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IES/GATE

CIVIL ENGINEERING

VOLUME – IX

Structure Analysis, Railway Eng.

SIERRA INNOVATIONS

Index

Structure analysis, Railway Engineering

1. Stability and indeterminacy 1

2. Influence line diagram 15

3. Arches 52

4. Moment distribution method 83

5. Slop deflection method 122

6. Stiffness method 163

7. Matrix method 166

Railway engineering

1. introduction 194

2. Vertical canes 230

3. Points and crossing 242

4. Traction and tractive efforts 260

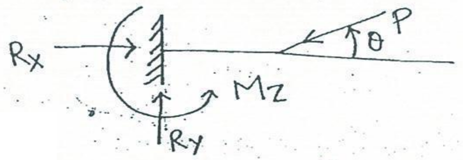
Chapter 1 - Stability and Indeterminacy

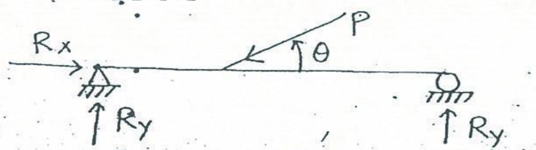
Stability

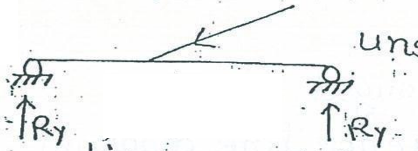
- **External** — related to support conditions.
- **Int.** — Related to geometry.

External stability. Large displacements of the supports & entire structure are not ~~permitted~~ permitted, therefore there should be enough reactions at supports to prevent movement & also reactions should be arranged in appropriate manner. It means there will not be rigid body-motion, however elastic deflection in the member may occur.

In plane structures (2D) there should be a min^m^ of 3 independent external reactions which should be non-parallel and non-concurrent

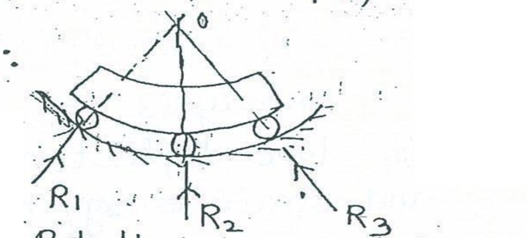






unstable

linear unstability



Rotational unstability

For stability of 2D structure forming three condition of static equilibrium should be satisfied.

(i) $\sum F_x = 0$ - - - - To prevent Δ_x

(ii) $\sum F_y = 0$ - - - To prevent Δ_y

(iii) $\sum M_z = 0$ - - - - To prevent θ_z.

In case of 3D structure, there should be a min^m^ of independent ext. reactions to prevent rigid body displacements at support.

The displacements to be prevented are,

$$\Delta x\ ,\ \Delta y\ ,\ \Delta z\ ,\ \theta_x\ ,\ \theta_y\ ,\ \theta_z$$

Therefore, there will be 6 equations of static equilibrium.

$$\Sigma F_x = 0 \qquad \Sigma F_z = 0 \qquad \Sigma M_y = 0$$
$$\Sigma F_y = 0 \qquad \Sigma M_x = 0 \qquad \Sigma M_z = 0$$

2D structures are called plane structures & 3D structures are called space structures. In 3D structure for stability all the reactions should be non-coplanar/non-parallel and non-concurrent.

Internal Stability - No part of the structure can move relative to the other part, so that geometry of the structure is preserved. However, small elastic deformations are permitted. To preserve the geometry, enough no. of members and adequate arrangement is required. For geometric stability, there should not be formation of condition of mechanism. It means there should not be 3 co-linear hinges.

