International Journal of Architectural, Civil and Construction Sciences
ISSN: 2415-1734
Vol:6, No:8, 2012

# Column Size for R.C. Frames with High Drift

Sunil S. Mayengbam and S. Choudhury

***Abstract*—**A method to predict the column size for displacement based design of reinforced concrete frame buildings with higher target inter storey drift is reported here. The column depth derived from empirical relation as a function of given beam section, target inter-story drift, building plan features and common displacement based design parameters is used. Regarding the high drift requirement, a minimum column-beam moment capacity ratio is maintained during capacity design. The method is used in designing four, eight and twelve story frame buildings with displacement based design for three percent target inter storey drift. Non linear time history analysis of the designed buildings are performed under five artificial ground motions to show that the columns are found elastic enough to avoid column sway mechanism assuring that for the design the column size can be used with or without minor changes.

***Keywords*—**Column size, point of contra flexure, displacement based design, capacity design.

## I. Introduction

THE most time consuming part in the design of reinforced concrete (R.C.) frame buildings is the repeated iteration to achieve an appropriate member size corresponding to the changing reinforcement. Beside torsion in case of R.C. frame buildings of irregular geometry, flexure and shear demand is closely related to member size via seismic weight and design generated lateral force. Therefore, before concluding into an appropriate set of member sections after fulfilling the required design constraints like demand, percentage reinforcement, column-beam moment capacity ratio, etc., iteration is unavoidable. In exact procedure, the involvement of all the frame analysis results is required.

Attempts were made to optimize both member size and reinforcement by different methods with different combinations of constraints in R.C. frame design (reported) by researchers like [11], [8], [10], [5], [1], [2], [9], etc. [21] reported the same for R.C. short-tied columns.

This study makes an approach to provide a fairly approximate method to generate the depth of column based on given beam size, target inter story drift ratio (IDR), building plan features, etc. for displacement based design (DBD) of R.C. frame buildings with higher target IDR. An ideal pattern of point of contra flexure is decided and used despite the fact that position of point of contra flexure varies directly with sectional moment of inertia and indirectly with the square of member length.

Sunil S. Mayengbam is with the National Institute of Technology, Silchar 788010 India (phone: +919401963068; e-mail: sunil_mayengbam@hotmail.com).

S. Choudhury is with the National Institute of Technology, Silchar 788010 India (e-mail: scnitsilchar@gmail.com).

Appropriate dynamic amplification of inter storey drift corresponding to the storey height is considered during the design.

## II. Column Size Generation Procedure

### *A. Background*

Avoiding soft story formation i.e. column sway mechanism and to maintain beam sway mechanism is a general mandatory requirement in displacement based design of R.C. frame buildings where all the column member except bottom ground floor and top floor columns are designed to behave elastically through capacity design. Therefore, the column section should be suitable that after design, supplying the required reinforcement, it behaves elastically with Non Linear Time History Analysis (NLTHA).

If $\theta_{yc}$ represents column yield rotation (Fig. 1), $l$ the distance between the point of contra flexure and the point of maximum bending moment and $\phi_{yc}$ the column yield curvature, the column tip displacement ($\Delta_f$) within elastic limit due to flexure [15] is given by

$$\Delta_f = \frac{\phi_{yc} l^2}{3} \tag{1}$$

If $\varepsilon_y$ represents yield strain at expected strength of rebar steel and $h_c$ the column depth in the direction of earthquake under consideration, yield curvature ($\phi_{yc}$) according to [19] for rectangular column section is given by

$$\phi_{yc} = \frac{2.1\varepsilon_y}{h_c} \tag{2}$$

The flexural displacement of column tip ($\Delta_f$) can be written by combining (1) and (2) as

$$\Delta_f = \frac{0.7\varepsilon_y l^2}{h_c} \tag{3}$$

If $V$ represents the maximum shear force applied to the member, $B$ the column width, $d$ the effective depth, $\rho$ Poisson's ratio and $E$ modulus of elasticity of the material, average column displacement due to shear ($\Delta_s$) according to [13] is given by

