INFLUENCE OF STRONG COLUMN & WEAK BEAM CONCEPT, SOIL TYPE AND SEISMIC ZONE ON SEISMIC PERFORMANCE OF R C FRAMES FROM PUSHOVER ANALYSIS

B Shivakumara Swamy[1], S K Prasad[2], Sunil N[3]

[1]*Professor and Head, Civil Engineering Department, Dr. Ambedkar Institute of Technology, Bengaluru, India*
[2]*Professor, Civil Engineering Department, Sri Jayachamarajendra College of Engineering, Mysuru, India*
[3]*Post-Graduate Student, Civil Structural Engineering, Dr. Ambedkar Institute of Technology, Bengaluru, India*

Abstract

Earthquakes are most devastating natural hazards among all the forces that structures are likely to be subjected to. Generally, structures are designed for expected seismic forces and designers rely on the reserve capacity and stiffness aspects of the structure to provide the necessary strength and ductility for resisting unexpected earthquakes. Hence it is very important to design the structure to resist moderate and severe earthquake. According to seismic design philosophy, the capacity design method which is currently used in practice indicates that the structure should have strong columns and not so strong beams to possess good ductility and preferable collapse mechanism. There are many instances of failure of structures during earthquakes due the poor construction practice of providing weaker columns and stronger beams. Pushover analysis is a nonlinear static approach for the seismic analysis of structures subjected to permanent vertical load and gradually increasing lateral load at very large strains up to failure. The present work focuses on emphasizing the need for "strong column-weak beam" concept to enhance the seismic performance of structures using Pushover analysis. The ratio of stiffness of column to that of beam is termed as stiffness ratio, which is varied by changing the cross sections of the columns and keeping the beam cross section the same. For this purpose, a 2D reinforced concrete frame is modeled in ETABS, a finite element software and analyzed is using pushover analysis. The effects of seismic zones and types of soil as per IS 1893 (Part 1): 2002 have been studied. Base shear carried, roof displacements experienced, status of performance point, ductility characteristics and vulnerability index are the parameters used to quantify the performance of RC frame. It is inferred that structures with weaker columns have low seismic capacity, and are most vulnerable to seismic excitations in severe zones and for loose soil condition.

Keywords: *Pushover analysis, performance point, pushover curve, stiffness ratio, ductility ratio, vulnerability index, Seismic Zone, Soil Type.*

---***---

1. INTRODCUTION

An earthquake resisting building is one of that has been deliberately designed to remain safe and suffer no appreciable damage during destructive earthquake. However, during past earthquakes, many buildings have collapsed due to failure of vertical members. Hence columns in the building should be strong and stiff so as to sustain the design earthquake without catastrophic failure. Capacity designing aims towards providing stronger vertical members compared to horizontal structural elements. A structure designed with capacity design concept does not develop any failure mechanism or modes of inelastic deformation that causes the failure of the structures. Hence, the concept of strong column and weak beam is introduced in the design of structures resisting the lateral loads.

Many structures collapsed due to the failure of weaker columns in previous earthquakes. The damage incurred to some apartment buildings during Bhuj earthquake, 2001 of magnitude 7.2 are due to the failure of columns as shown in Figure 1 and the formation of hinge in the column in Figure 2, which shows the poor construction practice. Many structures collapsed during Wenchuan earthquake, 2008 China of magnitude 8.0.due to the failure of columns. Figure 3 shows the first storey corner column showing damage at the top end due to the formation of hinge at Hanwang Town of Mianzhu City during Wenchuan earthquake 2008 and Figure 4 shows the failure of column at the second storey of Dujiangyan City during Wenchuan earthquake 2008.

