjected to load as shown in figure (a)

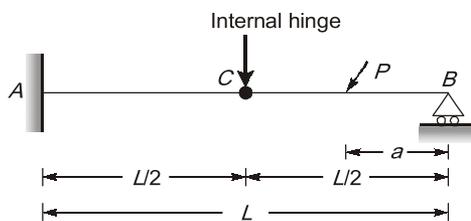


Fig. Internal hinge in beam

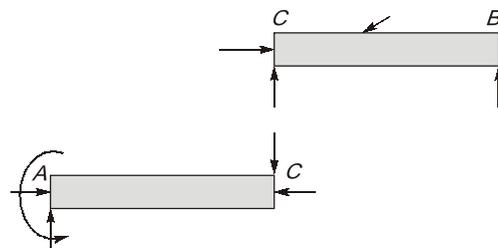


Fig. FBD of AC and CB

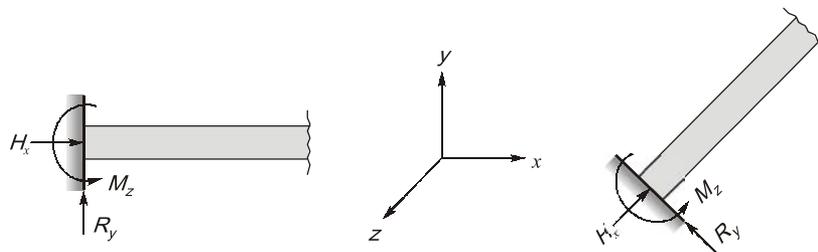
At hinge, C , axial force and shear force will transmit from BC to CA but moment will not transmit. So bending moment at hinge is zero.

1.4 SUPPORT SYSTEM

Structural members are joined together by rigid connections or flexible connections. Whenever loads act on the structural member, reactions are developed at supports to prevent translation or rotation of structural member. Different type of support are as follows:

1.4.1 2-D External Supports

(i) Fixed Support



At 2-D fixed supports, there can be 3 reactions:

- (i) One vertical reaction (R_y) which prevent translation of beam in vertical direction.
- (ii) One horizontal reaction (H_x) which prevent translation of beam in horizontal direction.
- (iii) One moment reaction (M_z) which prevent rotation of beam about z-axis at support.

(ii) Hinge Support

Hinge support is represented by symbol Δ .

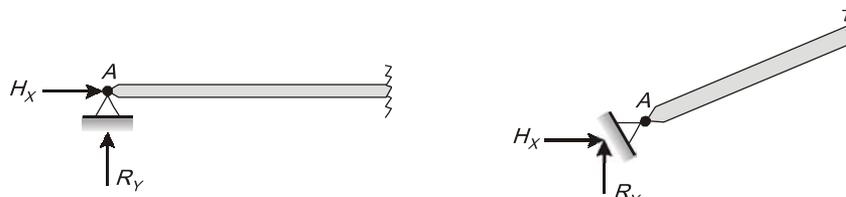


Fig. (i) Number of reactions = 2

Fig. (ii) Number of reactions = 2

At hinge support, there can be 2 reactions:

- (a) One vertical reaction R_y which prevent translation of beam in vertical direction.
- (b) One horizontal reaction H_x which prevent translation of beam in horizontal direction.

Thus, hinge support can resist translational movement of beam but it cannot resist rotation of beam at support.

(iii) Roller Support

Roller support is represented by symbol  or .

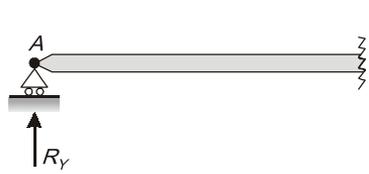


Fig. (i) Number of reactions = 1

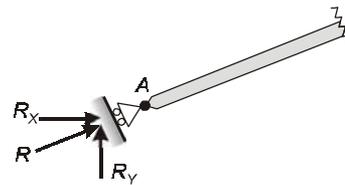


Fig. (ii) Number of reactions = 1

At roller support, there can be only one reaction that is a reaction that is perpendicular to contact surface. Thus, it can restrain translational movement of beam in one direction only.

(iv) Guided Roller Support

It differs from roller support in the fact that it can have two reactions.

