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Improved Design of Five Storey Building Frame Using Capacity Based Design

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ABSTRACT

Concept of capacity based design of structures is the spreading of inelastic deformation demands in a structure in such a way so that the formation of plastic hinges takes place at predetermined positions and sequences. The capacity design is therefore, an art of avoiding failure of structure in brittle mode. Shear failure is brittle mode of failure, hence shear capacity of all components capacity based design are made higher than their flexural capacities so as to avoid shear failure. Therefore, it is better to make beams to be the ductile weak links than columns. In the capacity design of structures for earthquake resistance, distinct elements of the primary lateral force resisting system are chosen and suitably designed and detailed for energy dissipation under severe imposed deformations. The critical regions of these members, often termed as plastic hinges, are detailed for inelastic flexural action.

The prime objective of this work is to demonstrate the utility of capacity based design method as compared to conventional design method. In this study, the building of five storeys have been analysed and designed by capacity based design method. Parametric study has been undertaken for the column moments, column shear and beam shear for the buildings. The building is designed by capacity based design for earthquake zone II. It has been shown that column moments, column shear and beam shear for the five storey building obtained from capacity based design method are more than those obtained from design method.

Keywords*:* Moment magnification factor, ductile response, strong column-weak beam, plastic hinge

INTRODUCTION

Capacity design procedure is popular and has significant utility because during earthquakes large numbers of buildings were collapsed due to improper strength hierarchy. Many of the buildings were collapsed in Ahmadabad (India) during '2001 Bhuj earthquake' due to this improper strength hierarchy. Earthquakes in different parts of the world also demonstrated the disastrous consequences and vulnerability of inadequate structures. Conventional structures are designed on the basis of strength and stiffness criteria. The strength is related to ultimate limit state, which assures that the forces developed in the structure remain in elastic range. The stiffness is related to serviceability limit state which assures that the structural displacements remains within the permissible limits. The main cause of failure of multi-storey multi-bay reinforced concrete frames during seismic motion is the soft storey sway mechanism or column sway mechanism. The seismic inertia forces generated at its floor levels are transferred through the various beams and columns to the ground. The failure of a column can affect the stability of the whole building, but the failure of a beam causes localized effect. Therefore, it is better to make beams to be the ductile weak links than columns.

Capacity design is a concept of designing flexural capacities of critical member sections of a building structure based on behaviour of the structure in responding to seismic actions. This behaviour is reflected by the assumptions that the seismic action is of a static equivalent nature increasing gradually until the structure reaches its state of near collapse and critical regions occur simultaneously at predetermined locations to form a collapse mechanism simulating ductile behaviour. In multi-storey multi bay reinforced concrete frames plastic hinges are allowed to form only at the ends of the beams. To achieve this flexural capacity of column sections at each joint are made stronger than the joining beam sections. This will eliminate the possible sway mechanism of the frame.

The philosophy of capacity design is introduced into the design of transfer-storey structures and a practical design method for transfer structures under severe earthquake. In multi-storey frame this can be achieved by allowing the plastic hinges to form, in a predetermined sequence only at the ends of all the beams while the columns remain essentially in elastic stage and by avoiding shear mode of failures in columns and beams.

Many Reinforced Concrete (RC) framed structures located in zones of high seismicity in India are constructed without considering the seismic codal provisions. Reinforced concrete (RC) framed structures located in zones of high seismicity in India were studied [1]. The vulnerability of inadequately designed structures represents seismic risk to occupants. Also, Hoffmeister *et al* [2] investigated the common requirements and differences between design concepts and capacity design rules for structures required to resist seismic actions and a blast wave caused by an external explosion. Victorsson *et al* [3] reported that Capacity design principles are employed in structural design codes to help ensure ductile response and energy dissipation in seismic resisting systems. Varghese *et al* [4] carried out study of this building an earthquake resisting buildings and buildings are designed in such a way that the structure remains safe and suffers no appreciable damage during destructive earthquake.

In view of the above discussions, a study is therefore needed to estimate the advantages of capacity design method over conventional design method. In this work, the building frames will be designed by capacity based design method. To show the importance of capacity based design method for varied seismic forces, the selected building frames is analyzed and design for Earthquake Zone II (Low Seismic Intensity). This systematic study has been carried out using structural software.

CONCEPT OF CAPACITY BASED DESIGN

The basic concept of capacity based design of structures is the spreading of inelastic deformation demands in a structure in such a way so that the formation of plastic hinges takes place at predetermined positions and sequences. In multi-storey multi bay reinforced concrete frames plastic hinges are allowed to form only at the ends of the beams. To achieve this flexural capacity of column sections at each joint are made stronger than the joining beam sections. This will eliminate the possible sway mechanism of the frame.

Capacity design approach therefore has distinct advantage over conventional design to assure predictable and satisfactorily inelastic response under conditions for which even sophisticated dynamic analysis techniques can yield no more than crude estimates. The applications of capacity design concept were already implied in some codes. In the capacity design of structures for earthquake resistance, distinct elements of the primary lateral force resisting system are chosen and suitably designed and detailed for energy dissipation under severe imposed deformations. The critical regions of these members, often termed as plastic hinges, are detailed for inelastic flexural action.

The main advantages of capacity design are: plastic deformations will occur in predetermined locations only; rational and suitable mechanisms for energy dissipation are established; a hierarchy of strength within the system is clearly defined; location within the structure where special detailing for ductility is required are uniquely established; local ductility demands can be better related to the global ductility demand.

Steps for Capacity Based Design [1]**:**

- Design loads i.e. dead loads, live loads and earthquake loads are calculated.
- Seismic analysis of the frame for all load combination specified in IS 1893 (Part I):2002 [5] are done.
- Members are designed as per IS 456:200[6] for maximum forces obtained from all load combinations. Beams are designed for maximum sagging and maximum hogging moments. Provided reinforcements are calculated following the norms given in code. Columns are designed for the combination for moment and corresponding axial force providing maximum interaction effect i.e. considering the eccentricity.
- The flexural capacities of the beams under sagging and hogging condition for the provided reinforcements are calculated.
- The flexural capacity of columns at a joint is compared with actual flexural capacity of joining beams. If the sum of capacities of columns is less than the sum of capacities of beams multiplied by over strength factor, the column moments should be magnified by the factor (moment magnification factor) by which they are lacking in moment capacity over beams. If the sum of the column moments is greater than sum of beam moments, there is no need to magnify the column moments.
- Columns are designed for the revised moments and the axial force coming on it from the analysis.
- Shear capacity of beams are calculated on the basis or their actual moment capacities and shear reinforcements are calculated.
- Similarly shear capacity of column is calculated on the basis of magnified moment capacities. Then the columns are designed for shear.

