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Capacity Design of Reinforced Concrete Framed Building for Earthquake Loading

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Abstract: Background: *The capacity design philosophy permits ductile components of a structural system to yield, whereas the brittle components are not permitted to fail. Therefore, brittle components should have sufficiently higher strength compared to ductile components. The "strong-column / weak-beam" design philosophy ensures good ductility and a preferable collapse mechanism in the building. The failure mode wherein the beams form hinges is usually considered to be the most favourable mode for ensuring good global energy-dissipation without much degradation of capacity at the connections. In order to en- sure this favourable failure mode design codes recommend a minimum value of Moment Capacity Ratio (MCR).* ***Methods:*** *MCR is defined as the ratio of cumulative column moment capacity to cumulative beam moment capacity framing to a particular joint. Calculation of MCR is complicated as the column bending strength varies with the axial load. A family of RC framed building models is analysed in this study for earthquake load considering various load combinations given in relevant Indian standards. A range of axial force that may arise in the column sections during an event of design earthquake are obtained.* ***Findings/Applications:*** *A simplified procedure to calculate MCR empirically is proposed. The proposed method is compu- tationally simple for calculating nominal design strength of the column to be used in determining MCR at a beam-column joint.*

Keywords: Capacity based Design, Earthquake Load, MCR, Reinforced Concrete, Strong Column Weak Beam.

1. Introduction

Designing a building to behave elastically during earthquake without any damages makes the project uneconomical. So the earthquake-resistant design philosophy allows damages in some predetermined structural components. The flexural capacities of members are determined on the basis of the overall response of a structure to earthquake forces. The capacity design procedure sets strength hierarchy first at the member level and then at the structure level. So, it needs adjusting of column strength to be more than the beams framing into it at a joint. Mathematically it can be expressed as,

$$\sum M_c \geq \sum M_b$$

Where, M_c and M_b are moment capacities at the end of column and beam meeting at a joint respectively. In order to ensure this favourable failure mode[1] design codes recommend a minimum value of Moment Capacity Ratio (MCR) which is defined as the ratio of summation of column moment capacity to the summation of beam moment capacity at a particular beam-column joint. Mathematically, it can be expressed as:

$$MCR = \frac{\sum M_c}{\sum M_b}.$$

Table 1 presents a list of minimum MCR recommended by major international codes and published literatures Design codes define the MCR as the ratio of summation of moment capacities of column sections framing into a joint evaluated at the joint faces considering factored axial loads resulting in the minimum column moment to the summation of moment capacities of the beam sections framing into it along the direction of lateral forces.

During an event of earthquake or wind a range of factored axial loads occurs in the column Design codes try to capture the upper bound and lower bound of the loads that may arise during an event of an earthquake through load combinations considering the cyclic nature of earth- quake load. Therefore, to calculate the MCR at a given joint, one has to consider the axial forces from various load combinations which is computationally cumber- some. This makes the procedure unattractive to the designer.

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This paper attempts to simplify this procedure through empirical formulation

Table 1. Minimum MCR recommended by design codes and published literature

Documents	MCR
Uma and Jain, 2006[2]	1.1
ACI 318M-14[3]	1.2
NZS3101:1995[4]	1.4×Ω
EN1998-1:2004[5]	1.3
IS 13920 (draft): 2014[6]	1.4
Ω is over strength factor for beams	

2. Structural Modelling

The present study is based on analyses of four multi-storied RC buildings. All of these buildings were designed as per Indian Standard 7 loading requirements, corresponding to the highest seismic zone (PGA = 0.36g) with the design of reinforced concrete elements conforming8. All the building models considered here have six bays (in the direction of the earthquake) with a uniform bay width of 5 m. It should be noted that bay width of 4m – 6m is the usual case, especially in Indian and European prac- tice. Four different height categories were considered for the study, ranging from 4 to 10 storeys (4-storey, 6-sto- rey, 8-storey, 10-storey), with a uniform storey height of 3.5 m. All the buildings are assumed to be symmetric in plan and representative plane frames subjected to loading only in the primary direction are considered for analyses. Figure 1 presents a typical building frame (8-storey) considered in this study. Commercial software9 is used for modelling and ana- lysing. Beams and columns in the present study were modelled as frame elements with the centerlines joined at nodes. The rigid beam column joints were modelled by using end offsets at the joints. The floor slabs were assumed to act as diaphragms, which ensure the integral action of all the vertical lateral load-resisting elements. The weight of the slab was distributed to the surrounding beams. M 25 grade of concrete and Fe 500 grade of rein- forcing steel was used to design the building. The column end of the foundation was considered as pinned for all the models in this study.