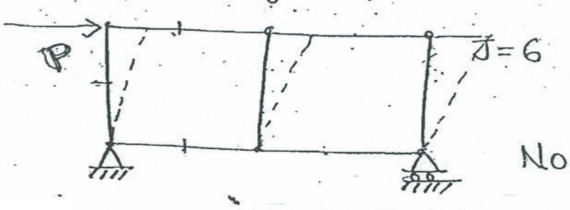
For 2D truss, the min^m no. of members neede for geometric stability is,

$$\boxed{m = 2j - 3}$$

and for 3D truss,

$$\boxed{m = 3j - 6}$$

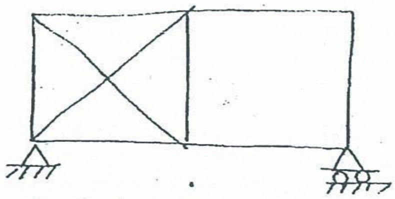
All the members should be arranged such tha truss is divided in triangular blocks, there should not be rectangular or polygonal blocks.



No. of members required for stability $= 2j - 3 = 6+3 = 9$

No. of members provided $= 7$.

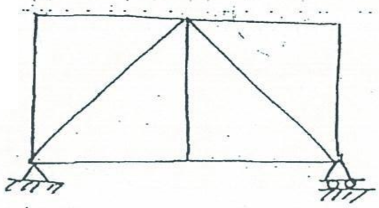
Hence, structure is having internally unstability.



$m = 9$

$= 2j - 3$

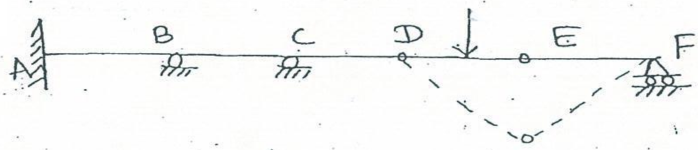
In above case arrangement of members is not adequate; Hence, right panel is unstable and left panel is over-stiff. For geometric stability all ~~plaplanet~~ panels of the truss should be stable.



$m = 9$

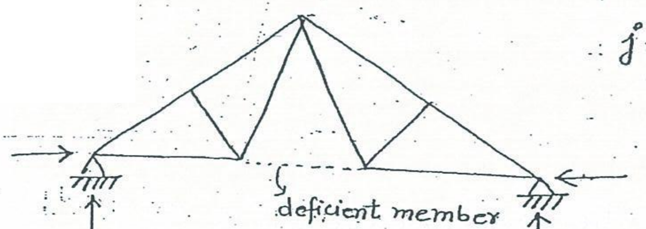
$= 2j - 3 = 2 \times 6 - 3 = 9$

Stable / Perfect



Mechansism.
3 collinear Hinges.

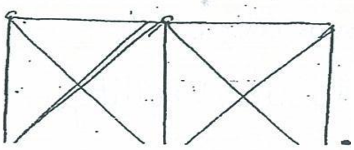
Overall Stability - For overall stability, extr. stability is compulsory. In some cases structure is overall stable but it may be overstiff externally & deficient internally, it means support rxns. are more than 3 and no. of truss members are less than $2j-3$.



$j = 7$, $2j - 3 = 11$

$m = 10$

In above case, truss is overall stable becau[se] there is one extra redundant reaction which prevent geometric deficiency. It is desirable for overall stability, structure should be externally and internally stable both.



In this structure,
externally unstable &
Internally stable but

Indeterminacy (D_i)

- Static ($D_{si} + D_{se} = D_s$) related to support conditions
  - External (D_{se})
  - Internal (D_{si})
- Kinematic (D_{k}) related to geometry & D.O.F.

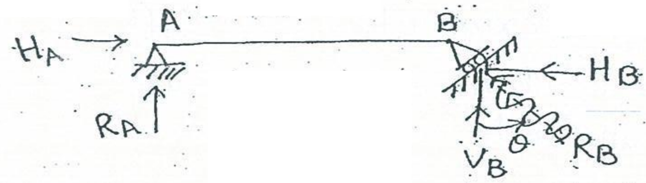
Static Indeterminacy - Those structures which cann' be analysed using conditions of static equilibriu alone, are called indeterminate structures (OR) hypersta structures. For indeterminate structures, to analyse additional ~~equilibrium~~ conditions are required, called compatibility conditions.

(1) External static indeterminacy (D_{se}) - It is related t support system of the structure and it is equ to no. of independent ext. rxns in ~~access~~ excess to available equlibrium conditions for stable equilibrium.