Fig 1: Failure of Column and Collapse of Structure at Bhuj, during Bhuj Earthquake, 2001 [4]

Fig 2: Failure of Column, Bhuj, during Bhuj Earthquake, 2001 [4]

Fig 3: First Storey Corner Column Showing Damage at the Top End, Mianzhu City, during Wenchuan Earthquake, 2008 [2]

Fig 4: Damaged RC Column at the Second Storey, Dujiangyan City, during Wenchuan Earthquake, 2008 [2]

2. STRONG COLUMN WEAK BEAM CONCEPT

At a particular beam-column joint, if beam is designed to be the weakest then failure of joints can also be avoided. This can be explained by ductile chain analogy (Figure 5). It is observed that the chain breaks at the link of least strength. If all links are brittle and one which is the weakest is ductile and a relative displacement is applied at the ends, internal forces are developed in the links and ultimately the weakest link which is ductile undergoes large final elongations before it fails. Hence, the system experiences ductile failure. Similarly the beam should be the weakest component to make the structure ductile. For this to happen, the beam should be under reinforced and made weak in flexure compared to column. Mathematically it can be expressed as

$$Mc \geq Mb$$

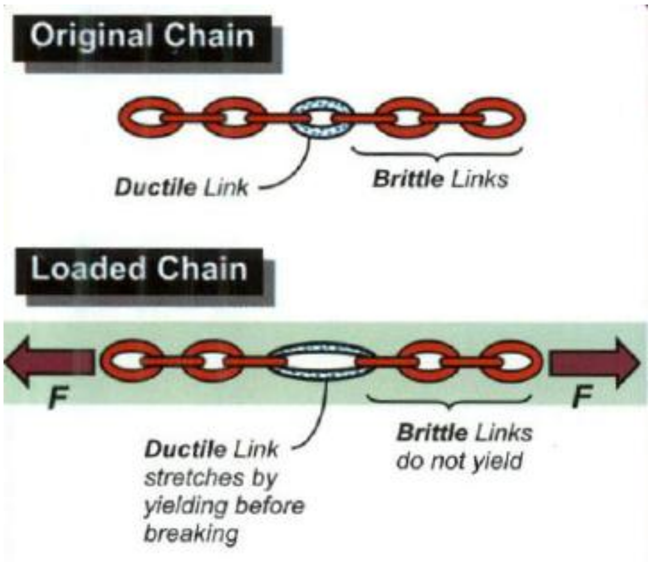

Fig 5: Ductile Chain Analogy [5]

According to seismic design philosophy, plastic hinging of columns is permitted only in the lower storey, while beam hinging is expected to occur at every storey level (Figure 6 a). This type of mechanism allows for more rotation and uniform ductility demands in the structural components of the building, in contrast to "strong beam weak column" concept in which large ductility demands are likely to be concentrated in only a few structural components (Figure 6b).

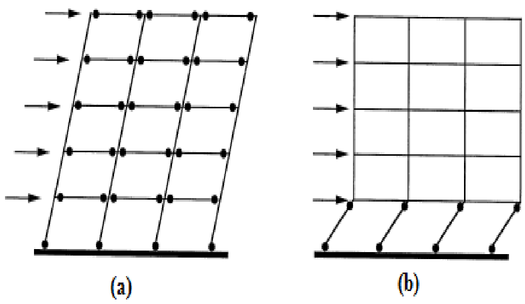

Fig 6: Mechanisms of Strong Column Weak Beam (a) and Weak Column Strong Beam (b) [7]

3. PUSHOVER ANALYSIS

Pushover analysis is basically a nonlinear static procedure in which the magnitude of lateral loads is incrementally increased, maintaining a predefined load pattern along the height of the building. With the increase in magnitude of loads, weak links and failure modes of the building are found. At each step, the base shear and the roof displacement can be plotted to generate pushover curve (Figure 7). Pushover analysis may be classified as displacement controlled pushover analysis when lateral displacement is imposed on the structure and its equilibrium determines the forces. Similarly, when lateral forces are imposed, the analysis is termed as force-controlled pushover analysis. The target displacement or target force is intended to represent the maximum displacement or maximum force likely to be experienced by the structure during the design earthquake. In the present study, displacement-controlled pushover method is used for analysis of RC bare frames. A finite element software package ETABS 9.6.0 has been used for the purpose. The point of intersection of capacity and demand spectrums is known as performance point which will be in Acceleration Displacement Response Spectrum (ADRS) format for 5% damping. Pushover curve with performance levels and ranges are as shown in Figure 8.