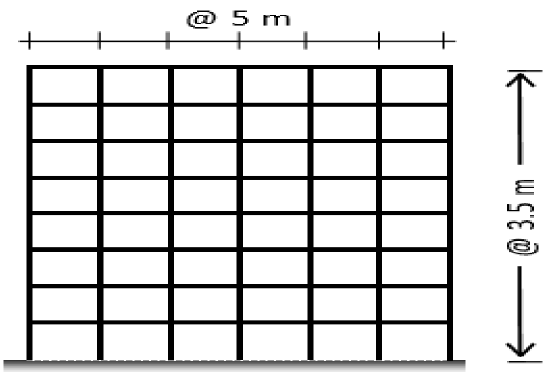

Figure 1 Typical building frame (8-storey) considered in this study

3. Development of Simplified Procedure for Estimating MCR

As discussed in the previous section many international design codes provide a limit of MCR of beam-to-column joint for capacity design of building frames. The MCR is defined as the ratio of cumulative column moment capacity to cumulative beam moment capacity framing at a particular joint. Although this appears to be a simple procedure the calculation of column moment capacity is a

Table 2. Column axial force for four-storey building

Storey Level	Exterior Column (4CE)		Interior Column (4CI)	
	$_1\eta = \frac{P_{max}}{P}$	$_2\eta = \frac{P_{min}}{P}$	$_1\eta = \frac{P_{max}}{P}$	$_2\eta = \frac{P_{min}}{P}$
G	0.124	0.052	0.245	0.109
1	0.089	0.036	0.176	0.077
2	0.064	0.025	0.127	0.053
3	0.023	0.006	0.046	0.015
mean	0.060	0.025	0.151	0.065
σ	0.025	0.008	0.084	0.040

P = maximum axial force carrying capacity of the column; P_{max} and P_{min} = maximum and minimum column axial force demand of the earthquake; σ =standard deviation

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Table 3. Column axial force for six-storey building

Storey Level	Exterior Column (6CE)		Interior Column (6CI)	
	$\eta_1 = \frac{P_{max}}{P}$	$\eta_2 = \frac{P_{min}}{P}$	$\eta_1 = \frac{P_{max}}{P}$	$\eta_2 = \frac{P_{min}}{P}$
G	0.180	0.073	0.343	0.157
1	0.148	0.060	0.281	0.128
2	0.135	0.054	0.255	0.114
3	0.097	0.039	0.183	0.081
4	0.064	0.024	0.120	0.050
5	0.024	0.006	0.044	0.014
mean	0.116	0.046	0.219	0.097
σ	0.058	0.024	0.110	0.053