Let, r_e = Total no. of support reactions (Independer

$$D_{se} = r_e - 3 \quad \text{For 2D}$$

$$= r_e - 6 \quad \text{For 3D}$$



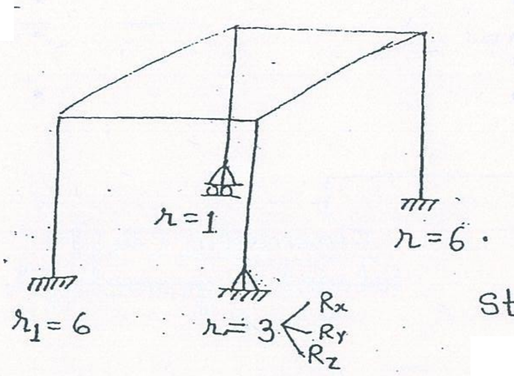
$$\left.\begin{aligned} R_B \cos\theta &= V_B \\ R_B \sin\theta &= H_B \end{aligned}\right\} \text{dependen}$$

r_e — H_A, R_A, R_B [Independent]

Question- For the structure shown in figure, determine D_{se} = ?

$r_e = 5$

$D_{se} = 5 - 3 = 2$



Total $r_e = 6+6+4$

$= 16$

$D_{se} = r_e - 6$

$= \underline{\underline{10}}$

Stable and Indeterminate.

Internal Static Indeterminacy (D_{si}) -

Case I- <u>Pin jointed plane frame (2 D truss)</u>

In trusses all joints are hinged and loading is applied only at joints & self wt. is ignored. Hence, all truss members will carry only axial forces. If there are 'm' members in the truss, hence there will be m internal reactions (axial forces). At each joint in the truss, ~~there~~ there are two equilibrium condition ($\Sigma F_x = 0$ & $\Sigma F_y = 0$). Let, there are 'j' no. of joints, hence total equilibrium conditions at all joints $= 2j$

Out of '2j' equations, three equations are used at supported joint to determine external rxns. Hence, net available eqns. to determine internal rxns $= (2j-3)$

Therefore, $\boxed{D_{si} = m - (2j-3)}$

If, $D_{si} = 0$, Internally determinate (Perfect Trusses)

$D_{si} > 0$, Internally indeterminate & overstiff

$D_{si} < 0$, Internally Deficient & geometrically unstable.

se II- <u>Three D Truss (Pin jointed space frame)</u>

In 3D truss also each member has 1 internal reaction i.e. axial force but each joint has 3 eqns. of equilibrium ($\Sigma F_x = \Sigma F_y = \Sigma F_z = 0$). Therefore, total equilibrium equations at 'j' joint $= 3j$

Out of these, 6 equations are used for external

$$\boxed{D_{si} = m - (3j - 6)}$$

Case III- 2D Rigid frames and 3D Rigid frames

In rigid frames, internal indeterminacy will not ex if it forms an open configuration like a tree. To check internal indeterminacy, following thumb rules can be applied -

If structure is internally determinate, then it is impossible to make a cut anywhere on the structure without splitting the structure in two parts.

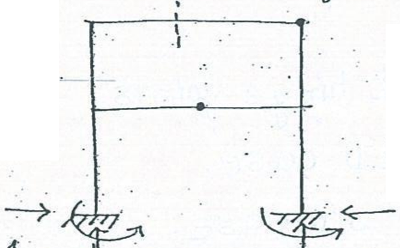
In case of internally determinate structure, it is impossible to return back at same point without retracing the path, it means internally determinate structures do not have cyclic loops.

In 2D rigid members, each member has 3 internal reactions (R_x, R_y and M_z) OR (S.F., Axial Thrust & B.M.) whereas in 3D rigid members, each membe has 6 internal reactions ($R_x, R_y, R_z, M_x, M_y, M_z$). It me each closed loop in 2D has 3 internal indetermina and in 3D, it has 6 internal indeterminacy.

$\boxed{D_{si} = 3C}$ for 2D Rigid frame

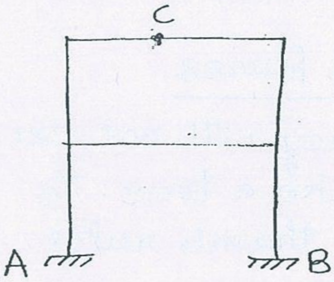
$= 6C$ for 3D ,, ,,

C = No. of closed loops.



