Rotation Capacity of Plastic Hinges & Allowable Degree of Moment Redistribution of Ductile Flexural Members

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Abstract- **The thesis aims to study the plastic hinge region behaviour of ductile concrete members with variations in mechanical properties, boundary conditions, and geometric properties. The particular areas of investigation will be reinforcement yielding location, plastic strain distribution, and curvature localization region.Proposed equations for plastic hinge length will be incorporated into a mechanics-based approach to predict rotational capacity of flexural members.he study will help practicing engineers and researchers simulate the performance of ductile concrete members in a computationally efficient manner.**

Keywords— ETABS, Ductile Concrete, Plastic Hinge, Rotation Capacity, Pushover Analysis

I. INTRODUCTION

Plastic hinge refers to deformation of part of beam wherever plastic bending occur. For RC flexural members, plastic deformation is localized in the plastic hinge zone after yielding of members. Generally formed at the supports, point of maximum bending, under concentrated load. Eg. : For a simply supported beam subjected to point load, plastic hinges will occur at the position of point load. For a steel, the stress-strain behaviour ends at elastic limit of the body, then it will vary at different rate. After the achievement of elastic state, the rate of strain is much larger than that of change in stress. At a point, stress got zero increment while the strain keep on increasing, this stress is called yield stress. Further force cause no increase in stress but an increase in strain, this state is called plastic state. In structural elements like beam, at maximum deflection condition, this stage is achieved. ie., the beginning of formation of plastic hinges.When the body become fully plastic, at point of application of load, it is said that it has infinite strain value. Strain is only resisted by a constant moment, which develops at plastic hinges, called plastic moment. The load at which this condition achieved is called collapse load, structure deforms at a greater rate with constant resisting moment.

Hinge means that having no capability to resist moment, so the plastic hinge behaves like a standard hinge permitting free rotation. The assessment of the plastic rotation of reinforced concrete members is an essential aspect to avoid structural brittle collapse. Rotation capacity of a joint in a structural member under constant moment depends on characteristics of the formation of plastic hinge. The value of plastic hinge length depends upon the load distribution and cross section of beams.

Moment redistribution refers to the behaviour of statically indeterminate structures that are not completely plastic, but have some reserve plastic capacity. When one location first yields, further application of load to the structure causes redistribution of moment. When the load is applied to the beam, it has the property to resist it. When the beam is indeterminate, it forms sufficient number of hinges to make itself determinate. Further increment in load does not increase the moment at the point where plastic hinges are formed. The increased load increases the moment in the less stressed section of beam. The process of shift of application of moment in the beam is termed as moment redistribution in a beam. It is economical to allow redistribution of negative moments, it exploits the ductility of RC beams. Reduces the complexity of reinforcement detailing at beam-column junction and accommodates more space for concrete pouring.

Ductility is an important property of structural members that allows large deformation and deflection to occur under overload condition. It is an important design parameter, where intense confinement should be provided to increase the ductility of members. It provides warning of failure for statically determinate beams and allows moment redistribution to occur in statically indeterminate beam at overload. The ductility of member can be determined from moment curvature relation, where large deformations indicate better ductility. Ductility can be increased by increasing compression steel content, increasing compressive strength and increase in ultimate concrete strain. It can be reduced by increasing tension steel content, increase in steel yield strength and increase in axial load.

II. OBJECTIVES

- To study and optimize the plastic hinge region behaviour of ductile concrete members
- To determine the ductility demand and maximum capacity of the structure with respect to percentage moment redistribution
- To determine the ductility demand and maximum capacity of structure with respect to rotation capacity of hinges
- To determine the relationship of percentage moment redistribution and rotation capacity of beam hinges on response of special moment resisting frame
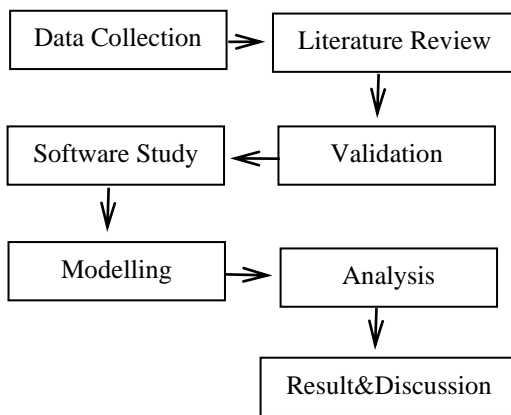
III. METHODOLOGY

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Data Collection ──> Literature Review
                           │
                           ▼
Software Study  <── Validation
     │
     ▼
Modelling ──> Analysis
                  │
                  ▼
              Result&Discussion
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TABLE 1: BUIDING DETAILS

Sl no.	Component	Values
1	Model	G+8
2	Storey height	3.2m
3	Beam	250x500mm
4	Column	450x450mm
5	Wall thickness	200mm
6	Material	M25
7	Grade of steel	Fe415
9	Slab thickness	150mm
10	Seismic zone	3
11	Importance factor	1
12	Type of soil	Medium
13	Type of structure	Concrete
14	Response reduction factor	5
15	Live load	$3kN/m^2$
16	Roof load	$1.5kN/m^2$

IV. MODELLING

The building is considered to be situated in zone-3(Kerala). As per IS 456, building is considered as SMRF. ETABS implement the plastic hinge properties as FEMA 356 or ATC 40. Hinges are assigned when once the structure is modelled.
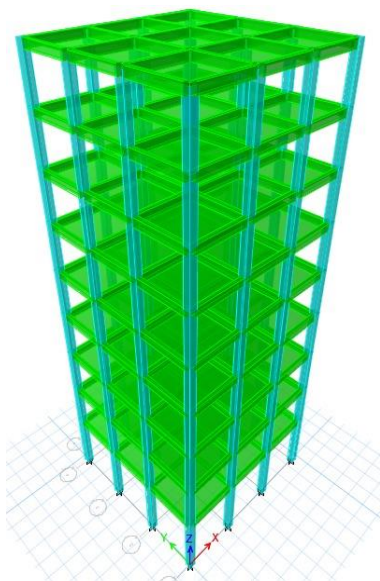
Fig 1: 3D-model

V. ANALYSIS

A. *Equivalent Static Analysis*

The natural period of building is calculated by the empirical expression prescribed in the code. The total design seismic base shear calculation and its distribution along the height are done as per IS 1893(part-I)-2002. The seismic weight is calculated using full dead load plus 25% of live load.

