Comparative Study on Direct Displacement Based Design and Force Based Design under Seismic Forces

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Abstract – *This paper provides a comparison between various performance levels of direct displacement based design and the conventional force-based design provided in the Indian Standard for a moment resisting RC framed building. The comparison is done with the help of various parameters like base shear to be resisted, cost of the structural members, displacement and inter-storey drift ratio. Non-linear Static pushover analysis is performed on all the cases and its results like pushover curve, performance point and failure hinge mechanism are also compared. From all the comparisons it is concluded that the building can be designed to achieve the desired performance with an acceptable increase in the price of the building. All the parameters show that the performance of the building increases in Direct Displacement based design than force-based design and it satisfies the desired seismic performance objective.*

Index Terms—*Direct Displacement-Based Design, Force-Based Design, Performance-Based Design, Seismic Demand*

I. INTRODUCTION

Earthquake is one of the natural disasters which can't be predicted in advance and has a devastating effect on the structure. Many RCC structures in various locations of India which are prone to seismic activity are constructed without considerations of seismic forces and its effect on the structure. Soft storey sway mechanism and column sway mechanism are the main causes of failure of the multi-storey building, comprising multi-bay reinforced concrete frames during earthquake motions. A normal gravity resisting design will fail in case of earthquake due to reversal and the lateral direction of action. Hence special attention has to be given to seismic force while designing a structure.

Currently, in India, the seismic design is done by a force based approach given in IS 1893 (Part 1)-2016[1]. It uses a strength parameter as the base for predicting the seismic demand. The problem with this method is as given by Priestley, et al., 2008[2]:

- Distribution of lateral forces is based on elastic estimates of stiffness which is illogical and tends to concentrate strength in elements with the greatest potential for brittle failure.
- Displacement-equivalence rules relating displacement demand based on initial elastic periods.
- Ductility capacity is a function of structural geometry, not just of structural type.
- Seismic design of building structures will generally be governed by drift limits when realistic estimates of building stiffness are used to determine displacements. Current design approaches require iteration to satisfy drift limits.

To overcome the above shortcomings, different approaches have been evolved across the globe. Direct displacement based design (DDBD) methodology is one of the most practised methods in developed countries. DDBD method is governed by target displacement which a structure has to satisfy and it is based on the type of structure, height and the level of performance one has to achieve. The major advantage of using DDBD approach over FBD approach is given by Kowalsky, et. al.,2013[3]:

- The structure is designed to achieve an expected level of performance when subjected to a predefined level of seismic intensity.
- It uses the concept of an equivalent single degree of freedom from the multi-degree of freedom system.
- The secant stiffness is evaluated at the maximum response to represent the response of a non-linear system.

Aidcer, et.al., 2013 [3] in his article found that the direct displacement-based design allows the engineer to relate drift to material strains at the beams, which are better indicators of damage in the sections, which further allows the designer to have a better idea of the level of damage that is acceptable during the design process. Ahmed, 2010 [4] in his thesis work concluded that DDBD is suitable for moment resisting frame buildings which have a number of storeys more than 8 and for high values of ground accelerations, while it gives small base shear forces for buildings which have a number of storeys less than 8 for the low value of ground accelerations. Muljati, et.al., 2015 [5] presented that DDBD procedure is more effective than FBD in predicting seismic demand of a concrete special moment resisting frame.

Currently, the basic difference in both methods is the way to determine the base shear to be applied to the building. DDBD also offers multi-level performance objective whereas FBD doesn't offer such flexibility.

II. FORCE BASED DESIGN APPROACH

Force-Based Design is done according IS 1893 (Part 1)-2016[1]. The force-based design uses acceleration response spectrum and elastic period of the building to determine the loading on the building [4]. Force-based design parameters are mostly by probability theory which considers the seismic force calculation without considering any damage and collapse risks directly into account [5].

The steps to determine the base shear of the structure is as follows:

i. The time period of the building is determined based on the type of structure and the total height of the structure.
ii. Spectral acceleration coefficient is determined based on the type of soil (i.e. Soft, Medium and Rock Soil) and the time period of the structure.
iii. Horizontal Seismic Coefficient is determined based on the Zone of the region, Importance factor of the building, Response Reduction factor and spectral acceleration coefficient.
iv. Base shear of the structure is determined based on the Seismic Weight of the building and the horizontal seismic coefficient.

