17th World Conference on Earthquake Engineering, 17WCEE
Sendai, Japan - September 13th to 18th 2020

QUANTIFYING PARAMETERS FOR IMPROVED ENERGY DISSIPATION CAPACITY IN LOW-RISE RC OPEN STOREY BUILDINGS

K. Vineela (1) and P. Sunitha (2)

(1) Former graduate student, IIIT Hyderabad, India, vineela286@gmail.com
(2) Visiting Assistant Professor, IIIT Hyderabad, India, sunitha.palissery@iiit.ac.in

Abstract

Past earthquakes have witnessed poor performance of buildings with irregularities, compared to performance of regular buildings. The detrimental effects of irregularities are more pronounced when they are due to stiffness and strength variations across the height of the building. In particular, these irregularities are more often observed in buildings with *open storeys*; buildings without infill walls in ground storeys and buildings without infill walls in intermediate storeys are two types of irregularities pertaining to stiffness and strength. Formation of storey mechanism (at the open storey) is the most crucial seismic behavior that jeopardizes seismic safety of these buildings. The inelastic energy dissipation capacities of buildings are substantially reduced due to formation of storey mechanism. Nevertheless, if architectural decisions demand presence of open storeys, precluding storey mechanism is crucial towards improving the seismic behavior and seismic safety of these buildings.

The work presented in this paper is aimed at to arrive at a desirable ductile mechanism that maximizes inelastic energy dissipation capacity in buildings with open storeys, by fine tuning two design parameters, namely relative lateral stiffness of columns and beams and relative flexural strength of columns and beams, at a moment resisting joint in reinforced concrete (RC) special moment frames. For the purpose, typical regular low-rise 5 storey buildings located in moderate to high seismic regions with typical bay sizes and storey heights are considered. The stiffness and strength irregularities are considered for study in the buildings by providing: (a) open storey in ground storey alone, and (b) open storey in an intermediate storey alone. The considered buildings are designed and detailed as per Indian standards, namely IS456:2000, IS1893(part1):2016 and IS13920:2016. Further, the designed buildings are assessed of the nonlinear behavior by performing nonlinear static analysis in commercial software SAP2000. The observed storey mechanism is precluded and poor seismic behavior improved of the study buildings, by increasing relative flexural stiffness of column and beams and relative flexural strength of column and beams in the open storeys; a stiffness ratio (ratio of stiffness of immediate upper storey to stiffness of open storey) of 1 and column-to-beam strength ratio (ratio of flexural strength of columns to flexural strength of beams) of 4 is required in typical buildings located in moderate seismic regions. For easy implementation in design practice, graphs are presented between stiffness ratio and column-to-beam strength ratio, to obtain the required column-to-beam strength ratio for a particular stiffness ratio, that help prevent formation of undesirable storey mechanisms. Also, values of design parameters required to preclude undesirable storey mechanisms in high seismic regions are also confirmed.

Keywords: Irregularities; open storey; storey mechanism; stiffness ratio; Column to beam strength ratio

1. Introduction

Moment frame is one of the structural systems employed in the construction of buildings. Moment frame can be regular or irregular along plan or elevation. Elevation irregularities include strength and stiffness irregularities, commonly found in open ground storey (provided mainly to facilitate parking) buildings Contribution of unreinforced masonry infills (URM) in seismic behaviour should be understood to predict the actual behaviour of the open storey buildings reasonably well.