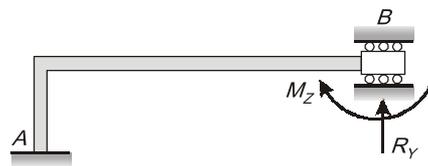


Fig. Number of reactions = 2

At guided roller support, there can be two reactions.

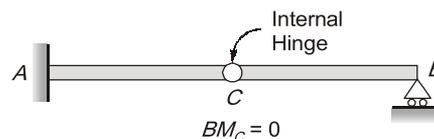
- (i) One vertical reaction (R_y) which prevent translation of beam in vertical direction.
- (ii) One movement reaction (M_z) which prevent rotation of beam about z-axis at support.

NOTE: In describing all the supports, it has been assumed that load acts in vertical direction only.

1.4.2 2-D Internal Joints

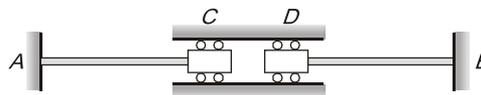
(a) Internal Hinge

At an internal hinge, moment will be released so bending moment will be zero at that hinge from left side as well as right side. Therefore, it provides one additional compatibility equation.

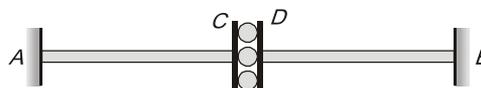


(b) Internal Roller

At internal roller, axial force or shear force can be released depending upon the position of rollers, so either axially force or shear force will be zero.



In fig. axially force at C and D is zero.



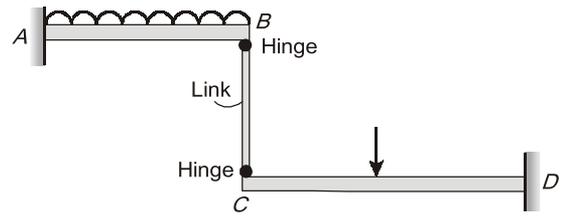
In fig. shear force at C and D will be zero i.e., $S_C = S_D = 0$

(c) Internal Link

If any member is connected by hinges at its end and subjected to no external loading in between then it can be termed as internal link and carry axial force only.

Here BC is a link, link BC carry only axial force

Also $BM_B = 0$ and $BM_C = 0$



NOTE: Internal link also provides additional equation for analysis of structure.

1.4.3 3-D Supports**(a) Fixed Support**

At 3-D fixed support there can be six reactions:

(i) three reactions R_x , R_y and R_z

(ii) three moment reactions M_x , M_y and M_z

The fixed support is also called **Built-in support**.

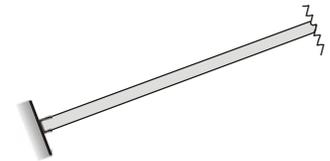


Fig. Number of reactions = 6

(b) 3-D Hinged Support

3-D hinged support there can be three reactions

(i) R_x (ii) R_y (iii) R_z

The 3-D hinged support is also called '**ball and socket joint**'.

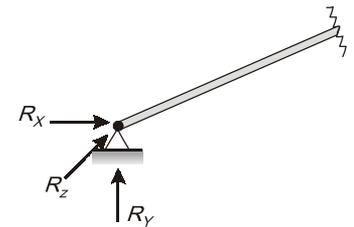


Fig. Number of reactions = 3

(c) Roller Support

At 3-D roller support there can be only one externally independent reaction which is perpendicular to the contact surface

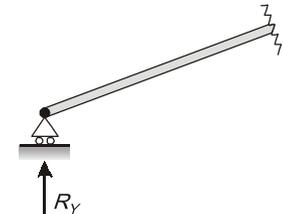


Fig. Number of reactions = 1

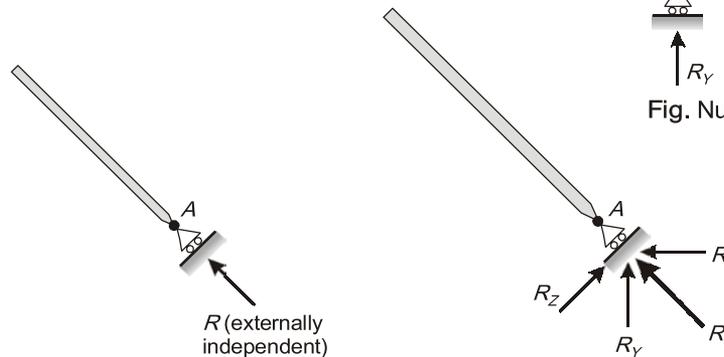


Fig. (i)

Fig. (ii)

In figure (ii), reactions at roller support A , R_x , R_y and R_z are externally dependent reactions which depends on reaction R .