B. *Pushover Analysis*

First pushover analysis is done for gravity loads incrementally under load control. Later the subsequent lateral pushover load case is specified to start from final conditions of gravity pushover load case. Lateral load applied is obtained from ESA. Moment rotation values are assigned to all members by carrying out moment curvature analysis based on section properties and reinforcement details at the hinge location. For column moment rotation values are obtained for constant axial compressive load. The flexural M3 hinges are assigned for beam elements and P-M2-M3 hinges are assigned for column elements. These values are generated based on material model for concrete and steel, by using equilibrium and compatibility equation for each element. Where, M3= rotational hinge about major axis, M2= rotational hinge about minor axis and P= compression hinge.

Various parameters are used to study the plastic hinge region behaviour of ductile flexural members. These parameters are varied by 50% from the actual and the plastic hinge region behaviour were analysed.

A. *Stiffness*

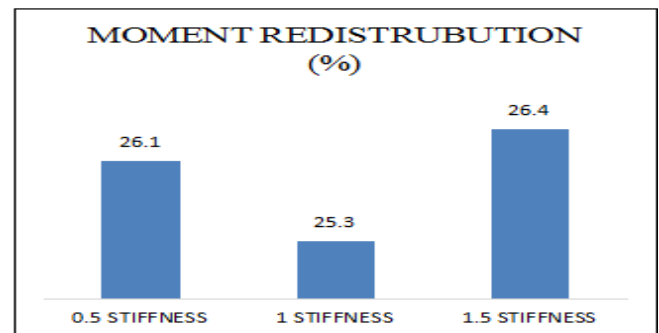Stiffness is increased and decreased by 50% from the actual and the behaviour is analysed.

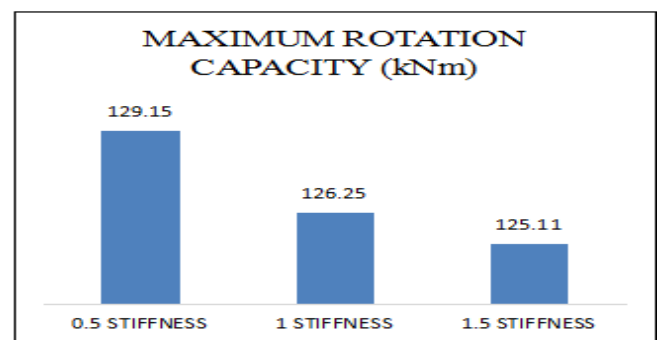Fig 2: Moment redistribution v/s stiffness

Fig 3: Maximum rotation capacity v/s stiffness

From the graph, Moment increases when stiffness is varied 50% and rotation capacity is higher for beam with less stiffness.
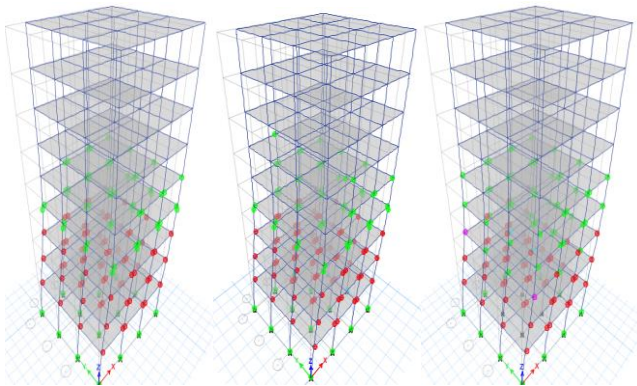

Fig 4: Hinge formation corresponds to stiffness

From the figure, Hinge formation is almost same when stiffness varied by 50%.

B.Shear area

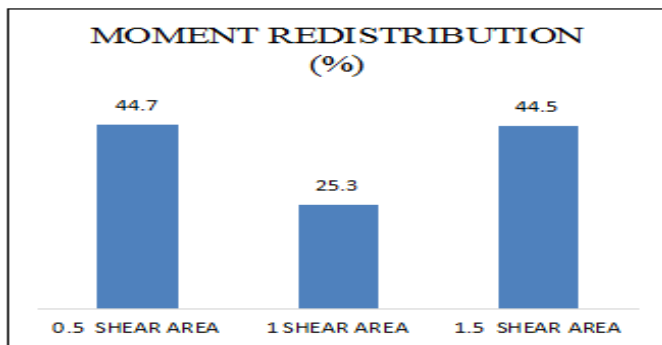Shear area is increased and decreased by 50% from the actual and the behaviour is analysed
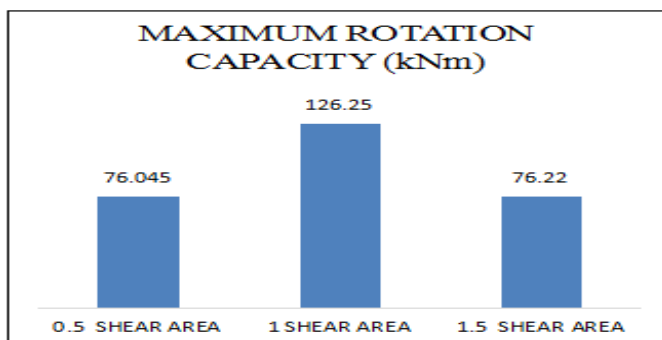

