13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 2377

A STUDY ON THE EFFECT OF VERTICAL GROUND ACCELERATION ON THE SEISMIC RESPONSE OF STEEL BUILDINGS

Mahmood HOSSEINI [1] and Maraym Firoozi Nezamabadi [2]

ABSTRACT

One of the main reasons behind those extensive damages to steel structures, designed by recent codes, has been claimed to be the effect of vertical ground acceleration on the behavior of columns and other main load bearing elements, which has not been considered adequately in the corresponding design codes. In this paper by considering three sets of 3- , 4-, and 5-story buildings, their seismic response have been calculated by a capable 3-dimensioanl nonlinear time history analysis program. Analyses have been performed once with considering and once without considering the vertical component of ground motion to find out the effect of vertical excitation in combination with horizontal excitations. The studied buildings are some existing steel buildings in Tehran, which have concentric and/or eccentric bracing systems in one or more bays. The accelerograms used in analyses belong to some Iranian earthquakes which represent satisfactorily the main soil categories expressed in the national seismic design code. All accelerograms have been normalized to 0.35g, as suggested by the code for the considered sites. The plastic hinges formation trends, the stories drifts, and the base shear values have been investigated, and charts depicting the story shear versus story drift as well as column moment versus its curvature have been presented in the paper. Numerical results show that the effect of vertical component of ground motion is very extensive in some cases in both compression and tension, and can lead to serious uplift problem. As expected, these effects are more remarkable in columns acting only as the members of moment frames rather than those acting as members of bracing systems as well.

INTRODUCTION

It has been observed in recent earthquakes that several steel buildings have suffered extensive damage despite of the fact that they had been designed based on the latest seismic design codes. One of the main reasons behind those extensive damages has been claimed to be the effect of vertical ground acceleration on the behavior of columns and other main load bearing elements, which has not been considered adequately in the corresponding design codes. The role of the vertical component of ground motion in the

[1] Associate Professor, Structural Engineering Group, Civil Engineering Department, Graduate School, Tehran South Branch of the Islamic Azad University (IAU); Email: mahhossnew@yahoo.com
[2] Ph.D. Student at Doctoral Program, and Instructor at Tehran South Branch of the Islamic Azad University (IAU), Tehran, Iran; Email: m_firoozi_n@yahoo.com

induced damage to non-building structures like bridges has been reported by some researchers in recent decade [1], particularly after North Ridge and Kobe earthquakes [2]. NEHRP provisions in 1994 has recommended the consideration of joint horizontal and vertical components by the simple formula of Equation (1), [3].

$$E = Q_E + 0.5C_a D \tag{1}$$

in which the first term is the horizontal earthquake force, C_a is the seismic coefficient which depends on the type of soil profile at the site, and D is for the effect of dead loads. NEHRP commentary claims that the second term in Equation (1) is for consideration of vertical component. Reyes-Salazar and Haldar by defining an error coefficient, as stated by Equation (2) for various design codes, have performed some nonlinear dynamic analyses on 3-, 5-, and 15-story plane frames to find out the effect of joint consideration of horizontal and vertical components of El Centro and North Ridge earthquakes on the axial forces in columns [4].

$$Error = \frac{code\ \ load - actual\ \ load}{code\ \ load} \tag{2}$$

They have stated that the underestimation error in axial forces of columns, calculated by Equation (2), with a damping ratio of 2%, is up to –50% for NEHRP provisions, and up to –70% for Mexican code. It is seen that although the existing codes have tried to consider the effect of vertical component of ground motion in some way, they have not been successful so much.

In this paper by considering three sets of 3- , 4-, and 5-story buildings, which are the most common building in Iran, their seismic response have been calculated by a capable nonlinear time history analysis (NLTHA) program, which can apply the three components of ground motions simultaneously. The torsion effects, if any, have been taken into consideration, as the analysis program is 3-dimensional. Analyses have been performed once with considering and once without considering the vertical component of ground motion to find out the effect of vertical excitation in combination with horizontal excitations. The plastic hinges formation trends, the stories drifts, and the base shear values have been investigated, and graphs depicting the story shear versus story drift as well as column moment versus its curvature have been plotted for the study.

.

THE BUILDINGS UNDER STUDY

The buildings considered for the study are some existing steel buildings in Tehran, which have concentric and/or eccentric bracing systems in one or more bays. General features of these buildings are given in Table 1, their plans, which show the locations of columns, in Figure 1, and their braced bays in Figures 2 to 4.

