Performance of a Multi-Story Isolated Building Subjected to Bidirectional Excitations in Protection of Critical Equipments from Earthquake Hazard

G. Ozdemir
Kocaeli University, Turkey

U. Akyuz
Middle East Technical University, Turkey

SUMMARY: (10 pt)
Typical examples of base isolated buildings are the structures where internal equipment is much more important than the structure's itself. The damping systems available to control the large displacements in these structures have the characteristic that the damping is strongly displacement dependent. To achieve the level of code-mandated displacements, isolation system will have higher damping and stiffness, and therefore behavior of the building may no longer be dominated by the fundamental isolated response. The incentive for the use of highly damped systems amplifies the response in higher modes of the isolated structure that in turn produces higher floor accelerations which can cause damage in the equipment. In this study, the variation in floor accelerations of a multi-story base isolated building is investigated under bi-directional earthquake excitations. Analyses are conducted to consider wide range of isolator characteristics such as characteristic strength to weight ratio and post-yield period of the isolated system.

Keywords: base isolation, bi-directional excitation, floor accelerations, damping.

1. INTRODUCTION

The basic problem with the design approach of seismically isolated structures in the current codes is that isolation systems are used mainly for buildings that house sensitive and expensive internal equipment. Thus, typical examples of base isolated buildings are emergency service centres, hospitals, and similar structures where the internal equipment is much more important than the structure's itself. The damping systems that are available to control the large displacements have the characteristic that the damping is strongly displacement dependent. To achieve the level of code-mandated displacements at the considered hazard level means that the isolation system will have higher damping and stiffness, and therefore the behavior of the building may no longer be dominated by the fundamental isolated response. It is worth noting that although the code permits the use of high damping in the isolation system to reduce the design displacement (or base shears), the higher modes in an isolated structure are orthogonal to base shears. Thus, reduction in base shear and isolator displacement will not necessarily end up with reduced floor accelerations. On the contrary, the incentive for the use of highly damped systems amplifies the response in the higher modes of the isolated structure (Skinner et al., 1993) that in turn produces higher floor accelerations which can cause damage in the internal equipment.

Response of isolated structures in terms of floor accelerations has been studied by several researchers. Kelly (1999), Hall (1999), Hall and Ryan (2000), Matsagar and Jangid (2004), Alhan and Gavin (2004), and Yang et al. (2010) are among those studies. The study conducted by Alhan and Gavin (2004) somehow differentiates from the others by applying the ground motions bi-directionally. However, authors did not consider any scaling for the considered ground motions which is mandatory to use in nonlinear dynamic analysis of isolated structures as described in specifications. On the other hand, Carballo and Cornell (2000) and Huang *et al*. (2006) stated that distribution of acceleration and displacements through the height of the structure depends highly on the scaling of the ground motions.

Moreover, Huang *et al*. (2006) strongly recommended the use of amplitude scaling method rather than the methods where spectral matching is used.

The purpose of the present study is to show the variation of floor accelerations in a multi-story base isolated structure as a function of isolation period, *T*, and characteristic strength to weight ratio, *Q*/*W*, in accordance with the code specifications (ASCE, 2005). Thus, a 7-story reinforced concrete (RC) building is subjected to bi-directional excitations of near-field ground motions. These ground motions are clustered in two groups according to their characteristics.

2. SELECTION AND SCALING OF RECORDS

As the accessibility of the ground motion records increases, the use of dynamic analyses becomes more popular in the last decades. However, the ease in obtaining the ground motion records comes up with a serious question: How reliable is the way an engineer use the records to acquire the response of a structure under dynamic analysis? Since the selection and scaling of the records highly affects the response, one should be very careful about the parameters used in both selection and scaling. The present study follows a selection and scaling compatible with the specifications (ASCE, 2005). ASCE (2005) assures that each pair of motions are scaled such that for the period range under interest, the average of the square root of the sum of the squares (SRSS) of the 5% damped spectral ordinates from all ground motion pairs does not fall below 1.3 times the corresponding 5% damped target spectrum by more than 10%. This method is an amplitude scaling method and rather than individual single-components of ground motions, pairs of components are considered by this procedure. ASCE (2005) also declares that one can use at least three or seven or more ground motions in dynamic analyses. If three pairs are used, the maximum response of the parameter of interest must be used. If seven or more pairs are used, the average value of the response parameter of interest can be used.

In the light of above criteria, two sets of near-field ground motion records (composed of 11 records each) were clustered and used in the dynamic analyses. These records have been compiled from well known and extensively studied seismic events occurred in United States, Turkey, Iran, Taiwan, and former USSR. Records are classified in two groups to be representative of two distinct response spectra. The magnitudes of the considered motions are in between 6.0 and 7.6 and the distances to the fault rupture are less than 15 km. Tables 1 and 2 presents the characteristics of the considered ground motions. Ground motions in bin 1 (Table 2.1) are selected to represent very dense soil and soft rock while those in bin 2 (Table 2.2) are selected to represent stiff soil profile. In these tables, M_w is the magnitude of the ground motion; *d* is the closest distance to fault rupture.