1.5 STRUCTURE

Structure is defined as a system of interconnected members that are assembled in a stable configuration and used to support loads under the equilibrium of external forces and internal reactions.

1.5.1 Elements of Structure

Some of the major elements of structure by which structures are fabricated are as follows:

(a) Beams: Beams are structural members which is predominantly subjected to bending. On the basic of support system beams can be classified as:

(i) Simply supported beam



(ii) Cantilever beam



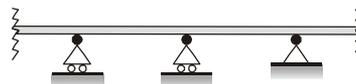
(iii) Propped cantilever



(iv) Fixed beam



(v) Continuous beam



(b) Columns: A column is a vertical compression member which is slender and straight. Generally columns are subjected to axial compression and bending moment as shown in figure.

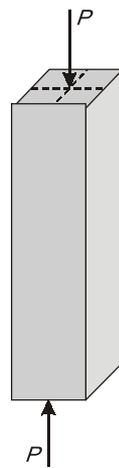


Fig. (i)

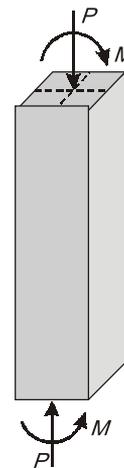


Fig. (ii)

(c) Tie Members: Tie members are tension members of trusses and frame, which are subjected to axial tensile force.



Fig. The rod

1.5.2 Types of Structures

(a) **Trusses:** A truss is constructed from pin jointed slender members, usually arranged in triangular manner. In trusses, loads are applied on joints due to which each member of truss subjected to only axial forces i.e., either axial compression or axial tension. Generally trusses are used when span of structure is large.

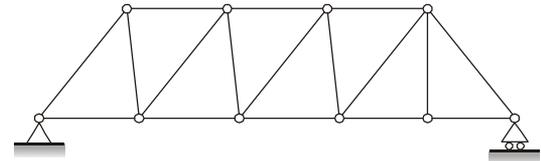


Fig. Truss

(b) **Frames:** A frame is constructed from either pin jointed or fixed jointed beam and columns. Generally loads are applied on beams and this loading causes axial force, shear force and bending to the members of frame.

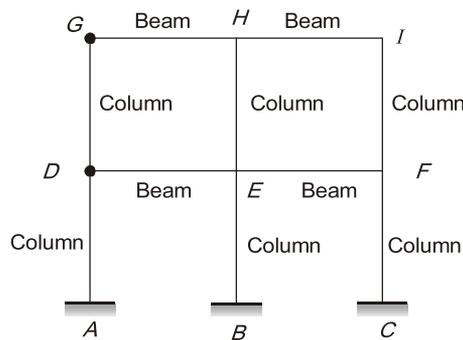


Fig. Frames

(c) **Arches:** Arches are used in bridges, dome roof, auditorium, where span of structures are relatively more due to external loading, Arch can be subjected to axial compression, shear force or bending moment.

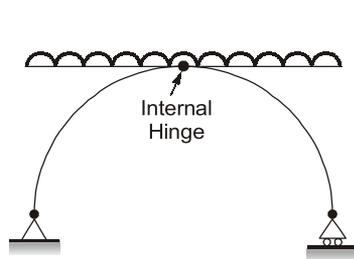


Fig. (i) Three Hinge Arch

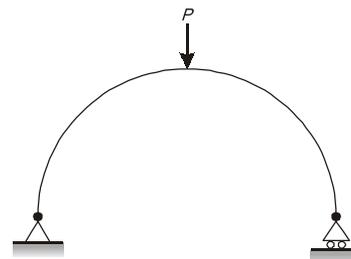


Fig. (ii) Two Hinge Arch

(d) **Cables:** Cables are used to support long span bridges. Cables are flexible members and due to external loading it is subjected to axial tension only.