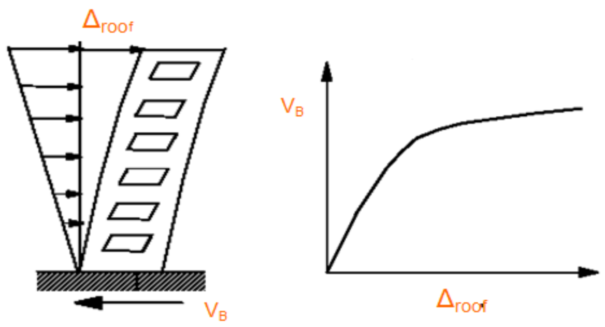

Fig 7: Building Model and Simple Pushover Curve [10]

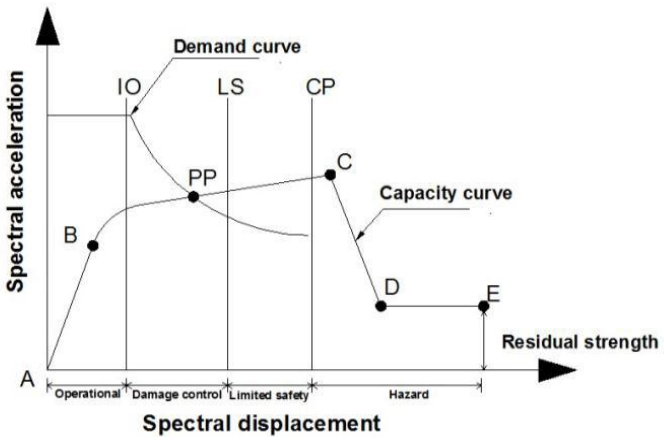

Fig 8: Capacity and Demand Spectrums with Performance Levels [10]

Here,
IO = Immediate Occupancy
LS = Life Safety
CP = Collapse Prevention

4. MODELING AND ANALYSIS

In the present work, a five-storey single bay RC frame (Figure 9) is modeled by using ETABS. To understand the behavior of stiffness variation between column and beam, the cross section of the column is varied while the cross section of beam is kept same. Here the stiffness ratio is defined as the ratio of stiffness of column to that of the beam. Table 1 shows the varied cross sections of columns and stiffness ratio. The grade of concrete for columns and beams is taken as M25. The live load of $4kN/m^2$ and the floor finish load of $1kN/m^2$ are assumed. The cross section of beams is 250mm X 400mm.

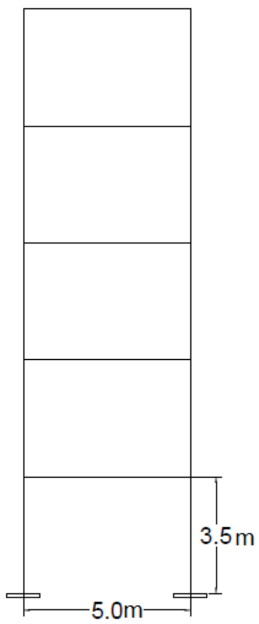

Fig 9: Model Considered in the Present Study

Table 1: Varied Cross Sections of Column

Stiffness Ratios	**Column Cross Sections (mm^2)**
1.60	400X400
0.95	350X350
0.50	300X300
0.25	250X250
0.10	200X200

Initially, the model is analyzed and designed as per IS 456: 2000 for gravity loads. Default hinge properties available in ETABS [3] as per ATC-40 are used to assign hinge properties (material non linearity). Hinges are considered at both the ends of beam and column elements. The hinge properties assigned are M3 (only moment) and PMM (axial force and biaxial moments) for beams and columns respectively. The pushover analysis is carried out, pushover curves are obtained, the status of performance point is studied and ductility characteristics are assessed from ductility ratio. Ductility ratio is the ratio of ultimate displacement to yield displacement. Then the fragility analysis is carried out using predefined values of spectral displacement, Table 2 shows the predefined values for the identification of global damage states [6]. Then the vulnerability index is obtained by multiplying the probability of expedience of a damage state with cost fraction associated with the damage state. Table 3 shows an example of cost fractions for various damage states [6].