ANALYTICAL STUDY

In this study, systematic study is carried out for a building frame of five storeys. Plan and elevation of this building have been shown in Fig. 1. Plinth beams are provided for the building frame as has shown in Fig. 1. Plinth beams helps to control seismic demands in RC frame buildings. Analysis of these frame have been carried out using structural software (STAAD Pro.). In this analysis, building frame is assumed in zone II (IS 1893-2002) [5] to show the maximum value for seismic forces. The building frame is designed for the forces obtained from STAAD Pro. [8] using capacity based design method.

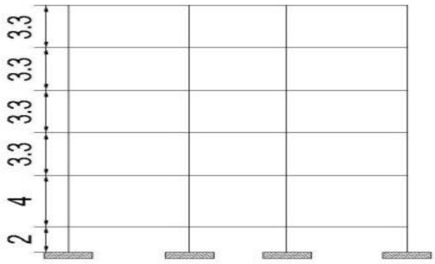

Fig. 1a Elevation of five storey buidling

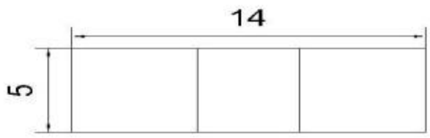

Fig. 1 b Plan of five storey building

Preliminary Member Property Assigning

A five storey Frames building was consider for analysis. The salient information of the building is shown in Table 1:

Table -1 General Data for Building Frames of Five Storeys

Type of structure	Ordinary RC moment resisting frame
Seismic zone (IS 1893: 2002)	II
Type of soil	Medium
Imposed Load	3.0 kN/m^2
Dead Load	3.75 kN/m^2
Floor finishes	1.0 kN/m^2
Thickness of slab	150 mm
Materials	M 30 concrete and Fe 415 steel
Unit weight of RCC	25 kN/m^3
Unit weight of Masonry	19.20 kN/m^3
Modulus of elasticity of concrete	2.73×10^7 kN/m^2
Width of building	5 m
Beams size	300 × 500 mm
Columns size	300 × 600 mm
Height of building	(2+4+4×3.3) = 19.2 m
Clear cover for beam	25 mm
Clear cover for column	40 mm

Used load combinations for analysis

1. 1.5(DL+ IL)
2. 1.2(DL+ IL+EL)
3. 1.2(DL+ IL-EL)
4. 1.5(DL+ EL)
5. 1.5(DL- EL)
6. 0.9DL+1.5EL
7. 0.9DL-1.5EL

Where, DL - Dead Load,
IL - Imposed Load and
EL- Earthquake Load

Analysis of building frames

In this work building frames of five have been analysed and designed using capacity based design methods for earthquake zone II to show the importance of capacity based design for varied seismic forces. The frames have been modelled and analysed in STAAD Pro [8]. In this process, member properties are first assigned and load is applied on each member of model. The model is the analysed for different combination of loads. Maximum moments, axial force and shear forces are noted from the analysis results.

The beam is then designed for the analysis moment as obtained from software using SP16:1980[7] and reinforcement is calculated for each beam. These reinforcements have been checked for various codal guidelines and provided in the beam. Beam capacity is then calculated for the provided reinforcement using IS 456:2000 [6] guidelines. Revised moments for the provided reinforcement in beam are compared with the maximum moment in column as obtained from the analysis. Moment magnification factor for the columns of all building frames have been then calculated as per guidelines of capacity based design. These moment magnification factor changes the column moment obtained from the analysis results. Column moments are then revised using moment magnification factors and these columns of all building frames are then being designed using SP16:1980[7]. Shear in beams for all building frames have been calculated using the equations of capacity based design method. After obtain shear in beams, beams are then designed for the controlling forces. Shear in the column have been calculated using guideline of capacity based design method. After obtain shear in columns, columns are then designed for the controlling forces.

RESULTS

In Fig. 2, Maximum hogging moment (indicated above the centre line of beam) and sagging moment (indicated below the centre line of beam) in beam obtained from the software results have been shown. Similarly, maximum shear forces in beam and in column are shown in Fig 3. Maximum axial force and bending moment of column is shown in Fig 4. The beam is designed for the analysis moment as shown in Fig. 2 using SP16:1980[7] and reinforcement is calculated for each beam [9].

Beam capacity is then calculated for the provided reinforcement using IS 456:2000 [6] guidelines. Capacity of various beams has been shown in Fig. 5. Revised moment for the provided reinforcement in beam as discussed above are shown with the maximum moment in column as obtained from the analysis in Fig. 6 and Fig. 7.

Moment magnification factor for columns have been calculated as per guidelines of capacity based design and these factors have been shown in Table 2. These moment magnification factor changes the column moment obtained from the analysis results. These revised column moments due to Moment magnification factors are shown in Fig. 8.

Columns are designed [9] for the column moment obtained from the magnification factor and analysis results obtained from the software. The design parameters for the columns have been shown in Table -3.

Shear in beams have been calculated using the equations of capacity based design method. These beam shears have been shown in Table -4. Shear force obtained from the analysis results from the software are also shown in Table -4. Beams are then designed for the controlling forces obtained from Table -4 [9]. Shear in the column have been calculated using guideline of capacity based design. The calculation of column shear using capacity based design is shown in Table -5. Shear force in Column from the analysis results of software have been also shown in Table -5. Columns are then designed for the controlling forces obtained from Table -5 [9].

