Capacity Based Earthquake Resistant Design of Multi-Storey RC Structure

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Abstract : Capacity based design method is a futuristic approach for the earthquake resistant design of RC structures. It eliminates the sway of the structure by strong-column and weak-beam mechanism. This method is very effective in the design of soft storeyed frames and eliminates the shear mode of failure by making the shear capacity of elements more than their moment capacity. IS 13920 (2016) explains the stipulations for the CBD of RC structures. In the present paper, earthquake resistant design of G+3 storeyed RC structure is done as per the stipulations given by IS 13920 (2016) for the capacity based design. Seismic analysis is performed by response spectrum method of IS 1893–Part 1 (2016). For the developed 2D frame models, moment and shear acting on beams and columns by Conventional Design and Capacity Based Design approaches are compared. Compared to the conventional design method, capacity based design method is more realistic and effective in resisting the earthquake forces as the calculations are based on provided reinforcement and the over strength of the structure which considerers the reserve strength beyond the elastic limit.

Keywords: Capacity based design, Moment magnification factor, Strong Column and Weak Beam.

I. INTRODUCTION

An earthquake is the sudden tremor of earth's crust which occurs at or below the surface due to seismic waves. It is one of the worst natural disasters. The fault surfaces on the earth are formed due to moving plates. An earthquake is measured by Richter's scale. Richter's scale value around 7 to 8 indicates devastating earthquake. The intensity of seismic shacking is measured in terms of Modified Mercalli (MM) scale. Conventional civil engineering structures are designed on the basis of two criteria i.e. strength and rigidity. The strength is related to ultimate limit state or damageability, for which force developed in the structures remain in the elastic range. The rigidity is related to serviceability limit state, assuring that the structural displacement must remain within the permissible limit as specified by standard codal provisions. In earthquake resistant design, a new demand viz. ductility is added along with rigidity and serviceability. Ductility is an important property of the structure which responds to the ground motion, absorbs seismic energy and reduces the transmitted force. Figure 1 shows the criteria for the design of civil engineering structures considering rigidity, strength and ductility.

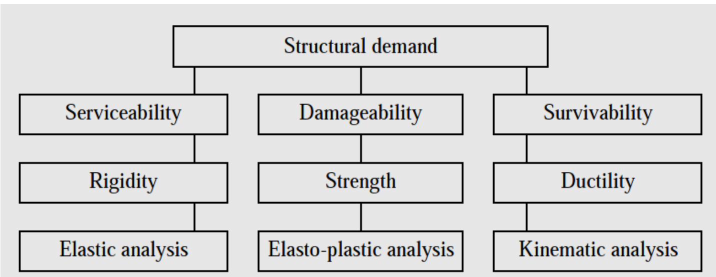

Fig. 1 : Criteria for the design of structures

[Photo courtesy : Agrawal and Shrikhande (2011)]

II. CONCEPT OF CAPACITY BASED DESIGN

In Capacity Based Design (CBD) method, the inelastic deformation demand is distributed throughout the structure so that the plastic hinges can be formed at the end regions of nearly all stories of the building while columns and walls remain essentially elastic in all the stories except at the base of the bottom storey. Here at yielding condition, the strength developed in weaker member is related to the capacity of the stronger member. This method allocates the strength and ductility in the structural elements for the successful response. Through this method, the collapse during earthquake is prevented by choosing the regions of energy dissipation and holding the pre decided energy dissipation mechanism throughout the seismic action. CBD method prevents the shear failure in columns and beams. The design procedure in CBD method is to stipulate the margin of strength which is required for the elements to remains elastic. IS 13920 (2016) explains the stipulations for the CBD of RC structures.

CBD considers Strong-Column and Weak-Beam (SCWB) mechanism. Under strong earthquake shaking, SCWB design philosophy controls the overall ductility of the structure, distributes the damage over the beams and achieves an ideal collapse mechanism. This process eliminates the damage to the columns as they are required to transfer the loads even after earthquake and also prevents the brittle shear failure of the frame. The columns are made stronger and beams are made to be weaker w.r.t. flexural moment carrying capacity. Figure 2 shows the proportioning of columns and beams in SCWB design.

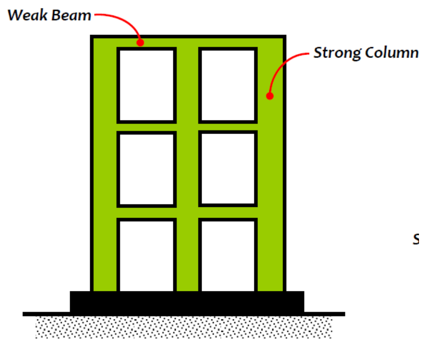

Fig. 2 : Proportioning of columns and beams in SCWB design

[Photo courtesy : Murty et al. (2012)]

SCWB mechanism is achieved in frames through Moment Magnification Factor (MMF). MMF is the ratio of sum of resisting moments of left and right beams at a joint with an over strength factor to the sum of resisting moments of top and bottom columns at the same joint.

Step by step procedure for capacity based design

1. Design loads viz. dead loads, live loads and earthquake loads acting on the frame are calculated as per IS 875–Part 1 (1987), IS 875–Part 2 (1987) and IS 1893–Part 1 (2016) codal provisions respectively.
2. Seismic analysis of the frame is performed for all load combinations as per IS 456 (2000).
3. For the worst load combination, the beams are designed for maximum moments (sagging and hogging) as per IS 456 (2000) codal provisions.
4. The flexural capacities (i.e. moment of resistance) of the beams for the provided reinforcement are recalculated as per IS 456 (2000) codal provisions.
5. The moments acting on columns at a joint is compared with moment of resistance of joining beams. If the sum of moments of columns is less than the sum of moment of resistance of beams multiplied by over strength factor [which is 1.4, as per Cl. 7.2 of IS 13920 (2016), the column moments should be magnified by the MMF by which they are lacking in moment capacity over the beams. If the sum of the column moments is greater than the sum of beam moments, then there is no need to magnify the column moments.
6. Columns are designed for the revised moments and maximum axial force as per IS 456 (2000) codal provisions.
7. Shear capacity of beams is calculated on the basis of their actual moment capacities as per Cl. 6.3 of IS 13920 (2016). The beams are then designed for shear as per IS 456 (2000) codal provisions.
8. Shear capacity of columns is calculated on the basis of magnified moment capacities as per Cl. 7.5 of IS 13920 (2016). The columns are then designed for shear as per IS 456 (2000) codal provisions.