Fig 5: Moment redistribution v/s shear area

Fig 6: Maximum rotation capacity v/s shear area

From the graph, Moment Redistribution increases very much when shear area is varied 50% and rotation capacity of hinge reduced very much when shear area varied 50%
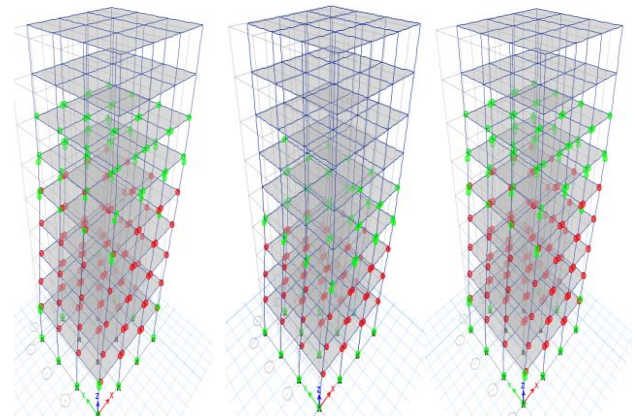
Fig 7: Hinge formation corresponds to shear area

From the figure, When actual shear area of beam is varied 50%, number of hinges increases.

C.Torsional modifier

Torsional modifier is increased and decreased by 50% from the actual and the plastic hinge region behaviour is analysed.
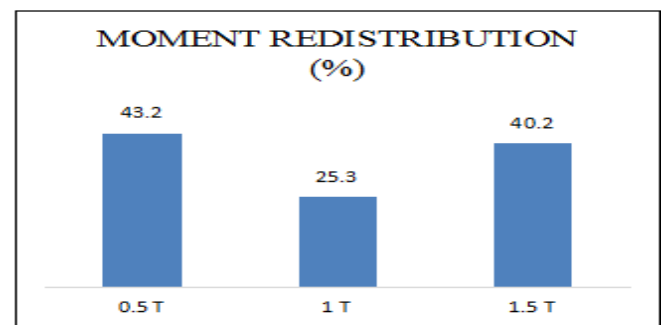
Fig 8: Moment redistribution v/s varying torsional modifier
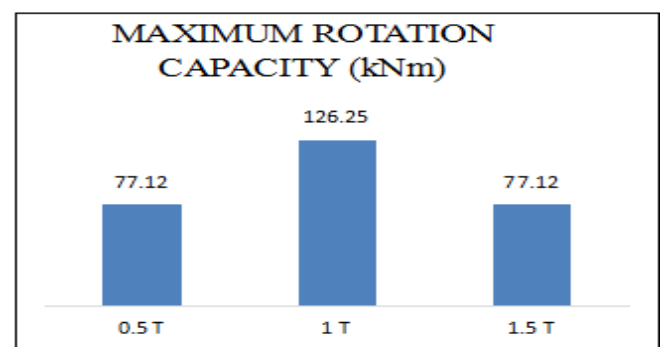
Fig 9: Maximum rotation capacity v/s torsional modifier

From the graph, Moment Redistribution increases very much when torsional constant is varied 50% and rotation capacity of hinge reduced very much when torsional constant varied 50%.
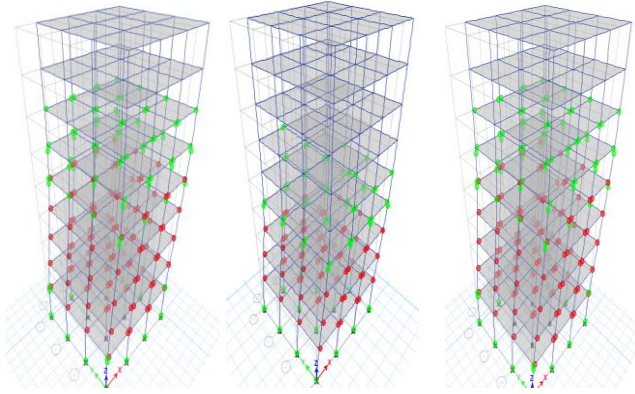
Fig 10: Hinge formation corresponds to torsional modifier

Fig 13: Hinge formation corresponds to shear reinforcement

From the figure, When torsional constant varied 50%, number of hinges increases slightly.

D.Shear reinforcement

Shear reinforcement is increased and decreased by 50% from the actual and the plastic hinge region behaviour is analysed.
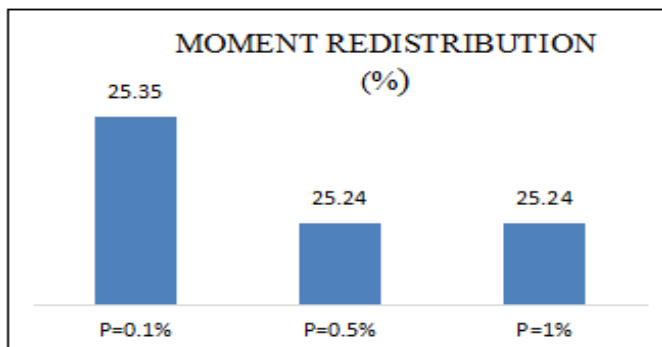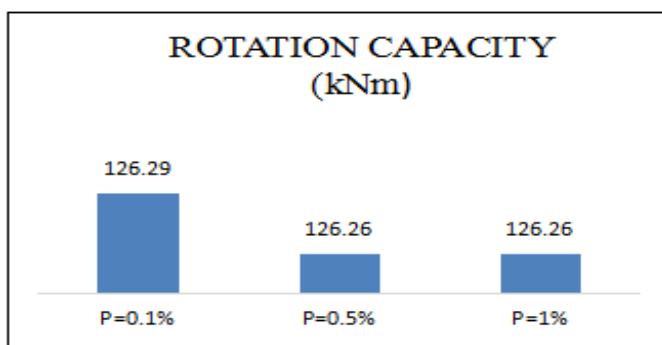
From the figure, Less shear reinforcement leads to more plastic hinges because it might not satisfy minimum shear reinforcement criteria.

