Structural Engineering and Mechanics, *Vol. 51, No. 3 (2014) 487-502*
DOI: http://dx.doi.org/10.12989/sem.2014.51.3.487

Seismic performance of lateral load resisting systems

K. Subramanian[*1] and M. Velayutham[2a]

[1]*Department of Civil Engineering, Coimbatore Institute of Technology,Tamil Nadu, Coimbatore, 641 014, India*
[2]*Anna University, Chennai, 600 025, India*

(Received April 29, 2013, Revised May 14, 2014, Accepted May 18, 2014)

Abstract. In buildings structures, the flexural stiffness reduction of beams and columns due to concrete cracking plays an important role in the nonlinear load-deformation response of reinforced concrete structures under service loads. Most Seismic Design Codes do not precise effective stiffness to be used in seismic analysis for structures of reinforced concrete elements, therefore uncracked section properties are usually considered in computing structural stiffness. But, uncracked stiffness will never be fully recovered during or after seismic response. In the present study, the effect of concrete cracking on the lateral response of structure has been taken into account. Totally 120 cases of 3 Dimensional Dynamic Analysis which considers the real and accidental torsional effects are performed using ETABS to determine the effective structural system across the height, which ensures the performance and the economic dimensions that achieve the saving in concrete and steel amounts thus achieve lower cost. The result findings exhibits that the dual system was the most efficient lateral load resisting system based on deflection criterion, as they yielded the least values of lateral displacements and inter-storey drifts. The shear wall system was the most economical lateral load resisting compared to moment resisting frame and dual system but they yielded the large values of lateral displacements in top storeys. Wall systems executes tremendous stiffness at the lower levels of the building, while moment frames typically restrain considerable deformations and provide significant energy dissipation under inelastic deformations at the upper levels. Cracking found to be more impact over moment resisting frames compared to the Shear wall systems. The behavior of various lateral load resisting systems with respect to time period, mode shapes, storey drift etc. are discussed in detail.

Keywords: 3 dimensional seismic analysis; effective structural system; response spectrum analysis; stiffness degradation; time period and mode shapes

1. Introduction

The dynamic behavior of structures under earthquake actions is dependent upon the lateral resisting system employed. To achieve satisfactory seismic performance, basically the structural systems should possess the following properties.

- Adequate stiffness
- Adequate strength
- High ductility

*Corresponding author, Professor, E-mail: drkscit@gmail.com
[a]Ph.D. Research Scholar and Practicing Structural Engineer, E-mail: velscit@yahoo.com

http://www.techno-press.org/?journal=sem&subpage=8 ISSN: 1225-4568 (Print), 1598-6217 (Online)

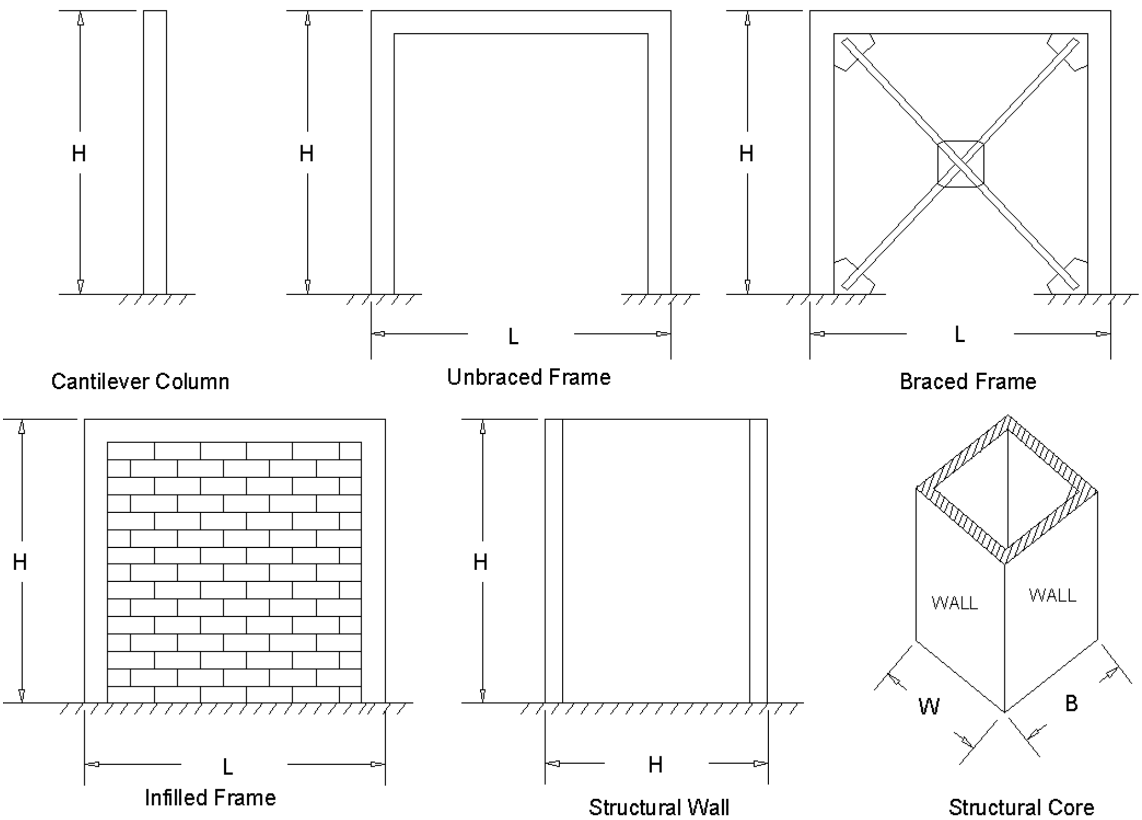


Fig. 1 Basic structural systems with increasing lateral stiffness (from top left to bottom right)

- High damping
- High stability
- High redundancy

Even though several structural systems are employed to resist the lateral forces, but few of the above properties are satisfied by them. In these cases, different structural components or systems may be combined to improve the global seismic response. For example, dual (or hybrid) systems, which combine frames with bracing components such as structural walls, are more effective than either of the components on their own.