Investigating performance of buildings in past earthquakes are crucial to identify the deficiencies in the design procedures recommended in design standards. Buildings with uniform infills along the full building height have performed better in many past earthquakes. Numerical and experimental research have proved the beneficial effect of presence of masonry too [1]. Observations after an earthquake are studied in detail by researchers, and the design standards are constantly revised to overcome the deficiencies. It is observed from past earthquakes that many open ground storey (soft storey) buildings incurred severe damages to the extent of collapse, due to the lack of stiffness and strength in the ground storey. This is because, masonry infills in the upper storeys of the building make the building stiff, attracting significantly higher earthquake forces. Failures by formation of storey mechanism and plastic hinges in columns are two major damage types of damage observed in buildings with soft storey. One of the early collapses occurred in the 1971 San Fernando earthquake, where the Olive View Hospital (Fig.1) was severely damaged due to the presence of discontinuous shear wall. This is because, when shear walls form the main lateral resistant elements of the building, they may be required to carry high lateral loads; any discontinuity in the flow of forces from roof to foundation demand indirect load paths resulting in serious overstressing at the locations of discontinuity [2]. Further, storey mechanism (soft storey effect) was observed in 1994 Kobe earthquake and 1995 Northridge earthquake in buildings with similar irregularities[3]. While, ground storeys used for parking in these buildings which were deficient in stiffness and strength compared to storeys above collapsed completely, top storeys acted as a rigid body without incurring any damage. 2001 Bhuj earthquake also witnessed many similar failures due to presence of soft and weak storeys in reinforced concrete frame buildings in Ahmedabad [4]. The collapse was evidently caused by the failure of the columns in the open storey. IS1893 (1) (2016) suggests preventive measures by providing RC structural walls or bracings at selected bays, to avoid soft storey effect. But sometimes these preventive measures may reduce the functional efficiency of the building. Hence, it is prudent to reduce the soft storey effect by not affecting the functionality and architectural preferences of the building, but by increasing lateral stiffness and flexural strength in the columns [5].

Thus, designing the building to achieve a desirable collapse mechanism is crucial to preclude such undesirable failures; increasing strength and stiffness of the soft storey at design stage is essential. Nevertheless, guidelines on design of such buildings to resist strong earthquake effects are not clear. This study is an attempt in this direction, wherein achieving desirable failure mechanism through design is focused. In this study, behaviour of open storey buildings by increasing lateral stiffness and flexural strength is investigated. In particular, design parameters stiffness ratio and Column-to-Beam Strength Ratio (CBSR) are quantified. The study is limited to normal, low-rise (5 storeys) RC moment frame buildings with regular frame grid (in plan). Soil-structure interaction is not considered. Beam-column joints are assumed to not accrue any damage because of infinite stiffness and strength. Capacity design is perfromed, assuming preclusion of any shear failure. Structural elements are designed to respond dominantly in flexural actions.

Fig. 1 – Collapse of Olive View Hospital due to presence of soft storey in 1971 San Fernando earthquake [1].

2. Numerical Study

A 5 storey special moment resisting frame building with: plan size 16 m × 12 m; storey height 3m; bay size 4m; located in seismic zone IV (Zone Factor of 0.24g) on a site of medium soil; 230mm thick exterior URM infill walls; columns fixed at base (Fig.2). Live load of $3kN/m^2$, and floor finish of $1kN/m^2$ are considered, in addition to dead loads [IS1893 (1), 2016] [6]. Material properties used are grade of concrete – M30, Grade of steel reinforcement bars – Fe415. Numerical modeling and linear elastic structural analysis are carried out in commercial software ETABS and nonlinear static analyses in SAP2000 [7]. Frame members are modeled using lineal elements and URM infills as equivalent single strut elements. Design and detailing conforms with the Indian Standards IS 456 (2000)[8], IS 1893 (1) (2016), and IS 13920(2016), and pertinent literature [9, 10, 11,12].

Masonry characteristics considered are: Clay Brick Class1 (North east India), with brick strength f_b = 19.2 MPa, mortar strength f_{mo} = 21.6 MPa (strong mortar). Characteristic strength of brick and mortar are used to estimate strut width for modelling infills.

Strut width is calculated using [6]:

$$w_{ds} = 0.175 \times \alpha^{-0.4} \times L_{ds} \tag{1}$$

$$\text{where, } \alpha_h = h_{col} \times \sqrt[4]{\frac{E_m \times t \times \sin 2\theta}{4 \times E_f \times I_c \times h_{inf}}} \tag{2}$$

$$\text{Modulus of elasticity of masonry infill (MPa) , } E_m = 550 \times f_m \tag{3}$$

$$\text{Compressive strength of masonry prism (MPa), } f_m = 0.443 \times f_b^{0.64} \times f_{mo}^{0.36} \tag{4}$$

where w_{ds} is the width of strut, t is thickness of the wall, θ is the angle of strut with horizontal, h_{col} is the height of the column, E_f is the modulus of elasticity of the frame, I_c is the moment of inertia of the column, h_{inf} is the height of infill.