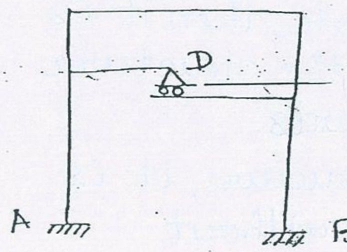
In above analysis, all the joints are considered rigi If some of the joints are hybrid (hinge), then some of the internal reactions will be released, Hence, Dsi will be reduced. Hence for hybrid frames,

$D_{si} = 6C - r_r$ for 3D case.



Hence, one internal reaction is released. (M_c)

$r_r = 1$.



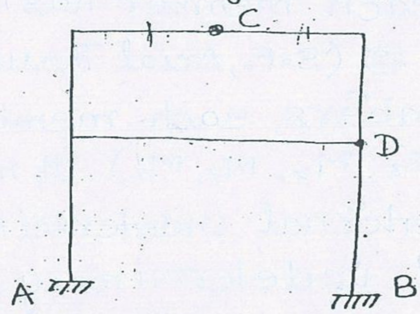
① Axial Force

② Bending Moment

$r_r = 2$

The no. of released reactions depend upon no. of members meeting at hybrid joints.

e.g. →



At C, one internal reaction is released.

At D, two internal reactions are released.

$r_r = 1 + 2 = 3$.

For plane structures,

$$r_r = \text{summation } (m'-1) = \sum(m'-1)$$

For space structures,

$$r_r = \sum 3(m'-1)$$

where, m' = No. of members meeting at hinge joints.

$$D_{si} = 3C - \sum(m'-1) \quad \text{for 2D case.}$$

$$= 6C - \sum 3(m'-1) \quad \text{for 3D case.}$$

Overall degree of static indeterminacy (D_s),

$$\boxed{D_s = D_{se} + D_{si}}$$

= External Indeterminacy + Int. Indeterminacy

Alternative approach to find overall (D_s) -

Case I → 2D Truss (plane truss)

$$D_s = m + R_e - 2j$$

where, m = no. of int. rxns

R_e = no. of ext. support rxns.

$2j$ = total available equilibrium equations

If $D_s = 0$, Truss is statically determinate

$D_s > 0$, Truss is statically indeterminate

$D_s < 0$, Truss is statically unstable.

Case II → 3D Truss (space truss)

$$D_s = m + R_e - 3j$$

Case III → 2D Rigid Frame

$$D_s = 3m + R_e - 3j$$

(when all joints are rigid.)

$$D_s = 3m + R_e - 3j - r_r$$

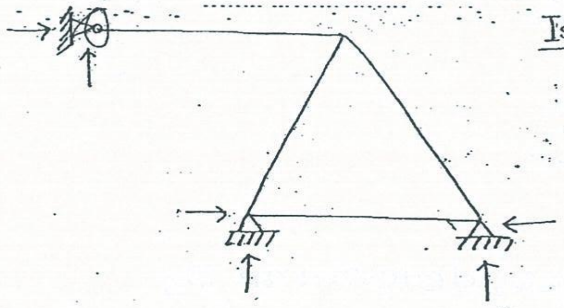
(when joints are hybrid.)

Case IV → 3D Rigid Frame

$D_s = 6m + R_e - 6j$ (when all joints are rigid).

$D_s = 6m + R_e - 6j - r_r$ (when joints are hybrid).

Example- For 2D truss shown in figure, find D_s=?



Ist Method,

$D_{se} = 6 - 3 = 3$

$D_{si} = m - (2j - 3)$

$= 4 - 2\times4 + 3$

$= -1$

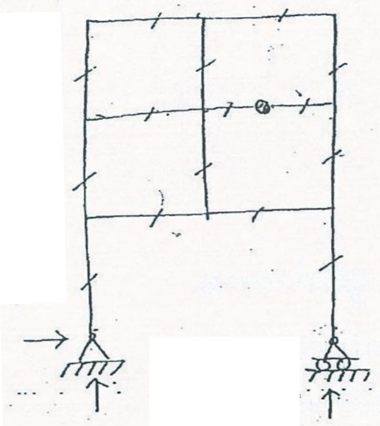
$\therefore D_s = 3 - 1 = 2$

IInd Method,

$D_s = m + R_e - 2j$

$= 4 + 6 - 8 = 2$

7)→ For 2D frame shown in figure, find D_s = ?