E.Tension reinforcement

Tension reinforcement is increased and decreased by 50% by actual and the behaviour of plastic hinge region is analysed.
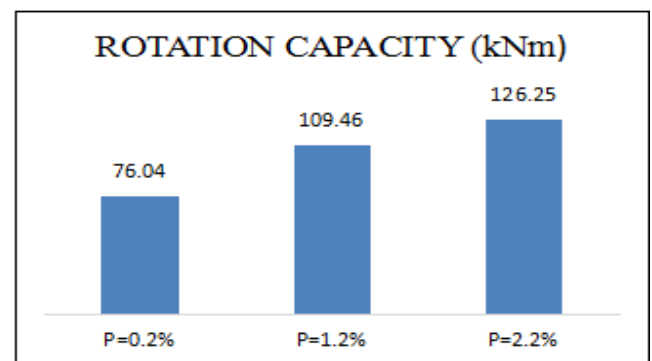

Fig 11: Moment redistribution v/s shear reinforcement
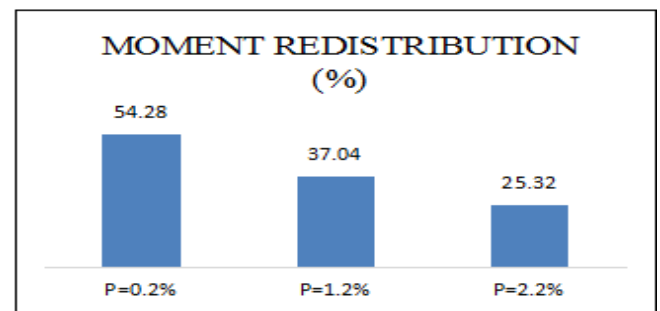
Fig 14: Moment redistribution v/s tension reinforcement

Fig 12: Maximum rotation capacity v/s shear reinforcement

Fig 15: Maximum rotation capacity v/s tension reinforcement

From the graph, very less percentage of shear reinforcement tends to more moment redistribution and rotation capacity.

From the graph, Moment redistribution decreases with increase in tension reinforcement and rotation capacity increases with increase in tension reinforcement.

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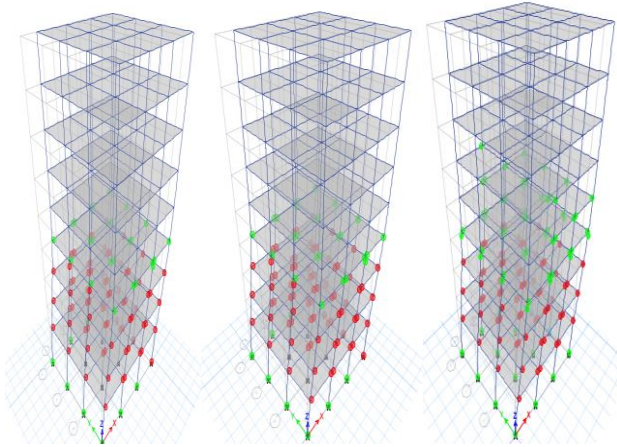**Vol. 10 Issue 06, June-2021**

Fig 16: Hinge formation corresponds to tension reinforcement

From the figure, For all percentage of tension reinforcement hinge formation is almost same.

F.Boundary condition
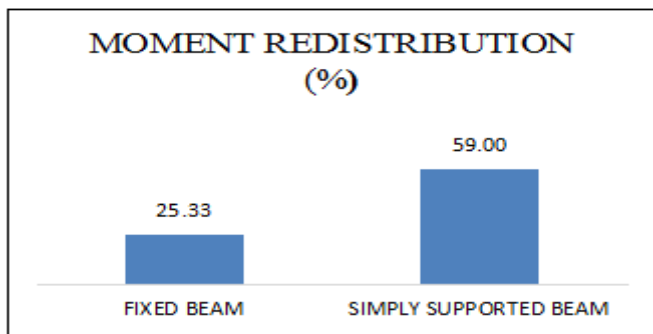Plastic hinge region behaviour is analysed by the beam is considered as simply supported and fixed.
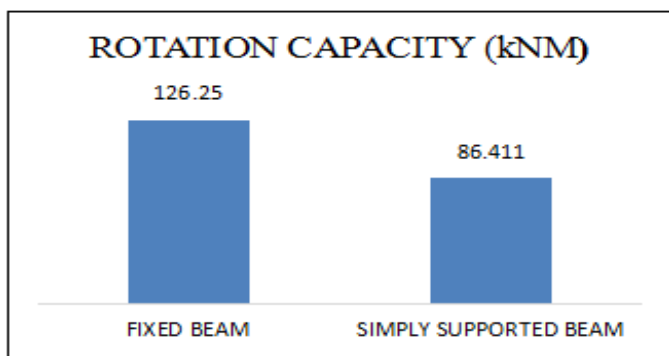

Fig 17: Moment redistribution v/s boundary condition

Fig 18: Maximum rotation capacity v/s boundary condition

From the graph, Moment redistribution is higher in case of simply supported beam and rotation capacity is less for simply supported beam.
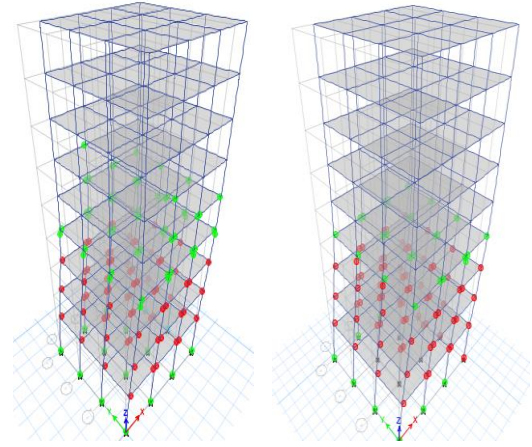
Fig 19: Hinge formation corresponds to boundary condition

From the figure, The damage probability is slightly higher for fixed beams than simply supported beam.