Cracked section properties are considered for analysis; beam property modifier as 0.35 and column property modifier 0.7 as per IS 1893(1) (2016). Linear elastic structural analysis is performed in commercial software ETABS and design is performed according to IS 456(2000), IS 1893(1)(2016), IS 13920(2016) [5] by hand-calculation approach. Nonlinear static analysis is carried out in SAP2000. A 2-D frame representing dynamic characteristics building is considered for nonlinear static analysis. Open storey is considered in the first storey and intermediate storey. In open ground storey, total 10 frames are considered for the study (Table 1) according to column sizes (stiffness ratios) of the open storey. For open ground storey increase in stiffness is attained by increasing the size of the columns of the open storey. Size of the columns in X and Y directions are considered equal. For intermediate open storey, column sizes as in building M1 are considered. This is because column sizes cannot abruptly change in intermediate open storeys.

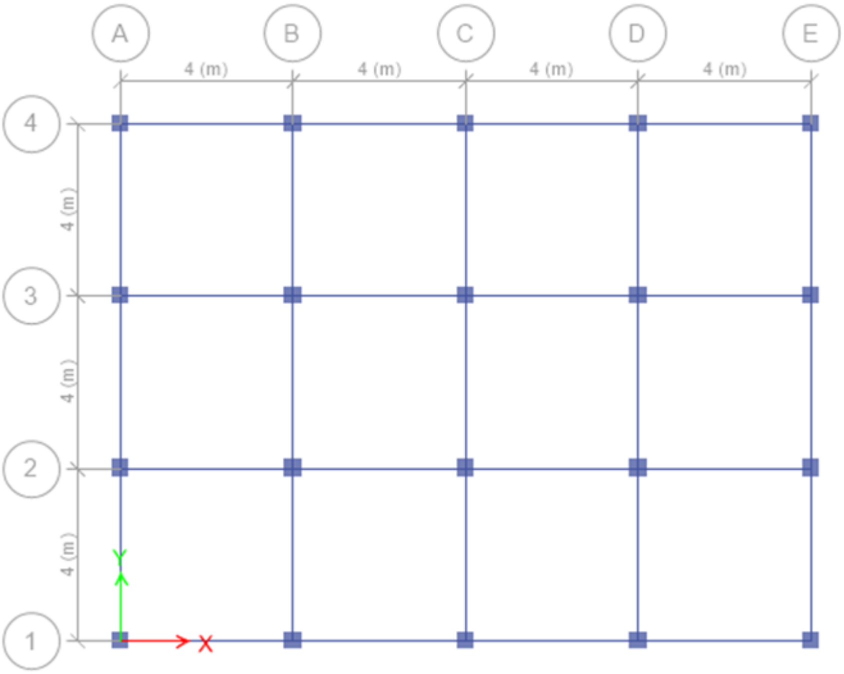


Fig. 2 – Plan of the study building considered

Table 1 – Column sizes (mm) for different models of open ground storey in every storey

	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10
Storey1	500	550	600	650	700	750	800	850	900	950
Storey2	500	500	500	500	500	500	500	500	500	600
Storey3	450	450	450	450	450	450	450	450	450	500
Storey4	450	450	450	450	450	450	450	450	450	500
Storey5	450	450	450	450	450	450	450	450	450	500

2.1 Estimation of storey stiffness.

Soft storeys are identified by estimating storey stiffness using fundamental mode shapes and mass of the building [k=mφ]. Storey stiffness is estimated using [13] and a sample estimation is presented for a frame with ω = 15.78 rad/sec (Table 2 and 3). According to IS1893(part1):2016, when $K_{i+1} > K_i$, it becomes a soft storey where K_i is the stiffness of the ith storey and K_{i+1} is the stiffness of i+1th storey. Definition of soft storey defined by ASCE 7 2010, IBC 2012 [14], BNBC 2015, 1893(part1):2002, NZ 1170 (Part 5) 2004 is $0.7K_{i+1} > K_i$. Both lateral stiffness and mass of the individual storeys shall remain constant or reduce gradually, without any abrupt changes, from the base to the top of a particular building according to EN 1998-1: Eurocode 8 [15].