Earthquake resistance can be achieved through a wide range of vertical systems, which can range from free-standing columns to complex three-dimensional framed tubes and cores. Fig. 1 shows the basic structural systems, which have been ranked according to their lateral stiffness. Columns are the simplest structural elements with lateral stiffness and strength. In the present study, three different structural systems are undertaken, namely Special Moment Resisting Frame, Shear wall and Dual system to assess the relative effectiveness based on the properties such as strength, stiffness, ductility etc.

In buildings structures, the flexural stiffness reduction of beams and columns due to concrete cracking plays an important role in the nonlinear load-deformation response of reinforced concrete structures under service loads. The concrete cracking amplifies the lateral deflection of the building. The excessive lateral deflection may cause out of order of nonstructural components.

Table 1 Reduction ractors

Element	Stiffness Considered
Slabs	0.25 Ig
Beams	0.35 Ig
Columns	0.70 Ig
Walls	0.70 Ig

Most world seismic standards do not establish effective stiffness for seismic analysis. But few researchers and some of the international codes suggested considering the effective stiffness. Some design codes recognize the influence of cracking. They consider stiffness of the cracked section EIe proportional to the stiffness of the gross uncracked section EIg, specifying reduction factors to be applied to the stiffness of the uncracked cross section. But Indian code is silent on the introduction of cracking effects for the global lateral response. The present work also has been carried out to study the quantitative effect of cracking and deflections amplification on the response of RCC building. The building with various lateral load resisting systems and different relative height are analyzed. The lateral loads are generated as per the Indian code IS 1893 (Part 1): 2002. The ACI 318M-08 guidelines for effective flexural rigidity shown in Table 1 are followed to include the concrete cracking in absence of Indian standard recommendations for cracking.

The earthquake ground acceleration is given as a digitized response-spectrum curve of pseudo-spectral acceleration response versus period of the structure. Three dimensional mode shapes and frequencies, modal participation factors, direction factors and participating mass percentages are being evaluated using Ritz-vector analysis. The peak response quantities such as member forces, displacements, storey forces, storey shears and base reactions shall be combined as per Complete Quadratic Combination method. The accidental eccentricity is considered in all floor diaphragms.

In general, it is difficult to evaluate all aspects of the complete seismic behavior of structures due to the complexity and number of parameters involved. However this study is focused on the overall global seismic behavior and the economic dimensions that achieve the saving in concrete and steel amounts thus achieve lower cost of high-rise RC buildings in order to provide both the seismic engineering research field and industry with a methodology for analysis & assessment which may be used reliably & conservatively to estimate global seismic behavior.

2. Literature review

A literature review has been performed to investigate current mathematical and analytical work which has been carried out with regard to efficient lateral load resisting systems against earthquake forces and few of them are explained.

Behavior of reinforced concrete structures with shear wall and infill for seismic forces was studied by Zaregarizi (2008) and suggested as combination of concrete and brick infill is very effective in resisting the earthquake forces. Duan *et al.* (2012) studied and investigated the seismic performance of a multi-story reinforced concrete frame building designed according to the provisions of the current Chinese seismic code (GB50011-2010). He has evaluated the frame structure using both a nonlinear static (push-over) analysis and nonlinear dynamic time-history analysis and found that the response intended by the code and satisfies the interstory drift and maximum plastic rotation limits suggested by ASCE/SEI 41-06. Chandler (2000) investigated on traditional force based seismic design method and displacement method. He concluded that the displacement based method easily facilitate a seismic assessment of an existing structure without taking detailed inelastic dynamic analysis for small number of frame systems. Kim *et al.* (2005) studied framed structure with shear wall for resisting horizontal forces effectively. In his study, Static and dynamic analyses of example structures with various types of opening were performed to verify the efficiency and accuracy of the proposed method and he was confirmed that the proposed method uses the super elements and fictitious beams can provide results with outstanding accuracy requiring significantly reduced computational time and memory. Paulay (1983) has given brief review of a deterministic design philosophy with respect to earthquake resisting ductile structures for reinforced concrete buildings and highlighted the capacity design procedures relevant to beams, columns and shear walls. Lu *et al.* (2001) studied and investigated regarding the selection of adequate ductility levels and the corresponding seismic force reduction factor for a specific class of structures, whereas the detailing requirements to ensure the desired ductility continue to be refined. In his investigation, three simple frames were designed for different ductility levels according to EC8 and confirmed the satisfactory performance was observed in the frame designed for medium ductility.