Scaling of the selected near-field ground motion pairs was carried out as described in Ozdemir and Constantinou (2010). It is composed of two complimentary phases. The first phase considers an amplitude scaling method in which sum of the weighted squared errors between the geometric mean of the two horizontal components and the target spectral values at various periods are minimized. Then, in the second phase, each pair of motions was further scaled so that the average of the SRSS spectra from all ground motion pairs does not fall below 1.3 times the corresponding ordinate of the target response spectrum by more than 10% to satisfy the code provisions (ASCE, 2005). Figure 2.1 presents the response spectra for both ground motion bins for maximum considered earthquake level together with the mean SRSS spectra of scaled motions. Dashed lines shown in Figure 1 represent the period ranges under consideration for each isolation system in accordance with ASCE (2005).

Scale factors applied to the selected ground motion records were calculated by simply multiplying the scale factors obtained in two complimentary phases described above. Tables 2.1 and 2.2 also present the scale factors applied to the ground motions during the dynamic analyses for bin 1 and bin 2, respectively. Final scale factors presented in Tables 2.1 and 2.2 are all less than four which is a value assumed to be an upper limit to prevent any bias in the analyses due to scaling of the records (Krinitzsky and Chang, 1977).

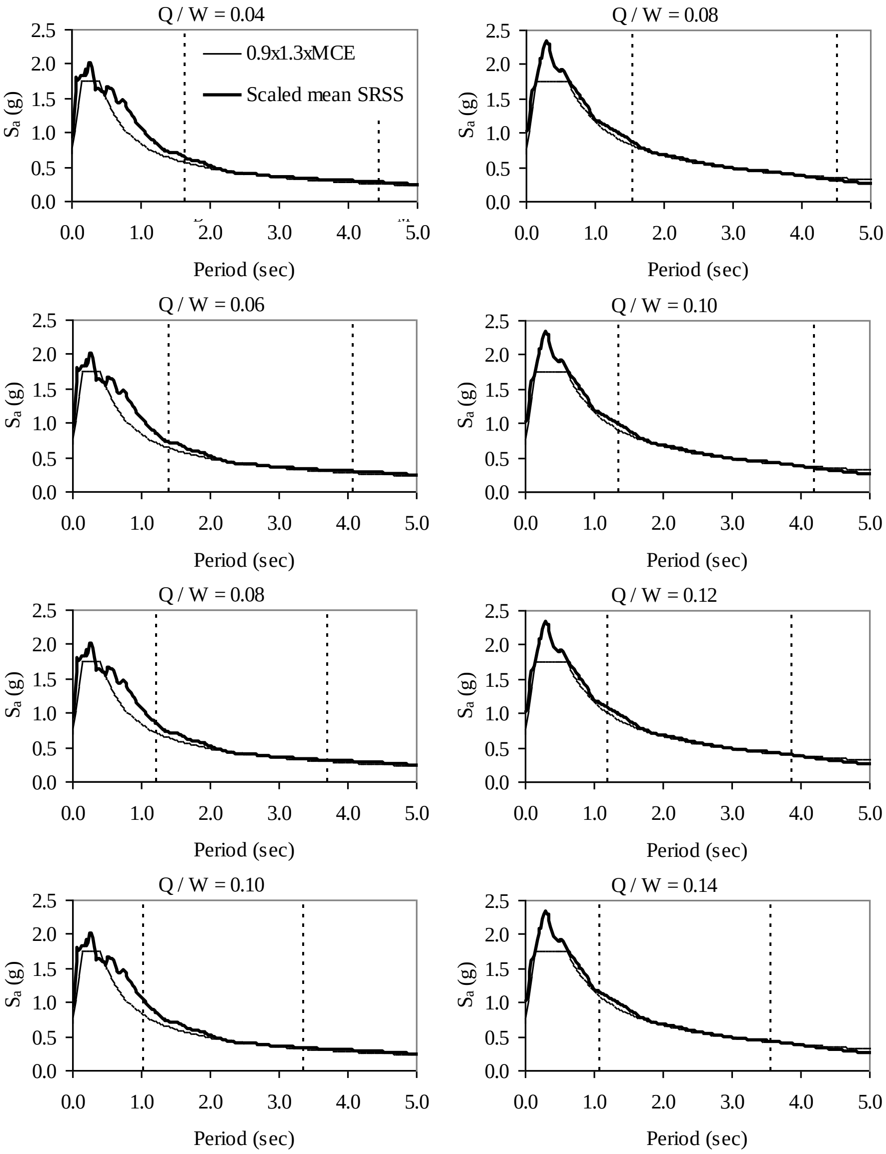

Figure 2.1 Target MCE response spectra and mean SRSS spectra of scaled motions after second phase of scaling for bin 1 (on the left) and bin 2 (on the right).