Above steps are summarized in Figure 1.

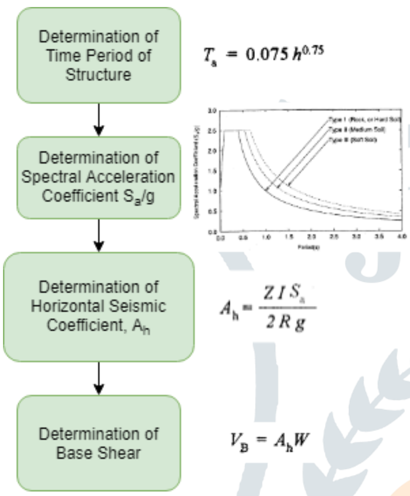


Figure 1 FBD Methodology

The above-obtained base shear is distributed along the whole building as per the distribution formula is given by IS 1893 (Part 1)-2016 given by:

$$Q_i = \frac{W_i * h_i^2}{\sum W_i * h_i^2} * V_B$$

Where,
W_i – Weight of i[th] floor
h_i – Height of i[th] floor
V_B – Base Shear of the building

III. DIRECT DISPLACEMENT BASED DESIGN APPROACH

Direct displacement based design parameters is determined by the guidelines published by the Structural Engineers Association of California (SEAOC) [4]. DDBD approach is based on the performance level to be achieved. Performance level selection is made by the client, in consultation with the design professional, based on consideration of the client's expectations, the seismic hazard exposure, economic analysis, and acceptable risk. Following are the performance level defined by them:

- **Fully Operational (SP1)**. The facility continues in operation with negligible damage.
- **Operational (SP2).** The facility continues in operation with minor damage and minor disruption in nonessential services.
- **Life Safe (SP3).** Life safety is substantially protected, the damage is moderate to extensive.
- **Near Collapse (SP4).** Life safety is at risk, the damage is severe, structural collapse is prevented.

As per the guidelines, the design steps involve determining the base shear as per performance level and designing the structure against that base shear. The design steps to determine the base shear is as follows:

i. Target displacement is computed based on the drift limit of each performance level, the effective height of the building and the shape factor which depends upon the height of the structure.
ii. The effective time period of the SDOF structure is determined from Spectral Displacement vs Time Period curve for the given earthquake zone and soil type. The curve is prepared using the response spectrum given in IS 1893 (Part 1)-2016 [1].
iii. Effective stiffness of the SDOF structure is determined based on the effective time period and effective mass of the structure.
iv. Base shear is determined from the effective stiffness and the target displacement of the building.

The above steps are summarized in Figure 2. The obtained base shear will be distributed to the whole building as per base shear distribution is given by IS 1893 (Part 1)-2016.

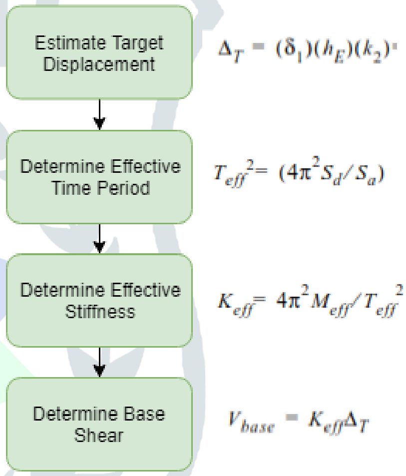


Figure 2 DDBD Methodology

IV. MODELLING OF RC MOMENT RESISTING FRAME BUILDING

To compare the design output of FBD and various performance level of DDBD, an RC moment resisting frame building of G+12 stories, having a bay spacing of 6m and 5m in X and Y directions respectively is used. The plan and elevation of the building are shown in Figure 3 and Figure 4.