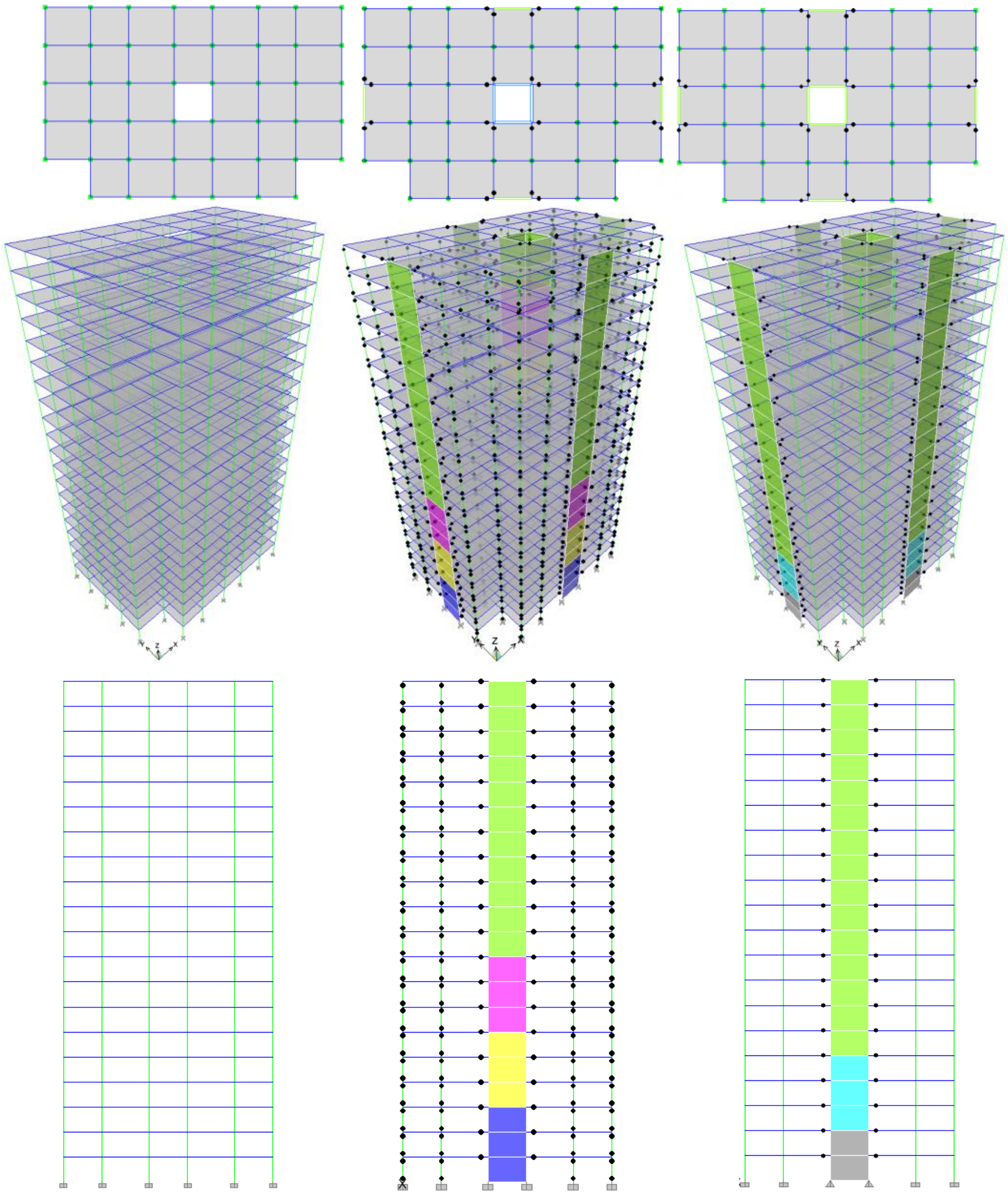
Most of the current research has focused on local behavior rather than overall global response. This study concentrates on global behavior of various structural systems used to resist the lateral forces such as seismic and wind forces to assess the relative effectiveness of different structural systems using the 3 dimensional analytical models.

3. Problem reported

This paper deals with 3 dimensional seismic analysis of typical multistory building consisting of 5, 10, 15, 20 and 25 stories used for office functionalities to be constructed in various critical seismic regions of India to assess the relative effectiveness of various lateral load resisting systems. Thick populated metropolitan city Chennai under seismic zone III with peak ground acceleration of 0.16, India Capital Delhi under seismic zone IV with PGA 0.24 and Bhuj(Gujarat) woke up to the deadliest earthquake in India's recorded history with highest PGA in Indian seismic zone map of 0.36 are taken in the present research. Three different structural systems are taken in the study, namely Special moment resisting systems, Shear wall systems and Dual systems. Ductile systems are taken in the study, where inelastic analysis procedures effectively account for several sources of force reduction.

Response Spectrum analysis of IS 1893 (Part 1):2002 is performed to analysis and design the structures. The ACI 318M-08 guidelines for effective flexural rigidity are followed to include the concrete cracking in absence of Indian standard recommendations for cracking. Totally 120 cases of 3Dimensional Dynamic Analysis which considers the real and accidental torsional effects are performed using ETABS to determine the effective structural system across the height, which ensures the performance and the economy. Basic Wind Speed is taken as 50m/s based on the metropolitan cities considered in the present study. Effect of wind across the height of the structure is studied and this concludes the severity of wind over the height compares to seismic region.

The base dimensions of the building are 39×25 m. The total height of building considered in the research study is varying from 16m to 80m respectively for 5 Story to 25 Story. The structural



(a) SMRF (b) Shear Wall (c) DUAL System

Fig. 2 20 Story Plan, 3D View and Elevation

system undertaken in the present study consists of conventional beam, column and slab system with lift walls and walls around periphery of the building acting as shear wall. Lateral Stability is provided by frames consisting of beams and columns in SMRF system. Both frames and shear walls contribute to the lateral stability in Dual systems, but 100% lateral force is considered to be resisted by walls in shear wall system. Totally 7 bays are considered in X direction and 5 bays in Y direction. Bays are assigned with 5m and 6m alternatively in X direction and 5 m bays in Y

Table 2 Members dimensions of 5, 10, 15, 20 and 25 Story building

STORY	SEISMIC ZONE	COLUMN (mm)			BEAM (mm)			WALL (mm)		
		SMRF	SW	DUAL	SMRF	SW	DUAL	SMRF	SW	DUAL
5	Z III	375×375	350×350	375×375	300×350	300×300	300×350	-	200	200
	Z IV	400×400	350×350	400×400	300×400	300×300	300×400	-	200	200
	Z V	450×450	350×350	450×450	400×400	300×300	400×400	-	300-200	200
10	Z III	500×500	475×475	500×500	300×350	300×400	300×350	-	400-200	200
	Z IV	550×550	475×475	550×550	400×450	300×400	400×550	-	500-200	200
	Z V	600×600	475×475	600×600	400×600	300×400	400×600	-	600-200	400-200
15	Z III	600×600	575×575	600×600	400×400	300×400	400×400	-	400-200	200
	Z IV	650×650	575×575	650×650	400×450	300×400	400×450	-	500-200	300-200
	Z V	700×700	575×575	700×700	450×600	350×400	450×600	-	700-200	400-200
20	Z III	675×675	675×675	675×675	400×400	350×400	400×400	-	400-200	300-200
	Z IV	700×700	675×675	700×700	400×500	350×400	400×500	-	500-200	300-200
	Z V	750×750	675×675	750×750	450×600	350×400	450×600	-	800-200	400-200
25	Z III	750×750	750×750	750×750	400×400	350×400	400×400	-	600-200	200
	Z IV	775×775	750×750	775×775	400×500	350×400	400×500	-	700-200	300-200
	Z V	825×825	750×750	825×825	450×600	400×600	450×600	-	900-200	500-200

direction. Floor and roof systems act as horizontal diaphragms in building structures. Diaphragms are of assigned with 200tk which collects and transmit inertia forces to the vertical elements of lateral resistant systems, i.e., columns and structural walls.