3. MODELING OF SUPERSTRUCTURE

In a recent study, a detailed research was carried out to report the characteristics of the RC buildings in Turkey (Yakut, 2008). The obtained data shows the average plan area, column orientation through the plan, number of bays in both long and short directions of the plan, and story heights for numerous RC buildings. In the light of that study, a 7-story (7S) RC building that has four identical bays in long direction and three identical bays in short direction is modeled in 3-D (Fig. 3.1). The plan dimensions of the RC building are 18mx12m. Story heights of the structure are 2.9 m and equal at each story level. It is regular in elevation and symmetric with respect to two main orthogonal axes both in mass and stiffness. In accordance with the study of Yakut (2008), the building under consideration was designed so that half of the columns are oriented in their strong direction while the other half in their weak directions. Column dimensions of the 7S RC building are 40cmx55cm, while the typical beam dimensions are 30cmx60cm. The concrete is selected to have a compressive strength, f_c, of 25 MPa. The distributed dead and live load values are 500 kg/m^2 and 200 kg/m^2, respectively in accordance with the Turkish Earthquake Code (TEC, 2007). Thus, the total weight of the structure is 9190 kN.

Table 2.1 Characteristics of near-field ground motions at bin 1 (very dense soil and soft rock profile).

Earthquake	Station	Magnitude (M_w)	*d* (km)	Component	Scale Factor
Chi Chi (TCU057)	TCU057	7.6	11.8	N W	2.31
Cape Mendocino (CMP)	Petrolia	7.0	8.2	0 90	1.10
Duzce (DB)	Bolu	7.1	12	0 90	0.93
Gazli (GK)	Karakyr	6.8	5.5	0 90	1.31
Kocaeli (KG)	Gebze	7.5	10.9	0 270	2.60
Kocaeli (KI)	Izmit	7.5	7.2	180 90	2.69
Landers (LL)	Lucerne	7.3	2.2	275 0	1.71
Northridge (NN)	Newhall	6.7	5.9	90 360	0.93
Northridge (NR)	Rinaldi	6.7	6.5	228 318	0.68
Northridge (NS)	Sylmar	6.7	5.4	52 142	0.60
Tabas (TT)	Tabas	7.4	2.1	LN TR	0.90

4. MODELING OF ISOLATION SYSTEM

Isolation systems considered in this study are represented by a generic bi-linear hysteretic force-deformation relation without considering cycle-to-cycle deterioration. Design of isolators was performed by an iterative solution described in ASCE (2005). The iteration starts with an assumption for the maximum isolator displacement and it continues until the assumed and calculated values are close enough. Employed two distinct response spectra during the iterative solutions are presented in Figure 2.1. The idealized force-deformation relations obtained at the end of iterations are given in Figures 4.1 and 4.2 for the analyses of ground motions in bin1 and bin 2, respectively.

In the analyses of ground motions in bin 1, post-yield periods, T, are selected as 3.0s, 3.5s, and 4.0s. The corresponding Q/W ratios for bin 1 are 0.04, 0.06, 0.08, and 0.10. On the other hand, the post-yield isolation periods investigated during the analyses of ground motions in bin 2 are 3.5s, 4.0s, and 4.5s with Q/W ratios of 0.08, 0.10, 0.12, and 0.14.

Simulations of LRB behavior are performed by means of structural analysis program SAP2000 (2008) where nonlinear link elements are utilized to model bi-linear force-deformation relations of isolators. Employed link elements developed by Park et al. (1986), have coupled plasticity properties for both of the deformations in orthogonal horizontal directions and located under each column at the base level.

Table 2.2 Characteristics of near-field ground motions at bin 2 (stiff soil profile).