III. DEVELOPMENT OF RC MODEL AND ANALYSIS

Figures 3 to 5 indicate the plan and elevations G+3 storeyed RC structure considered for the analysis. Dead loads and live loads are calculated as per IS 875–Part 1 (1987) and IS 875–Part 2 (1987) codal provisions respectively. Earthquake loads are calculated as per IS 1893–Part 1 (2016) for seismic zone II by response spectrum method. Analysis is done for different load combinations using STAAD Pro. software.

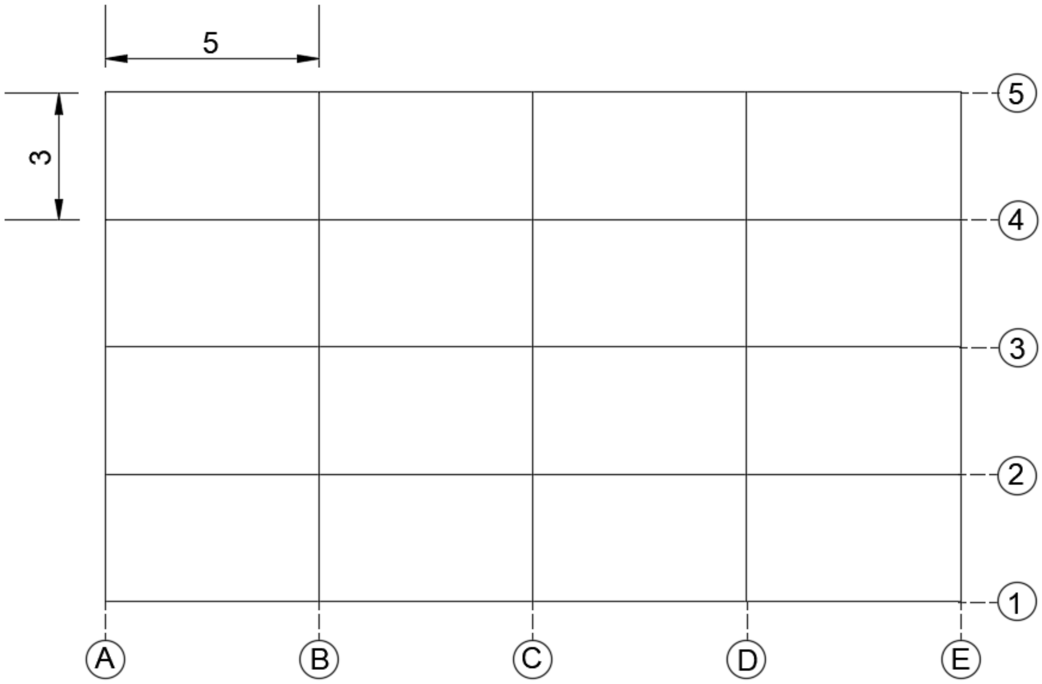

Fig. 3 : Plan

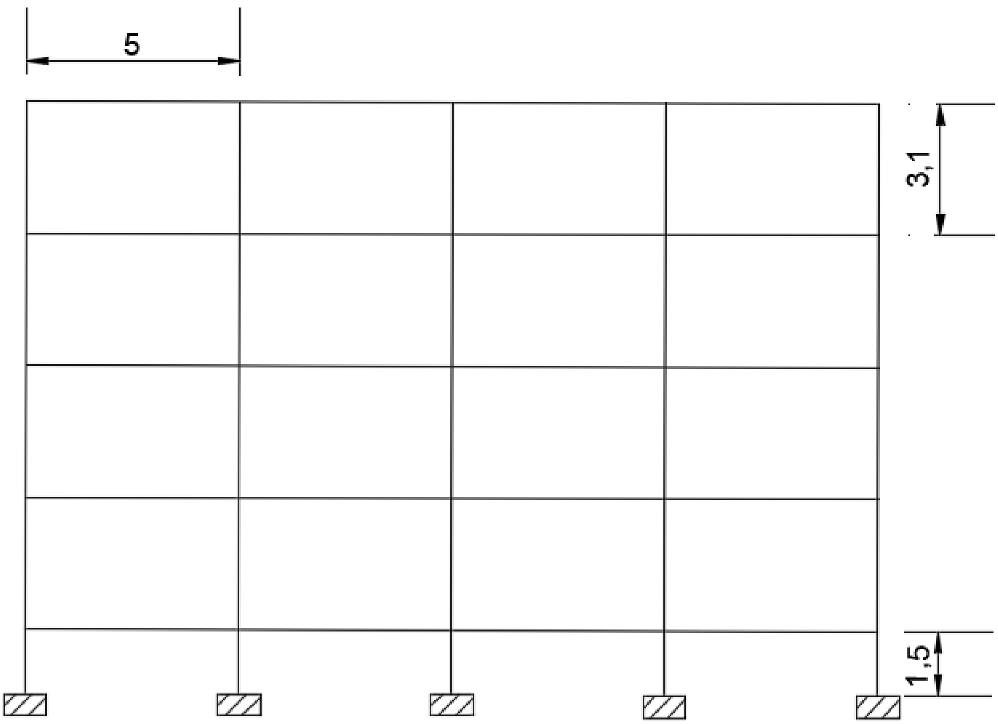

Fig. 4 : Elevation along longer direction

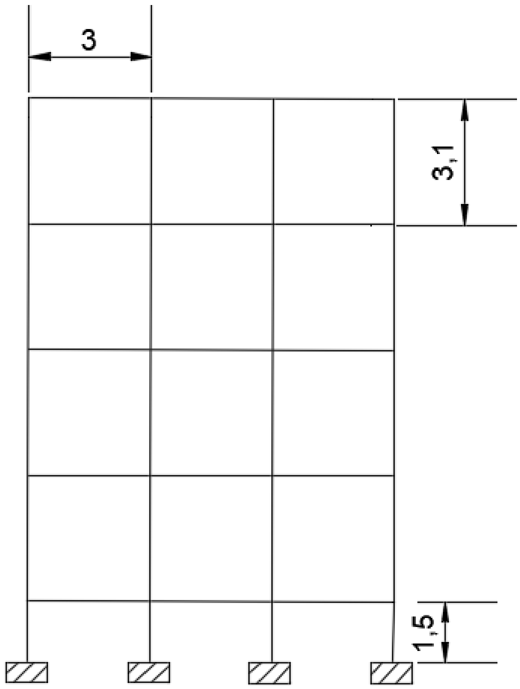

Fig. 5 : Elevation along shorter direction

Figures 6 and 7 show the joint and beam numbers of Grid 1-1 respectively.