The dimensions of the structural members required based on this research study are given in Table 2 for 5, 10, 15, 20and 25 story structures. Fig. 2(a)-2(c) shows the Structural Plan, 3D and Elevation view of 20 Story Analytical models of SMRF, SW System and DUAL Systems respectively.

4. Methodology

Buildings with regular, or nominally irregular plan configuration may be modeled as a system of masses lumped at floor levels with each mass having one degree of freedom, that of lateral displacement in the direction under consideration.

Undamped free vibration analysis of entire building modeled as spring - mass model shall be performed using appropriate masses and elastic stiffness of the structural system to obtain natural periods (T) and mode shapes $\{\varphi\}$ of those of its modes of vibration that needs to be considered. The number of modes to be used should be such that the sum of total of modal masses of all modes considered is at least 90% of total seismic mass.

In dynamic analysis the following expressions shall be used for the computation of various quantities:

4.1 Modal mass (M_k)

Modal mass of the structure subjected to horizontal or vertical as the case may be, ground motion is a part of the total seismic mass of the structure that is effective in mode k of vibration. The modal mass for a given mode has a unique value, irrespective of scaling of the mode shape.

$$M_k = (\Sigma\, Wi\, \varphi i_k)^2/(g\, \Sigma\, Wi\, \varphi i_k^2) \tag{1}$$

4.2 Modal participation factor (Pk)

Modal participation factor of mode k of vibration is the amount by which mode k contributes to the overall vibration of the structure under horizontal or vertical earthquake ground motions. Since the amplitudes of 95 percent mode shape can be scaled arbitrarily, the value of this factor depends on the scaling used for the mode shape.

$$P_k = (\Sigma\, Wi\, \varphi i_k)/(\Sigma\, Wi\, \varphi i_k^2) \tag{2}$$

4.3 Design lateral force at each floor in each mode (Qik)

The peak lateral force (Qi_k) at floor i in mode k is given by

$$Qi_k = A_k\, \varphi i_k\, P_k\, Wi \tag{3}$$

Where

$$A_k = (Z/2 * I/R * Sa/g)$$

4.4 Storey shear forces in each mode

The peak shear force (Vi_k) acting in storey i in mode k is given by

$$Vi_k = \Sigma\, Qi_k \tag{4}$$

4.5 Storey shear force due to all modes considered

The peak storey shear force (V_i) in storey i due to all modes considered is obtained by combining those due to each mode as per following rules:

4.5.1 CQC method

The peak response quantities shall be combined as per Complete Quadratic Combination (CQC) method

$$\lambda = \sqrt{\sum_{1}^{r} \sum_{1}^{r} \lambda i\, \rho ij\, \lambda j} \tag{5}$$

Where

$$\rho ij = \frac{8\zeta^2\ (1+\beta)\,\beta^{1.5}}{(1-\beta^2)^2 + 4\zeta^2\ \beta(1+\beta)^2}$$

4.5.2 SRSS method

If the building does not have closely spaced modes, than the peak response quantity (λ) due to all modes considered shall be obtained as per Square Root of Sum of Square method

$$\lambda = \sqrt{\sum_{1}^{r} (\lambda_k)^2} \tag{6}$$

If the building has a few closely spaced modes, then the peak response quantity (λ*) due to these modes shall be obtained as

$$\lambda^* = \sum_{c}^{r} (\lambda_k) \tag{7}$$

Where the summation is for the closely spaced modes only. This peak response quantity due to the closely spaced modes (λ*) is then combined with those of the remaining well separated modes by the method of SRSS.

4.6 The design base shear (VB)

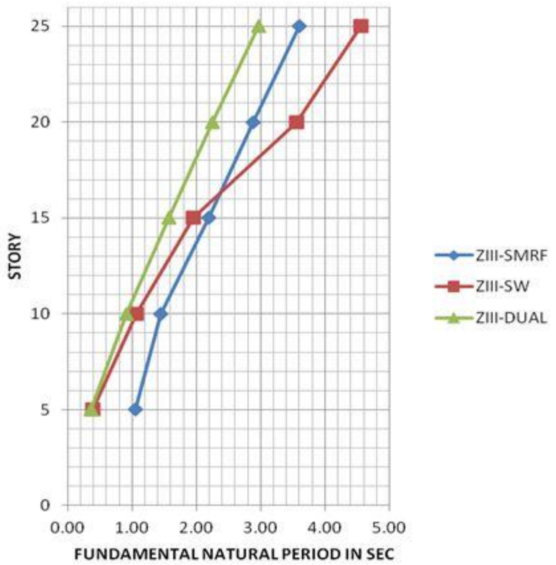
The design base shear V_B from the dynamic analysis shall be compared with base shear $\overline{V_B}$ calculated using a fundamental natural period T_a, as given by empirical formula of clause 7.6 of IS 1893 (Part 1):2002. Where V_B is less than $\overline{V_B}$, all the response quantities shall be multiplied by $\overline{V_B}/V_B$. The design base shear here onwards also called as Amplified Shear.