$$\text{First storey, } K_1 = \frac{\omega^2 \times \sum_{i=1}^{n} m_i \times \varphi_i}{\varphi_1} \tag{5}$$

$$\text{Intermediate storey, } K_{n\text{-}1} = \frac{\omega^2 \times \sum_{i=n\text{-}1}^{n} m_i \times \varphi_i}{\varphi_{n\text{-}1} - \varphi_{n-2}} \tag{6}$$

$$\text{Top storey, } K_n = \frac{\omega^2 \times m_n \times \varphi_n}{\varphi_n - \varphi_{n-1}} \tag{7}$$

Φ_i, m_i, ω^2, are the fundamental translational mode shape, mass and circular frequency.

Table 2 –Storey response of an example 2D frame (M7 model)

Storey	Elevation (m)	Mode shape (mm)	Mass (kg)
Story5	15	0.077	59930
Story4	12	0.069	66163
Story3	9	0.056	66163
Story2	6	0.038	67009
Story1	3	0.017	72642

Table 3– Storey stiffness of an example 2D frame (M7 model)

Storey	Elevation (m)	Storey Stiffness (kN/m)	Soft storey
Story5	15	254065.9	No
Story4	12	311024.3	No
Story3	9	315292.2	No
Story2	6	323658.2	No
Story1	3	431808.9	No

Further, stiffness ratio is estimated, defined as the ratio between stiffness of the storey above the open storey to stiffness of the open storey (Table 4).

Table 4 –Stiffness ratios of open ground story

Frames	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10
Stiffness Ratio	1.76	1.52	1.34	1.14	1	0.83	0.75	0.64	0.56	0.51
Soft Storey	Yes	Yes	Yes	Yes	No	No	No	No	No	No

Axial-flexure (P-M) interaction curves are developed for designed columns, and checked for compliance with axial stress ratio limitation and minimum CBSR stipulated in IS 13920 (2016). Axial stress ratio is verified for stress resultants from all the load combinations considered. Design is further iterated to comply with the code provisions.

Earthquake loads are dynamic but nonlinear static analysis can still be a useful tool for performance evaluation. Pushover analysis is performed of designed buildings in SAP2000. Inelasticity in frame members is modelled using section designer option in SAP2000, based on the design details of beams and columns obtained from hand calculations. Flexural hinges in beams, axial-flexure interacting hinges in columns, and axial hinges are defined in struts. Confinement effects of concrete are also considered, as per Mander's confinement model [16]. Pushover analysis is performed for all the 10 frame models. For a particular stiffness ratio, iterative analyses are carried out to obtain a reasonably good mechanism, by varying CBSR.

3. Discussion of Results

Pushover curves of all the buildings with open ground storey are drawn in one graph (Fig.3). It is observed that drift capacity increases with increase in size of columns, thereby increasing the energy dissipation capacity of the building. It is also observed from the mechanisms that presence of soft storey jeopardises the intended desirable mechanisms. Stiffness of the lower storey is less than stiffness of the upper storey in frame models M1-M4, demonstrating presence of soft storeys. But, in frame models M5-M10, the mechanism formed is nearly desirable one (except at one joint). Also, axial hinges are forming first during pushover analysis and later flexural hinges in beams, and then axial-flexure interacting column hinges. In most of the cases column hinges starts forming when drift is in the range 0.5 to 1% (Fig.4). But, for M10, desirable mechanism is not observed. Thus, increasing column sizes alone does not help improve seismic behaviour of such buildings. The drift capacity of the frames seems to be lower owing to the high stiffness contribution from the infill walls.

Preliminary investigations on intermediate open storey suggest that only increase in strength is a feasible solution to preclude the undesirable mechanisms as increasing sizes of columns at an intermediate storey will also lead to undesirable behaviour (Fig.5). Column hinges are forming at early stages of nonlinear behaviour of the building. This indicates that such soft storeys are not recommended in moderate to high seismic regions. Detailed studies are not carried out on the above and critical design parameters not quantified. Nonlinear dynamic analysis studies are required to more realistically quantify the design parameters for use in design of open ground storey and open intermediate storey buildings and thus improve their seismic behaviour under strong earthquake shaking.