Table 2: Predefined Values for the Identification of Global Damage States [6]

Damage State	Threshold Value
Slight Damage	S_{dy}
Moderate Damage	$1.5\ S_{dy}$
Extensive Damage	$0.5\ (S_{dy}+S_{du})$
Complete Damage	S_{du}

Here in the Table 2,
S_{dy} = Spectral displacement at the effective yield and
S_{du} = Maximum spectral displacement

Table 3: Cost Fractions for Various Damage States [6]

Damage State	Cost Fraction
No Damage	0
Slight Damage	2%
Moderate Damage	10%
Extensive Damage	50%
Collapse	100%

5. RESULTS AND DISCUSSIONS

An attempt is made to study the strong column weak beam concept by varying the stiffness between column and beam. Thus the cross section of columns are varied (Table 1). Further, the types of soil and different seismic zones as per IS 1893 (Part 1) are considered in the present work.

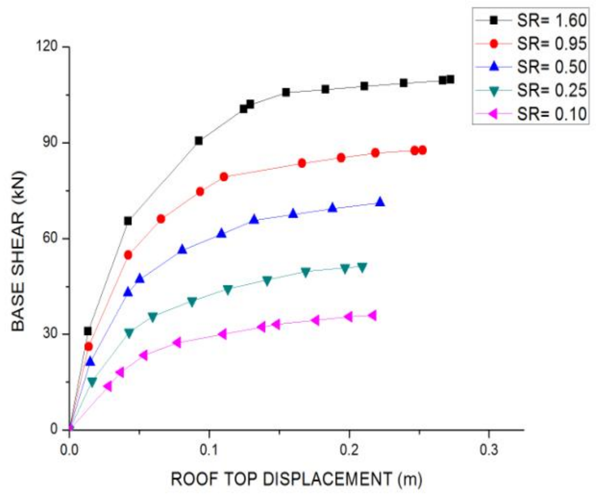

Fig 10: Pushover Curves for Varying Stiffness Ratio

The resulting pushover curves are shown in figure 10 which are obtained for different stiffness ratios. There is reduction of base shear carrying capacity of the frame with reduction in stiffness ratio. Hence as the columns become weaker compared to beams, there is reduction in base shear carrying capacity of the frame.

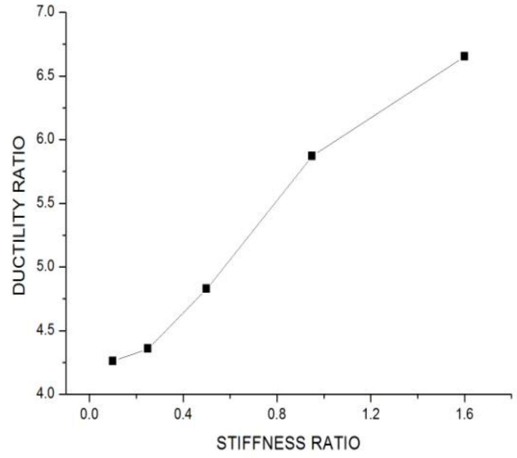

Fig 11: Ductility Ratio for Varying Stiffness Ratio

Figure 11 shows the variation of ductility ratio with different stiffness ratios. As the columns become weaker compared to beams, there is reduction in ductility demand of the structure.