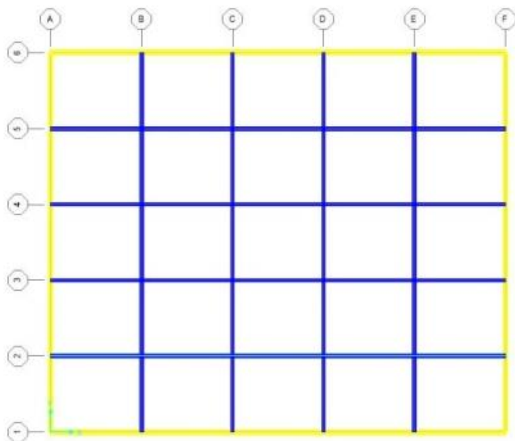


Figure 3 Plan of the building

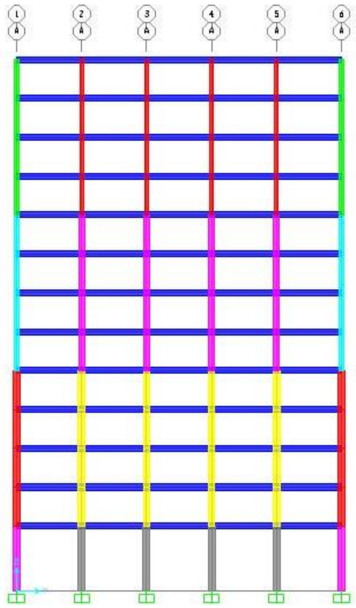


Figure 4 Elevation of the building

Beams are divided into two types depending upon the location namely Exterior Beam and Interior Beam. Columns are curtailed after ground floor, 5^{th} floor and 9^{th} floor and they are of three types based on their location namely Corner Column, Edge Column and Interior Column.

The other essential data considered are:

- Earthquake Zone – III
- Building Location – Surat, Gujrat
- Ground Storey – Open Parking
- Typical Storey Height – 3m
- Ground Storey Height – 5m
- Concrete Grade – M20
- Steel Grade – Fe500

The loadings considered for design are shown in Table 1.

Table 1 Loading Data

Dead Load	
Thickness of Slab	160mm
Floor Finish including Partition Wall	1.5 kN/m^2
Roof Finish Load	2 kN/m^2
Parapet Wall Load	5.88 kN/m
Exterior Masonry Wall Load	13.524 kN/m
Live Load	
On Typical Floor	4 kN/m^2
On Terrace	1 kN/m^2

The force-based design and direct displacement based design parameters for the building determined as per the steps explained above is shown in Table 2.

Table 2 FBD Parameters

Parameters	Value
Time Period (sec)	1.2152
Spectral Acceleration Coefficient, (S_a/g)	1.1191
Horizontal Seismic Coefficient, A_h	0.0179
Base Shear, V_B (kN)	2051.66

Table 3 DDBD Parameters

Parameters	SP-1	SP-2	SP-3	SP-4
δ_1	0.005	0.015	0.03	0.04
Δ_T (m)	0.10	0.32	0.64	0.86
T_{eff} (sec)	3.96	11.80	23.57	31.41
K_{eff} (kN/m)	239918.76	27053.12	6788.34	3821.97
V_{base} (kN)	25874.37	8752.74	4392.59	3297.49

The base shear obtained from both the methods is applied to building modelled in SAP 2000v20 and designed as per IS 456-2000 [5] in the software. Various parameters of the designed building are determined and compared among various performance levels and force-based design.

V. RESULTS AND DISCUSSION

After doing a number of iterations to design the building in SAP2000, final dimensions of the member are determined. In the case of SP1 performance level, the member dimensions go beyond feasible member dimensions and grade of concrete. Hence SP1 performance level results are not used for comparisons. All the parameters for comparison are discussed in the following section.

A. Member Dimensions

The final member dimensions for each performance level are shown in Table 4.

As seen from the table the dimensions increase with an increase in the performance level. The total concrete volume increase by 2%, 20% and 65% than FBD in SP4, SP3 and SP2 performance level.

B. Base Shear

As seen from Table 2 and Table 3, the base shear applied to the building increase with the increase in the performance level and it is least for FBD. The base shear increases by 1.6, 2.1, 4.2 and 12.6 times the base shear of FBD for SP4, SP3, SP2 and SP1 performance level respectively. The increase in base shear indicates that the building needs to resist more base shear and hence its member dimensions need to be increased

C. Cost of the Structural Members

After designing, the dimensions of beams and column are modified. As per the dimensions, SAP2000 also calculated the amount of reinforcement required in each member. The total cost of building in each performance level taken is the cost of concrete and cost of reinforcement for beams and columns. The price of concrete is taken as ₹4500 per m^3 and price of reinforcement is taken as ₹50 per kg. The cost of the building is shown in Figure 5. As seen from Figure 5 cost of the building increases by 10%, 26% and 67% with respect to FBD for SP4, SP3 and SP2 performance level respectively.