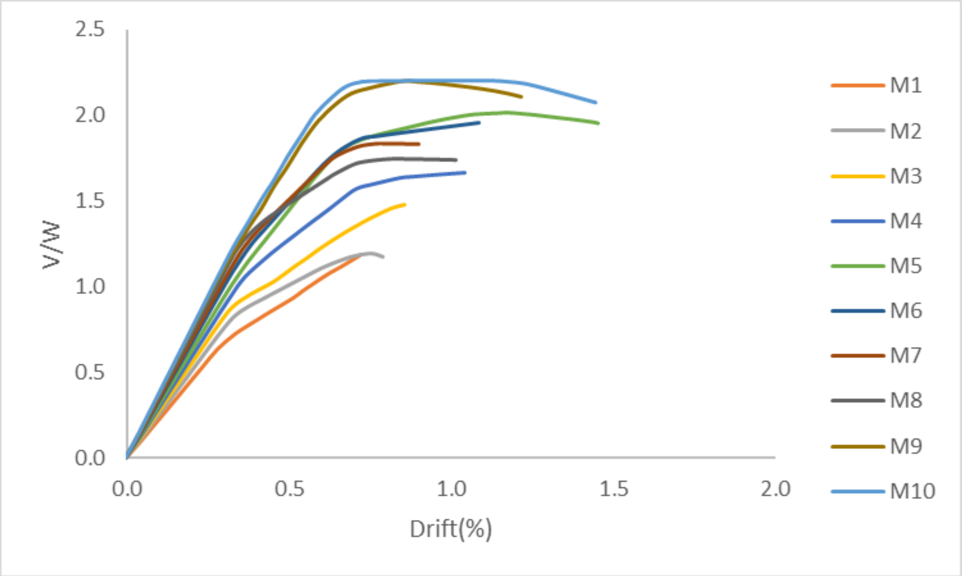


Fig. 3 – Pushover curves of buildings with open ground storey

3.1 Dependence of stiffness ratio with CBSR

In addition, investigations to understand the dependence of stiffness ratio with CBSR is carried out in buildings with open ground storey. An interior beam-column joint of the open storey is considered for the purpose. It is observed that stiffness ratio decreases with increase in CBSR. If the column sizes are significantly different between two storeys, CBSR required to achieve a reasonably good ductile mechanism is high. Thus, it is recommended to use a reasonable stiffness ratio; a stiffness ratio in the range of 1 to 0.6, in combination with a CBSR in the range 4 to 5 help achieve the desired behaviour.