Table 1- The general features of the considered buildings

The feature	3-story building	4-story building	5-story building
Total area	202 sq. meter	427 sq. meter	769 sq. meter
The site soil type	III	II	II
Aspect ratio	1.60	1.50	1.27

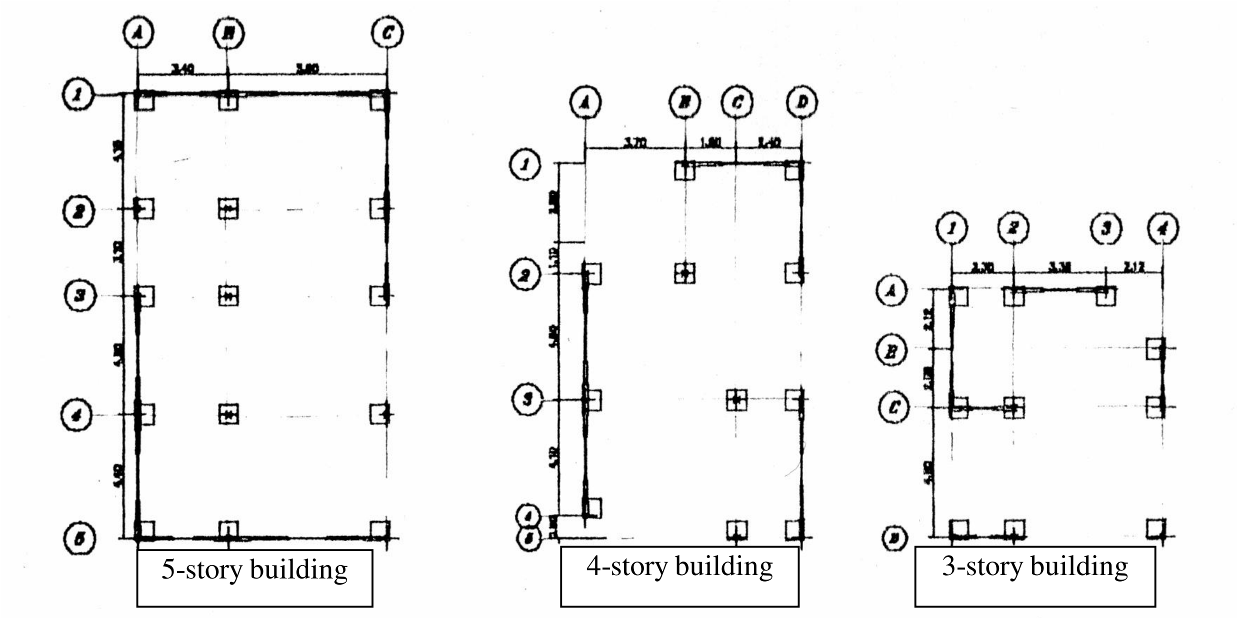

Figure 1- Plans of the considered buildings

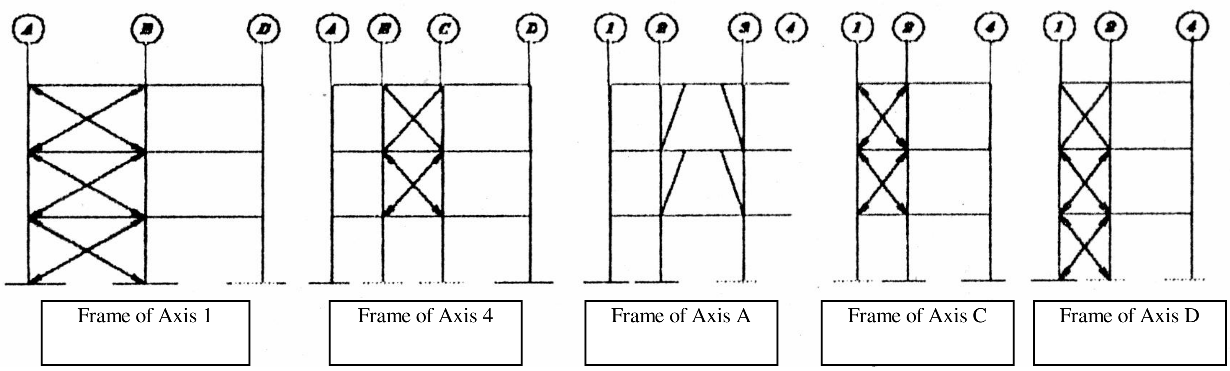

Figure 2- Braced bays of 3-story frames and the locations of yielded sections during NLTHA