$$\Delta_s = \frac{6V}{5Bd} \times \frac{2(1+\rho)}{E} \times 10 \tag{4}$$

Effective depth ($d$) of the section is assumed to be 0.9 times the overall depth ($h_c$). If $c_r$ is the ratio of column depth to the width i.e. $c_r = (h_c / B)$, (4) can be written as

$$\Delta_s = \frac{24V(1+\rho)c_r}{0.9h_c^2 E} \tag{5}$$

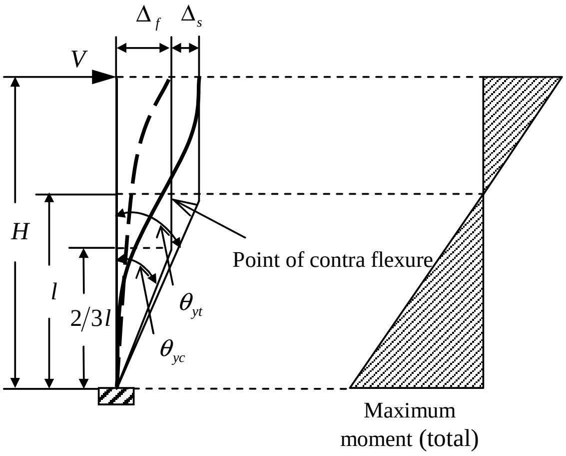



Fig. 1 Assumed elastic column deformation behavior.

Assuming that the column section are meant for elastic action only and neglecting the deformation due to slip, the overall column drift ($\Delta_{total}$) can be considered to be composed of only flexure ($\Delta_f$) and shear ($\Delta_s$) component represented in (6)

$$\Delta_{total} = \Delta_f + \Delta_s \tag{6}$$

Equation (6) can be written by using (3) and (5) as

$$\Delta_{total} = \frac{0.7\varepsilon_y l^2}{h_c} + \frac{24V(1+\rho)c_r}{0.9h_c^2 E} \tag{7}$$

If $\theta_{yt}$ represents the overall yield column rotation, rotates with the same $l$ as in (1)

$$\theta_{yt} l = \frac{0.7\varepsilon_y l^2}{h_c} + \frac{24V(1+\rho)c_r}{0.9h_c^2 E} \tag{8}$$

Or,

$$\theta_{yt} l h_c^2 - 0.7\varepsilon_y l^2 h_c - \frac{24V(1+\rho)c_r}{0.9E} = 0 \tag{9}$$

Dynamic amplifications due to column shear and moment are considered. According to [16], for one way frame having a design over strength factor, columns should be designed for

(1) $1.3\times\phi_o$ times the design column shear, and

(2) $\omega_m \times \phi_o$ times the design column moment. Where, $1.3 \le \omega_m \le 1.8$, $\omega_m = 0.5T + 0.85$ and $T$ is the natural period of the structure. However, $\omega_m$ is not restricted to 1.8 in this study.

The main intention of including dynamic amplification factor is to give a provision for an appropriate column beam moment capacity ratio (C/B) for the capacity design.

Therefore, (9) can be written as

$$\theta_{yt} l h_c^2 - 0.7\varepsilon_y l^2 h_c \phi_o \omega_m - \frac{31.2V(1+\rho)c_r\phi_o}{0.9E} = 0 \tag{10}$$

The position of the point of contra flexure changes with the ratio of moment of inertia of the section and square of the member length. To avoid complexities, a pattern of average position of point of contra flexure for column members is decided according to experience. The relative distance ($pc$ i.e. $l = pc\times$column height) between the column point of contra flexure and the point of maximum bending moment is generalized as follows

For 1st floor,

$$pc = 1.56\times10^{-3} n^2 - 6.25\times10^{-3} n + 0.6 \tag{11a}$$

For 2nd floor,

$$pc = 5.6\times10^{-5} n^3 - 1.9\times10^{-3} n^2 + 2.17\times10^{-2} + 0.4904 \tag{11b}$$

For 3rd floor,

$$pc = 7.0\times10^{-5} n^3 - 2.26\times10^{-3} n^2 + 2.43\times10^{-2} + 0.4546 \tag{11c}$$

For 4th floor,

$$pc = 5.31\times10^{-5} n^3 - 1.83\times10^{-3} n^2 + 2.1\times10^{-2} + 0.4418 \tag{11d}$$

For remaining floor,

$$pc = 0.5 \tag{11e}$$

Here, $n$ represents the total number of floors.