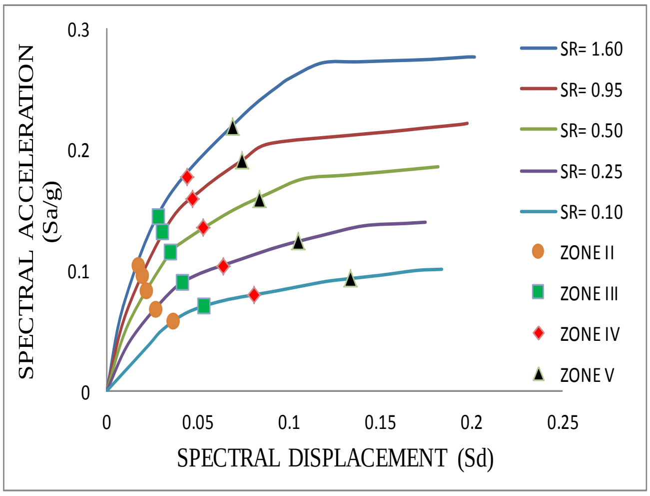

Fig 12: Performance Point for Type I Soil

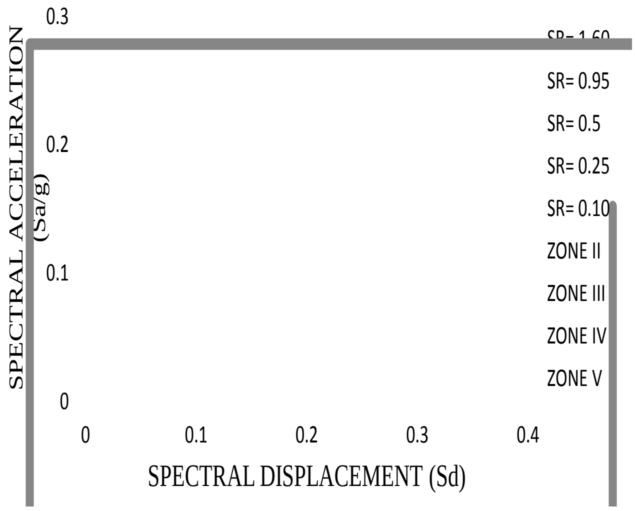

Fig 13: Performance Point for Type II Soil

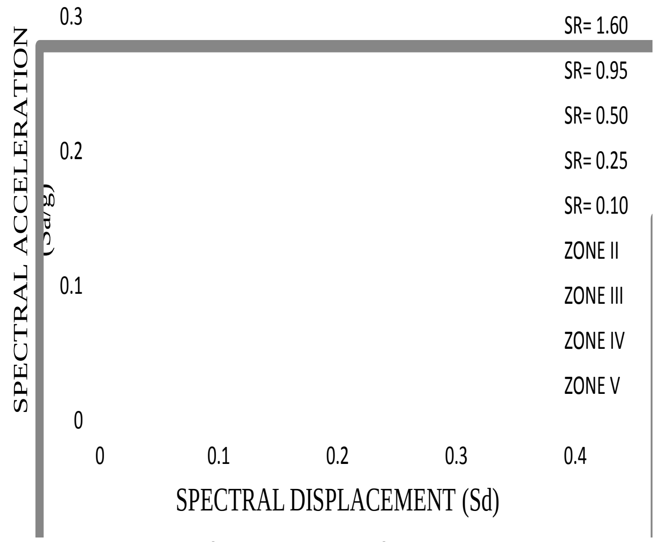

Fig 14: Performance Point for Type III Soil

Figure 12, Figure 13 and Figure 14 show the performance point for soil Type I, II and III respectively, for different seismic zones and also for different stiffness ratios. There is shift of performance point from linear stage for lower seismic zone to collapse stage for severe seismic zone. Besides, loose soil condition increases the vulnerability to seismic action.