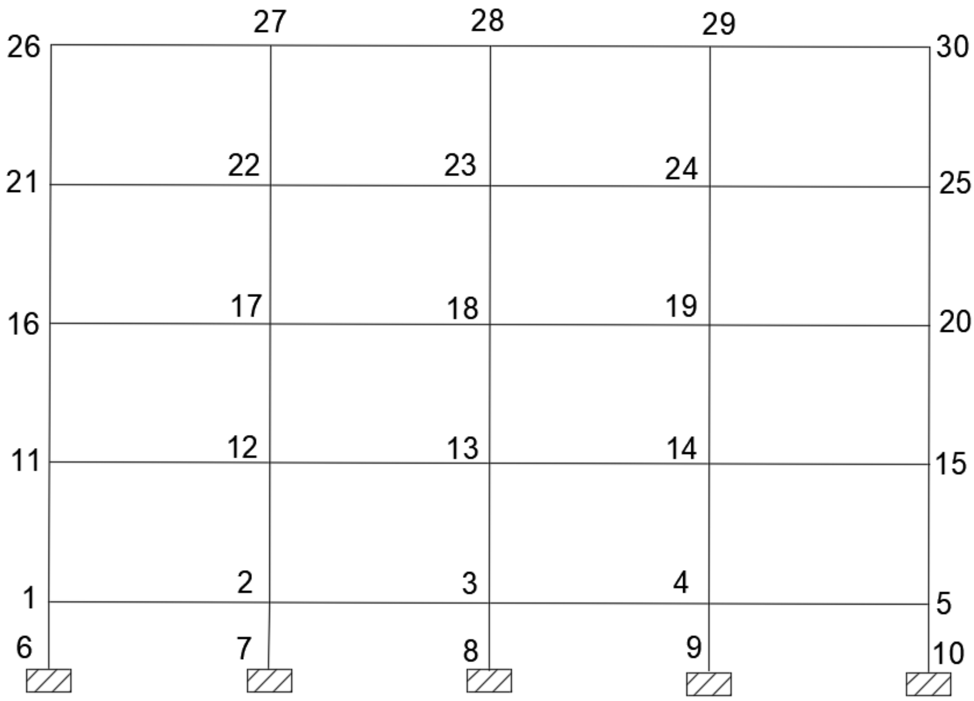

Fig. 6 : Joint numbers of Grids 1-1

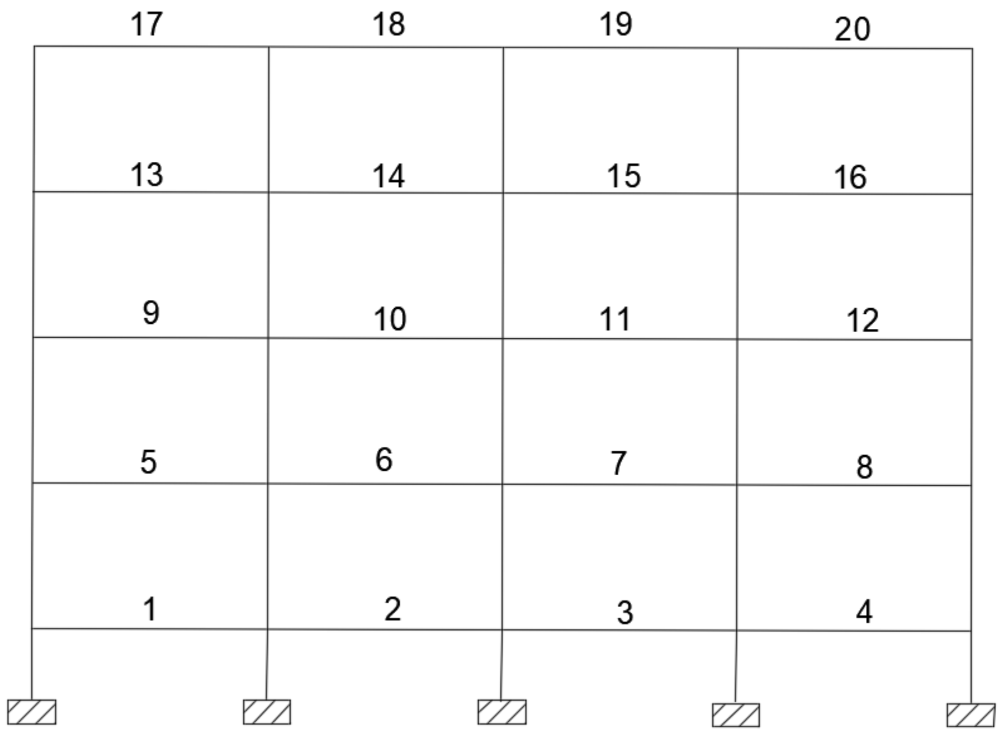

Fig. 7 : Beam numbers of Grids 1-1 and 2-2

IV. PARAMETERS CONSIDERED IN MODELLING

Table 1 shows the parameters considered for the development of RC framed structure models. Dead loads and live loads are calculated as per IS 875–Part 1 (1987) and IS 875 Part–2 (1987) codal provisions respectively. Earthquake loads are calculated as per IS 1893–Part 1 (2016) for seismic zone II by response spectrum method. Cross sectional dimensions of the beams and columns are chosen by trial and error method in such a way that the model is safe for all the load combinations mentioned in IS 456 (2000).

Table 1 : Parameters of the developed RC frame models

Sl. No.	Parameter	Remarks
1	Structure type	Commercial
2	Total No. of stories	G+3
3	Total height of the building	13.9 m
4	Bay width in X-direction	5 m
5	Bay width in Y-direction	3 m
6	Size of the column	300 x 450 mm
7	Size of the beam	300 x 600 mm
8	Thickness of the slab	150 mm
9	Storey height	3.1 m
10	Depth of foundation	1.2 m
11	Grade of concrete	M30
12	Grade of steel	Fe500
13	SBC of soil	200kN/m^2
14	Live load on floor	4 kN/m^2
15	Live load on roof	1.5 kN/m^2
16	Damping ratio	5%

Sl. No.	Parameter	Remarks