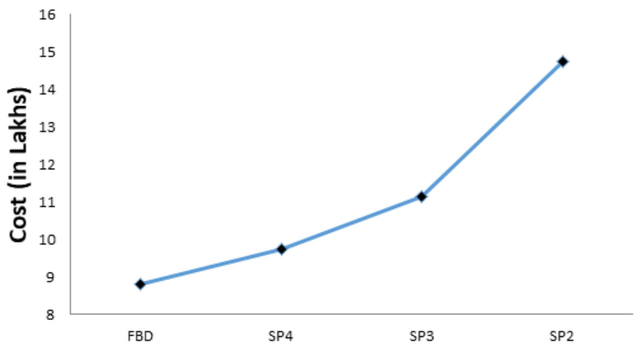


Figure 5 Cost of the structural members

Table 4 Member Dimensions of Building

	FBD	SP4	SP3	SP2
Beam				
Exterior Beam	0.30 X 0.45	0.30 X 0.45	0.30 X 0.50	0.40 X 0.55
Interior Beam	0.23 X 0.45	0.23 X 0.45	0.30 X 0.45	0.30 X 0.55
Column (Ground Floor)				
Corner Column	0.50 X 0.50	0.50 X 0.50	0.60 X 0.60	0.65 X 0.65
Edge Column	0.55 X 0.55	0.55 X 0.55	0.60 X 0.60	0.65 X 0.65
Interior Column	0.55 X 0.55	0.55 X 0.55	0.60 X 0.60	0.70 X 0.70
Column (1st – 4th Floor)				
Corner Column	0.45 X 0.45	0.45 X 0.45	0.55 X 0.55	0.55 X 0.55
Edge Column	0.50 X 0.50	0.50X 0.50	0.55 X 0.55	0.60 X 0.60
Interior Column	0.50 X 0.50	0.50 X 0.50	0.55 X 0.55	0.65 X 0.65
Column (5th – 8th Floor)				
Corner Column	0.40 X 0.40	0.40 X 0.40	0.40 X 0.40	0.45 X 0.45
Edge Column	0.45 X 0.45	0.45 X 0.45	0.45 X 0.45	0.55 X 0.55
Interior Column	0.45 X 0.45	0.45 X 0.45	0.45 X 0.45	0.55 X 0.55
Column (9th – 12th Floor)				
Corner Column	0.30 X 0.30	0.35 X 0.35	0.35 X 0.35	0.45 X 0.45
Edge Column	0.30 X 0.30	0.35 X 0.35	0.35 X 0.35	0.55 X 0.55
Interior Column	0.30 X 0.30	0.35 X 0.35	0.35 X 0.35	0.55 X 0.55

C. Storey Displacement

Displacement of the building at each floor level and for each performance level in X and Y directions are shown in Figure 6.

The maximum roof displacement for each performance level increases by almost 15% and 13% in X and Y direction respectively. There is also a change in the rate of increase of displacement at 1st, 5th and 9th floors due to the curtailment of the column.