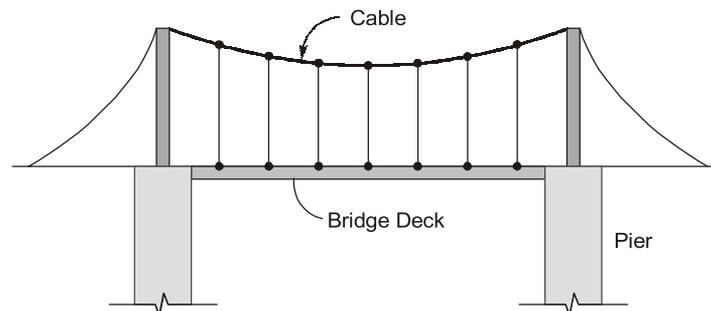


Fig. Cable and Bridge

1.6 TYPES OF LOADING

- (a) **Point load:** A point load is considered to be acting at a point. It is also called concentrated load. In actual practice point loads are distributed load which are distributed over very small area.

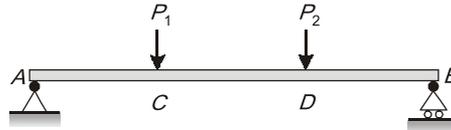


Fig. Point Load

- (b) **Distributed loads:** Distributed loads are those loads, which acts over some measurable area. Distributed loads are measured by the intensity of loading per unit length along the beam.

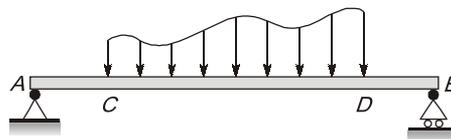


Fig. Distributed Loads

- (c) **Uniformly distributed loads:** Uniformly distributed loads are those distributed loads which have uniform intensity of loading over the area.

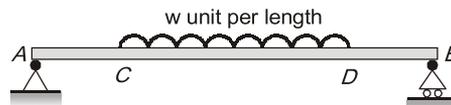


Fig. Uniformly Distributed Loads

- (d) **Uniformly varying loads :** A uniformly varying load, commonly abbreviated as UVL, is the one in which the intensity of loading varies linearly from one end to other. For example, intensity is zero at one end and w at other end.

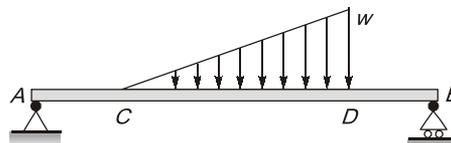


Fig. Uniformly Varying Loads

- (e) **Couple :** A system of forces with resultant moment, but no resultant force is called couple. It is statically equivalent to force times the offset distance.

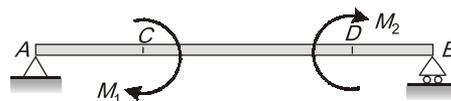


Fig. Couple

1.7 STABILITY OF STRUCTURES

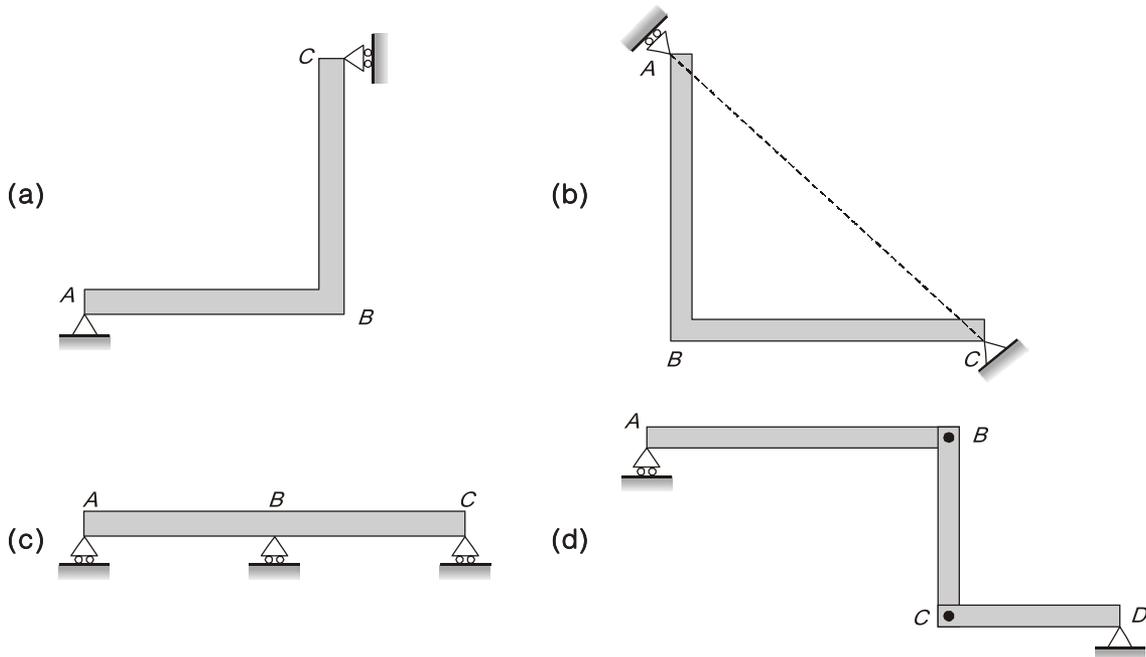
Structural stability is the major concern of the structural designer. To ensure the stability, a structure must have enough support reaction along with proper arrangement of members. The overall stability of structures can be divided into