17	Soil type	Medium soil
18	Seismic zone	II
19	Importance factor	1.5
20	Response reduction factor	5

Table 2 shows the different load combinations given in C1. 19 of IS 456 (2000) considered for the analysis.

Table 2 : Load combinations considered for the analysis

Sl. No.	Load combination	Remarks
1	1.5(DL+LL)	DL = Dead Load LL = Live Load EQ = Earthquake Load
2	1.2(DL+LL+EQ)	
3	1.2(DL+LL–EQ)	
4	1.5(DL+EQ)	
5	1.5(DL–EQ)	
6	0.9DL+1.5EQ	
7	0.9DL–1.5EQ	

V. ANALYSIS OF RC FRAME MODELS

Using STAAD Pro. software, Grid 1-1 is subjected to response spectrum analysis as per IS 1893–Part 1 (2016). The maximum moments (i.e. hogging and sagging) and shear forces in beams, and maximum moments, shear forces and reactions in columns are obtained from the analysis for the worst load combination.

VI. RESULTS

Figure 8 shows the maximum values of sagging (below) and hogging (above) moments of beams obtained from STAAD Pro. analysis of the developed 2D frame model of Grid 1-1 for the worst load combination.

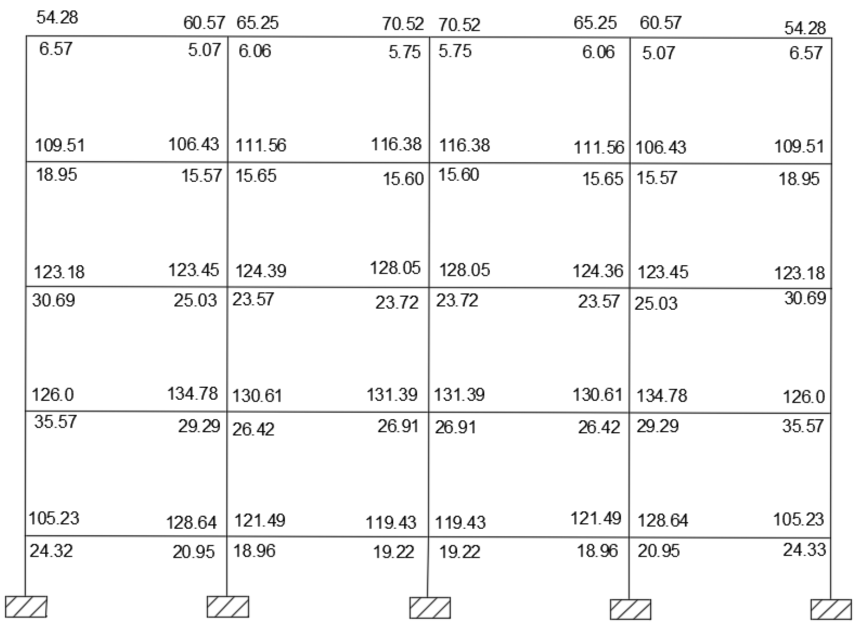

Fig. 8 : Maximum moments (in kN-m) of beams of Grid 1-1

For the above moments, the reinforcement is calculated as per annex G of IS 456 (2000). Figure 9 shows the moment of resistance of beams of Grid 1-1 as per the provided reinforcement.