G.Span to depth ratio
Span to depth ratio is varied from the actual and there by plastic hinge region behaviour is analysed.
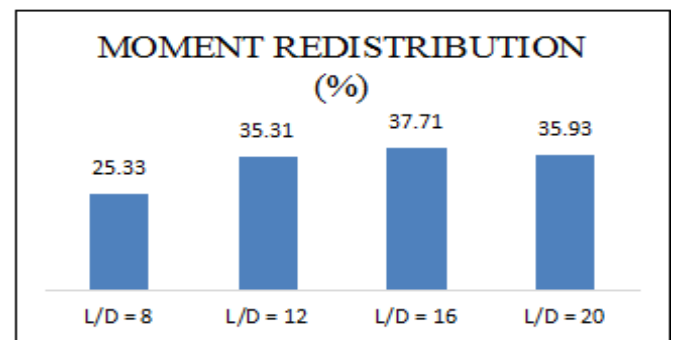

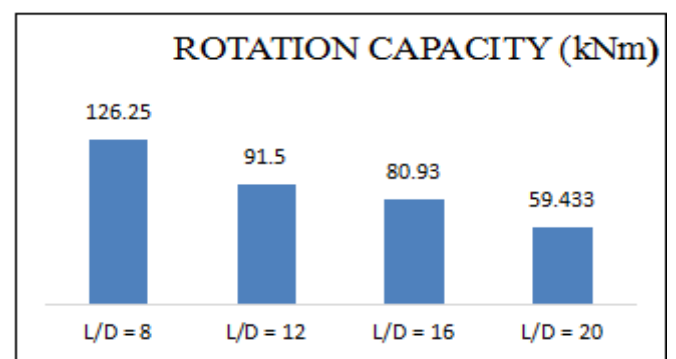Fig 20: Moment redistribution v/s span to depth ratio

Fig 21: Rotation capacity v/s span to depth ratio

From the graph, Span to depth ratio is directly proportional to moment redistribution and inversely proportional to rotation capacity.
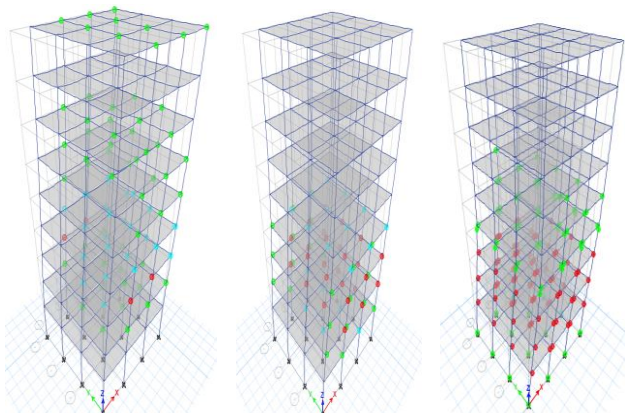
Fig 22: Hinge formation corresponds span to depth ratio

From the figure, When L/D ratio increases hinge formation also increases.

H. Column size

Column size is varied from the actual and there by plastic hinge region behaviour is analysed.
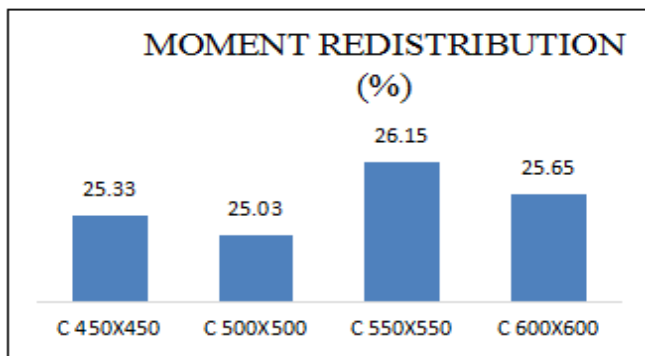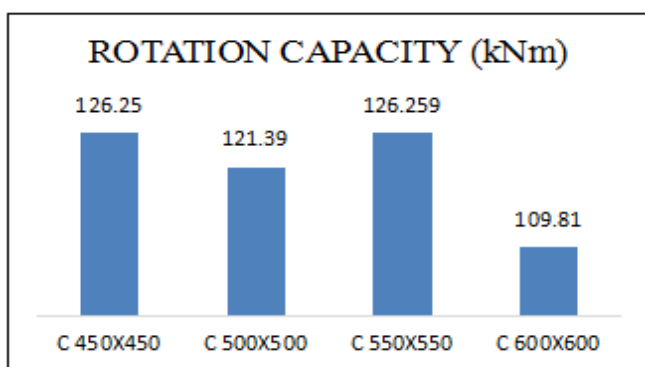