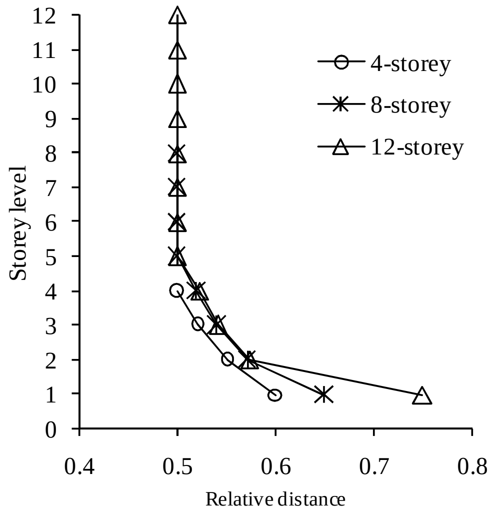



Fig. 2 Value of assumed relative distance for different heights

*B. Algorithm*

An algorithm is used to solve (10), presented stepwise as follows

(A) Input: The input parameters are listed below

1) Description/detail of a closed symmetric plan
2) Beam size
3) Target drift
4) Material properties
5) A trial bottom column depth, $h_{ci}$

(B) Derive the trial column width for other floors as 0.9 times that of the lower floor until 3rd storey. The rest are set the same as that of the 3rd storey. This is being done just to reduce the number of iterations. The significance of the multiplier 0.9 vanishes with consecutive iterations.

(C) Calculate the seismic weight for column depth $h_{ci}$

(D) Calculate the floor wise design lateral force according to the general DBD procedure and hence individual column shear force.

(E) Calculate the corresponding column depth $h_{ci+1}$ from (10) using Newton-Raphson method as follows

$$f(h_{ci}) = \theta_{yt} l h_{ci}^{\ 2} - 0.7\varepsilon_y l^2 h_{ci}\phi_o\omega_m - \frac{31.2V(1+\rho)c_r\phi_o}{0.9E} = 0 \tag{12a}$$

$$f'(h_{ci}) = 2\theta_{yt} l h_{ci} - 0.7\varepsilon_y l^2\phi_o\omega_m = 0 \tag{12b}$$

$$h_{ci+1} = h_{ci} - \frac{f(h_{ci})}{f'(h_{ci})} \tag{12c}$$

The tolerance of convergence is taken as $1\times10^{-6}$ during the application.

(F) Check for $(h_{ci+1} - h_{ci}) < 0.0001$ assuring that the resulting shear force from the iterative DBD matches for two consecutive iterations and hence the column depth for each floor column.

If so, the last value of column depth for each floor gives the required depth for the respective floor.

Else, go to step (C).

Based on this algorithm, a program is written in Matlab which is used throughout the column size generation in this report.

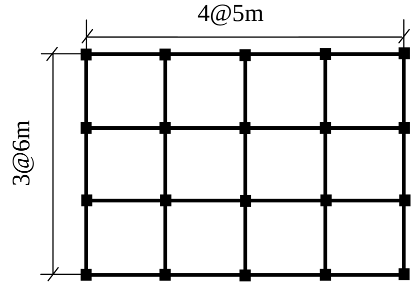



Fig. 3 Building plan

## III. Design and Validation

The method is applied for 3% target IDR to a closed symmetrical plan having four beam spans of 5 meters each in the long direction and three beam spans of 6 meters each in the short direction shown in Fig. 3. A constant floor height of 3.3 meters is used throughout in buildings of 4-storey, 8-storey and 12-storey.