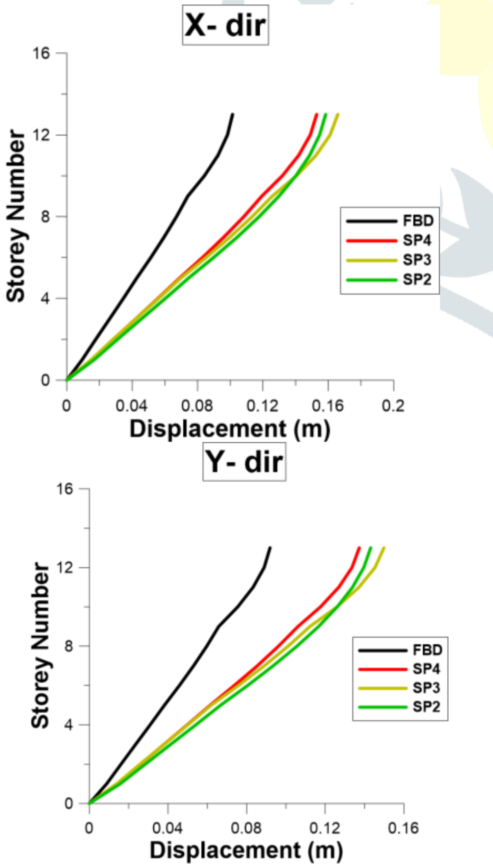
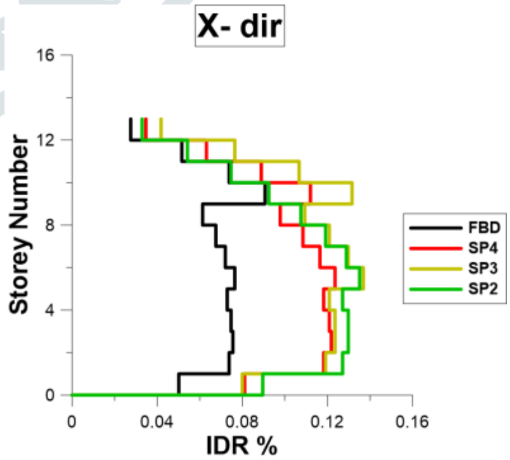


Figure 6 Displacement of building in X and Y directions

D. Inter-storey drift ratio

Inter-storey drift (IDR) ratio is defined as the ratio of the relative displacement of adjacent floor level to the floor height. IDR variation in X and Y directions is shown in Figure 7. Maximum values of IDR come, where the column is curtailed. For FBD it is after the 9th floor while for all performance level it is after the 5th floor.

The maximum IDR values increases by 36% and 25% for SP4 performance level & 50% and 42% for SP3 and SP2 performance level with respect to FBD in X and Y direction respectively. All the values for each performance level are well below their desired value and the major reason for it is due to the fact that IS 456-2000 only considers the elastic region for the design and gives conservative values for member dimensions.



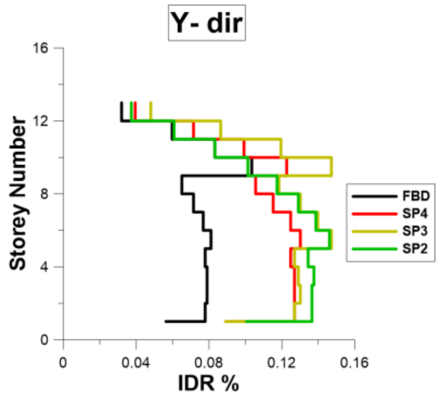


Figure 7 IDR in X and Y direction

E. Stiffness of the building

The stiffness of the building is determined by taking the ratio of the base shear resisted by the building to the maximum roof displacement. It is determined in both X and Y directions and shown in Figure 8.

From the figure, it can be seen that for all the cases the stiffness in the Y direction is 10% more than that in the X direction. This is due to less bay spacing in the Y direction as compared to that in the X direction. In both the directions the stiffness increases by 8%, 36% and 174% from FBD, for SP4, SP3 and SP2 performance level. This indicates that the base shear resisting capacity increases by that much amount.

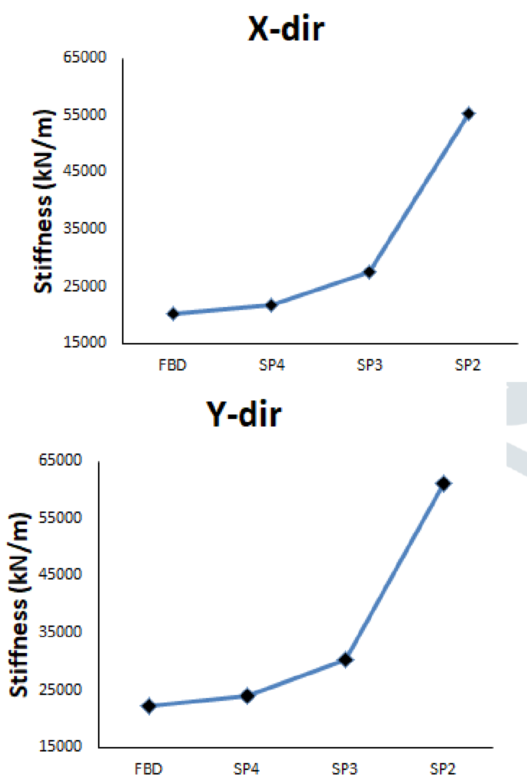


Figure 8 Stiffness of the building in X and Y direction

F. Pushover Analysis

Non-linear static pushover analysis is performed for all the performance levels with the help of the tool provided in the SAP2000. The pushover curve for all the performance levels in X and Y directions are shown in Figure 9.