5. Analysis results

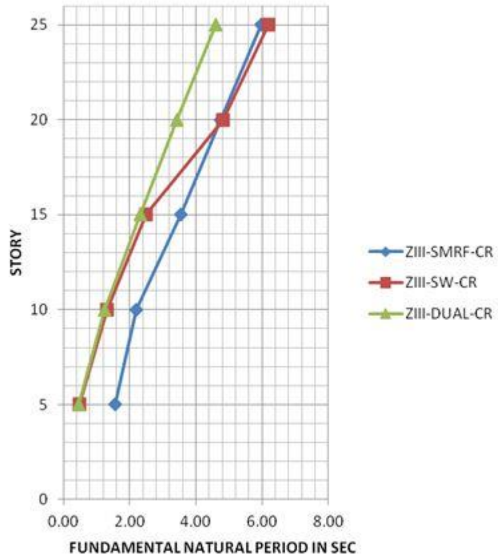
Fig. 3(a)-(b) shows the Story Vs Fundamental natural time period of structures over the various heights of the structures for Zone III. It is found from the graph of uncracked analysis that, the SW system is stiff compared to SMRF systems at lower level till 15th floor and over the 15th the SW is found to be flexible by 25%, 40%, and 50% respectively for Zone III, IV and V at 25th story. But from the cracked analysis, it is found that SW system is flexible compared to SMRF system by only 4%, 16% and 27% respectively for Zone III, IV and V at 25th story. The reason is that cracking has more impact over moment resisting frames compared to the Shear wall systems.

It is generally found that the Dual and SW system are more stiff compared to SMRF system for the lower story structures up to 10-15 stories. Beyond 15 stories, it is found that the SW system is flexible compare to SMRF. DUAL system is also hardly stiff by 15-20% over 15 story compared to SMRF system, but more than even 100% stiff compared to SMRF at lower stories. From this study, the time period of the structure founds to be generally 0.14, 0.12 and 0.09 times the story height for SMRF, SW and DUAL systems respectively, which can be taken as thumb rule while forming the various structural systems for multi story building. Table 3 shows fundamental natural period of 5 to 25 stories of various lateral load resisting structural systems and for various zones. Fig. 4 shows the Time period Vs Modes for 20 Story structures of SMRF, SW and DUAL System for various zones.

A sample Analytical result is explained for 20 Story DUAL system which is assumed to be



(a) Un-cracked section



(b) Cracked section

Fig. 3 Story Vs rundamental natural period

Table 3 Time Period of 5, 10, 15, 20 and 25 Story buildings with different lateral load resisting systems

STORY	ZONE	Un Cracked Analysis			Cracked Analysis		
		SMRF	SW	DUAL	SMRF	SW	DUAL
5	ZIII	1.05	0.39	0.37	1.57	0.48	0.46
	ZIV	0.94	0.39	0.36	1.39	0.48	0.46
	ZV	0.81	0.39	0.36	1.22	0.47	0.46
10	ZIII	1.44	1.06	0.91	2.21	1.33	1.26
	ZIV	1.21	0.87	0.85	1.83	1.08	1.18
	ZV	1.08	0.79	0.72	1.64	0.97	0.99
15	0.16	2.19	1.95	1.58	3.56	2.51	2.32
	0.24	1.81	1.59	1.32	2.89	1.99	1.92
	0.36	1.50	1.51	1.12	2.33	1.89	1.59
20	ZIII	2.88	3.56	2.26	4.75	4.81	3.43
	ZIV	2.41	3.18	2.00	3.88	4.22	3.02
	ZV	2.00	2.66	1.70	3.12	3.41	2.52
25	ZIII	3.60	4.56	2.97	5.98	6.20	4.61
	ZIV	3.01	4.23	2.58	4.87	5.66	3.94
	ZV	2.50	3.78	2.22	3.91	4.97	3.30

located in Bhuj (Gujarat, India) with peak ground acceleration of 0.36. Time period of the structure and modal participating mass ratios are displayed in Table 4. It is found that the first and second mode is in translation mode. First mode is in Y direction translation and excites 70.63% of the total mass. Second mode is in X direction translation and excites 70.68% of the total mass. It is found that 7^{th} and 9^{th} modes are satisfied with more than 90% of total mass participated by

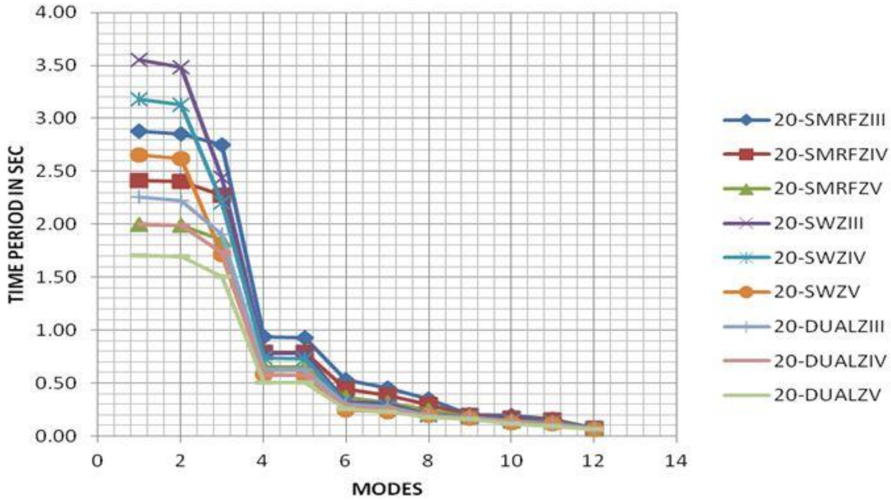


Fig. 4 Time period Vs Modes for 20 Story structures for various lateral load resisting systems

Table 4 Time period and modal participating mass ratios

Mode	Period (in sec)	% of mass participated in X direction acceleration	% of mass participated in Y direction acceleration	% of mass participated in Z direction acceleration	Sum of % mass in X Dir.	Sum of % mass in Y Dir.	Sum of % mass in Z Dir.
1	1.70	0.00	70.63	0.00	0.00	70.63	0.00
2	1.69	70.68	0.00	0.00	70.68	70.63	0.00
3	1.50	0.28	0.00	0.00	70.97	70.63	0.00
4	0.51	12.78	0.00	0.00	83.74	70.63	0.00
5	0.51	0.00	13.10	0.00	83.74	83.73	0.00
6	0.26	0.02	5.53	0.00	83.76	89.26	0.00
7	0.22	9.21	0.05	0.00	92.97	89.31	0.00
8	0.18	0.00	0.00	77.74	92.97	89.31	77.74
9	0.16	0.36	2.95	0.17	93.33	92.26	77.91
10	0.12	0.00	0.98	2.07	93.33	93.24	79.98
11	0.09	0.33	4.02	0.93	93.66	97.27	80.91
12	0.06	0.04	0.11	14.42	93.70	97.38	95.33

acceleration in X and Y direction respectively.