TABLE I
Generated Column Size

| % IDR | | Building | Floor wise column depth in millimeter (square column) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Target | design | heights | 1st | 2nd | 3rd | 4th | 5th | 6th | 7th | 8th | 9th | 10th | 11th | 12th |
| 3.0 | 2.25 | 4-storey | 590 | 542 | 511 | 489 | - | - | - | - | - | - | - | - |
| 3.0 | 2.55 | 8-storey | 571 | 502 | 476 | 459 | 441 | 439 | 438 | 437 | - | - | - | - |
| 3.0 | 3.0 | 12-storey | 744 | 539 | 500 | 500 | 500 | 500 | 498 | 498 | 497 | 497 | 496 | 495 |

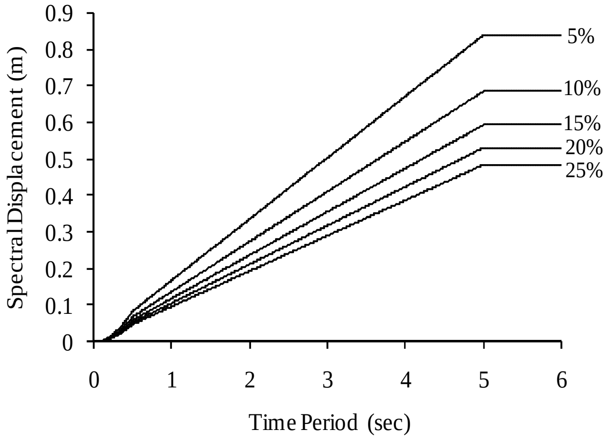



Fig. 4 Design displacement spectra

TABLE II
DETAILS OF SPECTRUM COMPATIBLE GROUND MOTION

| Sl. No. | Name | Background Earthquake | Record No. | Duration (sec) |
|---|---|---|---|---|
| 1 | GM1 | Duzce 1999 | Duzce, 270 (ERD) | 25.9 |
| 2 | GM2 | El Centro 1940 | N-S Component | 31.8 |
| 3 | GM3 | Gazli 1976 | Karakyr, 090 | 16.3 |
| 4 | GM4 | Kocaeli 1999 | Sakarya, 090 (ERD) | 30.0 |
| 5 | GM5 | N. Palm Spring 1986 | 0920, USGS station 5070 | 20.0 |

Design spectrum of 0.45g acceleration level for type B soil is considered as per [3]. Design displacement spectra set is shown in Fig. 4. A corner period extension of 5 seconds is applied to tackle larger displacement demand for higher storey buildings and also to incorporate the significance of magnitude on the corner period as per [6]. Materials used in the design include concrete of cube strength 30 MPa and reinforcing rebar steel with yield strength 415 MPa, for both expected material strengths as per FEMA-356 are used. Buildings are modeled using SAP2000. The design procedure is similar to that of [17] and [18] without considering dynamic amplification of column shear and column moment, and no similar effort for bottom storey column is taken to assure beam sway mechanism. However, dynamic amplification of IDR is considered according to the capacity design.

The basic concept of capacity design is to avoid column sway mechanism by making the designed column moment capacity greater than those of the adjacent beams.

If, $\sum M_{Rc}$ represents the sum of the design moments of resistance of the columns framing into the joint and $\sum M_{Rb}$ is the corresponding sum of the design moments of resistance of the beams, capacity design criteria suggested as per [3] is given in (13).

$$\sum M_{Rc} \leq 1.3 \sum M_{Rb} \tag{13}$$

However, considering the fact that the design is done for high target drift (3%) in which high beam plastic rotation is expected, $\sum M_{Rc}$ is maintained at least 2.0 times $\sum M_{Rb}$ instead of 1.3. On the other hand, maintaining an overall high C/B throughout the storey height may reduce the IDR for longer period or taller buildings. Therefore, no dynamic amplification of IDR is considered for the 12-storey building while for the 4 and 8 storey building, their target IDR are reduced by 0.75 and 0.85 times as per [14] i.e. they are designed for 2.25% and 2.55% target drift respectively as more drift is expected for less height buildings in this case. Plastic bottom column hinges at the ground level is not made compulsory in this study though it may lead to uneven distribution of %IDR and plastic hinges in the frame members.