Fig 23: Moment redistribution v/s column size

Fig 24: Maximum rotation capacity v/s column size

From the graph, Moment redistribution is less when stiffness ratio of beam and column becomes almost equal and rotation capacity depends on the distance from column to hinge location.
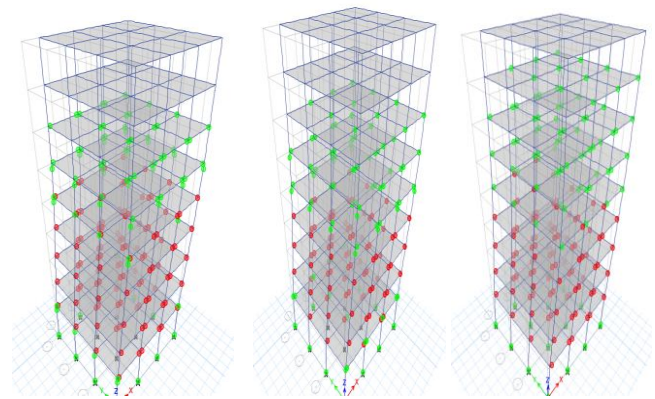

Fig 25: Hinge formation corresponds to column size

From the figure, Hinge formation is highest for larger columns, due to larger column to beam linear stiffness ratio.

Plotted moment redistribution and rotation capacity pushover curve by the values obtained from analysis on the various parameters for plastic hinge region behaviour of ductile flexural members.
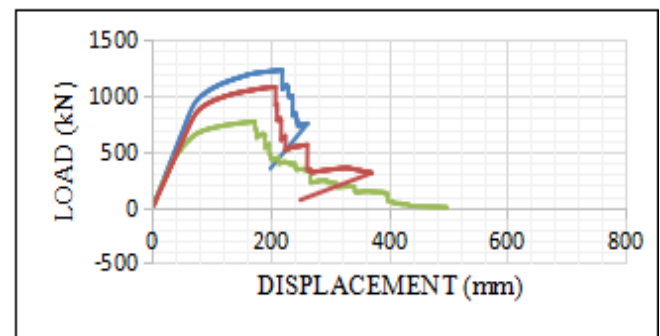

Fig 26: Moment redistribution pushover curve

From the graph, Lower percentage of moment redistribution in beam leads to more stronger structure. Higher percentage of moment redistribution in beam leads to more ductile and economic structure. As per cl.37.1.1 of IS 456:2000,the maximum moment redistribution should be within 30%. So optimum percentage of moment redistribution lies in between 25% to 30%.

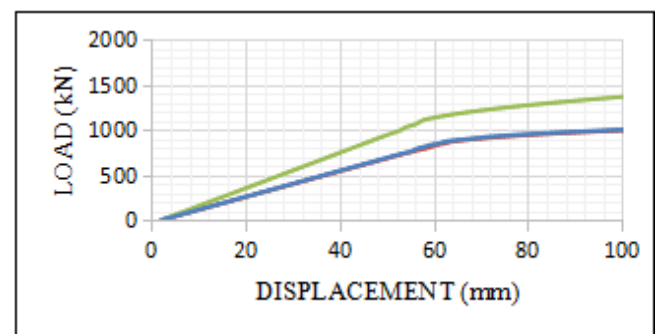

Fig 27: Rotation capacity pushover curve

From the figure, Rotation capacity around 100kNm leads to more stronger section.Corresponding moment redistribution around 100kNm rotation capacity is 25% to 37%.

Based on the values obtained from moment redistribution and rotation capacity pushover curve, yield capacity of the structure is analysed.
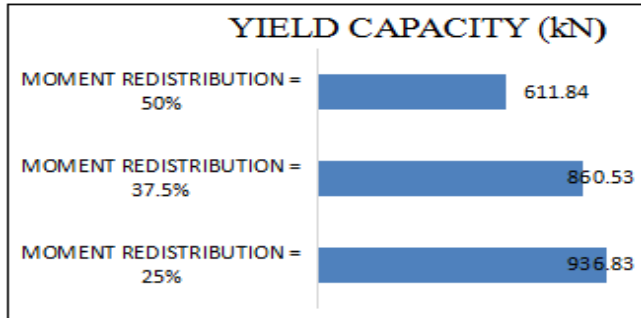

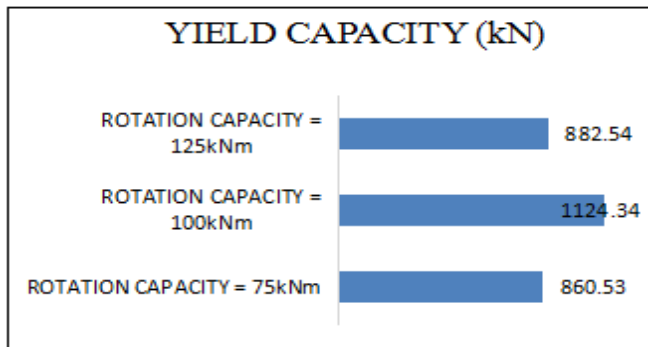Fig 28: Yield capacity v/s moment redistribution

Fig 29: Yield capacity v/s rotation capacity

From the graph, Upper limit of force that can be applied without producing permanent deformation increases with decrease in moment redistribution.But lower percentage of moment redistribution leads to less ductile structure. Yield capacity is higher for structure with rotation capacity around 100kNm.