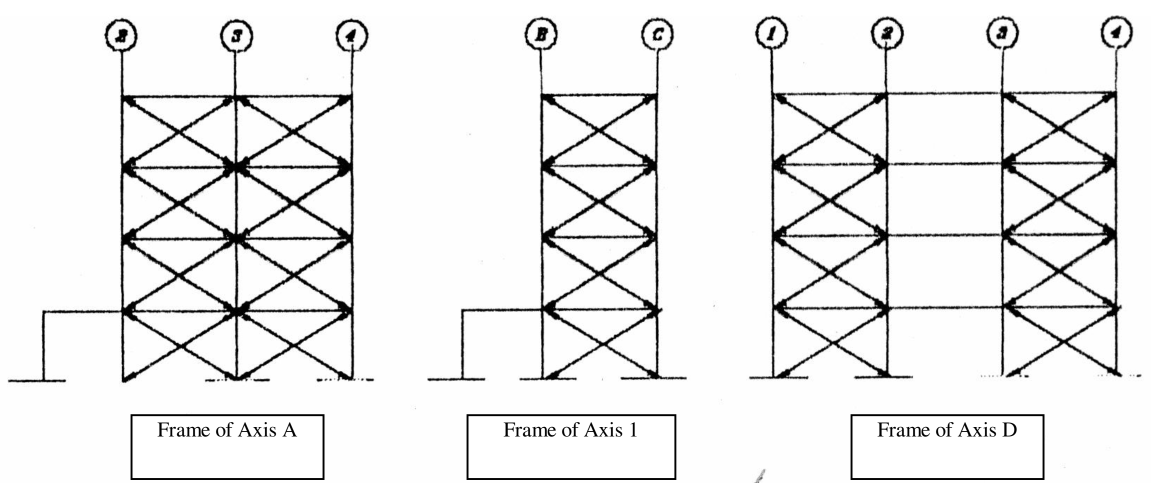

Figure 3- Braced bays of 4-story frames and the locations of yielded sections during NLTHA

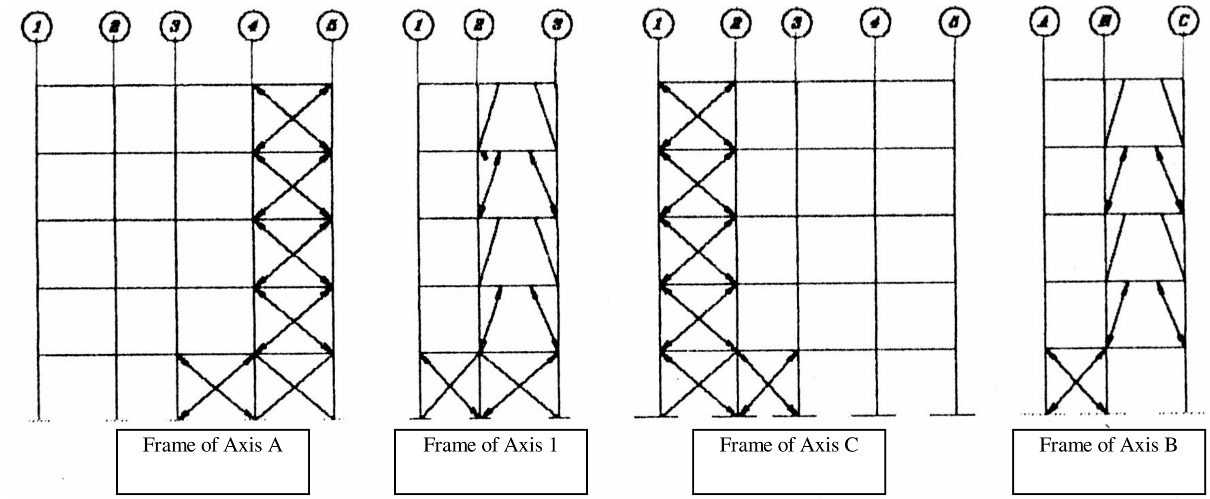

Figure 4- Braced bays of 5-story frames and the locations of yielded sections during NLTHA