Earthquake	Station	Magnitude (M_w)	*d* (km)	Component	Scale Factor
Chi Chi (TCU101)	TCU101	7.6	2.1	N W	2.43
Erzincan (EE)	Erzincan	6.7	4.4	NS EW	1.24
Imperial Valley (IVA4)	Array 4	6.5	7.1	140 230	1.75
Imperial Valley (IVA5)	Array 5	6.5	4.0	140 230	1.48
Imperial Valley (IVA6)	Array 6	6.5	1.4	140 230	1.24
Imperial Valley (IVA10)	Array 10	6.5	6.2	50 320	2.70
Kocaeli (KD)	Duzce	7.5	15.4	180 270	1.74
Kocaeli (KY)	Yarimca	7.5	4.8	60 330	1.39
Loma Prieta (LPCor)	Corralitos	6.9	3.9	0 90	2.20
Loma Prieta (LPSar)	Saratoga	6.9	8.5	0 90	2.41
Parkfield (PC)	Cholame 2	6.0	14.3	90 360	1.73

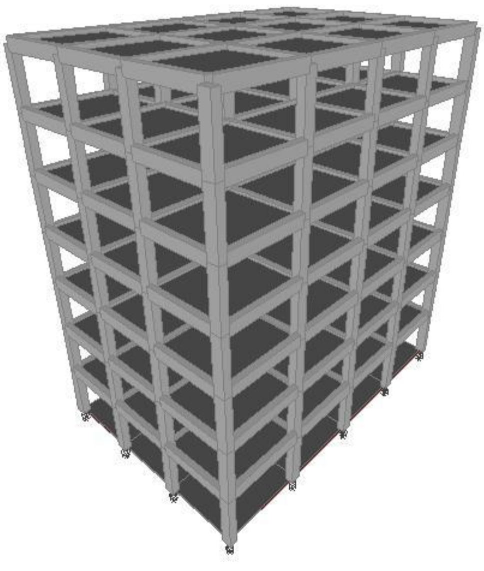

Figure 3.1 3-D model of 7-story RC structure in SAP2000.

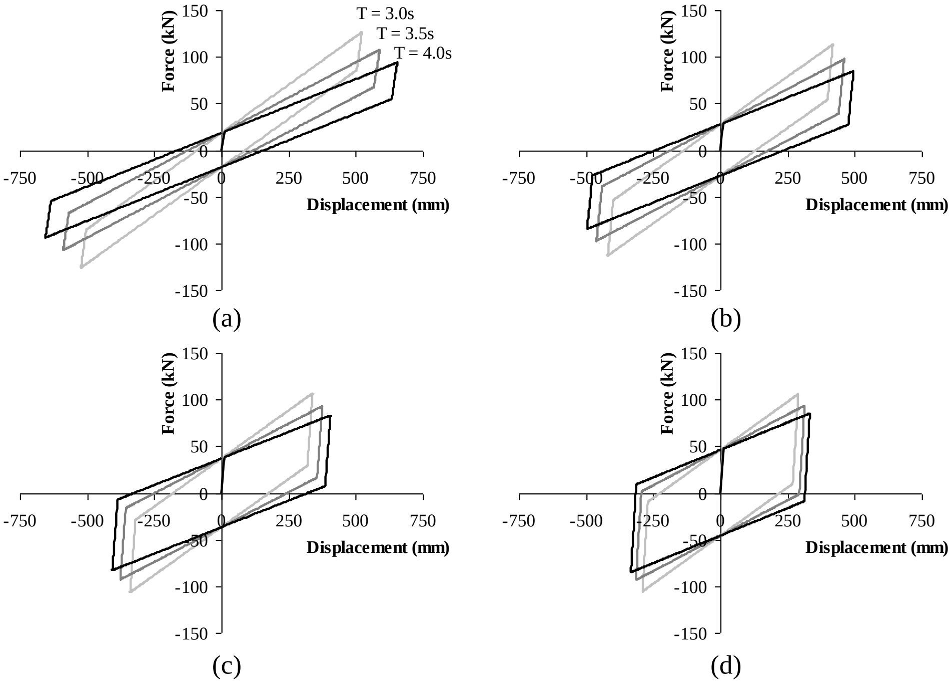

Figure 4.1 Bi-linear force-deformation relation of a LRB in stiff soil for 7S RC structure: a)Q/W=0.04; b)Q/W=0.06; c)Q/W=0.08; d)Q/W=0.10**.**