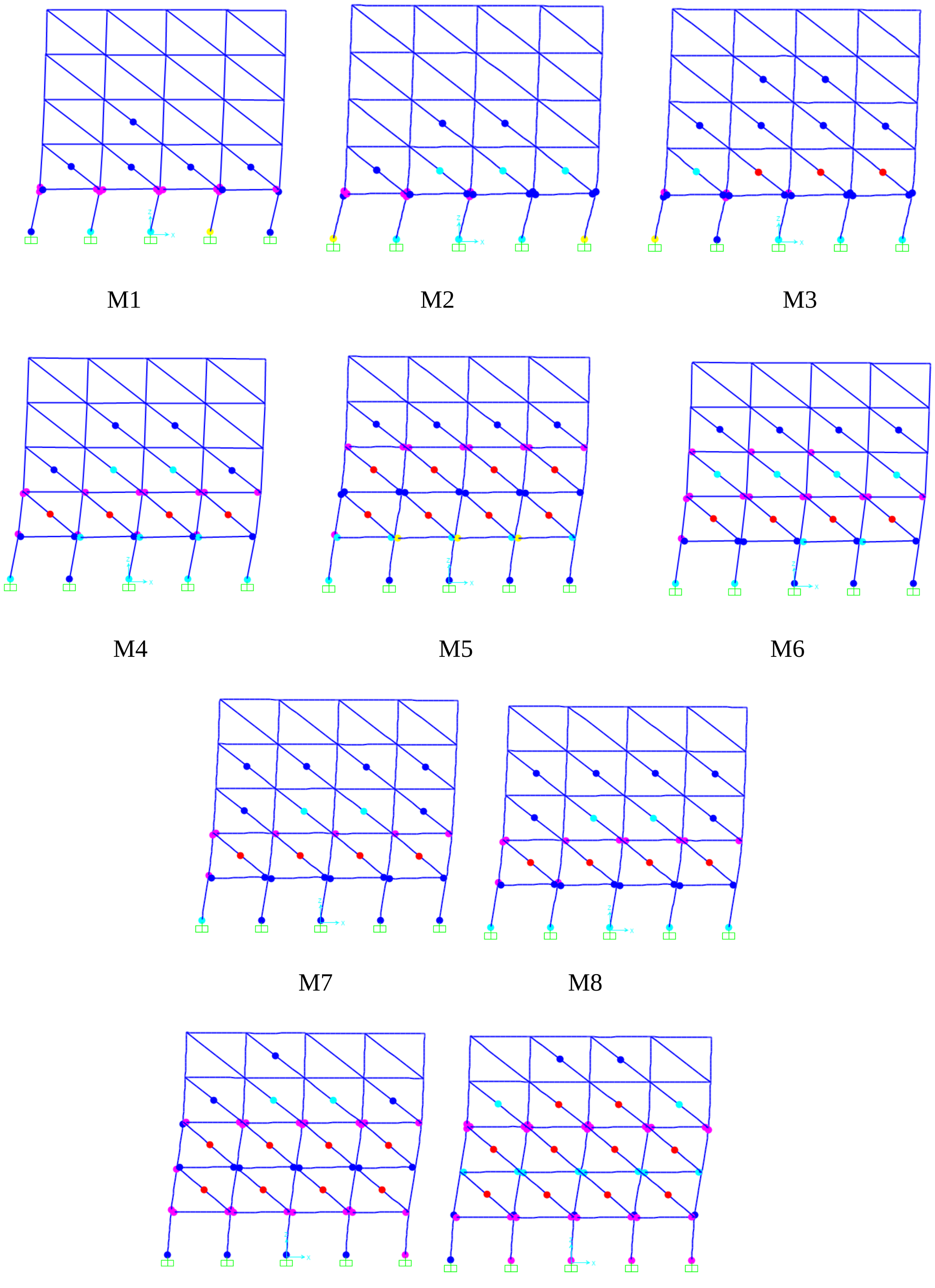
4. Conclusions

The salient conclusions drawn from the detailed study on seismic behaviour of open ground storey buildings and pilot studies on intermediate open storey buildings are:

(1) Increasing stiffness of the open storey and flexural strength of beam-column joints together help preclude the undesirable open storey mechanism in open ground storey buildings,

(2) Desirable stiffness ratio range is 1 to 0.6, alongside a CBSR range of 4 to 5, to preclude the undesirable open storey mechanism in open ground storey buildings,

(3) Intermediate open storey buildings demonstrate extremely poor seismic behaviour, and hence are not recommended.