$D_{se} = 3 - 3 = 0$

$D_{si} = 3C - r_r$

$= 3 \times 4 - 1$

$= 11$

$D_s = D_{si} + D_{se} = \underline{11}$

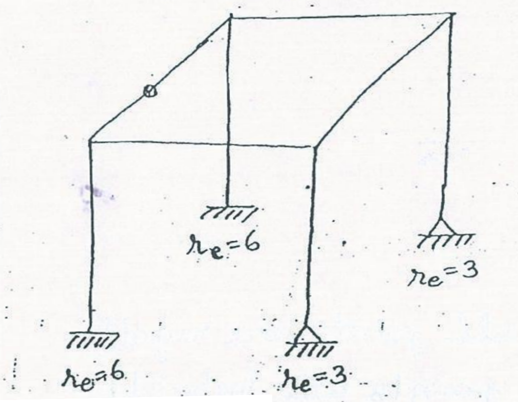
second method,

$D_s = 3m + r_e - 3j - r_r$

$= 3 \times 15 + 3 - 3 \times 12 - 1$

$= 48 - 37 = \underline{11}$

8)→ For 3D hybrid frame shown in figure, find D_s,



Total, $R_e = 6 + 6 + 3 \times 2$

$= 18$

$r_r = 3(m' - 1)$

$= 3(2 - 1) = 3.$

$D_{se} = 18 - 6 = 12$

$D_{si} = 6C - r_r$

$= 6 \times 1 - 3 = 3$

$D_s = D_{si} + D_{se} = \underline{\underline{15}}$

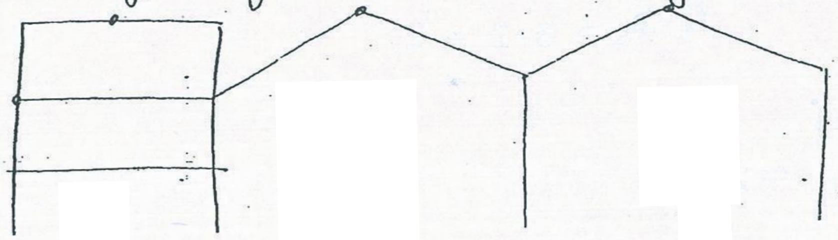
second method,

$D_s = 6m + R_e - 6j - r_r$

$= 6 \times 9 - 6 \times 9 + 18 - 3$

$= \underline{\underline{15}}$

)→ For rigid frame shown in figure, determine D_s,



$r_e = 12$

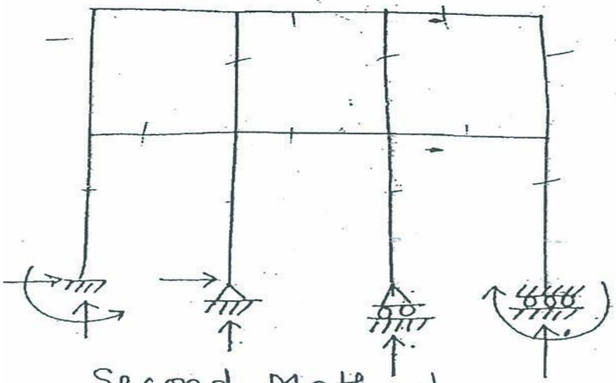
$D_{se} = 12 - 3 = 9$

$$D_{si} = 3C - r_r$$
$$= 3\times 2 - 5 = 1$$
$$D_s = D_{si} + D_{se} = 9 + 1 = \underline{\underline{10}}$$

<u>Second method</u>,

$$D_s = 3m + r_e - 3j - r_r$$
$$= 3\times 16 + 12 - 3\times 15 - 5$$
$$= \underline{\underline{10}}$$

(Q)→ Find the overall D_s = ?