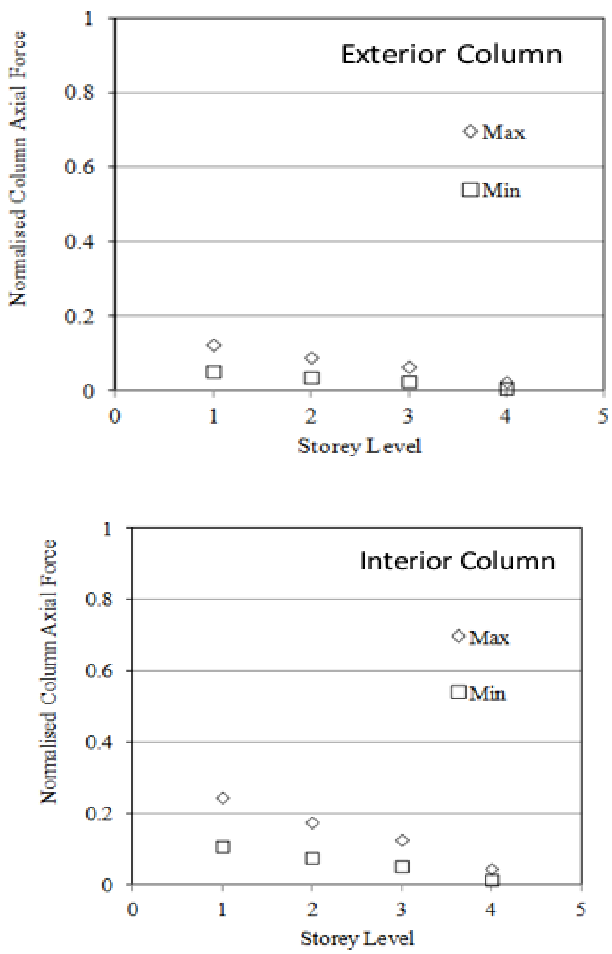

Figure 2. Column axial force for four-storey building

matter of concern for the design office as it depends on the axial force level the column is subjected to. During cyclic earthquake loading column experience a range of axial force due to various combinations of load and unlike beam col- umn does not have a unique moment capacity. That makes the calculation of MCR cumbersome. The present study is an attempt to simplify this procedure. Four code designed.

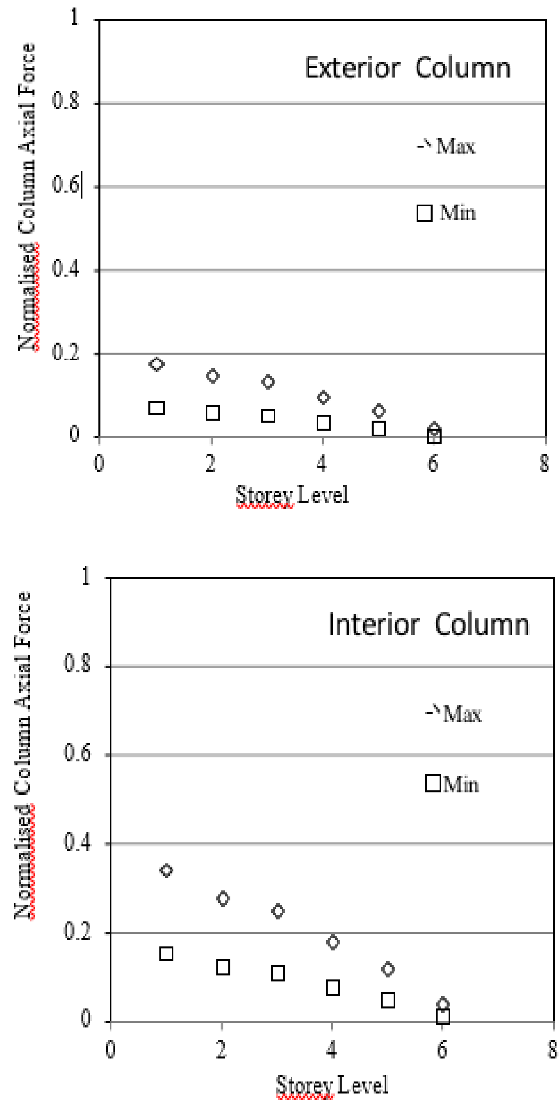

Figure 3. Column axial force for six-storey building

building models are analysed for earthquake load using an equivalent static approach to find out the axial force range of the various columns in the buildings. Tables 2-5 show the variation of axial force in different columns. Axial force has taken for one representative exterior and one representative interior column for each building model. Figures. 2-5 pres- ent these data graphically.