As per clause 7.8.2 of IS 1893 the design base shear V_B shall be compared with base shear $\bar{V}_B$ calculated using a fundamental period T_a. It is found from dynamic analysis that the design base shears V_{Bx} and V_{By} are 6885 kN and 6283 kN respectively which is less than $\bar{V}_B$ calculated using a fundamental period T_a, so that all the response quantities such as member forces, displacements, storey forces, storey shear and base reactions shall be multiplied by $\bar{V}_B/V_B$.

The value of damping for the structure is taken as 5% of the critical for the dynamic analysis of reinforced concrete building. The seismic weight of each floor considered as full dead load plus appropriate amount of imposed load, as specified in the clause 7.3.1 and 7.3.2 of IS 1893 (Part 1):

2002.
Base shear calculation:

T_{ax} = 0.09 h / sqrt(d_x)

T_{ay} = 0.09 h / sqrt(d_y)

For medium soil $(Sa/g)_x$ =1.36/T_{ax}

For medium soil $(Sa/g)_y$ =1.36/T_{ay}

$V_B = Ah$ W

W = 234561 kN

Ah = (Z/2* I/R* Sa/g)

Base shear $\overline{V}_{Bx}$ = 12451 kN

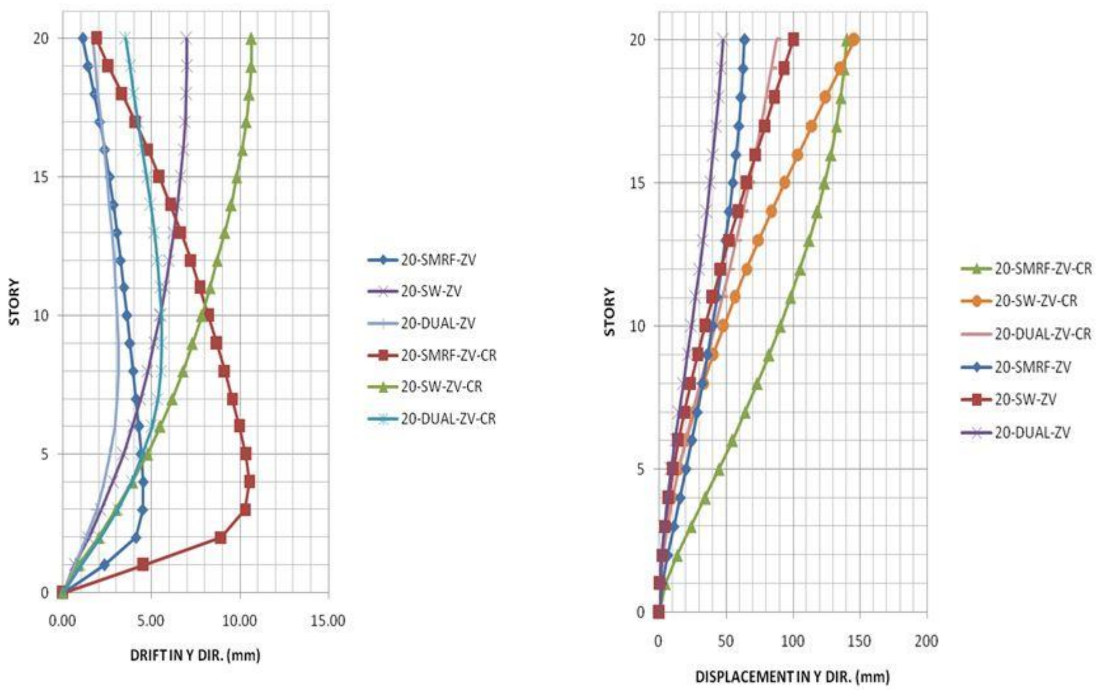
Base shear $\overline{V}_{By}$ = 9968 kN

Base shear from 3D dynamic analysis in X direction V_{Bx} = 6885 kN

Base shear from 3D dynamic analysis in Y direction V_{By} = 6283 kN

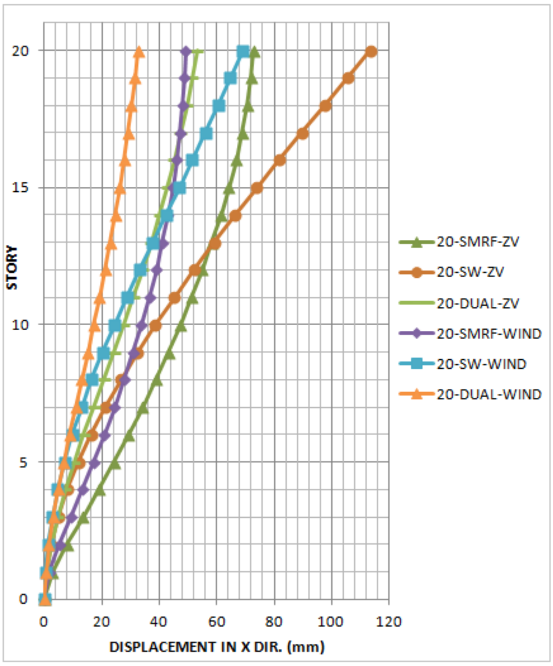
Hence $\overline{V}_B$ >V_B. Hence all the response quantities are scaled up in the ratio of 12451/6885 = 1.81 and 9968/6283 = 1.58 times in the X and Y direction respectively.

As per Table 7 of IS 1893 (Part 1): 2002, the moment resisting frames are designed to independently resist at least 25 percent of the design seismic base shear for dual systems. It is found from dynamic analysis that the column attracts 19.9% and 20.5% of shear in X and Y direction, where these values are less than 25% of design seismic base shear. The moment resisting frames in DUAL system are designed for 1.25 and 1.22 times more force than actual in X and Y direction respectively to satisfy the codal provisions.