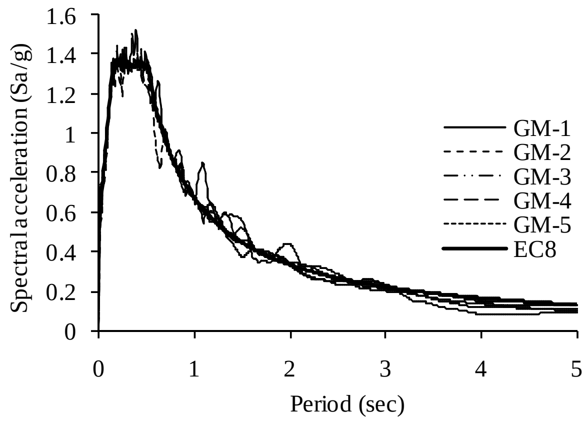



Fig. 5 Comparison of Design spectrum with SCGM Response spectrum

Beam sizes of $300mm \times 500mm$ and $350mm \times 600mm$ are used in long and short direction respectively throughout the building height for all buildings as per [4]. The floor wise column sizes are generated (Table I) for the design IDR corresponding to 3% target IDR using (10) with the algorithm.

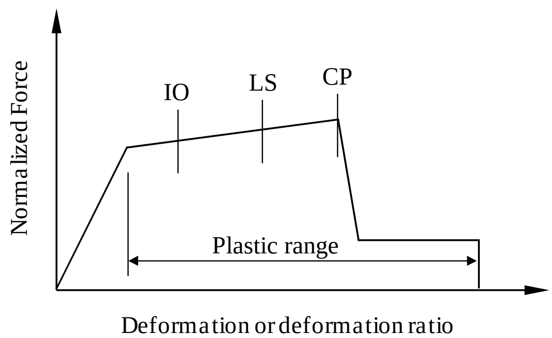



Fig. 6 Force-Deformation behavior (FEMA-356)

The spectrum compatible ground motions (SCGM) shown in Table II are generated by using the software developed by [12]. The phase angle, frequency content and duration of the background earthquake are incorporated in the SCGM. Fig. 5

shows the matching comparison between design spectrum and response spectrum for 0.45g acceleration level and 5% damping.