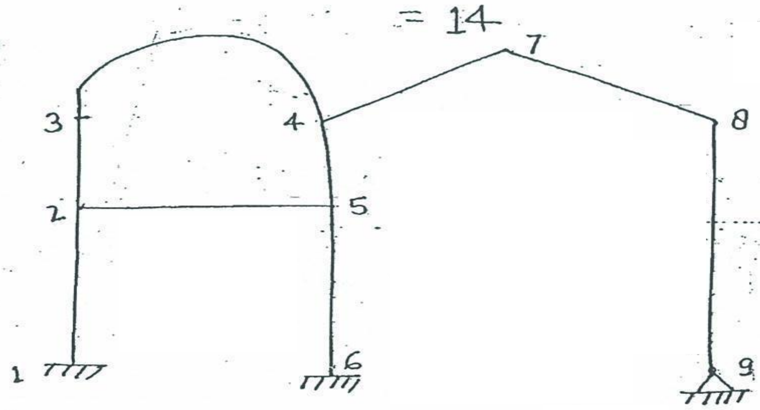


$$D_{se} = 8 - 3 = 5$$
$$D_{si} = 3C - r_r$$
$$= 3\times 3 - 0$$
$$= 9$$
$$D_s = D_{si} + D_{se} = \underline{\underline{14}}$$

<u>Second Method</u>

$$D_s = 3m + r_e - 3j - r_r$$
$$= 3\times 14 + 8 - 3\times 12 - 0$$
$$= 14$$

(Q)→



$$D_{se} = r_e - 3$$
$$= 3\times 2 + 2 - 3$$
$$= 5$$
$$D_{si} = 3C - r_r$$
$$= 3\times 1 = 3$$
$$\therefore D_s = 5 + 3 = \underline{8}$$

<u>Second method</u>,

$$D_s = 3m + r_e - 3j - r_r$$
$$= 3\times 9 + 8 - 3\times 9$$
$$= \underline{\underline{8}}.$$

Degree of Kinematic Indeterminacy.

It refers to the total no. of available degree of freedom at all joints.

(OR)

It is equal to total no. of unrestrained displac^{nt} components at all joints.

D_K = Total no. of D.O.F available at all joints

Type of Joint	Possible no. of D.O.F.
1). 2D Truss joint	2 — Δx, Δy
2). 3D Truss joint	3 — Δx, Δy, Δz
3). 2D Rigid joint	3 — Δx, Δy, θz
4). 3D Rigid joint	6 — Δx, Δy, Δy, θx, θy, θz

Type of Structure	D_K
2 D Truss (Plane truss)	$= 2j - R_e$
3D Truss (Space truss)	$= 3j - R_e$
2D Rigid frame	$= 3j - R_e$
3D Rigid frame	$= 6j - R_e$

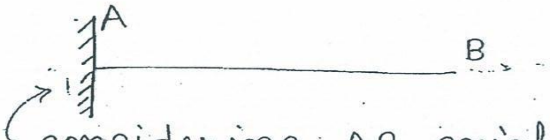
In above analysis, all members are considered axially flexible & all above displacements are elastic displacement.

Case I → In rigid frames, if some of the members are axially rigid, then in such members, axial displace^{nt} may not be available. Hence, D_K will be reduced.

For 2D rigid frames,

$$\boxed{D_K = 3j - R_e - m''}$$

In above case, if axial displacement is already no present, then no need to substract.



$D_K = 3 \times 2 - 3 = 3 \begin{cases} \Delta_{bx} \\ \Delta_{by} \\ \theta_{bz} \end{cases}$

considering AB axially flexible.

If AB is axially rigid, then D_K will be,

$$D_K = 3 \times 2 - 3 - 1 = 2 \begin{cases} \Delta_{by} \\ \theta_{bz} \end{cases}$$

consider axially flexible,

$$D_K = 3 \times 2 - 4 = 2 \begin{cases} \theta_A \\ \theta_B \end{cases}$$

consider axially rigid,

$$D_K = 3 \times 2 - 4 = 2 \begin{cases} \theta_A \\ \theta_B \end{cases}$$

∵ because there is no axial displacement.