Table 4: Coordinates of Performance Points for Soil Type I, Different Stiffness Ratios and Seismic Zones

SR	**Zones**	**Sa**	**Sd**	**V_B (kN)**	**Δ_R (m)**
1.60	II	0.104	0.018	42.962	0.023
	III	0.144	0.029	59.03	0.037
	IV	0.178	0.044	72.369	0.056
	V	0.22	0.069	88.47	0.089
0.95	II	0.095	0.02	37.441	0.0025
	III	0.131	0.031	51.653	0.039
	IV	0.159	0.047	62.646	0.058
	V	0.191	0.074	74.29	0.092
0.50	II	0.083	0.022	31.584	0.028
	III	0.114	0.035	43.502	0.043
	IV	0.135	0.053	51.435	0.064
	V	0.16	0.084	60.317	0.103
0.25	II	0.067	0.027	24.975	0.033
	III	0.089	0.042	33.063	0.051
	IV	0.104	0.064	38.575	0.077
	V	0.124	0.105	45.441	0.125
0.10	II	0.058	0.037	20.727	0.045
	III	0.07	0.054	25.502	0.066
	IV	0.08	0.081	28.995	0.097
	V	0.094	0.134	33.594	0.158

Table 5: Coordinates of Performance Points for Soil Type II, Different Stiffness Ratios and Seismic Zones

SR	**Zones**	**Sa**	**Sd**	**V_B (kN)**	**Δ_R (m)**
1.60	II	0.131	0.026	53.733	0.032
	III	0.171	0.04	69.825	0.051
	IV	0.209	0.063	84.304	0.08
	V	0.261	0.103	102.745	0.135
0.95	II	0.119	0.028	46.975	0.034
	III	0.153	0.043	60.273	0.053
	IV	0.183	0.067	71.507	0.083
	V	0.209	0.113	81.625	0.141
0.50	II	0.104	0.031	39.787	0.038
	III	0.13	0.048	49.75	0.059
	IV	0.154	0.076	58.379	0.092
	V	0.179	0.129	67.335	0.158
0.25	II	0.084	0.037	31.226	0.045
	III	0.101	0.058	37.435	0.07
	IV	0.12	0.094	43.998	0.111
	V	0.139	0.164	50.758	0.196
0.10	II	0.067	0.048	24.334	0.059
	III	0.078	0.074	28.304	0.088
	IV	0.091	0.119	32.542	0.141
	V	0.059	0.33	21.095	0.379

Table 6: Coordinates of Performance Points for Soil Type III, Different Stiffness Ratios and Seismic Zones

SR	**Zones**	**Sa**	**Sd**	**V_B (kN)**	**Δ_R (m)**
1.60	II	0.15	0.031	61.658	0.039
	III	0.188	0.05	76.256	0.064
	IV	0.233	0.079	93.07	0.101
	V	0.272	0.129	106.258	0.17
0.95	II	0.137	0.033	53.971	0.041
	III	0.168	0.053	66.2	0.066
	IV	0.202	0.085	77.966	0.106
	V	0.214	0.145	84.537	0.182
0.50	II	0.117	0.037	44.775	0.045
	III	0.142	0.06	54.007	0.073
	IV	0.169	0.097	63.08	0.118
	V	0.184	0.169	70.237	0.206
0.25	II	0.091	0.044	33.976	0.054
	III	0.109	0.073	40.322	0.087
	IV	0.13	0.121	47.345	0.144
	V	0.097	0.288	35.96	0.338
0.10	II	0.072	0.057	26.075	0.069
	III	0.083	0.092	30.051	0.11
	IV	0.097	0.155	34.692	0.183
	V	N/A			

Table 4, Table 5 and Table 6 show the values of spectral acceleration, spectral displacement, base shear and roof top displacement at performance points for varying stiffness ratios and different seismic zones for soil type I, II and III respectively.

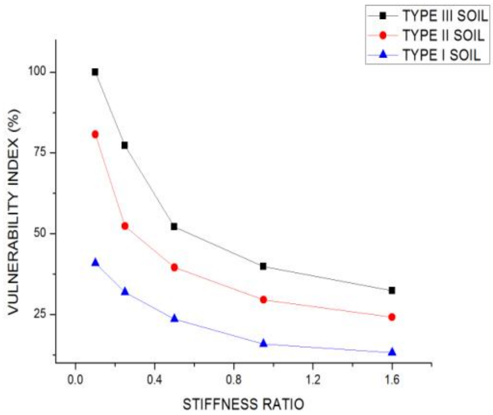

Fig 15: Vulnerability index for different stiffness ratios and types of soil

Figure 15 shows the variation of vulnerability index for different stiffness ratios and types of soil. The structure with least stiffness ratio (weaker columns) is most vulnerable to seismic excitation than the structures with stronger columns and also structures on soft soil experiences higher vulnerability index.