$$\phi_{yb} = 1.7 \frac{\varepsilon_y}{h_b} \tag{15b}$$

$$EI_{eff,column} = \frac{M_c}{\phi_{yc}} \tag{15c}$$

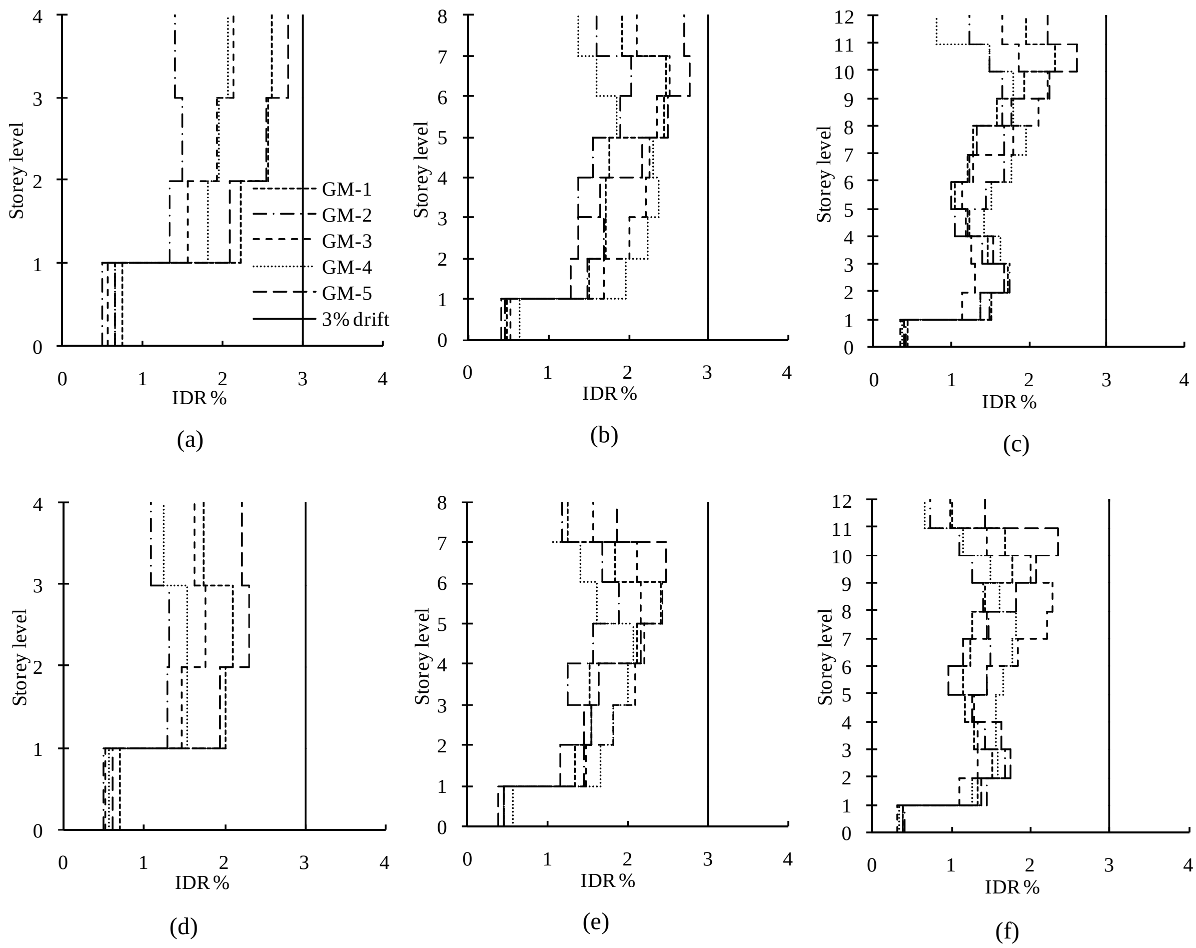



Fig. 7 Inter storey drift diagram in long and short directions; (a and d) 4 storey, (b and e) 8 storey, (c and f) 12 storey

Effective member section properties are used according to [19] for non linear analysis. The yield moments are derived from resulting design steel. If E is modulus of elasticity, $I_{eff,beam}$ and the effective moment of inertia of beam and column, $I_{eff,column}$ and the beam and the column yield moment, and $\phi_{yb}$ and $\phi_{yc}$ the beam (15b) and column (2) yield curvature, the effective beam and column flexural rigidity is given by (15a) and (15c) respectively