(i) External stability

(ii) Internal stability

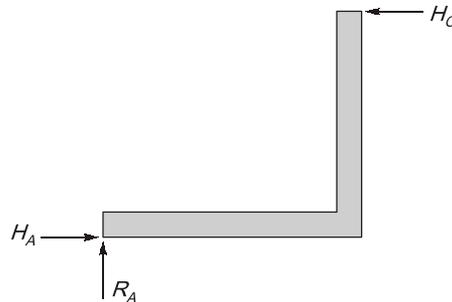
Example 1.1

Which one of the following structures is stable?

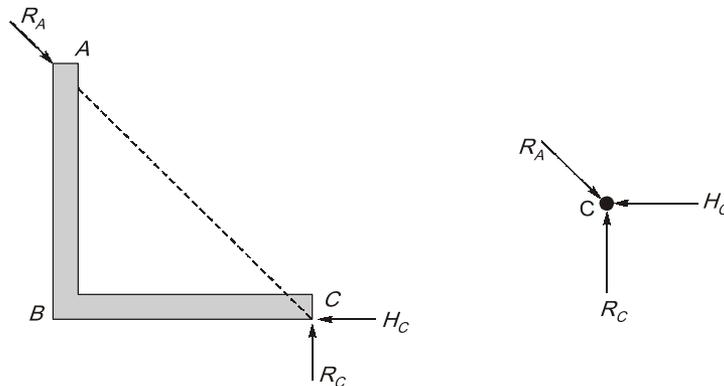


Ans. (a)

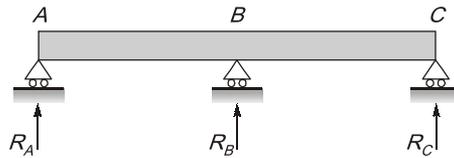
Member (a) is stable, since reactions are non-parallel and non-concurrent.



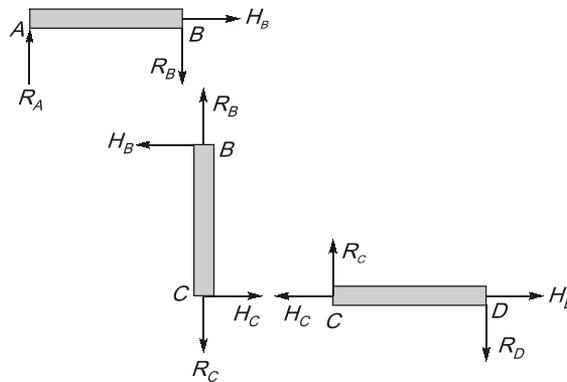
Member (b) is unstable since all the reactions are concurrent at C.



Beam (c) is unstable, since all three reactions are parallel.



Structure (d) is unstable, since the member AB can move horizontally without any restraint. i.e. $\Sigma F_x \neq 0$



1.7.2 Internal Stability

For the internal stability, no part of the structure can move rigidly relative to the other part so that geometry of the structure is preserved, however small elastic deformations are permitted. To preserve geometry, enough number of members and their adequate arrangement is required. For the geometric stability, there should not be any condition of mechanism. Mechanism is formed when there are three collinear hinges, hence to preserve geometric stability there should not be three collinear hinges.