TIME HISTORY ANALYSES AND THEIR RESULTS

The accelerograms used in analyses belong to some Iranian earthquakes, including Bandar Abbas, Bajestan, Manjil, and Tabas, which represent satisfactorily the main soil categories expressed in the national seismic design code. All accelerograms are three-component and they have been normalized to 0.35g for the dominant horizontal components, as suggested by the code for the considered sites. As the employed program is a 3-dimensional nonlinear time history analysis (THA) program, both torsion and p-delta effects have been taken into consideration. Some samples of numerical results, obtained for the 3-story building is presented hereinafter. Sample results of the other two buildings can not be presented here because of lack of space. In the case of 3-story building the eccentric bracings did not yield under the effect of any of the applied accelerograms (Figure 2). This is while almost all of the link beams experienced plastic deformations. In this building concentric bracings did yield because of buckling. A comparison between the results of linear THA and NLTHA is presented in Table 2.

Table 3- Comparison of base shear forces obtained by various methods for 3-story building

Ratio of Linear base shear to nonlinear base shear		Ratio of linear base shear to the code base shear		NLTHA		LINEAR THA		Earthquake Record
Y-DIR	X-DIR	Y-DIR	X-DIR	y-DIR	X-DIR	Y-DIR	X-DIR	
1.06	1.34	3.25	3.00	53.60	46.90	56.90	63.10	BANDAR ABBAS
1.57	1.31	1.93	2.15	31.80	35.6	50.0	46.70	BAJESTAN
1.31	1.58	3.01	2.51	49.7	41.45	64.9	65.58	MANJIL
1.93	1.61	3.77	2.83	62.23	46.65	88.9	75.32	TABAS

It is seen in Table 2 that the maximum ration of linear base shear to nonlinear base shear is 1.57 and the maximum ratio of nonlinear shear force is 3.77 the code value. Figures 5 and 6 show respectively the force-displacement and hysteretic responses of 3-story building.