M1 M2 M3

M4 M5 M6

M7 M8

M9 M10

Fig. 4 – Inelasticity in buildings with open ground storey

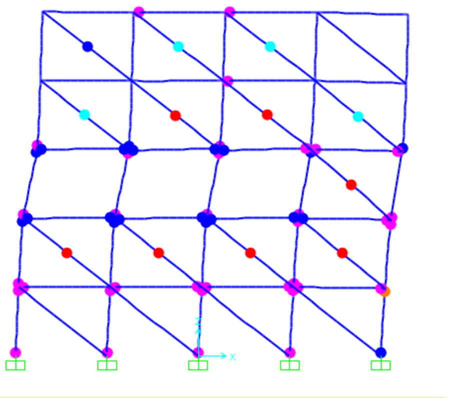


Fig. 5 – Inelasticity in buildings with intermediate open storey

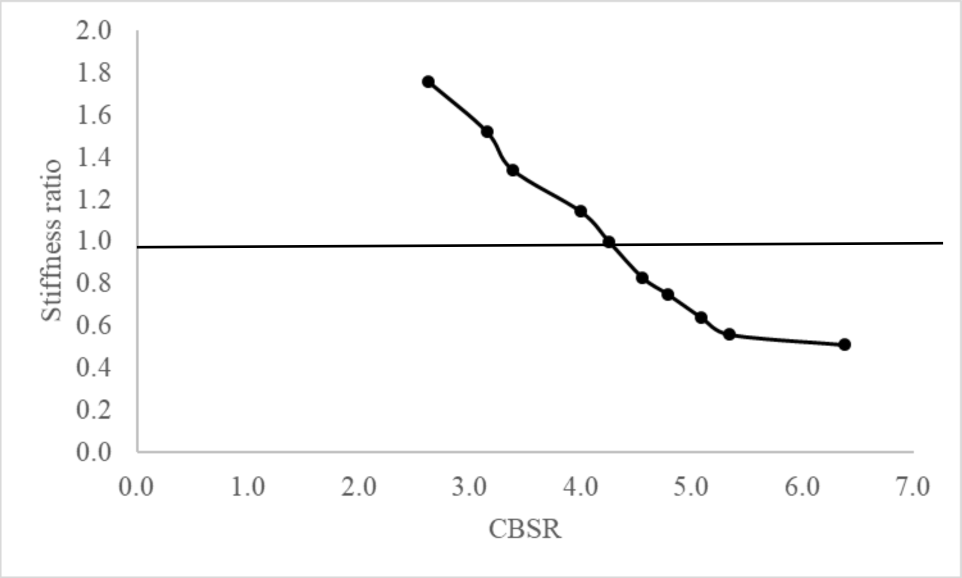


Fig. 6 – Dependence of stiffness ratio with column-to-beam strength ratio for open ground storey

5. References

[1] Murty CVR, Goswami R, Vijayanarayanan AR, Mehta VV (2012): Some Concepts in Earthquake Behavior of Buildings. *Gujarat State Disaster Management Authority, Gandhinagar,* 190-195.

[2] Arnold C, Reitherman R (1982): Building Configuration and seismic design. *John Wiley & Sons, New York*.

[3] Jaswant NA, Sudhir KJ, Murty CVR (1997): Seismic Response of RC Frame Buildings with Soft First Storeys. *Proceedings of the CBRI Golden Jubilee Conference on Natural Hazards in Urban Habitat, New Delhi*.

[4] Mohan HJ, David L, Robert PJ (2001): Performance of buildings during 2001 Bhuj earthquake. *NRC Canada*.

[5] Elnashai S, Sarno LD (2008): Fundamentals of earthquake engineering. *John Wiley & Sons, New York*.

[6] Bureau of Indian Standards (BIS), (2016): Criteria for Earthquake Resistant Design of Structures Part1 General provisions and buildings(IS 1893(Part1):2016), New Delhi,India.

[7] Powell GH (2010): Modelling for structural Analysis, behavior and basics. *Computers and Structures, Inc., Berkeley, California, USA.*

[8] Bureau of Indian Standards (BIS), (2000): Indian Standard Plain and Reinforced Concrete - Code of Practice (IS 456: 2000), New Delhi, India.

[9] Bureau of Indian Standards (BIS), (2016) : Ductile Detailing of reinforced concrete structures subjected to seismic forces – Code of practice(IS 13920(Part1):2016), New Delhi,India.

[10] Paulay T, Priestley MJN (1992): Seismic Design of Reinforced Concrete and Masonry Buildings. *John Wiley & Sons, New York*

[11] Shah HJ, Sudhir KJ (2009):Design example of a six storey building. *IITK-GSDMA-EQ*26-*V*3.0.

[12] Menon D, Pillai U (2005): Reinforced Concrete design. *Tata McGraw-Hill Publishing Company Limited*.

[13] Vijayanarayanan AR, Goswami, R., Murty CVR (2017): Identifying stiffness irregularity in buildings using fundamental lateral mode shape. *Earthquakes and structures Vol*, 12, *No*. 4, 437-448.

[14] IBC (2010): International Code Council (ICC) International Building Code, Birmingham, AL, USA.

[15] EN 1992-1-1 Eurocode 2 (2004): Design of concrete structures - Part 1-1: General rules and rules for buildings.

[16] Mander JB, Priestley MJN, Park R (1988): Theoretical stress strain model for confined concrete. *Journal of Structural Engineering* 114(8): 1804-1826.