Based on the values obtained from moment redistribution and rotation capacity pushover curve, Ultimate capacity of the structure is analysed.
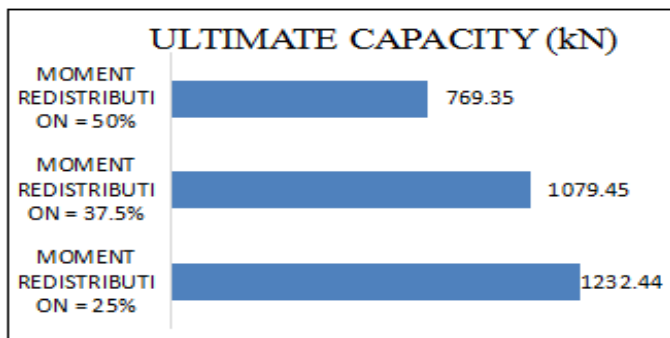

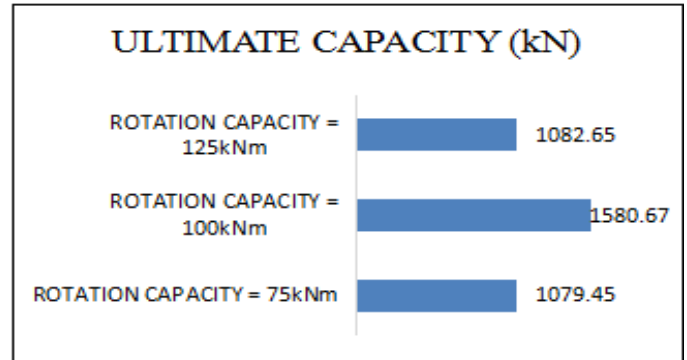Fig 30: Ultimate capacity v/s moment redistribution

Fig 31: Ultimate capacity v/s rotation capacity

From the graph, Ultimate capacity should be higher to prevent necking of the members due to strains. Ultimate capacity is highest for moment redistribution 25% and Rotation capacity 100kNm.

Relationship of moment redistribution and rotation capacity of beam hinges on response of special moment resisting frame is analysed.
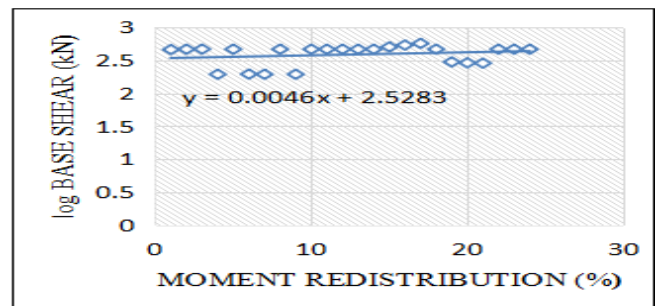
A.Base shear

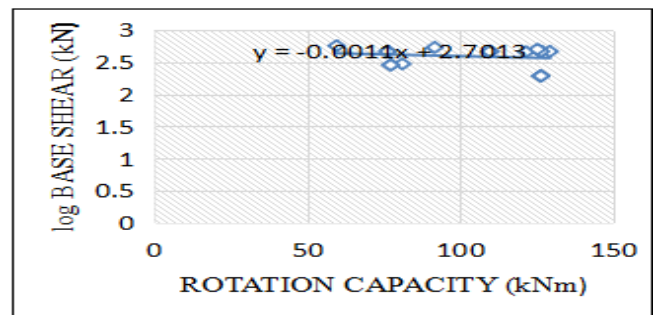Fig 31: Moment redistribution v/s base shear

Fig 32: Rotation capacity v/s base shear

From the graph, The ratio of moment redistribution to base shear is 0.0046. Base shear increases with increase in % moment redistribution. The ratio of rotation capacity to base shear is 0.0011. Base shear decreases with increase in rotation capacity.
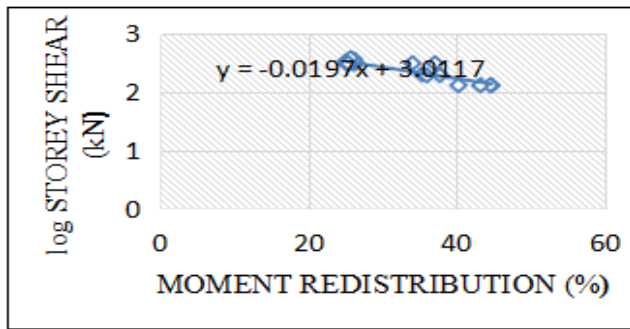
B. Storey shear

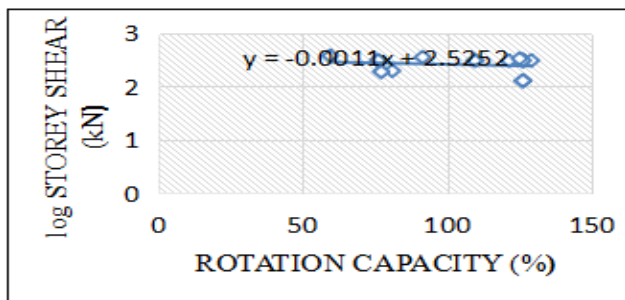

Fig 33: Moment redistribution v/s storey shear

Fig 34: Rotation capacity v/s storey shear

From the graph, The ratio of moment redistribution to maximum story shear is 0.0197. Maximum story shear decreases with increase in % moment redistribution.The ratio of rotation capacity to story shear is 0.0011. Maximum storey shear decreases with increase in rotation capacity.
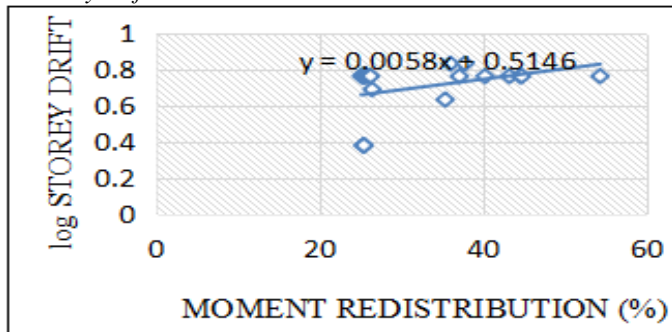
C. Storey drift