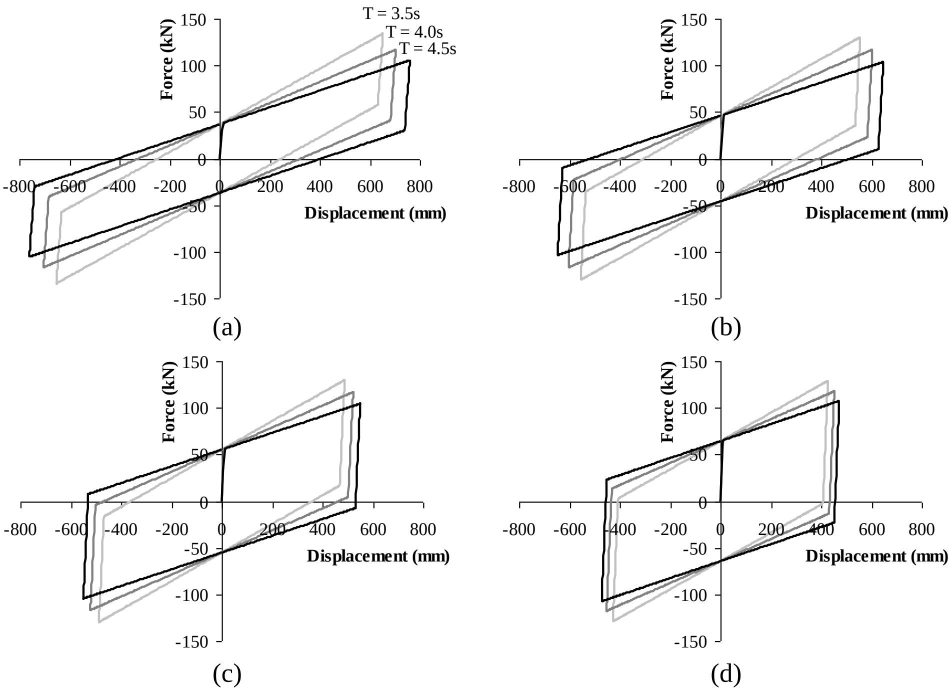

Figure 4.2 Bi-linear force-deformation relation of a LRB in soft soil for 7S RC structure: a)Q/W=0.08; b)Q/W=0.10; c)Q/W=0.12; d)Q/W=0.14.

5. PERFORMED ANALYSES

In this section, floor accelerations obtained by applying bi-directional excitations are depicted to show how they change by increasing both isolation period T and Q/W ratio. In the following subsections, bi-directional accelerations are represented by Acc_{bi} and are computed by taking the SRSS of accelerations in both orthogonal horizontal directions ($Acc_{bi}=(Acc_x^2+Acc_y^2)^{1/2}$). This process was performed at each time step of the analyses and the maximum values at each floor level were considered only. The data presented in the related graphs are the mean values of eleven analyses for both of the ground motion bins.

5.1. Effect of Post-Yield Period, *T*

In Figures 5.1 and 5.2, variations in Acc_{bi} of 7S RC building are presented for both ground motion bins as a function of isolation period. Those figures reveal the effect of isolation period on variation of floor accelerations through the height of the structure.

In Figure 5.1, it is clear that the maximum floor accelerations through the height of the structure decrease when isolation period increases at small *Q*/*W* ratios (i.e. *Q*/*W* = 0.04 and 0.06). On the other hand, increasing the isolation period to reduce the Acc_{bi} through the height of the structure becomes less effective at higher *Q*/*W* ratios compared to lower ones. This observation is especially valid for *Q*/*W* ratio equals to 0.08 and 0.10 for bin 1. For these two cases, Acc_{bi} also tends to be equal at ground and top story levels as isolation period, *T*, increases.