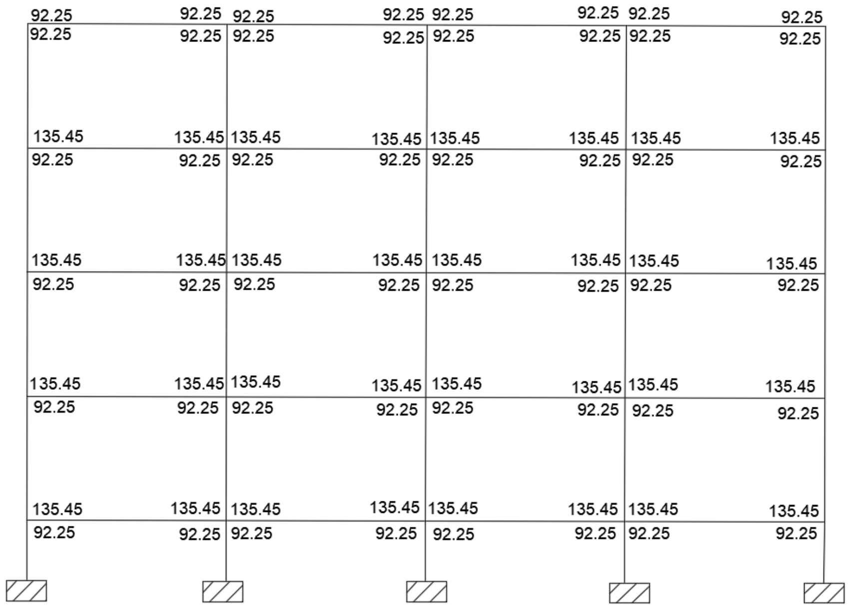

Fig. 9 : Moment of resistance (in kN-m) of the beams of Grid 1-1 as per the provided reinforcement

Figure 10 shows the maximum values of shear force in beams and columns obtained from STAAD Pro. analysis of the developed 2D frame model of Grid 1-1.

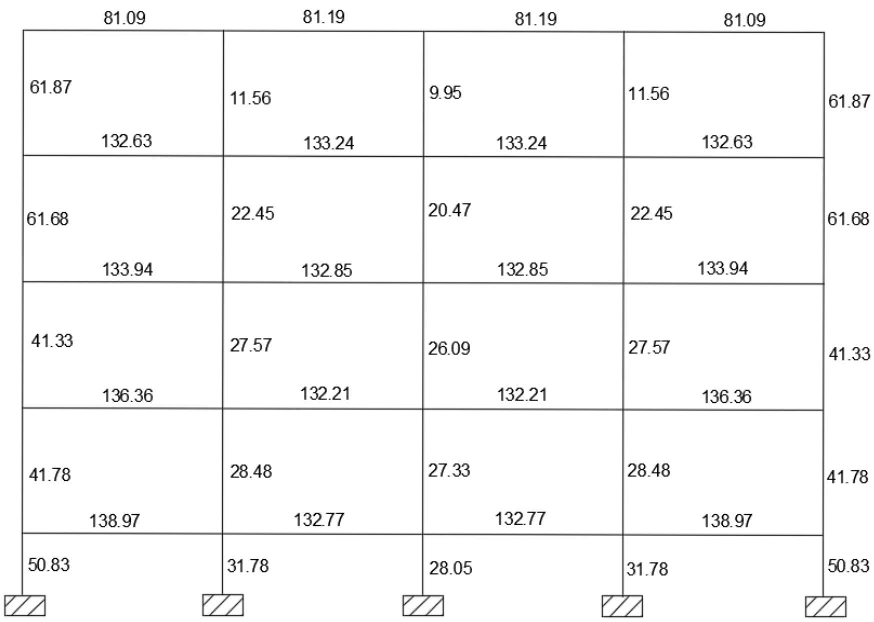

Fig. 10 : Maximum shear force (in kN) in beams and columns of Grid 1-1

Figure 11 shows the axial force and uniaxial moment in columns obtained from STAAD Pro. analysis of the developed 2D frame model of Grid 1-1.

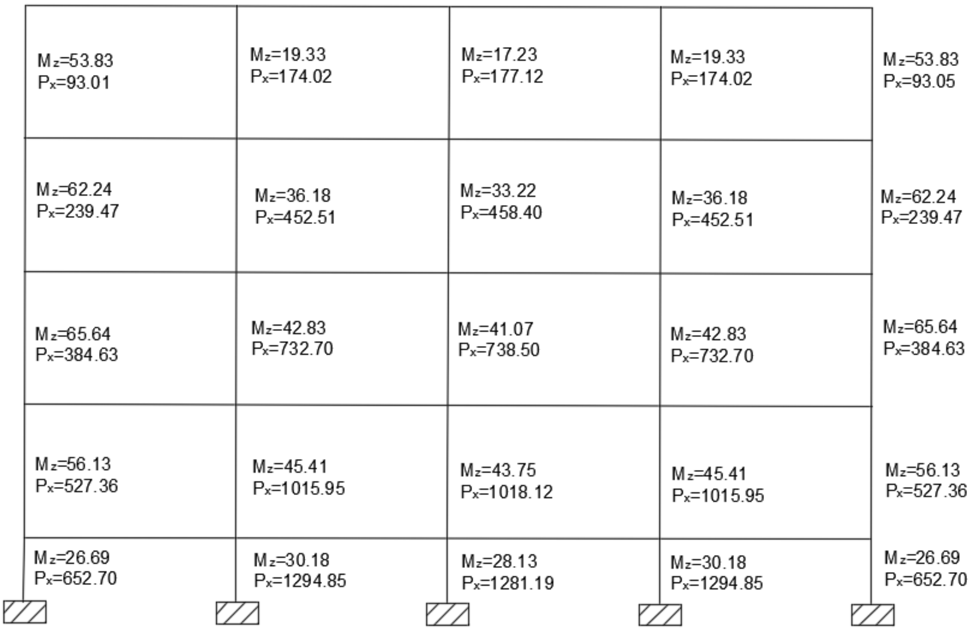

Fig. 11 : Design axial force (in kN) and uni-axial moment (in kN-m) in columns of Grid 1-1

Figures 12 and 13 show the moment of resistance of the beams and the initial column moments acting along seismic directions 1 and 2 respectively on Grid 1-1.