Table -2 Moment Magnification Factor for Five Storey Frames

Joint no	Seismic direction	Sum of resisting member top and bottom columns at joint (1)	Sum of resisting moments of left and right beam at joint with an over strength factor of 1.4(2)	Check of (1)>=(2)	Moment magnification factor
49,52	1	0 + 67.53 = 67.53	1.4(0 + 37.08) = 51.91	Ok	1.0
	2	0 + 67.53 = 67.53	1.4(0 + 68.11) = 95.35	Not Ok	1.412
50,51	1	0 + 39.49 = 39.49	1.4(68.11 + 37.08) =147.26	Not Ok	3.729
	2	0 + 39.49 = 39.49	1.4(37.08 + 54.45) =133.04	Not Ok	3.369
59,62	1	67.55 + 67.29 =134.82	1.4(0 + 54.95) = 76.93	Ok	1.0
	2	67.55 + 67.29 =134.82	1.4(0 + 115.2) = 161.28	Not Ok	1.196
60,61	1	39.49 + 52.77 = 92.23	1.4(115.2 + 37.08) =213.19	Not Ok	2.311
	2	39.49 + 52.77 = 92.23	1.4(54.95 + 82.04) =191.78	Not Ok	2.079
69,72	1	67.29 + 70.35 = 137.64	1.4(0 + 54.95) = 76.93	Ok	1.0
	2	67.29 + 70.35 = 137.64	1.4 (0 + 128.1) = 179.34	Not Ok	1.302
70,71	1	63.63 + 52.74 = 116.37	1.4(128.1 + 37.08) =231.25	Not Ok	1.987
	2	63.63 + 52.74 = 116.37	1.4(54.95 + 95.24) =210.26	Not Ok	1.806
79,82	1	70.35 + 70.25 = 140.6	1. 4(0 + 54.95) = 76.93	Ok	1
	2	70.35 + 70.25 = 140.6	1.4(0 + 138.7) = 194.18	Not Ok	1.381
80,81	1	70.55 + 63.63 = 134.18	1.4 (138.7 + 54.95) = 271.1	Not Ok	2.020
	2	70.55 + 63.63 = 134.18	1.4 (54.95 + 111.5) = 233.0	Not Ok	1.736
89,92	1	70.25 + 81.34 = 151.59	1.4 (0 + 54.95) = 76.93	Ok	1
	2	70.25 + 81.34 = 151.59	1.4 (0 + 138.7) = 194.18	Not Ok	1.280
90,91	1	82.13 + 70.55 =152.68	1.4(54.95 + 111.5) =233.03	Not Ok	1.775
	2	82.13 + 70.55 =152.68	1.4 (138.7 + 54.95) = 271.1	Not Ok	1.526

Table -3 Column Design of Five Storey Frames

Storey no.	Column no.	Size (mm x mm)	Capacity based /Conventional		Mz kN-m		Capacity based design	
			Pu (KN)	My kN-m	Conventional	Capacity based	% steel	Interaction ratio
5th	41,44	300 × 600	145.42	45.66	67.55	95.35	1.1	.995
	42,43	300 × 600	193.39	52.63	39.49	146.9	1.35	.998
4th	33,36	300 × 600	366.47	51.98	67.29	87.47	1.1	.992
	34,35	300 × 600	510.31	62.22	52.74	121.8	1.15	.996
3rd	25,28	300 × 600	586.76	57.53	70.35	97.08	1	.907
	26,27	300 × 600	827.98	67.02	63.63	128.5	1.1	.987
2nd	17,20	300 × 600	805.97	61.60	70.25	96.94	1.1	.998
	18,19	300 × 600	1146.74	71.33	70.55	142.5	1.2	.877
1st	9,12	300 × 600	1027.99	63.04	81.34	104.1	1.1	.729
	10,11	300 × 600	1472.14	66.34	82.13	148.9	1.2	.818

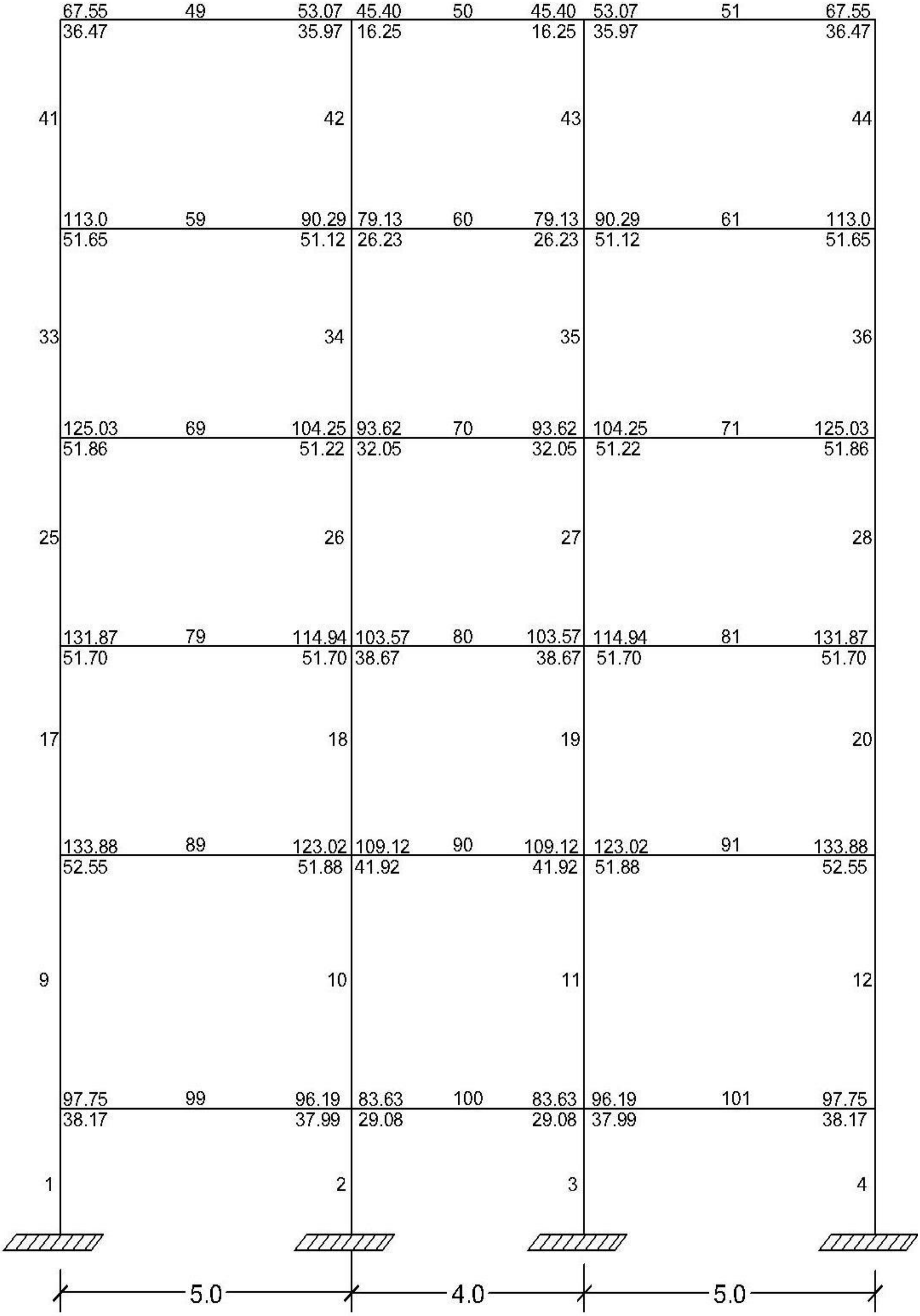

Fig. 2. Maximum hogging (above) and sagging (below) Moments at joints in beams five storey frames