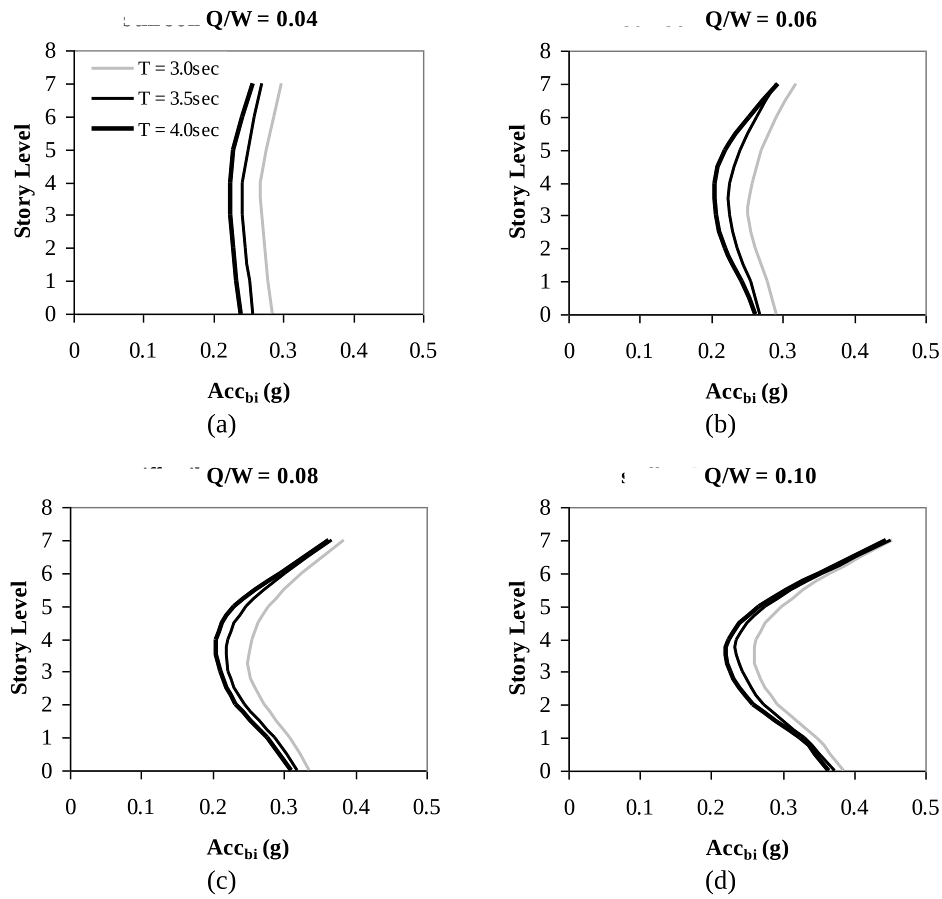

Figure 5.1 Variations in Acc_{bi} of 7-story RC building in the analyses in ground motion bin 1 as a function of isolation period *T* for various *Q*/*W* ratios.

The similar comparisons are given in Figure 5.2 for ground motion bin 2. For almost all of the *Q*/*W* ratios under consideration, the maximum Acc_{bi} values observed in the superstructure are almost the same and not sensitive to change in isolation period (with the exception of *Q*/*W* = 0.08). Moreover, the distributions of the floor accelerations become identical at higher *Q*/*W* ratios regardless of the isolation period (*Q*/*W* = 0.12 and 0.14).

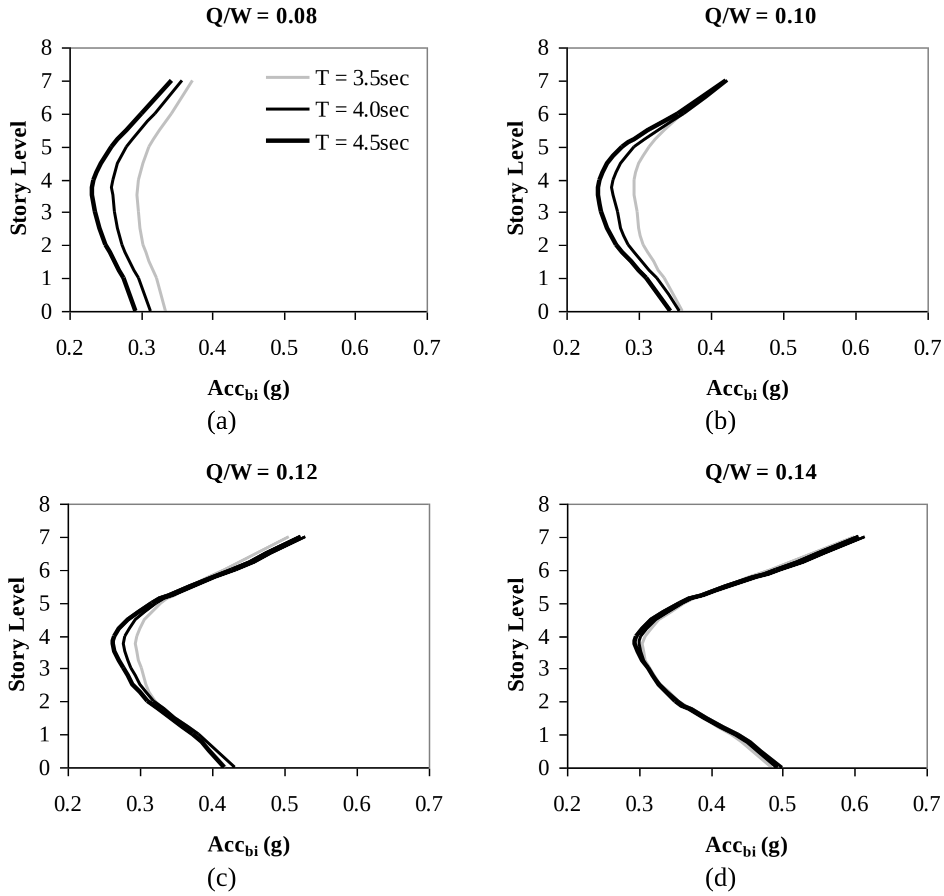

Figure 5.2 Variations in Acc$_{bi}$ of 7-story RC building in the analyses in ground motion bin 2 as a function of isolation period *T* for various *Q*/*W* ratios.