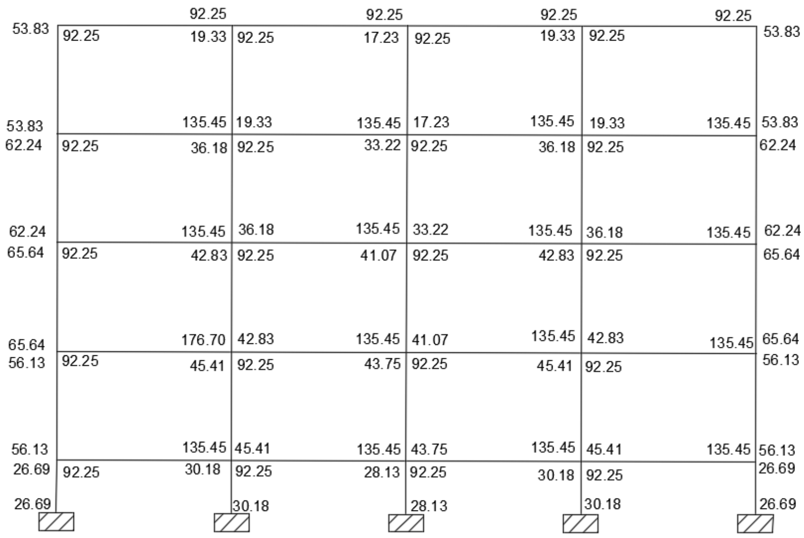

Fig. 12 : Moment of resistance (in kN-m) of the beams and initial column moments (in kN-m) of Grid 1-1 at every joint in seismic direction 1

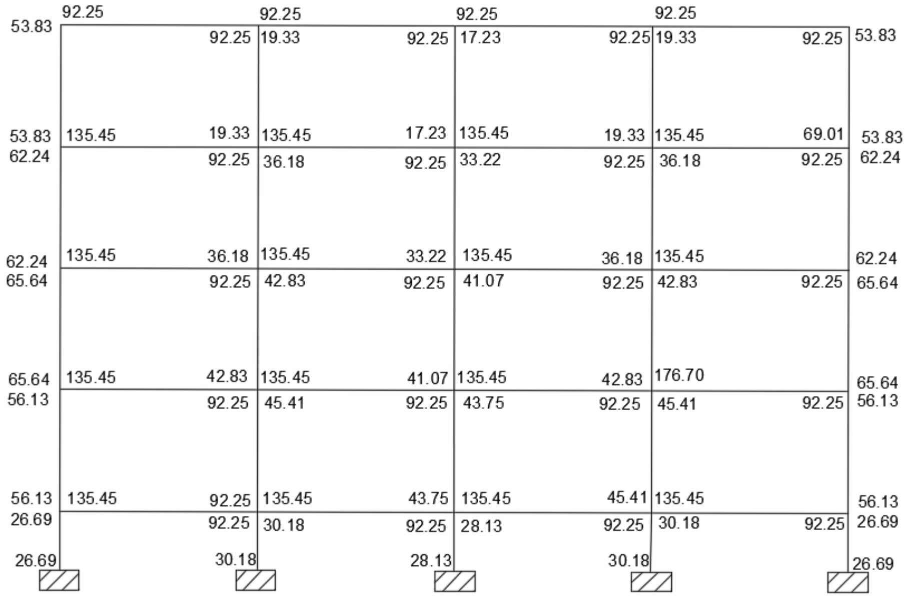

Fig. 13 : Moment of resistance (in kN-m) of the beams and initial column moments (in kN-m) of Grid 1-1 at every joint in seismic direction 2

Figure 14 shows the revised column moments (in kN-m) of Grid 1-1 as per CBD method.

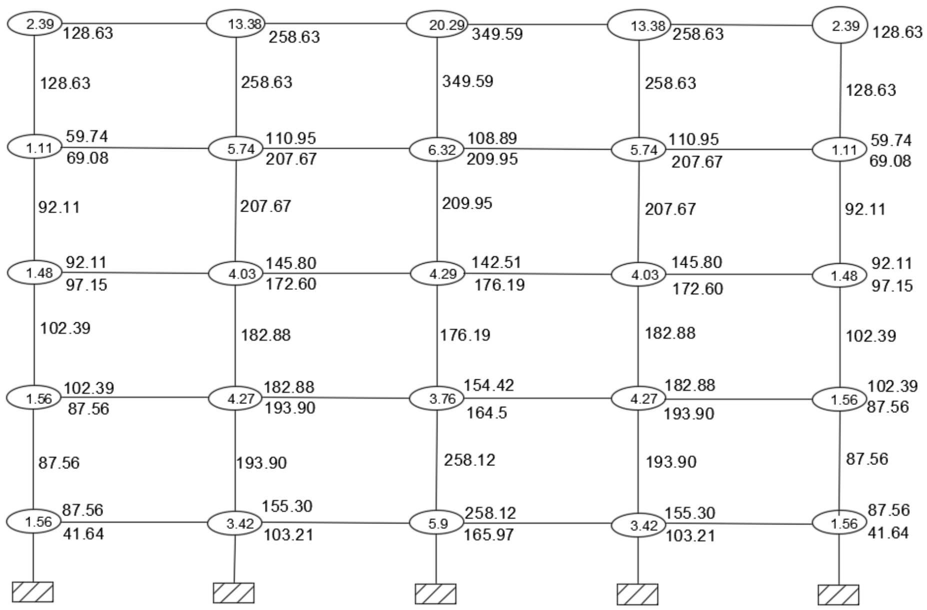

Fig. 14 : Revised column moments (in kN-m) of Grid 1-1 as per CBD method

Table 3 shows the values of Moment Magnification Factor (MMF) at each joint of Grid 1-1 in seismic directions 1 and 2 to establish strong-column and weak-beam mechanism.