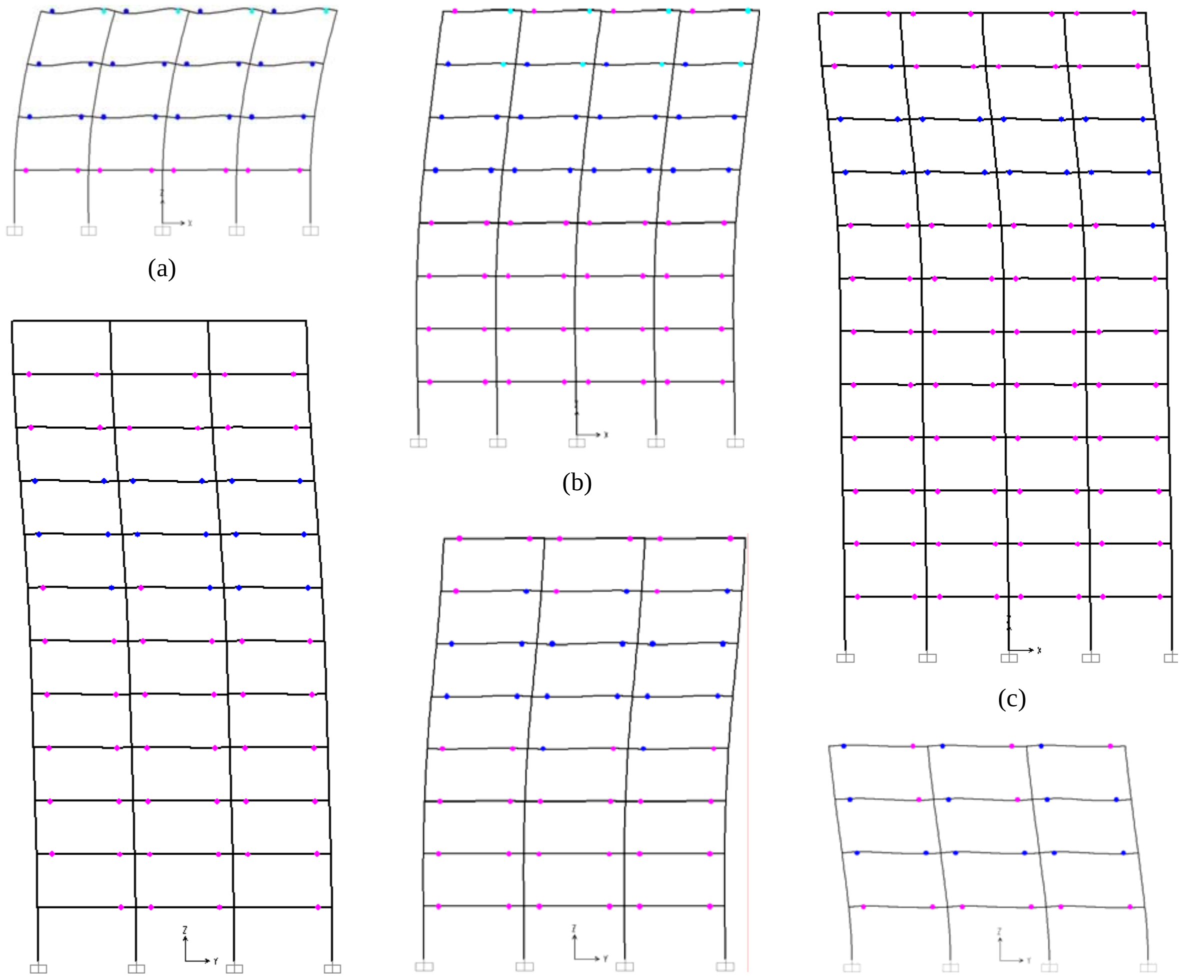
$$EI_{eff,beam} = \frac{M_{yb}}{\phi_{yb}} \tag{15a}$$

The post-elastic force-deformation behavior for the members (Fig. 6) is adopted as per [6].

The buildings are subjected to NLTHA under SCGM (Table 2) shown in Fig. 5 which assures that the energy levels of the ground motions are set to the level of design spectrum for NLTHA.

The IDR achieved by the buildings shown in Fig. 7 is well within the expected target drift.

No columns develop plastic hinges avoiding column sway mechanism (Fig. 8). The maximum angle of plastic rotation allowed for beams controlled by flexure in radian for immediate occupancy (IO) , life safety (LS) and collapse prevention (CP) levels are 0.00625, 0.01125 and 0.01875 respectively (taken as average from FEMA-356). Hinges formation on beams at last step in time history analysis are found to be within CP level shown by cyan hinges in Fig. 8(a) and 8(b) while majority hinges are of IO and LS level represented by pink and blue hinges (Fig. 8).



(a) (b) (c) (d) (e) (f)

Fig. 8: Hinges in typical frames in long and short direction; (a and f) 4 storey under GM1, (b and e) 8 storey under GM5, (c and d) 12 storey under GM3

## IV. Conclusion

This article reports an approach to fairly predict the floor wise column size of reinforced concrete frame buildings for displacement based design meant for higher target drift. An algorithm based on empirical relations is used which requires given beam section, target inter-story drift, building plan features and regular displacement based design parameters as the inputs.

To maintain a smooth descending column width with building height, a pattern of point of contra flexure is used as a parameter required in the process. Another parameter, giving provision for capacity design is also included in the form of dynamic amplification for column shear and moment in the formulation, not during design.

Some usual adjustments regarding column beam capacity ratio and target inter storey drift are made while designing.The generated column size using the method may or may not undergo minor changes in the dimension according to the designer’s wish, can be effectively used for designing reinforced concrete frame buildings of high target drift using displacement based design with some usual necessary adjustments for high inter storey drift in the design method.