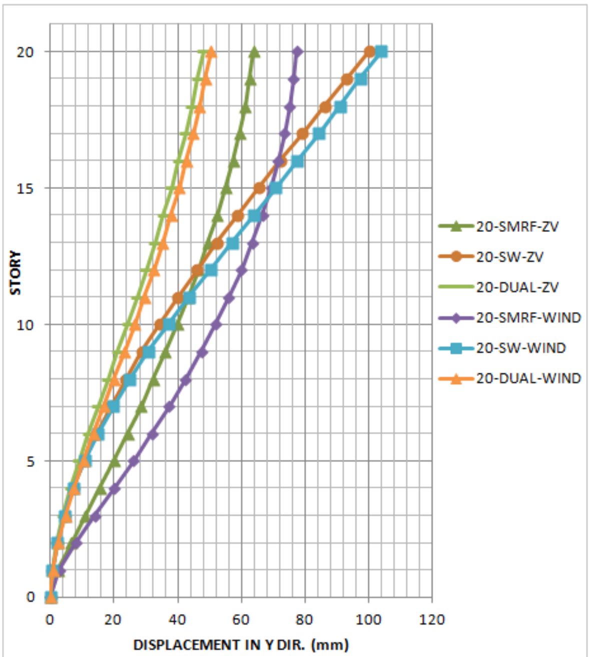


(a) 20-Story Vs Seismic drift (b) 20-Story Vs Displacement

Fig. 5 Seismic drift & displacement due to spectral Y direction force



(a) X Direction displacement



(b) Y Direction displacement

Fig. 6 20-Story Vs displacement due to Seismic & Wind force

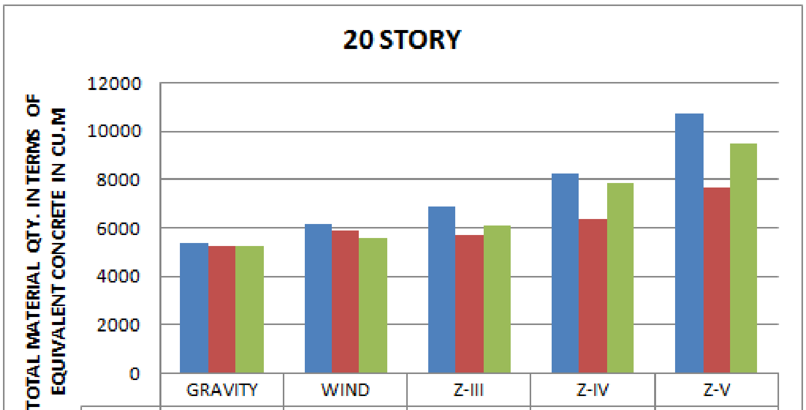
Fig. 5(a)-(b) shows the 20-Story Vs Seismic drift & 20-Story Vs displacement due to Spectral Y direction force for various Structures with Uncracked and Cracked Properties. Fig. 6(a)-(b) shows the 20-Story Vs displacement due to Seismic and Wind forces in X and Y direction for Zone V region for various structural systems. It is found that the displacement in Y direction due to wind is dominating seismic for 20 story structure.

Fig. 7 displays the total material quantity required in terms of Equivalent concrete in Cu.m for various structural systems and for various laterals loads such as wind and seismic zones for 20 Story structure. Structural design is carried out for all 120 cases of structures under taken in this study using IS 456: 2000. Material quantity estimated in this study includes for Columns, Walls and Beams only. Considering the practical difficulties in construction site, the design percentages of main reinforcement are restricted to 3%, 2% and 1.5% in Columns, Walls and Beams respectively. It is found from the seismic analysis that the SW system is cheaper in terms of strength resistance, but worst in satisfying the serviceability criteria. But for wind resistance, the DUAL system performs well in overall aspects compared to SMRF and SW systems.

6. Discussion of results

• During the Schematic stage, the lateral load resisting members are placed in a position by trial and error method, such that the overall mass of the building coincides with the rigidity of lateral load resisting member as far as possible to avoid the torsion in the building during initial modes.

• It is found that the translation mode occurs in first and second mode in all structural system



	GRAVITY	WIND	Z-III	Z-IV	Z-V
SMRF	5356	6150	6881	8278	10730
SW	5228	5918	5711	6356	7684
DUAL	5228	5557	6108	7874	9478

Fig. 7 20-Story total material quantity in terms of equivalent concrete in Cu.m

considered in the present study. In SMRF System, almost 80% of mass participated in initial mode, whereas 70% and 60% of mass excited during initial mode in Dual and Shear wall systems respectively.

• It is found from 5 to 25 story analysis that the frames are attracted only 15% to 20% of shear in Dual Systems. So the frames are designed taking minimum 25% of total base shear in all dual systems.

• Base shear found to be varying from 2.5% up to 11% of total seismic weight of building for the various systems considered in the present study.

• The results shows that the dual system was the most efficient lateral load resisting system based on deflection criterion, as they yielded the least values of lateral displacements and inter-storey drifts.

• Shear Wall system was the most economical lateral load resisting compared to moment resisting frame and dual system but they yielded the large values of lateral displacements in top stories. But it is found that up to 15story, the displacement in shear wall system also reasonably less than SMRF system.

• Wall systems execute tremendous stiffness at the lower levels of the building, while moment frames typically restrain considerable deformations and provide significant energy dissipation under inelastic deformations at the upper levels. But in cracked analysis, it is found that the lateral displacements are relatively high in SMRF systems compared to wall system at higher levels, since the cracking influence much impact on frames rather than stiff walls.

• It is found that the Dual/Shear Wall systems attracts relatively higher story shear in the lower stories and vice versa in upper stories compared to SMRF system.

• It is found that the displacement due to wind is dominating seismic for 20 story structure onwards.

• In cracked analysis the buildings are undergoing large displacement due to decrease in stiffness and increase in the natural fundamental period.