From the curve, it is seen that the base shear that can be resisted by the structure increases with an increase in the performance level. The maximum base force increases by 49%, 112% and 246% with respect to FBD in the X direction and by 48%, 107% and 176% with respect to FBD in Y direction for SP4, SP3 and SP2 performance level respectively.

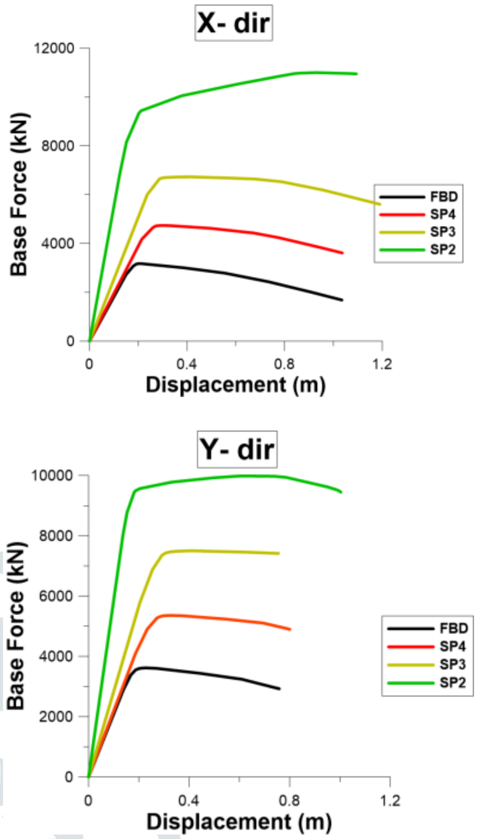
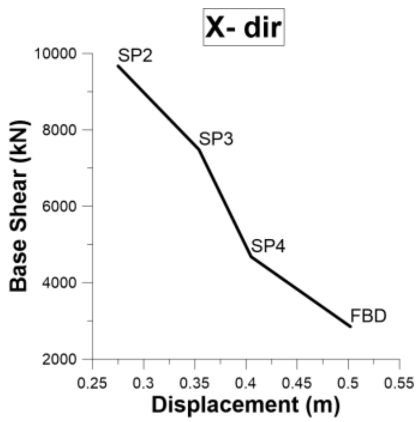


Figure 9 Pushover Curve in X and Y directions

G. Performance Point of the Structure

Performance point of the building is obtained by the intersection of the demand curve from ATC-40 and the capacity curve of the building. The performance point of the building in X and Y directions for all the performance levels are shown in Figure 10.

The performance point of the building in X and Y direction increases with the increase in the performance level and confirms the objective of the direct displacement based design of multi-level performance of the building.



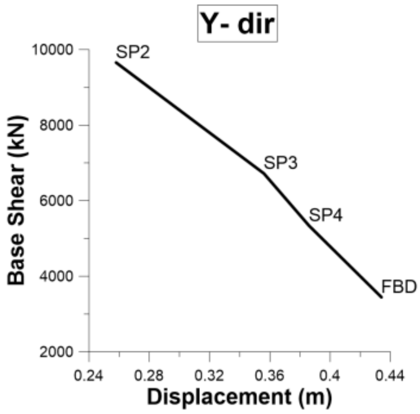


Figure 10 Performance Point in X and Y directions

H. *Failure Hinge Mechanism*

Hinge mechanism formed in the building for each performance is obtained in each case for the ultimate step in the pushover over analysis curve and shown in Figure 11. All the failure mechanism is almost similar and conforms to the strong column and weak beam concept of the design philosophy.