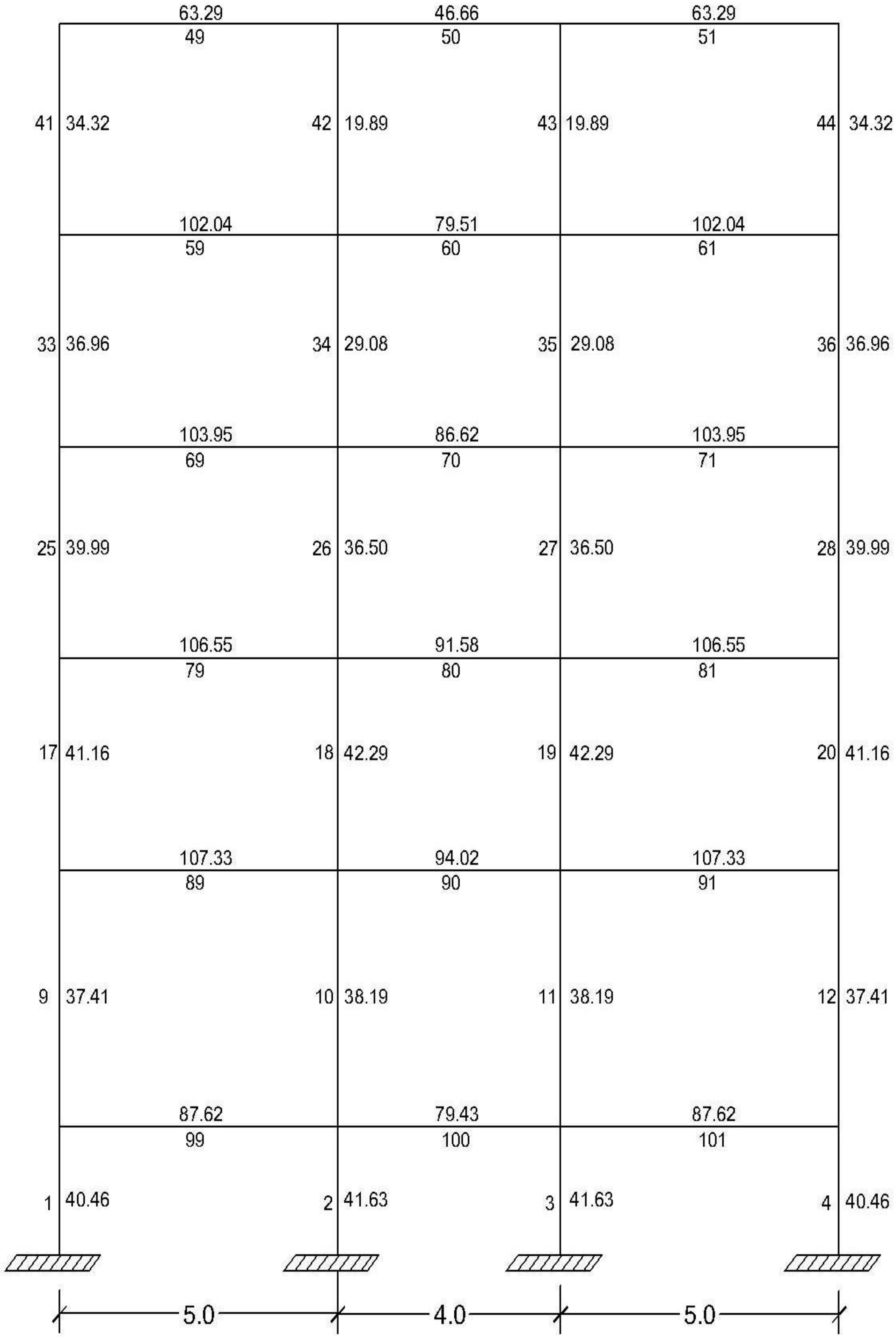

Fig. 3. Maximum shear Force in beams and columns

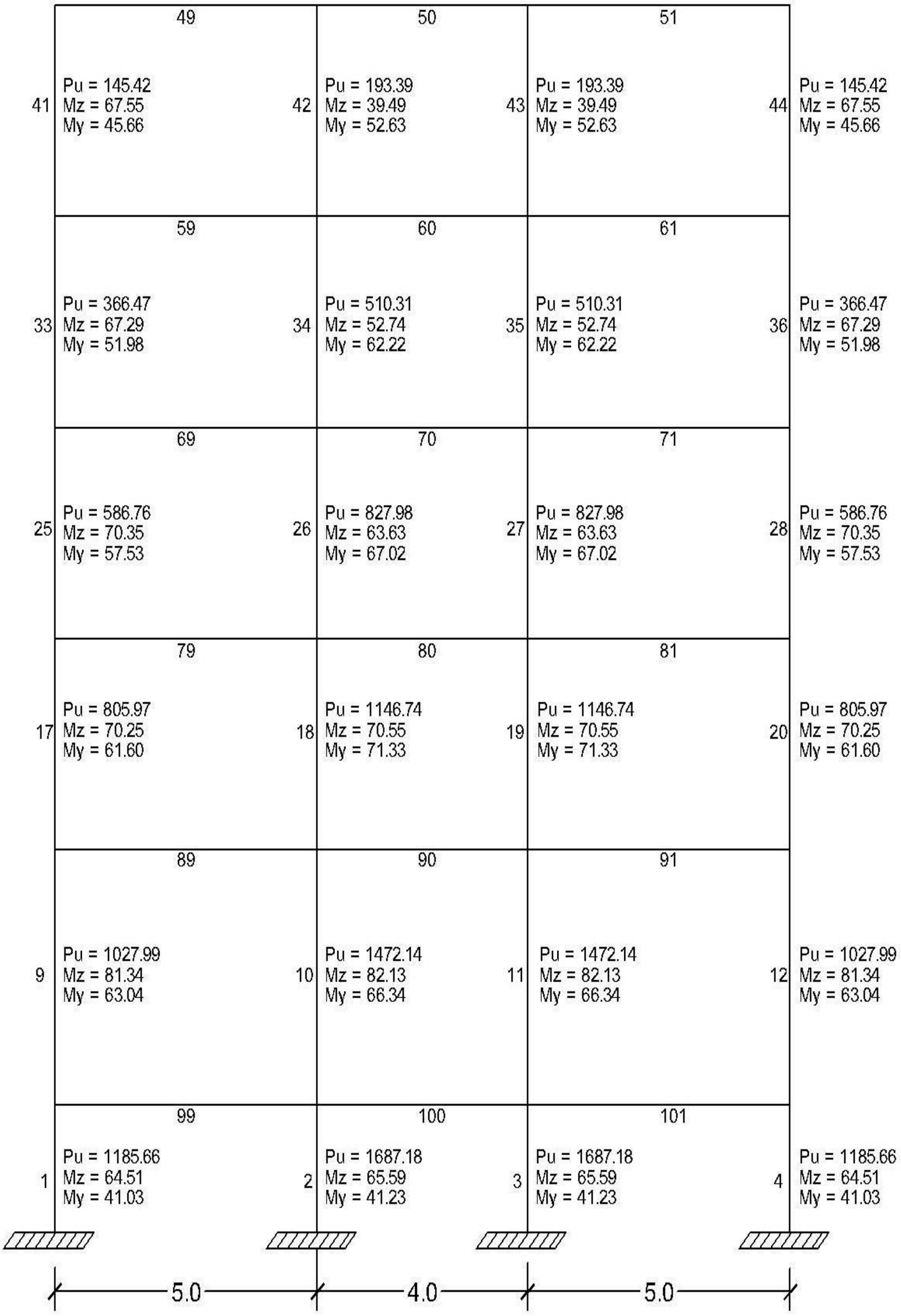

Fig. 4. Axial force and moments in columns

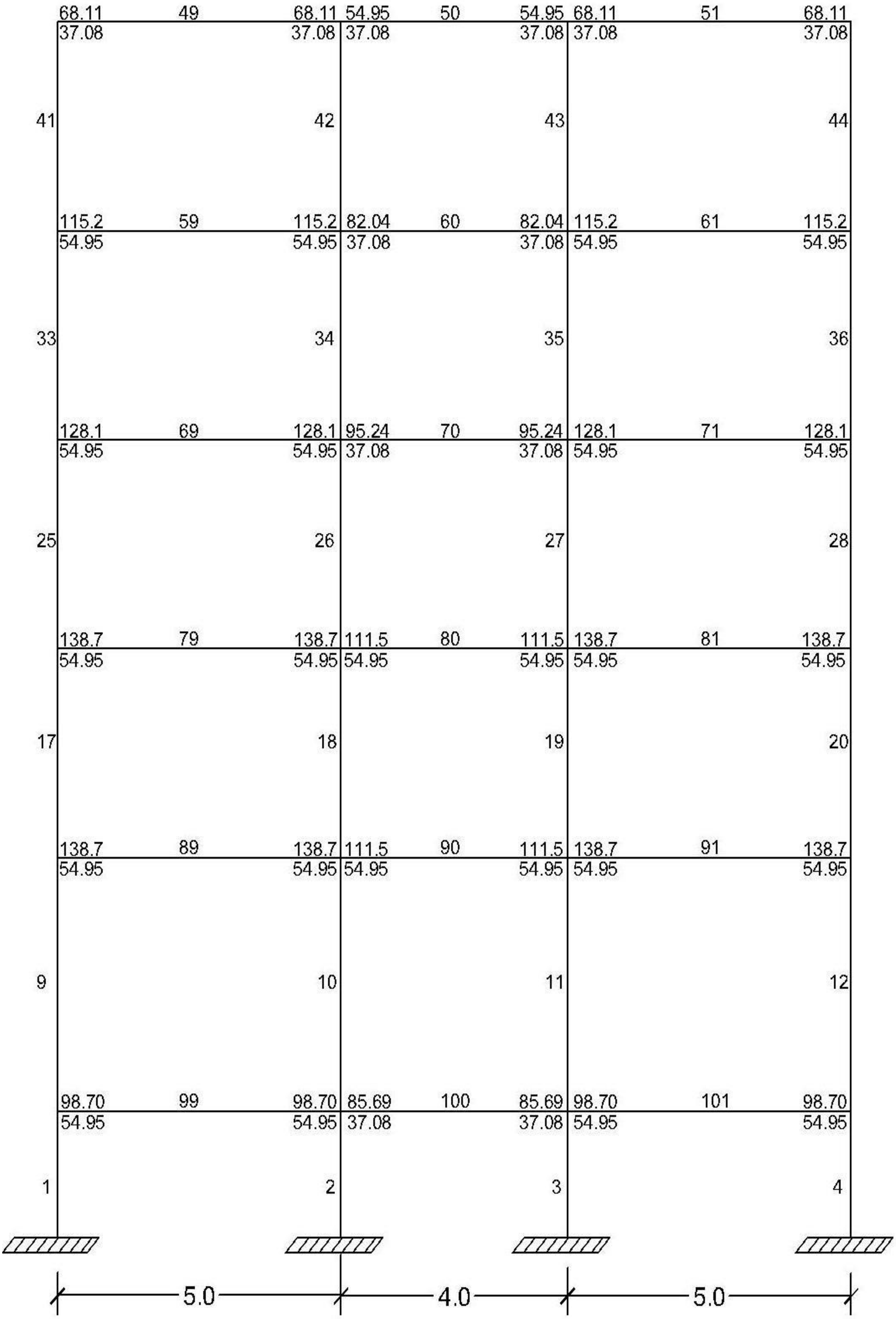

Fig. 5. Moment capacity of beams for provided reinforcement in beams