## References

[1] Balling, R. J., and Yao, X., ‘‘Optimization of reinforced concrete frames,’’ *Journal of Structural Engineering*, 123(2), 1997, 193–202.
[2] Camp, C.V., Pezeshk, S. and Hansson, H., “Flexural design of reinforced concrete frames using a genetic Algorithm,” *Journal of Structural Engineering*, 129(1), 2003, 105-115.

[3] CEN, European Prestandard ENV 1998-1-4: Eurocode 8 — Design Of Structures for Earthquake Resistance, Part 1: General Rules, Seismic Actions and Rules for Buildings, Draft No. 5, May 2002, Doc CEN/TC250/SC8/N317, *Comit´eEurop`een de Normalisation, Brussels.*
[4] Choudhury, S., Mayengbam, S. S., Singh, Y. and Paul D. K., "A Unified Approach to Performance-Based Design of R. C. Frame Buildings," *Earthquake Engineering and Engineering Vibration*, submitted for publication.
[5] Chung, T. T., and Sun, T. C., ''Weight optimization for flexural reinforced concrete beams with static nonlinear response,'' *Structural Optimization*, (8), 1994, 174 –180.
[6] Faccioli, E., Paolucci, R. and Rey, J., "Displacement spectra for long periods," *Earthquake Spectra*, 20(2), 2004, 347–376.
[7] FEMA-356, "Prestandard and Commentary for the Seismic Rehabilitation of Buildings," *US Federal Emergency Management Agency*, Washington D.C., 2000.
[8] Goldberg, D. E., and Samtani, M. P., ''Engineering optimization via genetic algorithm,'' *Proceedings of 9th Conference on Electronic Computation*, ASCE, New York, 1986, 471– 482.
[9] Guerra, A and Kiousis, P. D., "Design optimization of reinforced concrete structures," *Computers and Concrete*, 3(5), 2006, 313-334.
[10] Jenkins, W. M., ''Plane frame optimum design environment based on genetic algorithm,'' *Journal of Structural Engineering*, 118(11), 1991, 3103–3112
[11] Krishnamoorthy, C. S., and Munro, J., ''Linear program for opti-mal design of reinforced concrete frames,'' *Proceedings of IABSE,* 3(1), 1979, 119–141
[12] Kumar, A., "Software for generation of spectrum compatible time history," *Proceedings of 13th World Conference on Earthquake Engineering*, Canada, 2004, 2096
[13] Matamoros, A. B., "Drift Limits of High-Strength Concrete Columns," PhD. Thesis, Department of Civil Engineering, University of Illinois at Urbana Champaign, 1999.
[14] Mayengbam, S.S and Choudhury, S, "Control of different target drifts for R.C. frame buildings," unpublished.
[15] Park, R., and Paulay, T., *Reinforced Concrete Structures*, John Wiley and Sons, New York, 1975, 769 pp
[16] Paulay, T. and Priestley, M. J. N., *Seismic design of reinforced concrete and Masonry buildings*. John Wiley and Sons, Inc., New York, 1992.
[17] Pettinga, J.D. and Priestley, M.J.N., "Dynamic behavior of reinforced concrete frames Designed with Direct Displacement-Based Design," *Journal of Earthquake Engineering*, 9 (2), 2005, 309-330.
[18] Pettinga, J.D. and Priestley, M.J.N., "Accounting for p-delta effects in structures when using direct displacement-based design," *Research Report ROSE (European School for Advanced Studies in Reduction of Seismic Risk)*, IUSS Press, Pavia, 2007.
[19] Priestley, M.J.N., "Myths and fallacies in earthquake engineering, revisited," *European School for Advanced Studies in Reduction of Seismic Risk*, 9th Mallet-Milne Lecture, 2003.
[20] SAP2000 V. 10.12, "Structural analysis program," *Computer and Structures Inc.*, Berkley, CA, 2006.
[21] Zielinski, Z. A., Long, W., and Troitsky, M. S., ''Designing rein-forced concrete short-tied columns using the optimization technique,'' ACI Structural Journal, 92(5), 619– 626, 1995.