For 2-D truss the minimum number of members needed for geometric stability are:

$$m = 2j - 3$$

and for 3-D truss,

$$m = 3j - 6$$

where, j = Number of joint in truss

m = Number of Members required for geometrical stability.

All the members should be arranged in such a way that truss can be divided into triangular blocks. i.e. no rectangular or polygonal blocks.

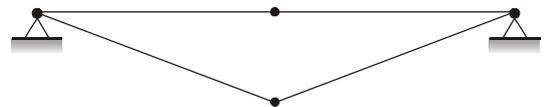
Hence, for overall geometrical stability of truss:

(i) Minimum number of member should be present

$$m = 2j - 3 \quad (2\text{-D truss})$$

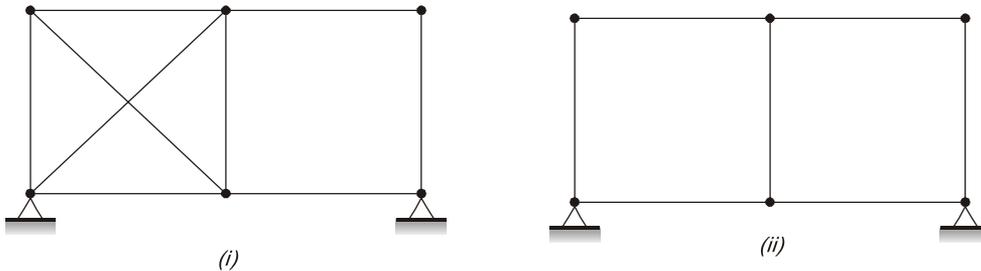
$$\text{and} \quad m = 3j - 6 \quad (3\text{-D truss})$$

(ii) There should be no condition of mechanism i.e. no three collinear hinges.



Example 1.2

Check geometrical stability for given trusses.



Solution:

(i) In case (i), arrangement of members is not adequate, hence right panel is unstable and left panel is over stiff. For geometric stability, all panels of truss should be stable so given truss is geometrical unstable.

For right panel: $j = 4$
 Number of member present, $m = 4$
 But minimum number of member needed $= 2j - 3 = 2 \times 4 - 3 = 5$
 Hence Right panel is deficient.

For left panel: $j = 4$
 Number of member present, $m = 6$
 But minimum number of member needed $= 2j - 3 = 2 \times 4 - 3 = 5$
 Hence left panel is over stiff.

(ii) $j = 6$
 Number of members present, $m = 7$
 But minimum number of member needed $= 2j - 3 = 2 \times 6 - 3 = 9$
 Hence, above truss is geometrically unstable and it can be called 'deficient structure'.
 \therefore Number of deficiency = 2

1.7.3 Overall Stability

For overall stability, external stability is compulsory. In some cases structure is overall stable but it may be over stiff externally or deficient internally. It mean support reactions are more than three and number of member are less then $2j - 3$.

Consider a truss shown in figure (a),

Here,

External reaction, $r_e = 4$
 Number of member present, $m = 10$

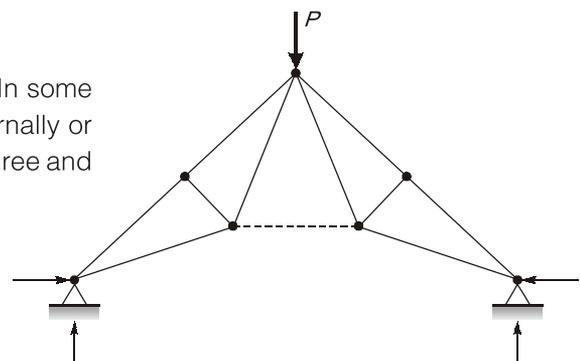


Fig. (a)

But, min. number of members needed

$$= 2j - 3 = 2 \times 7 - 3 = 11$$

It means truss is deficient to 1 degree.

But above truss is overall stable because there is one extra redundant reaction which prevent geometric deficiency.

In fig. (b), external reactions,

$$r_e = 8$$

Number of member present, $m = 8$

But min. no. of member needed = $2j - 3 = 2 \times 8 - 3 = 13$

it means truss is deficient to 5 degree

But above structure is overall stable because there are five extra redundant reaction which prevent geometric deficiency.