Table 3 : Determination of MMF at all the joints of Grid 1-1

Joint No.	Seismic direction	Sum of moments of top & bottom of columns at joint (1)	Sum of resisting moments of left & right beams at joint with an over strength factor of 1.4 (2)	Check for (1) ≥ (2)	MMF
26, 30	1	0+ 53.84 = 53.84	1.4 (0+ 92.25) = 129.15	Not OK	2.39
	2	0 + 53.84 = 53.84	1.4 (0+ 92.25) = 129.15	Not OK	2.39
27, 29	1	0 + 19.33 = 19.33	1.4 (92.25 + 92.25) = 258.3	Not OK	13.38
	2	0 + 19.33 = 19.33	1.4 (92.25 + 92.25) = 258.3	Not OK	13.38
21, 25	1	(53.84 + 62.24) = 116.08	1.4 (0 + 92.25) = 129.15	Not OK	1.11
	2	(53.84 + 62.24) = 116.08	1.4 (0 + 135.45) = 189.63	Not OK	1.11
22, 24	1	(19.33 + 36.18) = 55.51	1.4 (135.45 + 92.25) = 318.78	Not OK	5.74
	2	(19.33 + 36.18) = 55.51	1.4 (135.45 + 92.25) = 318.78	Not OK	5.74
16, 20	1	(62.24 + 65.64) = 127.88	1.4 (0 + 92.25) = 129.15	Not OK	1
	2	(62.24 + 65.64) = 127.88	1.4 (0 + 135.45) = 189.63	Not OK	1.48
17, 19	1	(36.18 + 42.83) = 79.01	1.4 (135.45 + 92.25) = 318.78	Not OK	4.03
	2	(36.18 + 42.83) = 79.01	1.4 (135.45 + 92.25) = 318.78	Not OK	4.03
11, 15	1	(65.64 + 56.13) = 121.77	1.4 (0 + 92.25) = 129.15	Not OK	1.06
	2	(65.64 + 56.13) = 121.77	1.4 (0 + 135.45) = 189.63	Not OK	1.56
12, 14	1	(42.83 + 45.41) = 88.24	1.4 (176.70 + 92.25) = 376.54	Not OK	4.27
	2	(42.83 + 45.41) = 88.24	1.4 (92.25 + 135.45) = 318.78	Not OK	3.6
1, 5	1	(26.69 + 56.13) = 82.82	1.4 (0 + 92.25) = 129.15	Not OK	1.55
	2	(26.69 + 56.13) = 82.82	1.4 (0 + 135.45) = 189.69	Not OK	2.28
2, 4	1	(30.18 + 45.41) = 75.59	1.4 (135.45 + 92.25) = 318.78	Not OK	4.22
	2	(30.18 + 45.41) = 75.59	1.4 (135.45 + 92.25) = 318.78	Not OK	4.22
28	1	(0 + 17.23) = 17.23	1.4 (92.25 + 92.25) = 258.3	Not OK	20.29
	2	(0 + 17.23) = 17.23	1.4 (92.25 + 92.25) = 258.3	Not OK	20.29
23	1	(17.23 + 33.22) = 50.45	1.4 (135.45 + 92.25) = 318.78	Not OK	6.32
	2	(17.23 + 33.22) = 50.45	1.4 (135.45 + 92.25) = 318.78	Not OK	6.32
18	1	(33.22 + 41.07) = 74.29	1.4 (135.45 + 92.25) = 318.78	Not OK	4.29
	2	(33.22 + 41.07) = 74.29	1.4 (135.45 + 92.25) = 318.78	Not OK	4.29
13	1	(41.07 + 43.75) = 84.82	1.4 (135.45 + 92.25) = 318.78	Not OK	3.76
	2	(41.07 + 43.75) = 84.82	1.4 (135.45 + 92.25) = 318.78	Not OK	3.76
3	1	(0 + 43.75 = 43.75	1.4 (135.45 + 92.25) = 318.78	Not OK	7.28
	2	(0 + 43.75 = 43.75	1.4 (135.45 + 92.25) = 318.78	Not OK	7.28

Figure 15 shows the revised column moments due to MMF of Capacity Based Design (CBD) method.

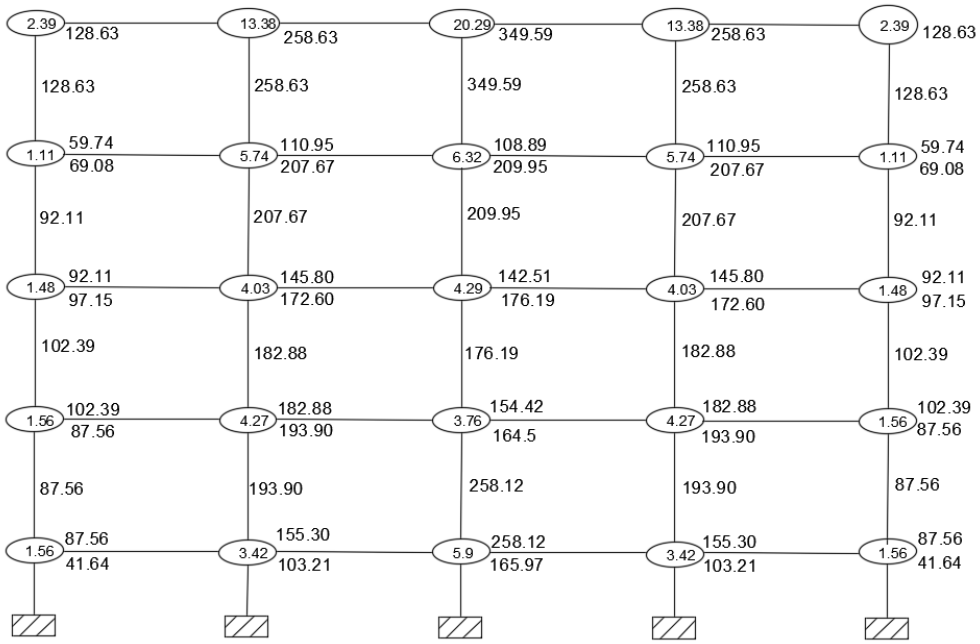

Fig. 15 : Revised column moments (in kN-m) of Grid 1-1 as per CBD method

Table 4 shows the moments acting on columns of Grid 1-1 obtained by Conventional Design (CD) and CBD methods.