6. CONCLUSIONS

In the present study, an attempt is made to understand the concept of "Strong Column Weak Beam" of RC frames by varying the stiffness of columns with respect to that of beams. A five-storey single-bay 2D RC frame is modelled and analysed (pushover analysis) using ETABS 9.6.0. Following are the conclusions drawn from the present study.

- The base shear carrying capacity of the structure reduces with reduction in stiffness ratio, indicating the vulnerability of structures with weak columns and strong beams. Hence structures with strong columns weak beams are preferred.
- As the columns become weaker compared to beams, there is reduction in ductility demand of the structure.
- There is shift of performance point from linear stage for lower seismic zone to collapse stage for severe seismic zone.
- There is shift of performance point from linear stage for structure on loose soil condition to that on denser soil conditions.
- Vulnerability index increases with increase in stiffness of columns compared to that of beams and structure on hard rock / soil condition performs better.

The present study emphasizes the importance of adopting capacity design procedure with "Strong Column Not so strong Beam" concept while designing the structures so that the structures can resist severe earthquakes better. Further, a better foundation soil can always enhance the performance of structures during earthquakes.

REFERNCES

[1] Applied Technical Council (ATC-40: 1996), "*Seismic Evaluation and Retrofit of Concrete Buildings*", California Seismic Safety Commission, Redwood City, California.

[2] Bin Zhao, Fabio Taucer and Tiziana Rossetto (2009), "*Field investigation on the performance of building structures during the 12 May 2008 Wenchuan earthquake in China",* Engineering Structures 31, 1707-1723, London, UK.

[3] CSI (2013), "CSi Analysis Reference Manual", Computers and Structures, Inc., Berkeley, California.

[4] D'Ayala D, (2013), "*Assessing the seismic vulnerability of masonry buildings",* Handbook of Seismic Risk analysis and management of civil infrastructure systems, Wood head publishing, 334-365.

[5] Federal Emergency Management Agency (FEMA 454: 2006) "*NEHRP Risk Management Series, Design for Earthquakes, a Manual for Architects*", Washington D.C.

[6] IS- 1893- Part I: 2002, "*Criteria for Earthquake Resistant Design of Structures*", Bureau of Indian Standards, New Delhi.

[7] IS- 456: 2000, "*Indian Standard Code of practice for Plain and Reinforced Concrete*", Bureau of Indian Standards, New Delhi.

[8] Murthy. C. V. R, Svetlana Brzev, Heidi Faison, Craig D. Comartin and Ayhan Irfanoglu, (2006), "*AT RISK: The Seismic Performance of Reinforced Concrete Frame Buildings with Masonry Infill Walls",* Publication Number WHE-2006-03, Earthquake Engineering Research Institute, Oakland, California.

[9] Murthy. C. V. R (2005), "*Earthquake Tips*", Learning Earthquake Design and Construction.

[10] Sujay Deshpande, (2009), „"*Seismic Performance Study of R.C. Frames With Stiffness Irregularities Using Pushover Analysis*", M.Tech Thesis, Department of Civil Engineering, SJCE, Mysuru.

BIOGRAPHIES

Dr. B. Shivakumaraswamy is a Professor and the Head of Department, Civil Engineering at Dr. Ambedkar Institute of Technology with over 25 years of teaching experience and research experience and has many technical papers at national and international levels to his credit.

Dr. S.K. Prasad is a Professor of Civil Engineering at S.J. College of Engineering with over 30 years of teaching & research experience and has more than 100 technical papers at national and international levels to his credit.

Sunil N is a Post Graduate Student in Structural Engineering at Dr. Ambedkar Institute of Technology, Bengaluru.