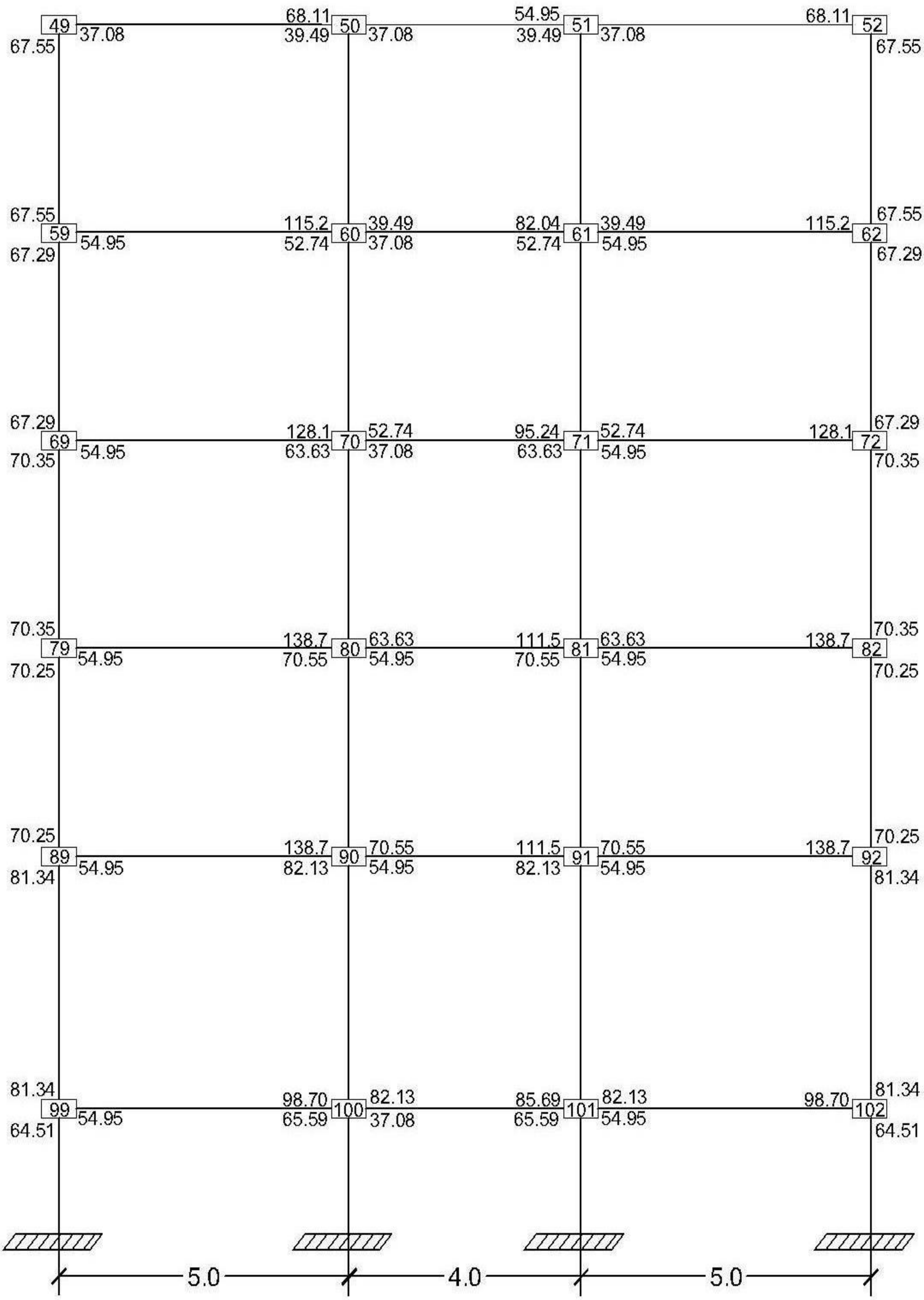

Fig. 6. Beam and column moments along direction 1

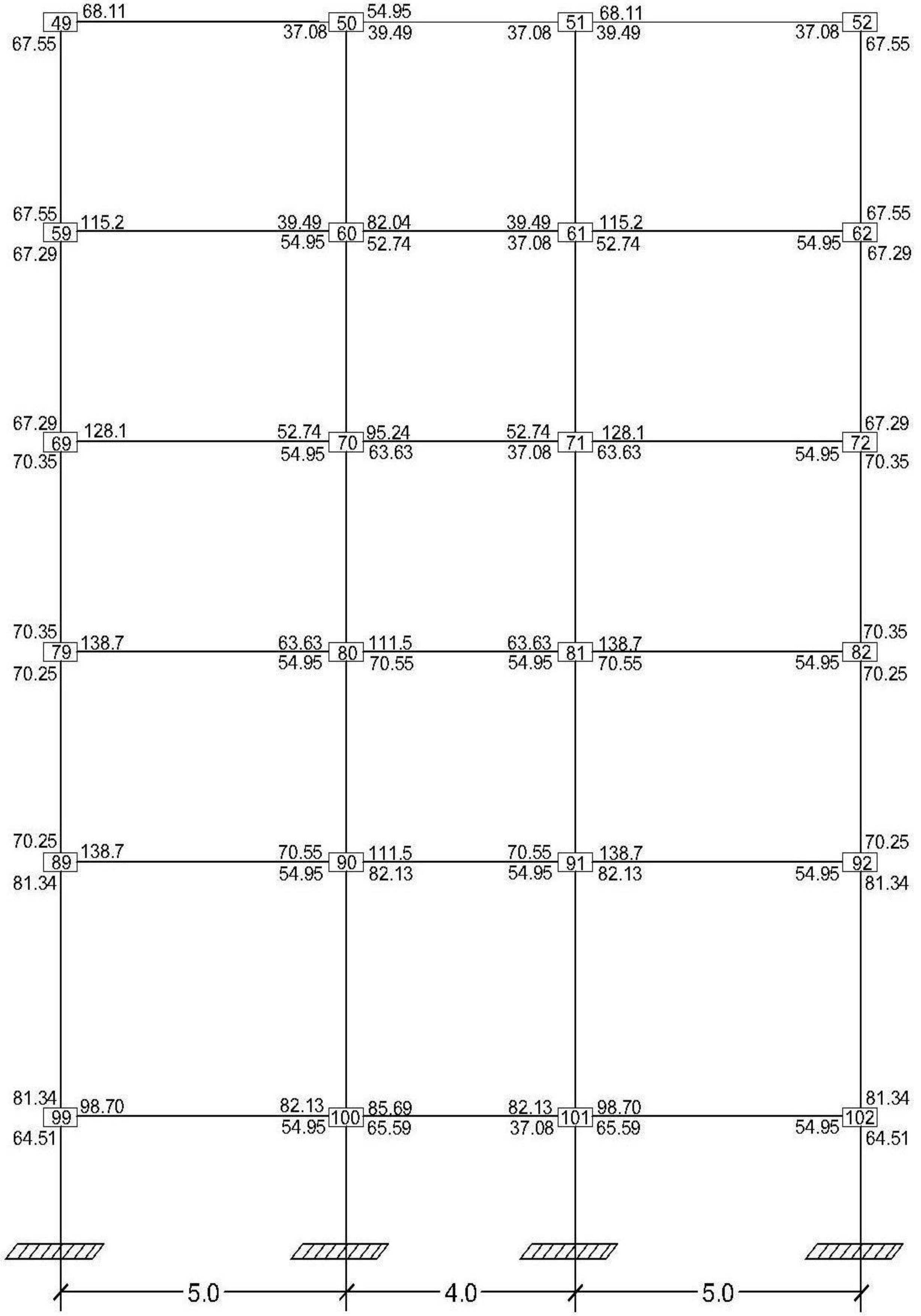

Fig. 7. Beam and column moments along direction 2

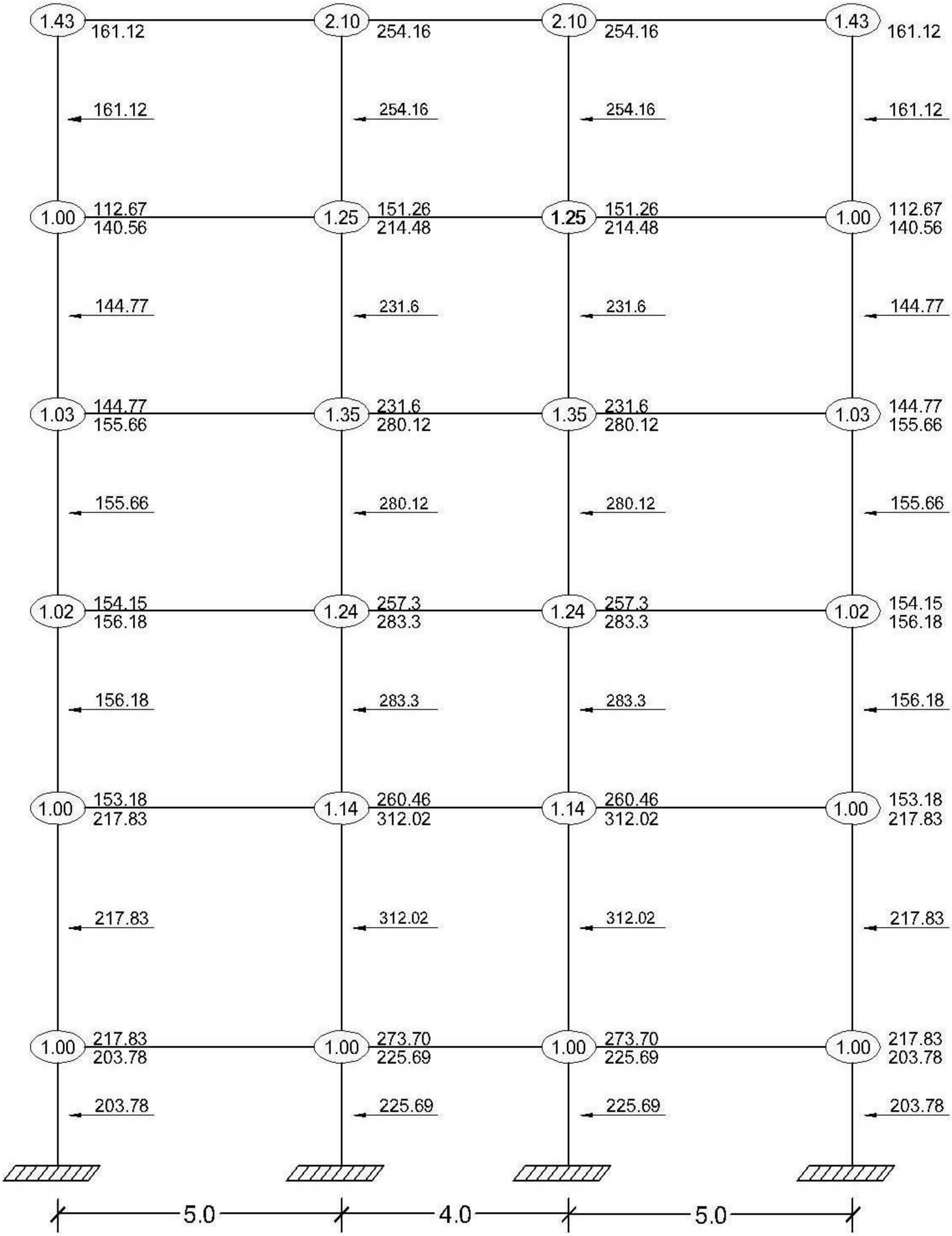

Fig. 8. Revised column moments as per moment magnification factors

Table -4 Shear in Beams for Five Storey Frames

Beam no.	Shear (kN) (Capacity based design)		Shear (kN) (Conventional Design)	Design shear (kN)
	Direction 1	Direction 2		
49,51	13.5 71.72	71.72 13.5	63.29	71.72
50	2.68 67.1	67.1 2.68	46.66	67.1
59,61	1.41 96.7	96.7 1.41	102.04	102.04
60	-.07 82.68	82.68 -.07	79.51	82.68
69,71	-2.2 100.3	100.3 -2.2	103.95	103.95
70	-5.32 87.3	87.3 -5.32	86.62	87.3
79,81	-5.17 103.28	103.28 -5.17	106.55	106.55
80	-17.27 99.28	99.28 -17.27	91.58	99.28
89,91	-5.17 103.28	103.28 -5.17	107.33	107.33
90	-17.27 99.28	99.28 -17.27	94.02	99.28