Case II → If in rigid frames, some of the joints are hybrid then additional degrees of freedom will be available. Hence, increase in D_K will be equal to no. of reactions released at hybrid joint.

$$\boxed{D_K = 3j - r_e - m'' + r_r}$$ For 2D Rigid frame with hybrid joints.

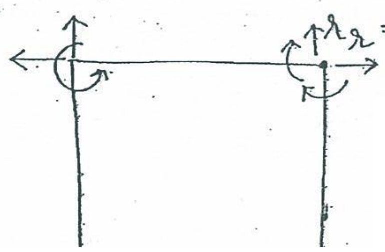
j = Total no. of joint (Rigid + Hybrid) & supported + unsupported.

$r_r = \Sigma (m' - 1)$

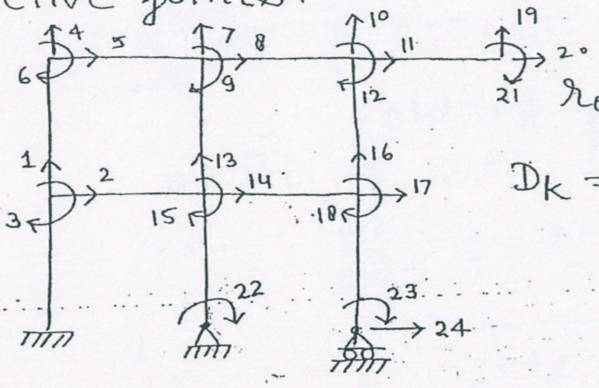
For, 3D Rigid frame,

$$D_K = 6j - r_e - m'' + r_r$$

$$r_r = \Sigma 3(m' - 1)$$



(Q)→ For 2D Rigid frame shown in figure, find D_K and show all displacement components at respective joints.



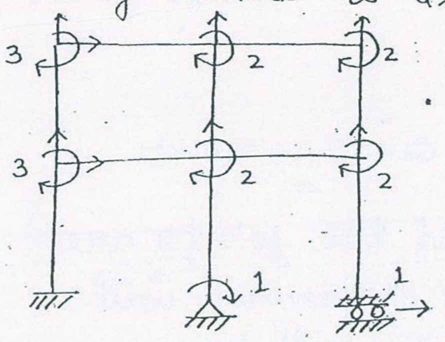
$r_e = 3 + 1 + 2 = 6$

$D_K = 3j - r_e$

$= 3 \times 10 - 6$

$= \underline{\underline{24}}$

Q)→ For rigid jointed frame shown in figure, find D_K. assuming beams as axially inextensible.



$m'' = 4$

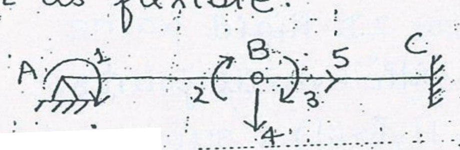
$r_e = 3 + 2 + 2 = 7$

$D_K = 3j - R_e - m''$

$= 3 \times 9 - 7 - 4$

$= 20 - 4 = \underline{\underline{16}}$

)→ For beam shown in figure, find D_K considerir eam as flexible.



$D_K = 3j - R_e - \cancel{m''} + r_r$

$= 3 \times 3 - 5 - 0 + 1$

$= \underline{\underline{5}}$

If above beams are axially rigid, then near axial displacement components at joint B ill not be available. ⇒

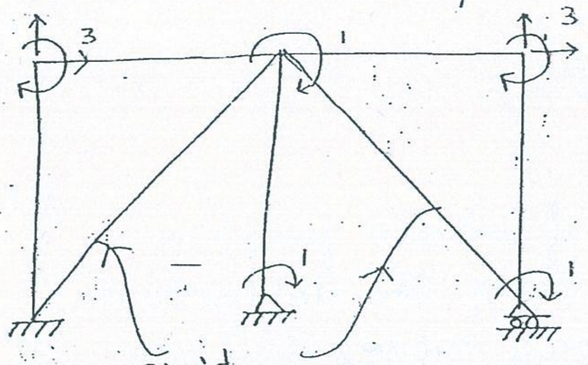
$D_K = 4$

θ_A $\quad$ θ_{B_2}

θ_{B_1} $\quad$ Δ_{BY}

$\boxed{\Delta B_x = 0}$

→ In braced frame shown in figure, find degree of kinematic indeterminacy.