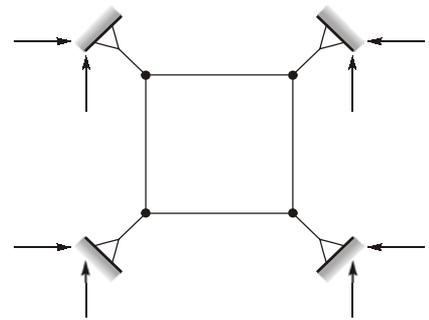


Fig. (b)

Example 1.3

Comment on the stability of pin-jointed frame shown in figure.

Solution:

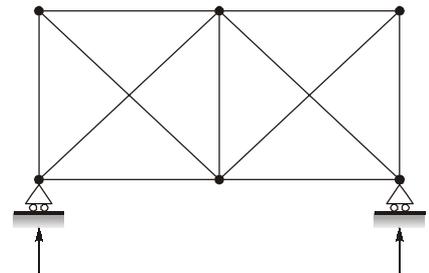
External reaction, $r_e = 2$

No. of member present = 11

No. of joints = 6

Min. no. of members needed = $2j - 3 = 2 \times 6 - 3 = 9$

Above truss is internally stable (over stiff) but externally unstable. Hence this truss is overall unstable.



Example 1.4

Comment on the stability of pin-jointed frame shown in figure.

Solution:

External stability:

Number of external reaction = 3

All three reactions are non-parallel but all three reactions are concurrent at point D , hence given frame is externally unstable.

Internal stability:

Number of joint, $j = 9$

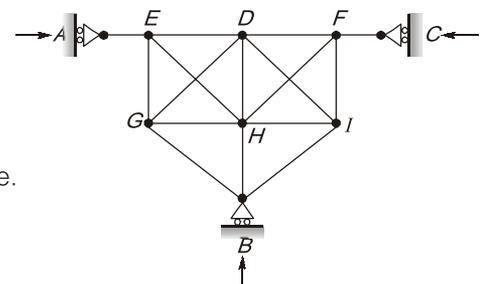
Number of member present, $m = 16$

Number of member needed = $2j - 3$

$$= 2 \times 9 - 3 = 15$$

Above frame is internally stable (over stiff).

Since frame is externally unstable. Hence given frame is overall unstable.



Remember: It is desirable for overall stability, structure should be stable externally and internally both.

1.8 DETERMINACY AND INDETERMINACY OF STRUCTURES

The degree of indeterminacy of a structure can be classified as:

- (a) Static indeterminacy (D_s)
- (b) Kinematic indeterminacy (D_k)

1.8.1 Statically Determinate Structures (D_s)

Statically determinate structures are those in which all the forces can be determined using conditions of static equilibrium alone.

(a) For 2-D

In 2-D, there are 3 conditions of static equilibrium, so for a structure to be determinate, maximum number of unknown forces can be 3.

(b) For 3-D

In 3-D, there are 6 conditions of static equilibrium, so for a structure to be determinate, maximum number of unknown forces can be 6.

Properties of Statically Determinate Structures

- (i) Bending moment and shear force are independent of properties of material and cross-sectional area.
- (ii) No stresses are induced due to temperature changes.
- (iii) No stresses are induced due to lack of fit and support settlement.

1.8.2 Statically Indeterminate Structures

Statically indeterminate structures are those in which conditions of static equilibrium are not sufficient to determine unknown forces in structure.

(a) For 2-D

If number of unknown forces are more than 3, then structure is statically indeterminate.

(b) For 3-D

If number of unknown forces are more than 6, then structure is statically indeterminate.

Properties of Statically Indeterminate Structures

- (i) Bending moment and shear force depends upon properties of material and cross-sectional area.
- (ii) Stresses are induced due to temperature variation.
- (iii) Stresses are induced due to lack of fit and support settlement.

To have a better understanding of determinacy, consider a cantilever beam of length L as shown in figure (a)

Here, the number of unknown forces,

$$r_e = 3 \text{ (at A)}$$

i.e., independent support reaction.

No. of condition available, $r = 3$

So, degree of static indeterminacy, $D_s = r_e - r$

i.e., independent support reactions = $3 - 3 = 0$

Hence, a cantilever beam is a statically determinacy structure.

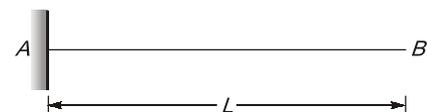


Fig. (a)