5.2. Effect of *Q*/*W* Ratio

Evaluation of change in Acc$_{bi}$ due to increased *Q*/*W* ratios at 7S RC building is performed in the light of Figure 5.3. The maximum Acc$_{bi}$ increases substantially for both of the analyses conducted with ground motions in bin 1 and bin 2. When the maximum floor accelerations corresponding to case with highest *Q*/*W* ratios are normalized with that of the lowest *Q*/*W* ratio, the amount of increments are obtained as 50%, 65% and 69% in bin 1 for *T* = 3.0s, 3.5s and 4.0s., respectively. When the same comparison is conducted for bin 2, increments are 62%, 69% and 76% for *T* = 3.5s, 4.0s and 4.5s, in the same order. Variation of Acc$_{bi}$ through the height of the structure shows the counterproductive effect of increasing damping.

Figure 5.3 indicates that floor accelerations of isolated structures analyzed with ground motions in bin 2 are more sensitive to increase in *Q*/*W* ratio than the ones in bin 1. Increments in the floor accelerations with increasing damping are due to contribution of higher modes. Transfer of energy to higher modes associated with a small reduction in first mode accelerations is able to produce relatively large higher mode accelerations, because higher modes require much smaller energies to achieve a given maximum acceleration (Skinner et al., 1993).

6. CONCLUSIONS

In this study, dynamic analyses of an isolated 7-story reinforced concrete building are investigated under bi-directional earthquake excitations of near-field ground motions. Two sets of near-field ground motion records (representative of different response spectra) are used, and each set have eleven records. Selected near-field ground motions are used to investigate the variation in floor accelerations through the height of the considered reinforced concrete building. Dynamic analyses are conducted by structural analysis program SAP2000 where the isolation system is modeled by non-linear link elements.