Table 4. Column axial force for eight-storey building

Storey Level	Exterior Column (8CE)		Interior Column (8CI)	
	$\eta_1 = \frac{P_{max}}{P}$	$\eta_2 = \frac{P_{min}}{P}$	$\eta_1 = \frac{P_{max}}{P}$	$\eta_2 = \frac{P_{min}}{P}$
G	0.218	0.085	0.407	0.187
1	0.190	0.074	0.352	0.162
2	0.183	0.072	0.339	0.155
3	0.151	0.060	0.278	0.126
4	0.137	0.054	0.251	0.113
5	0.099	0.039	0.181	0.079
6	0.066	0.025	0.120	0.050
7	0.025	0.007	0.044	0.014
mean	0.144	0.057	0.265	0.119
σ	0.066	0.027	0.124	0.059

Table 5. Column axial force for 10-storey building

Storey Level	Exterior Column (10CE)		Interior Column (10CI)	
	$\eta_1 = \frac{P_{max}}{P}$	$\eta_2 = \frac{P_{min}}{P}$	$\eta_1 = \frac{P_{max}}{P}$	$\eta_2 = \frac{P_{min}}{P}$
G	0.227	0.062	0.407	0.189
1	0.222	0.067	0.395	0.183
2	0.204	0.059	0.363	0.169
3	0.193	0.060	0.342	0.158
4	0.186	0.060	0.328	0.150
5	0.153	0.051	0.269	0.122
6	0.133	0.045	0.232	0.104
7	0.096	0.034	0.167	0.073
8	0.060	0.020	0.102	0.042
9	0.023	0.005	0.038	0.011
mean	0.170	0.055	0.298	0.136
σ	0.070	0.020	0.127	0.061

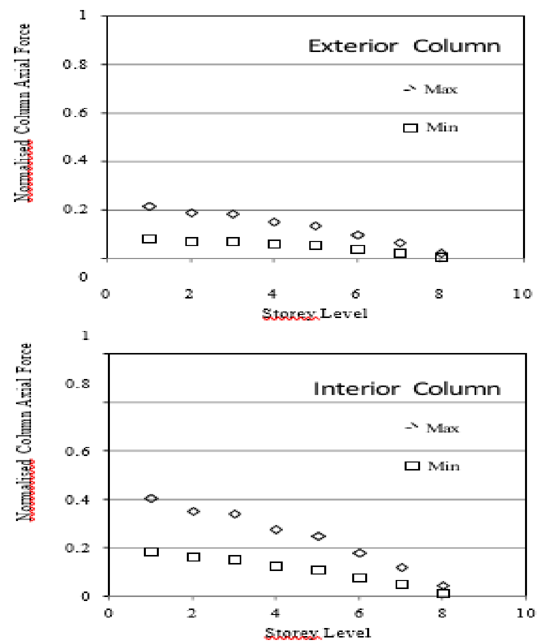

Figure 4. Column axial force for eight-storey building.

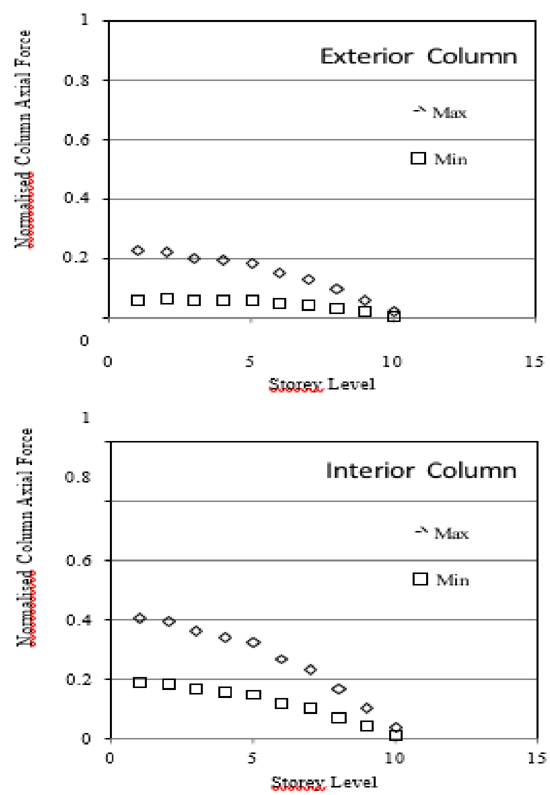

Figure 5. Column axial force for 10-storey building.