Table 4 : Moments acting on columns of Grid 1-1 as per CD and CBD methods

Column No.	Storey No.	Size (m x m)	CD (kN-m)	CBD (kN-m)
C1, C5	3	0.3 x 0.45	53.824	128.64
C2, C4	3	0.3 x 0.45	19.33	258.63
C3	3	0.3 x 0.45	17.23	349.59
C1, C5	2	0.3 x 0.45	62.24	92.11
C2,C4	2	0.3 x 0.45	36.18	207.67
C3	2	0.3 x 0.45	33.22	209.95
C1, C5	1	0.3 x 0.45	65.64	102.39
C2, C4	1	0.3 x 0.45	42.83	182.88
C3	1	0.3 x 0.45	41.07	176.19
C1, C5	G	0.3 x 0.45	56.134	87.56
C2, C4	G	0.3 x 0.45	45.41	193.90
C3	G	0.3 x 0.45	43.75	258.12

Table 5 shows the shear acting on beams of Grid 1-1 as per Conventional Design (CD) and Capacity Based Design (CBD) methods.

Table 5 : Shear acting on beams of Grid 1-1 as per CD and CBD methods

Beam No.	Shear – CBD (kN)		Shear – CD (kN)	Shear – CBD (kN)
	Direction 1	Direction 2		
17, 20	-15.67	111.84	81.09	111.84
	111.84	-15.67		

Beam No.	Shear – CBD (kN)		Shear – CD (kN)	Shear – CBD (kN)
	Direction 1	Direction 2		
18, 19	-15.67	111.84	81.66	111.84
	111.84	-15.67		
13, 16	33.74	161.25	132.63	161.25
	161.25	33.74		
14, 15	33.74	161.25	133.24	161.25
	161.25	33.74		
9, 12	33.74	161.25	133.94	161.25
	161.25	33.74		
10, 11	33.74	161.25	132.85	161.25
	161.25	33.74		
5, 8	33.74	161.25	136.36	161.25
	161.25	33.74		
6, 7	33.74	161.25	132.21	161.25
	161.25	33.74		
1, 4	33.74	161.25	138.97	161.25
	161.25	33.74		
2, 3	33.74	161.25	132.77	161.25
	161.25	33.74		

Table 5 shows the shear acting on columns of Grid 1-1 as per Conventional Design (CD) and Capacity Based Design (CBD) methods.

Table 6 : Shear acting on columns of Grid 1-1 as per CD and CBD methods

Column No.	Storey No.	Shear – CD (kN)	Shear – CBD (kN)
C1, C5	3	61.87	1.4(128.64+128.64)/3.1=116.19
C2, C4	3	11.56	1.4(258.63+258.63)/3.1=233.6
C3	3	9.95	1.4(349.59+349.59)/3.1=315.76
C1, C5	2	61.68	1.4(69.09+69.09)/3.1= 62.40
C2, C4	2	22.45	1.4(207.67+207.67)/3.1= 187.57
C3	2	20.47	1.4(209.95+209.95)/3.1= 189.63
C1, C5	1	41.33	1.4(97.15+97.15)/3.1= 87.75
C2, C4	1	27.57	1.4(172.6+172.6)/3.1= 155.89
C3	1	26.09	1.4(176.19+176.19)/3.1= 159.14
C1, C5	G	41.78	1.4(87.56+87.56)/3.1= 79.09
C2, C4	G	28.48	1.4(139.9+139.9)/3.1= 126.36
C3	G	27.33	1.4(164.5+164.5)/3.1= 148.58

Similar to the above procedure, the remaining grids of the structure are analysed and designed.

VII. CONCLUSIONS

In the present paper, earthquake resistant design of G+3 storeyed RC structure is done as per the stipulations given by IS 13920 (2016) for the capacity based design. Seismic analysis is performed by response spectrum method of IS 1893–Part 1 (2016). For the developed 2D frame models, moment and shear acting on beams and columns by Conventional Design (CD) and Capacity Based Design (CBD) approaches are compared. The structural members are designed for the revised moments, shear forces and axial forces as per IS 456 (2000) and SP 16 (1983) codal provisions. Reinforcement detailing is done as per SP 34 (1987) codal provisions.

The important conclusions drawn are as follows.

1. Column moments obtained by CBD method are more than those obtained from CD method. The increase in column moments using CBD method is insignificant for exterior columns and is significant for interior columns.
2. Column shear values obtained by CBD method are more than those obtained from CD method. The increase in column shear using CBD method is significant for both exterior and interior columns.
3. Beam shear values obtained by CBD method are more than those obtained from CD method. The increase in beam shear using CBD is insignificant for exterior beams and is significant for interior beams.

Concluding remarks: Capacity based design method is a futuristic approach for the earthquake resistant design of RC structures. It eliminates the sway of the structure by strong-column and weak-beam mechanism. This method is very effective in the design of soft storeyed frames and eliminates the shear mode of failure by making the shear capacity of elements more than their moment capacity. Compared to the conventional design method, capacity based design method is more realistic and effective in resisting the earthquake forces as the calculations are based on provided reinforcement and the over strength of the structure which considerers the reserve strength beyond the elastic limit.

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