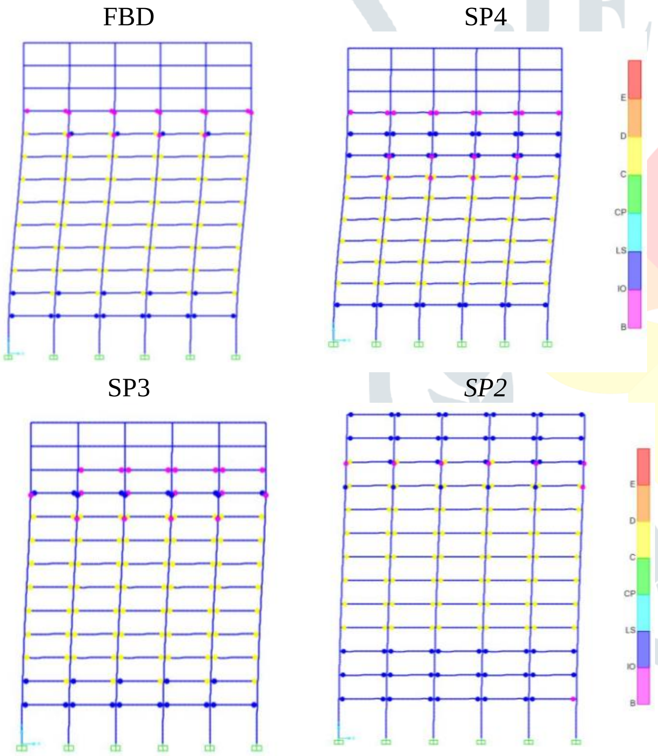


Figure 11 Failure Hinge Mechanism

VI. SUMMARY AND CONCLUSION

Following points can be concluded after comparing all the parameters between force-based design method and direct displacement based design method:

i. The base shear experienced by the building increases with an increase in performance level and it is least for FBD.
ii. Design for SP1 performance level is not possible within the feasible size of the structural members.
iii. The cost of the building increases with an increase in the performance level to achieve the required performance.
iv. There is a change in the rate of increase of displacement at the locations where column dimensions are changed.
v. IDR values also increase with the increase in the performance level and the maximum IDR is well within the performance level objective. The maximum value of IDR occurs at the column curtailment locations only.
vi. Due to smaller bay spacing in the Y direction, the stiffness of the building is more in Y direction than that of the X direction.
vii. Pushover analysis results show that the base shear resisted by the building for the same displacement increases with the performance level.
viii. Performance point obtained from the pushover analysis confirms the basic objective of the direct displacement based design and an increase in the performance of the building is obtained.
ix. Failure hinge mechanism shows that the basic design philosophy of strong column-weak beam is followed in all the cases.
x. The major advantage of using direct displacement based design is that the desired performance of the building can be achieved and the increase in the cost with performance is acceptable.

REFERENCES

[1] IS 1893 (Part 1) - 2016, *Criteria for Earthquake Resistant Design of Structures Part 1 General Provisions and Buildings.*

[2] M. Priestley, G. Calvi and M. Kowalsky, "Displacement-based seismic design of structures," 2008.

[3] V.-V. L. Aidcer and M. J. Kowalsky, "Drift, strain limits and ductility demands for RC moment frames designed with displacement-based and force-based design methods," Engineering Structures, 2013.

[4] . A. A. E. I. M. Fawzy, "Comparison between force based design and direct displacement based design for reinforced concrete frame or walled structures.," FACULTY OF ENGINEERING, CAIRO UNIVERSITY, 2010.

[5] I. Muljati, F. Asisi and K. Willyanto, "Performance of force based design versus direct displacement based design in predicting seismic demands of regular concrete special moment resisting frames," Procedia Engineering, 125, 1050-1056, 2015.

[6] A. ElAttar, A. Zaghw and A. Elansary, "Comparison between the direct displacement based design and the force based design methods in reinforced concrete framed structures," Istanbul, 2014.

[7] A. Mathew and A. Mathai, "COMPARISON OF FORCE BASED DESIGN AND DISPLACEMENT BASED DESIGN ON REGULAR BUILDINGS," International Research Journal of Engineering and Technology (IRJET), 2018.

[8] Structural Engineers Association of California (SEAOC), *Recommended Lateral Force Requirements and Commentary*, 1999.

[9] IS 456-2000, *Plain and Reinforced Concrete - Code of Practice.*