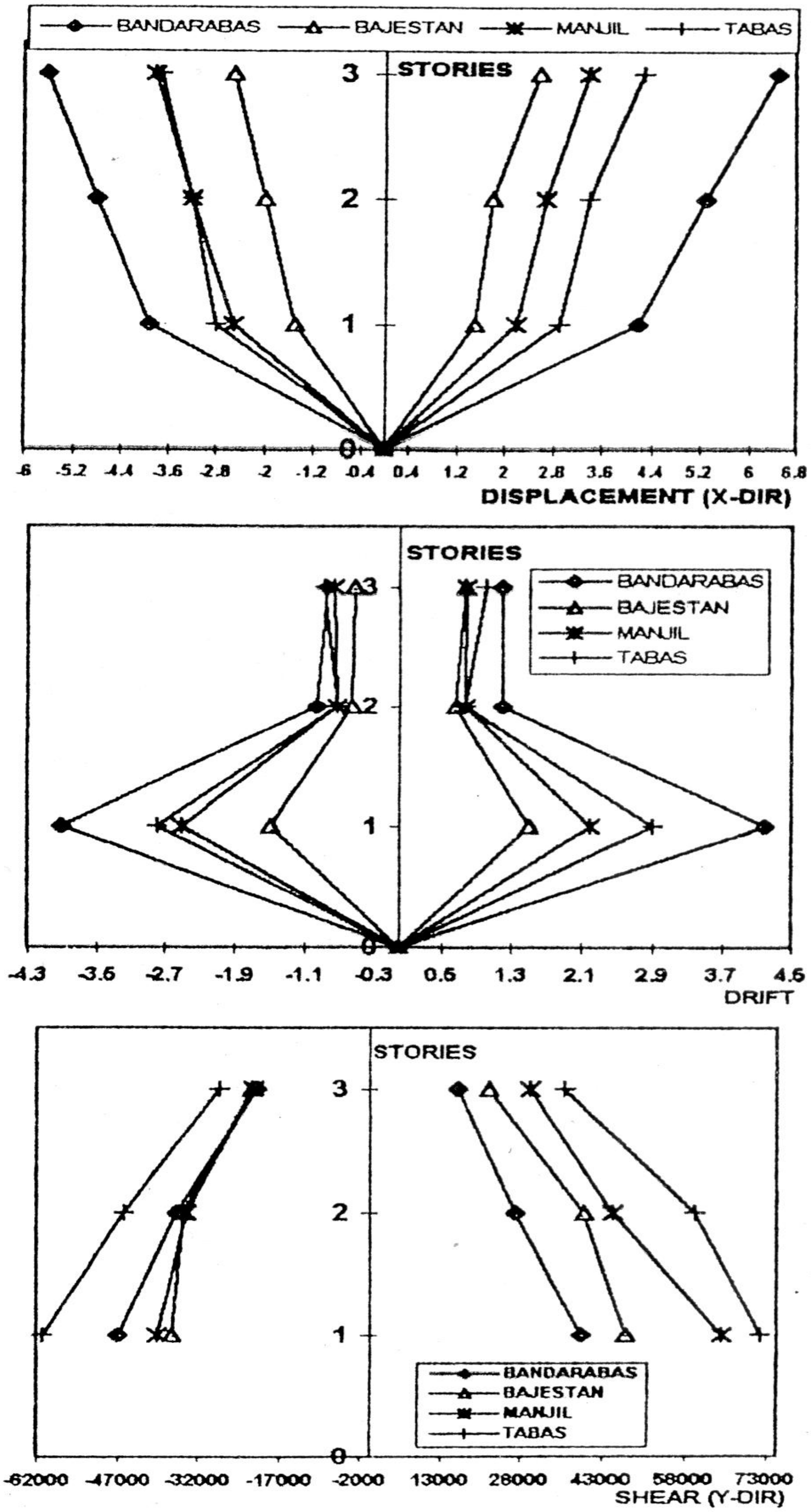

Figure 5- Maximum NLTHA displacement response (cm) and maximum story shears (kgf) of the 3-story building for various applied earthquakes

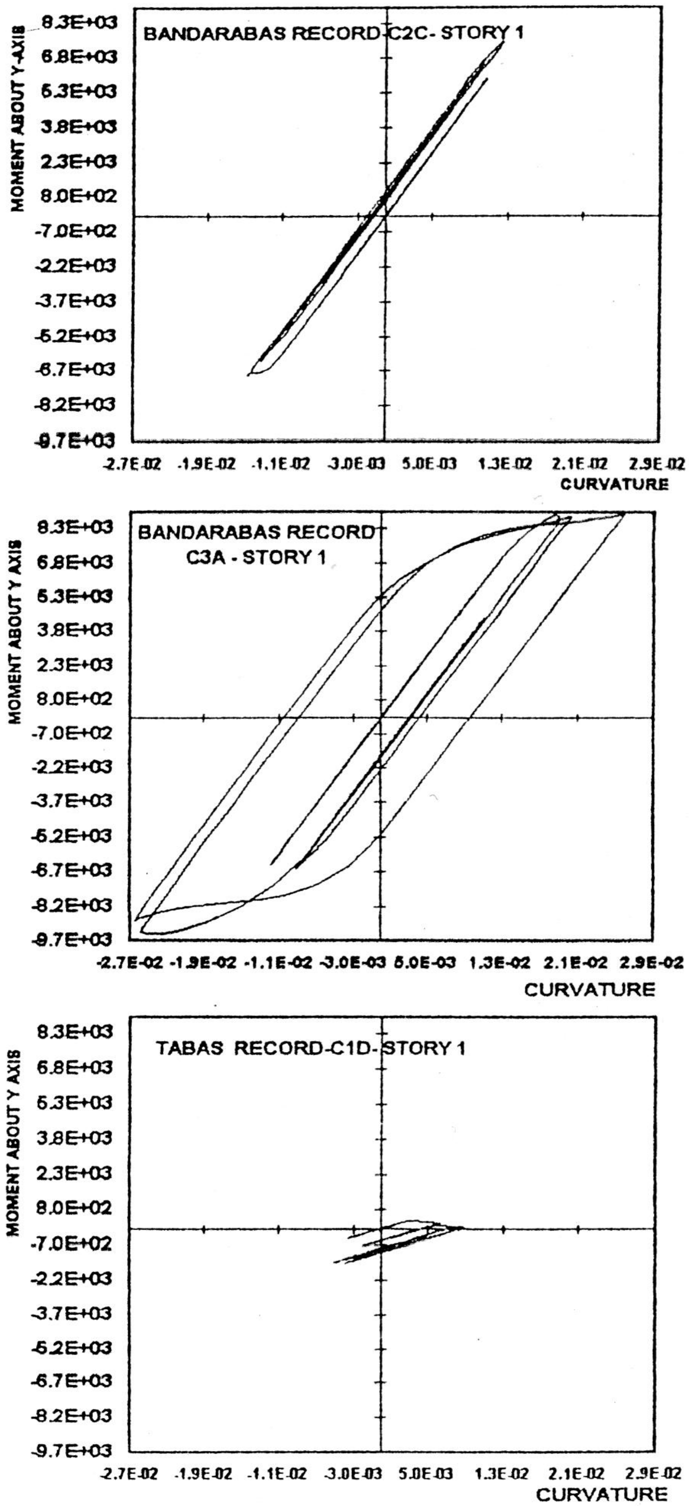

Figure 6- Samples of moment (kgf.rad) vs curvature in some of columns of the 3-story building obtained by NLTHA for Bandar Abbas and Tabas earthquakes