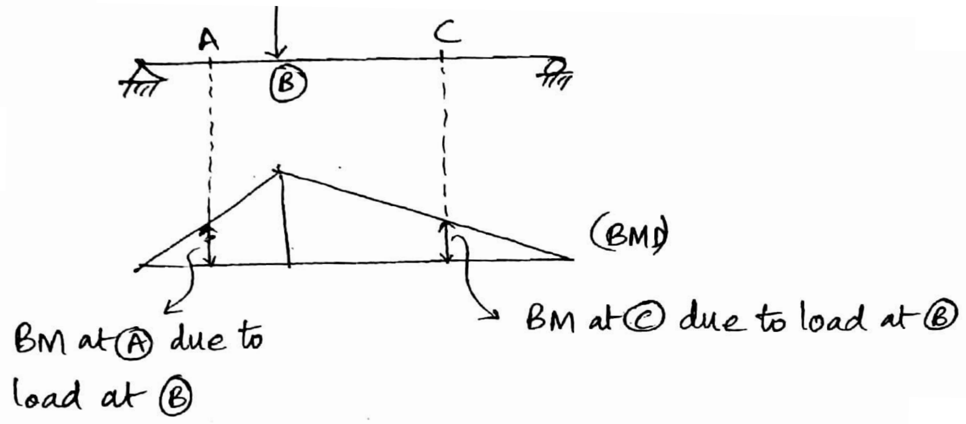


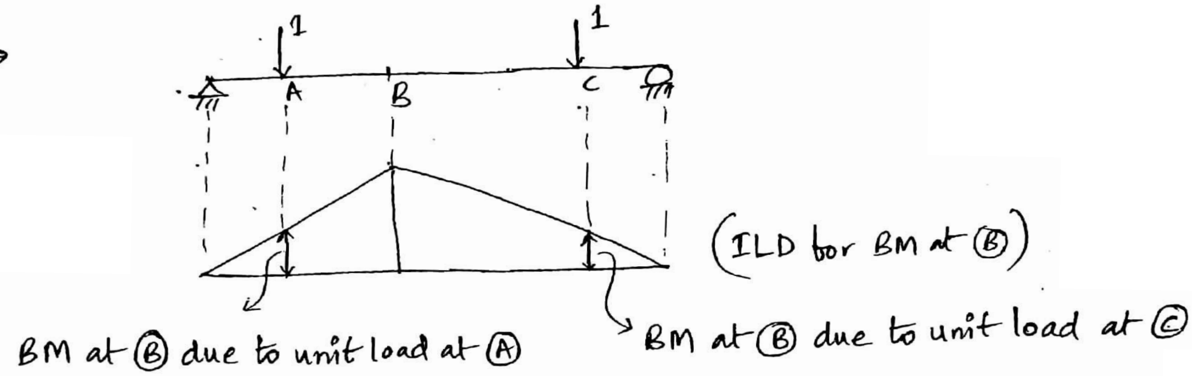
$D_K = 3 + 1 + 3 + 1 + 1$

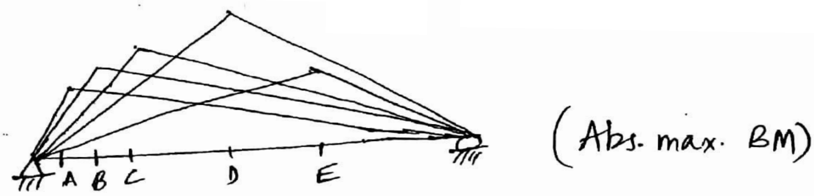
$= 9$

Braced members are rigid which prevent linear displacement component at braced joints.

Chapter 2 - Influence Line Diagram

→ 

→ 

→ 

→ An Influence line represents the variation of either the reaction, shear, Moment or deflection at a specified point in a member as a concentrated unit force moves over the member.

→ Influence line helps in deciding where should be the moving load will be placed on the structure so that it creates a greatest influence at a specific point.