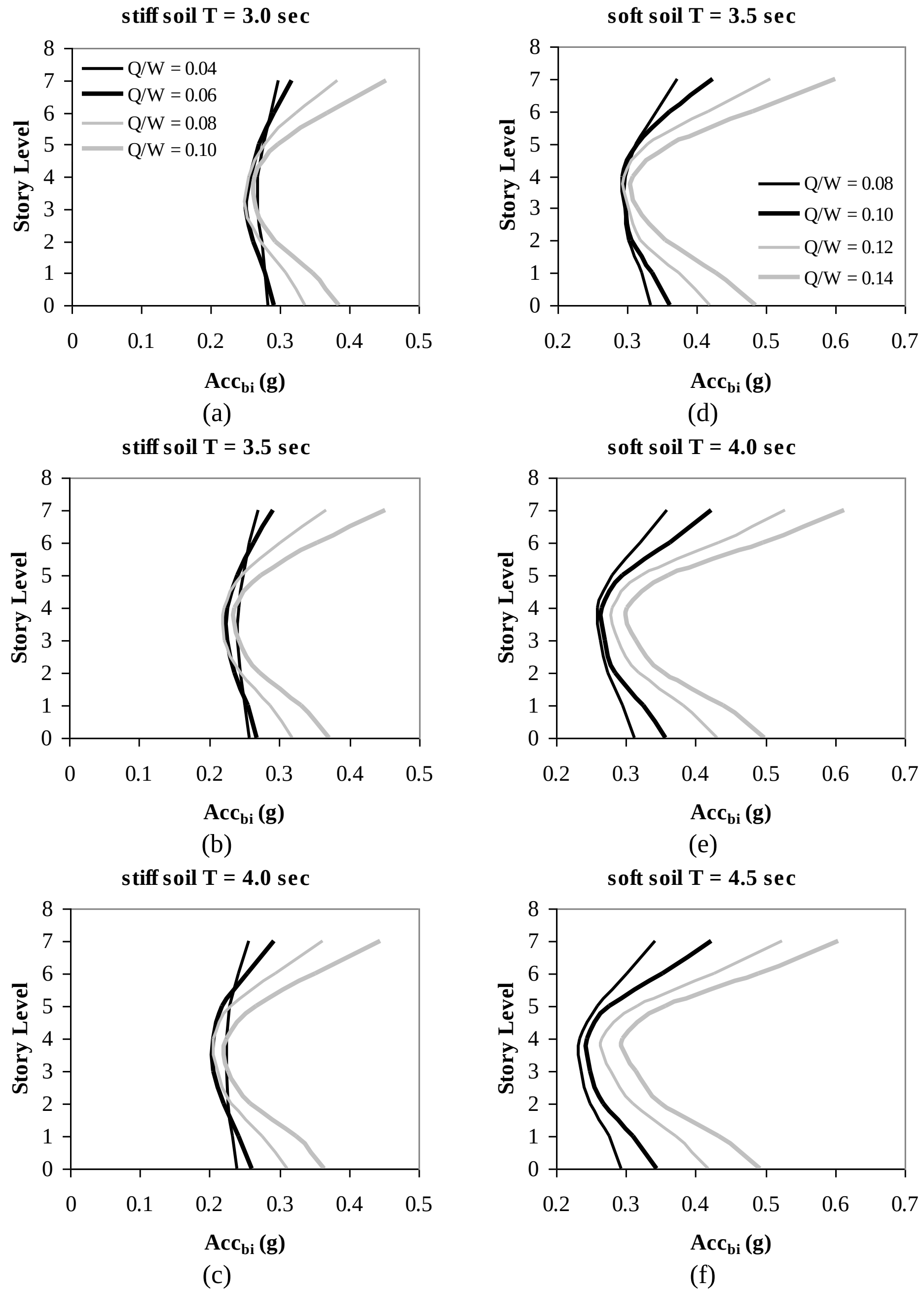

Figure 5.3 Variations in Acc$_{bi}$ of 7-story RC building as a function of Q/W ratios for various isolation periods T under stiff (left) and soft (right) soil conditions.

Assessing results of the parametric study described in this study, the following conclusions can be revealed:

Increasing isolation period may not necessarily reduce the floor accelerations. This is especially valid for large Q/W ratios. For such cases, distribution of floor accelerations throughout the structure height becomes almost identical regardless of the isolation period. This observation is also valid for both of the ground motion bins considered.

Increasing Q/W ratio leads to increased maximum accelerations in the superstructure which are at the top floor level at both ground motion bins. However, for the considered characteristics of the isolation systems, in the analyses performed by employing bin 1, some reduction in accelerations of mid-level floors is observed when Q/W was increased. On the other hand, for bin 2, accelerations increase at all floor levels with increasing Q/W ratio.

REFERENCES

Skinner, R.I., Robinson, W.H. and McVerry, G.H. (1993). *An introduction to seismic isolation*. John Wiley and Sons Inc. New York.

Kelly, J.M. (1999). The role of damping in seismic isolation. *Earthquake Engineering and Structural Dynamics*,, **28:1**, 3-20.

Hall, J.F. (1999). Discussion of "The role of damping in seismic isolation". *Earthquake Engineering and Structural Dynamics*, **28:12**,1717-1720.

Hall, J.F. and Ryan, K.L. (2000). Isolated buildings and the 1997 UBC near-source factors. *Earthquake Spectra*, **16:2**, 393-412.

Matsagar, V.A. and Jangid, R.S. (2004). Influence of isolator characteristics on the response of base-isolated structures. *Engineering Structures*, **26:12**, 1735-1749.

Alhan, C. and Gavin, H. (2004). A parametric study of linear and non-linear passively damped seismic isolation systems for buildings. *Engineering Structures*, **26:4**, 485-497.

Yang, T.Y., Konstantinidis, D. and Kelly, J.M. (2010). The influence of isolator hysteresis on equipment performance in seismic isolated buildings. *Earthquake Spectra*, **26:1**, 275-293.

Carballo, J.E. and Cornell, C.A. (2000). *Probabilistic seismic demand analysis: spectrum matching and design*. Report No. RMS-41, Reliability of Marine Structures Program, Department of Civil and Environmental Engineering, StanfordUniversity, Stanford, CA.

Huang, Y.N., Whittaker, A.S. and Constantinou, M.C. (2006). Seismic demands on secondary systems in conventional and isolated nuclear power plants. *Proceedings, Eighth US National Conference on Earthquake Engineering*, Earthquake Engineering Research Institute, San Francisco, California.

ASCE, (2005). *Minimum Design Loads for Buildings and Other Structures (ASCE 7-05)*. American Society of Civil Engineers., Reston, Virginia.

Ozdemir, G. and Constantinou, M.C. (2010). Evaluation of equivalent lateral force procedure in estimating seismic isolator displacements. *Soil Dynamics and Earthquake Engineering*, **30:10**, 1036-1042.

Krinitzsky, E.L. and Chang, F.K. (1977). *Specifying peak motions for design earthquakes*. State-of-the-Art for Assessing Earthquake Hazards in the United States, Report 7, Miscellaneous Paper S-73-1. US Army Corps of Engineers, Vicksburg, Mississippi.

Yakut, A. (2008). Capacity related properties of RC frame buildings in Turkey. *Journal of Earthquake Engineering*, **12:2**, 265-272.

Turkish Earthquake Code (2007). *Specifications for the buildings to be constructed in disaster areas*. Ministry of Public Works and Settlement, Ankara, Turkey.

Computers and Structures, Inc., 2008. SAP 2000 Nonlinear, Version 12.0.0, Structural Analysis Program, Berkeley, CA.

Park, Y.J., Wen, Y.K. and Ang, A.H. (1986). Random vibration of hysteretic systems under bi-directional ground motions. *Earthquake Engineering and Structural Dynamics*, **14:4**, 543-557.