The above tables and figures show the statistical range of axial forces that generally the building columns experience. In order to investigate what moment capac- ity a column may pose under these ranges of axial force, respective column interaction diagrams given10 are super-posed with the obtained axial force. A typical example is shown in Figure. 6. The results are summarised in Table 6. The above discussions conclude that the ratio of axial force with the ultimate capacity of the section normally lies between 0.12-0.41 or by rounding off 0.1-0.4. This range of vertical force gives a minimum moment carrying capacity of 0.8-1.05 times the column moment at zero axial force as per the corresponding design chart of SP 16:1980. Table 6 shows that the value of the multiplier is less for interior joint and more for exterior joint. Considering a conservative value of the multiplier a simplified procedure for estimating MCR is proposed as follows:

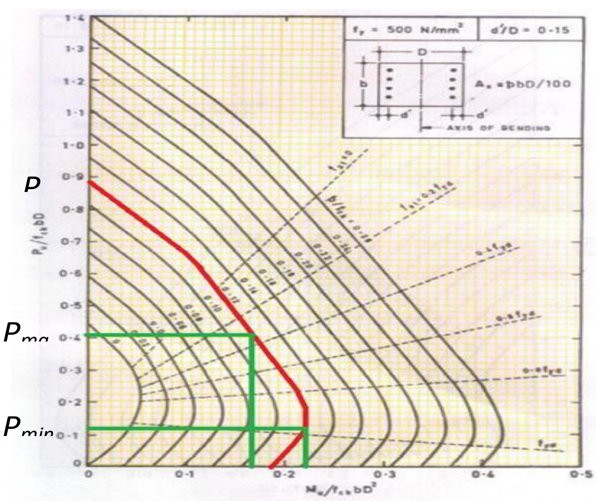

Figure 6. Column axial force range (typical) shown in design chart of SP 16[10].

Table 6. Column Moment Capacities

Col. Id	$\frac{P_{max}}{f_{ck}bD}$	$\frac{M(P_{max})}{f_{ck}bD^2}$	$\frac{P_{min}}{f_{ck}bD}$	$\frac{M(P_{min})}{f_{ck}bD^2}$	$\frac{M_{min}}{f_{ck}bD^2}$	$\frac{M_{P=0}}{f_{ck}bD^2}$	$\frac{M_{min}}{M_{P=0}}$
4CE	0.21	0.22	0.08	0.22	0.22	0.24	0.92
4CI	0.42	0.23	0.19	0.26	0.23	0.26	0.88
6CE	0.26	0.18	0.10	0.19	0.18	0.18	1.05
6CI	0.50	0.13	0.22	0.17	0.13	0.15	0.87
8CE	0.27	0.18	0.11	0.19	0.18	0.18	1.00
8CI	0.51	0.14	0.23	0.17	0.14	0.17	0.82
10CE	0.30	0.13	0.08	0.16	0.13	0.13	1.00
10CI	0.52	0.12	0.25	0.16	0.12	0.15	0.80

$$MCR = 0.8 \times \frac{\sum M_c}{\sum M_b}$$

Where, the column moment capacity is to be calcu- lated from zero axial force. This multiplier of 0.8 is arrived at from the limited results presented in Table 6. Additional studies are required for a statistically significant value of this multiplier.

4. Summary and Conclusion

Design codes recommend minimum MCR for capacity design of the RC moment resisting frame. MCR is defined as the ratio of cumulative column moment capacity to cumulative beam moment capacity framing to a particular joint. The nominal design strength of beams are a function of the beam section only and therefore there is no difficulty to calculate it. However, the nominal design strength of columns depends on the level of axial force in the column in addition to the column section proper- ties. Different axial forces may arise in a column when the building is subjected to the dynamic loading like an earthquake. It is computationally very difficult to find the appropriate axial force which results least column nominal design strength. The present study develops a computationally simple procedure for calculating nominal design strength of the column (0.8 times the column strength at zero axial force) to be used in determining MCR at a beam-column joint.

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