• From this study, time period of the structure founds to be generally 0.14, 0.12 and 0.09 times the story height for SMRF, SW and DUAL systems respectively, which can be taken as thumb rule while forming the various structural systems for multi story building.

• Compared to Chennai region, the building designed in Delhi and Bhuj (Gujarat) region requires 20-25% and 50-55% more cost respectively in both SMRF and DUAL systems. (Material Cost calculated and compared in this study includes only for columns, walls and beams and not included for all other structural members/total project cost).

• In SW system, the building designed in Delhi and Bhuj (Gujarat) region requires 10-15% and 30-35% more cost respectively, when compared to Chennai seismic region.

• Cracked analysis yield large displacement compare to uncracked analysis. Generally it is found that, 2.2 to 3 times, 2.0 to 2.4 times and 1.4 to 2 times displacements are higher in cracked analysis compared to uncracked analysis at roof levels for SMRF, DUAL and SW Systems respectively.

• There is no much variation between the cracked and uncracked analysis in terms of strength requirements and the difference is hardly 5% in material cost for vertical members.

7. Conclusions

In this study, it was found that the dual system was the most efficient lateral load resisting system based on deflection criterion, as they yielded the least values of lateral displacements and inter-storey drifts. The shear wall system was the most economical lateral load resisting compared to moment resisting frame and dual system, but they yielded the large values of lateral displacements in top stories. Also it is found from the dynamic analysis that the wall systems execute tremendous stiffness at the lower levels of the building, while moment frames typically restrain considerable deformations and provide significant energy dissipation under inelastic deformations at the upper levels. In cracked analysis the buildings are undergoing large displacement due to decrease in stiffness and increase in the natural fundamental period. Strength criteria is not governing in Cracked analysis, but serviceability criteria found major impact compared to uncracked analysis which leads the structural engineers to consider the flexural stiffness reduction of beams and columns due to concrete cracking. Even though the structural systems are chosen based on relative effectiveness of individual systems considering the performance and quantity measures, but functional requirements also has important role in deciding the structural systems.

References

ACI 318M (2008), *Building Code Requirements for Structural Concrete,* American Concrete Institute, U.S.A.

Chandler, A.M. and Mendis, P.A. (2000), “Performance of reinforced concrete frames using force and displacement based seismic assessment methods”, *Eng. Struct.*, **22**(4), 352-363.

Duan, H.J. and Hueste, M.B.D. (2012), *“*Seismic performance of a reinforced concrete frame buildings in China”, *Eng. Struct.*, **41,** 77-89.

IS 1893 - Part 1 (2002), *Criteria for Earthquake Resistant Design of Structures*, Part 1: General provisions and building, Bureau of Indian Standards, New Delhi.

IS 456 (2000), *Plain and Reinforced Concrete Code of Practice*, Bureau of Indian Standards, New Delhi.

Kim, H.S., Lee, D.G. and Kim, C.K. (2005), “Efficient three-dimensional seismic analysis of a high-rise building structure with shear walls”, *Eng. Struct.*, **27**(6)**,** 963-976.

Lu, Y., Hao, H., Carydis, P.G. and Mouzakis, H. (2001), "Seismic performance of RC frames designed for three different ductility levels", *Eng. Struct.*, **23**(5), 537-547.
Paulay, T. (1983), "Deterministic seismic design procedures for reinforced concrete buildings" *Eng. Struct.*, **5**(1)**,** 79-86.
Zaregarizi, S. (2008), "Comparative investigation on using shear wall and infill to improve seismic performance of existing buildings", *14th World Conference on Earthquake Engineering,* China, October.

Notations

A_k	-	Design horizontal spectrum value using natural period of vibration T_k of mode k
A_h	-	Design horizontal spectrum value using natural period T_a for a structure
CQC	-	Complete Quadratic Combination
CR	-	Cracked Analysis
d_x	-	Base dimension in X direction in m
d_y	-	Base dimension in Y direction in m
g	-	Acceleration due to gravity
h	-	Height of the building in m
I	-	Importance Factor
Ig	-	Gross Moment of Inertia
M_X	-	Moment about X axis in kNm
M_Y	-	Moment about Y axis in kNm
M_k	-	Modal mass of mode k
P	-	Axial force in kN
P_k	-	Modal Participation factor of mode k
Qi_k	-	Peak lateral force at floor i in mode k
r	-	Number of modes being considered
R	-	Ductility Factor
Sa/g	-	Spectral acceleration coefficient
SMRF	-	Special Moment Resisting Frame
SRSS	-	Square Root of Sum of Square
SPECX	-	Earthquake force in X direction in kN
SPECY	-	Earthquake force in Y direction in kN
SW	-	Shear Wall System
T	-	Torsion in kNm
T_a	-	Fundamental natural period
T_k	-	Natural period of vibration of mode k
$\underline{V_B}$	-	Base shear calculated from dynamic analysis in kN
$\overline{V_B}$	-	Base shear calculated using fundamental natural period T_a in kN
V_i	-	The peak storey shear force in storey i in kN
Vi_k	-	The peak shear force acting in storey i in mode k
V_X	-	Shear Force in X direction in kN
V_Y	-	Shear Force in Y direction in kN
W	-	Seismic weight of structure in kN
Wi	-	Seismic weight of floor i in kN
Z	-	Zone Factor

Z III	-	Seismic Zone III as per IS 1893 (Part 1): 2002
Z IV	-	Seismic Zone IV as per IS 1893 (Part 1): 2002
Z V	-	Seismic Zone V as per IS 1893 (Part 1): 2002
β	-	Frequency ratio = $\omega i/\omega j$
λ	-	Peak response quantity
λi	-	Response quantity in mode i including sign
λj	-	Response quantity in mode j including sign
λ_k	-	Absolute value of quantity in mode k
λ^*	-	Peak response quantity due to the closely spaced modes
ζ	-	Modal damping ratio (in fraction) 2% and 5% for steel and reinforced concrete building respectively.
ρij	-	Cross-modal coefficient
φi_k	-	Mode shape coefficient at floor i in mode k
ωi	-	Circular frequency in ith mode
ωj	-	Circular frequency in jth mode