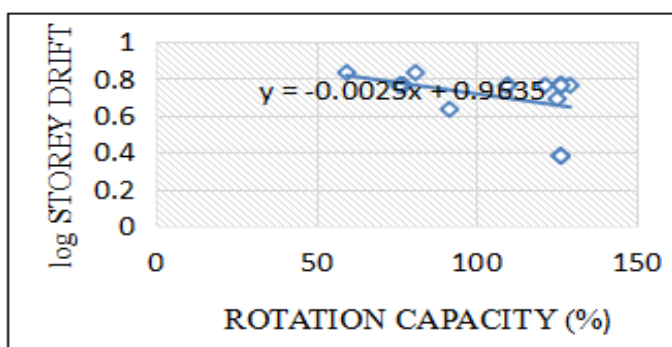Fig 35: Moment redistribution v/s storey drift

Fig 36: Rotation capacity v/s storey drift

From the graph, The ratio of moment redistribution to inter story drift is 0.0058. Drift increases with increase in % moment redistribution.The ratio of rotation capacity to inter story drift is 0.0025. Drift decreases with increase in rotation capacity.

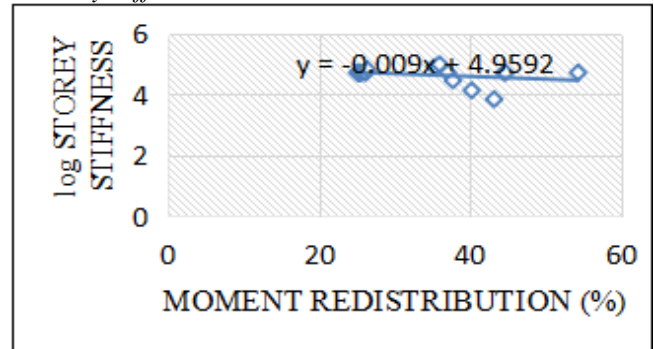### D. Storey stiffness

Fig 37: Moment redistribution v/s storey stiffness

Fig 38: Rotation capacity v/s storey stiffness
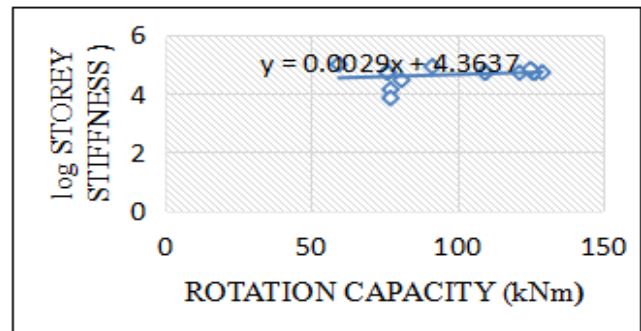
From the graph, The ratio of moment redistribution to maximum story stiffness is 0.009. Maximum story stiffness decreases with increase in % moment redistribution. Ratio of rotation capacity maximum story stiffness is 0.0029. Maximum story stiffness increases with increase in rotation capacity.
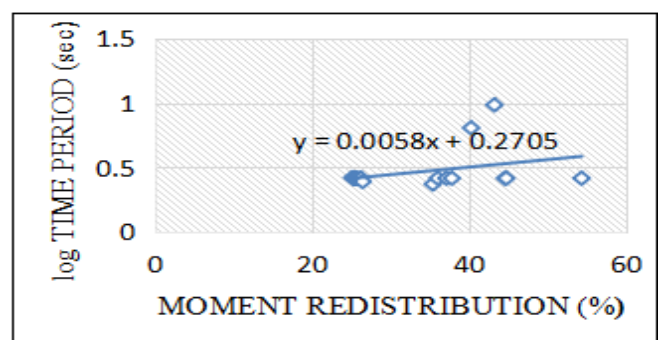
E. Fundamental time period

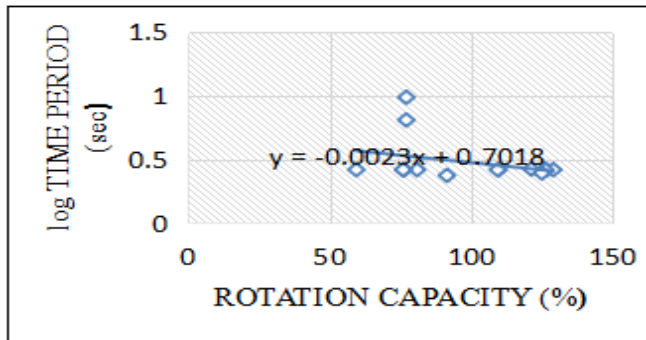Fig 39: Moment redistribution v/s time period

Fig 39: Rotation capacity v/s time period

From the graph, The ratio of moment redistribution to time period is 0.0058. Time period increases with increase in % moment redistribution. The ratio of rotation capacity to time period is 0.0023. Time period decreases with increase in rotation capacity.

VI.CONCLUSION

While doing performance based design following points should consider to limit the moment redistribution within 30%.

- Shear area and torsional constant should not vary above 25%
- Avoid simply supported beam as possible
- Provide percentage tension reinforcement above 1.2
- Span to Depth ratio should be within 12 including modification factor

Rotation Capacity of the hinges decrease with increase in Stiffness, Shear reinforcement and span to depth ratio of the beam. Column size does not cause much rise in moment redistribution. Percentage moment redistribution is proportional to Base shear, Story drift, Fundamental time period and ductility demand.Percentage moment redistribution is inversely proportional to story shear, story stiffness, yield capacity and ultimate capacity.Rotation capacity is proportional to story stiffness and inversely proportional to base shear, story shear, story drift and fundamental time period.

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