Table -5 Shear in Column for Five Storey Frames

Column	Shear (kN) (Capacity based design)	Shear (kN) (Conventional design)	Shear (kN) (Design)
41,44	1.4 (95.35 + 95.35) / 3.3 = 80.90	34.32	80.90
42,43	1.4 (146.9 + 146.9) / 3.3 = 124.6	19.89	124.6
33,36	1.4 (87.47 + 87.47) / 3.3 = 74.21	36.96	74.21
34,35	1.4 (121.82 + 121.82) / 3.3 = 103.36	29.08	103.36
25,28	1.4 (97.08 + 97.08) / 3.3 = 82.37	39.99	82.37
26,27	1.4 (128.53 + 128.53) / 3.3 = 109.05	36.50	109.05
17,20	1.4 (96.94 + 96.94) / 3.3 = 82.25	41.16	82.25
18,19	1.4 (142.51 + 142.51) / 3.3 = 120.91	42.29	120.91
9,12	1.4 (104.11+ 1.4.11) / 4 = 72.87	37.41	72.87
10,11	1.4 (148.97 + 148.97) / 4 = 104.27	38.19	104.27

Table -6 Comparison of Moments in Columns of Five Storey

Storey No.	Column no.	Size (mm x mm)	Conventional design Mz kNm	Capacity based design Mz kNm
5th	41,44	300 × 600	67.55	95.35
	42,43	300 × 600	39.49	146.9
4th	33,36	300 × 600	67.29	87.47
	34,35	300 × 600	52.74	121.82
3rd	25,28	300 × 600	70.35	97.08
	26,27	300 × 600	63.63	128.53
2nd	17,20	300 × 600	70.25	96.94
	18,19	300 × 600	70.55	142.51
1st	9,12	300 × 600	81.34	104.11
	10,11	300 × 600	82.13	148.97

Table -7 Comparison of Shear in Columns of Five Storeys

Storey no.	Column no.	Size (mm x mm)	Conventional design (kN)	Capacity based design (kN)
5^{th}	41,44	300 × 600	34.32	80.90
	42,43	300 × 600	19.89	124.6
4^{th}	33,36	300 × 600	36.96	74.21
	34,35	300 × 600	29.08	103.36
3^{rd}	25,28	300 × 600	39.99	82.37
	26,27	300 × 600	36.50	109.05
2^{nd}	17,20	300 × 600	41.16	82.2
	18,19	300 × 600	42.29	120.91
1^{st}	9,12	300 × 600	37.41	72.87
	10,11	300 × 600	38.19	104.27

Table -8 Comparison of Shear in Beams of Five Storeys

Storey no.	Beam no.	Size (mm x mm)	Conventional design (kN)	Capacity based design (kN)
5th	49,51	300 × 500	63.29	71.72
	50	300 × 500	46.66	67.1
4th	59,61	300 × 500	102.04	96.7
	60	300 × 500	79.51	82.68
3rd	69,71	300 × 500	103.95	100.3
	70	300 × 500	86.62	87.3
2nd	79,81	300 × 500	106.55	103.28
	80	300 × 500	91.58	99.28
1st	89,91	300 × 500	107.33	103.28
	90	300 × 500	94.02	99.28

DISCUSSION

In this work the building frame of five storeys have been analysed and designed using conventional and capacity based design methods. It can be seen from the results presented in Tables and Figures of five storeys building frame that capacity based design method needs more computational effort. In the building frame column moment and shear of capacity based design method is modified as compared to the results obtained by conventional design method. Also, beam shear is modified as compared to the results obtained by conventional design method.

Column Moments

Column moments for five storeys building frame have been compared in Table 6 using conventional and capacity based design method for zone II. Following observation can be made from Tables 1-5:

- Column moments obtained by capacity based design method is more than those obtained from conventional design method for building frames of five storey.
- The increase in column moments using capacity based design method is significant for exterior column. The column moment at first storey of five storey building frame obtained by capacity based design method is 104.11 kN-m (Table 6) whereas column moment at the same location by the conventional design method is 81.34 kN-m (Table 6).
- The increase in column moments using capacity based design method is significant for interior column of all selected building frames. The column moment at first storey of five storey building frame obtained by capacity based design method is 148.97 kN-m (Table 6) whereas column moment at the same location by the conventional design method is 82.13 kN-m (Table 6).

Column Shear

Column shear for five storeys building frame have been compared in Table 7 using conventional and capacity based design method for zone II. Following observation can be made from above Tables 1-5:

- Column shear obtained by capacity based design method is more than those obtained from conventional design method for building frames of five storeys.
- The increase in column shear using capacity based design method is significant for exterior column. The column shear at third storey of five storey building frame obtained by capacity based design method is 82.37 kN for (Table 7) whereas column shear at same location as obtained from the conventional design method is 39.99 kN (Table 7).
- The increase in column shear using capacity based design method is significant for interior column. The column shear at third storey of five storey building frame obtained by capacity based design method is 109.05 kN (Table 7) whereas column shear at the same location by the conventional design method is 36.50 kN (Table 7).

Beam Shear

Beam shear for five storeys building frame have been compared in Table -8 using conventional and capacity based design method for zone II. Following observation can be made from above Tables:

- Beam shear obtained by capacity based design method is more than those obtained from conventional design method for all building frames of five storeys.
- The increase in beam shear using capacity based design method is significant for exterior beam. The beam shear at fifth storey of five storey building frame obtained by capacity based design method is 71.72 kN (Table -8) whereas beam shear at same location as obtained from the conventional design method is 63.29 kN (Table -8).
- The increase in beam shear using capacity based design method is significant for interior beam. The beam shear at fifth storey of five storey building frame obtained by capacity based design method is 67.1 kN (Table -8) whereas beam shear at the same location by the conventional design method is 46.66 kN (Table -8).

CONCLUSIONS

This elaborate study for five storey building under minimum seismic Zone II as per IS 1893 has been carried out to show the importance of capacity based design. Following conclusions can be drawn from this study:

- Column moments obtained by capacity based design method is more than those obtained from conventional design method. The increase in column moments using capacity based design method is insignificant for exterior column whereas the increase in column moments using capacity based design method is significant for interior column.
- Column shear obtained by capacity based design method is more than those obtained from conventional design method. The increase in column shear using capacity based design method is significant for exterior and interior columns.
- Beam shear obtained by capacity based design method is more than those obtained from conventional design method. The increase in beam shear using capacity based design method is insignificant for exterior beam of the selected building frame whereas the increase in beam shear using capacity based design method is significant for interior beam of the selected building frame.
- It has been shown that the capacity based design method for earthquake resisting structures is little costlier but is more effective in resisting the earthquake forces.
- Capacity based design method of design is more realistic because the calculations are based on provided reinforcement and the over strength of the structure which takes into account the reserve strength beyond elastic limit.

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