To evaluate the effect of vertical component of earthquake on the axial forces of columns the results of analysis with and without the effect of vertical component have been compares in both linear and nonlinear analyses, as shown respectively in Tables 4 and 5.

Table 4- Variations of columns axial forces (%) in four sample columns of 3-story building with and without the effect of vertical component in linear analyses

MANJIL		BAJESTAN		BANDAR ABBAS			
Max	Min	Max	Min	Max	Min	STORIES	COLUMNS
-	0.4	-	-	-	0.6	1st	C1D
7*	3	-2*	0.5	0.7*	1	2nd	
16*	4	-2*	-	1*	-	3rd	
-	-	-	-	-	-	1st	C4D
-	-	-	-	-	-	2nd	
-	-	-	-	-	-	3rd	
19*	-2	10*	-1	3*	3	1st	C2C
12*	-2	4*	-2	2*	4	2nd	
270*	11	50	-4	8*	7	3rd	
0.4	-	-	-	0.4	0.4	1st	C3A
-	-	0.7	0.3	0.8	0.4	2nd	
-	-0.5	-	-0.5	7	-0.4	3rd	

* : Tension in Column

Table 4- Variations of columns axial forces (%) in four sample columns of 3-story building with and without the effect of vertical component in nonlinear analyses

MANJIL		BAJESTAN		BANDAR ABBAS			
Max	Min	Max	Min	Max	Min	STORIES	COLUMNS
14*	-	3	0.3	6*	1	1st	C1D
114	-3	4*	-1	-4*	0.6	2nd	
120	5	-2*	-2	0.8*	0.3	3rd	
-25	25	-4	3	7	9	1st	C4D
-36	38	-7	7	-10	9	2nd	
-49	52	-9	9	-13	11	3rd	
45*	2	-6	-1	10*	3	1st	C2D
62*	2	-25	-2	10*	2	2nd	
-38	4	-8	-2	4	4	3rd	
-42	4	-2	-	8	5	1st	C3D
-27	10	-6	-	4	6	2nd	
-41	13	0.4	-	6	12	3rd	

*: Tension in Column

It can be seen in Tables 4 and 5 that the variation of axial force in corner columns is more than other columns, particularly in nonlinear analyses. Similar results have been obtained from the two other buildings and can be found in detail in reference [6] if desired.

CONCLUSIONS

Numerical results show that the effect of vertical component of ground motion is very extensive in many cases in both compression and tension, and can lead to serious uplift problem. Surprisingly, the effect of vertical component in higher stories is higher than lower stories. The ratio of base shear values in linear analysis to the corresponding values in nonlinear analysis varies from 0.34 to 1.89. As expected, these effects are more remarkable in columns acting only as the members of moment frames rather than those acting as members of bracing systems as well.

REFERENCES

1. Sadeghvaziri, M. A. and D. A. Foutch (1991), Nonlinear Response of R/C Highway Bridges Under the Combined Effect of Horizontal and Vertical Earthquake Motions, Journal of Earhquake Engineering and Structural Dynamics, Vol. 20, No. 6.
2. Hosseini, M. and Tavoosi Tafreshi, Sh. (1999), Seismic Response of a Multi-Span Highway R/C Bridge to Simultaneous Horizontal and Vertical Ground Motion, Proceedings of the 39th Scientific Week of Syria, Damascus, SYRIA.
3. BSSC (1994, 1997), NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures, FEMA 302, Building Seismic Safety Council (BSSC).
4. Reyes-Salazar, A. and A. Haldar (2000), Consideration of Vertical Acceleration and Flexibility of Connections on Seismic Response of Steel Frame, Proc. of the 12th WCEE, New Zealand.
5. Firoozi Nezamabadi M. (1999), Vulnerability Evaluation of Some Existing Steel Buildings by Visual Inspection and Dynamic Analyses, Masters Thesis submitted to the Tehran South Branch of the Islamic Azad University.