AN INVESTIGATION ON THE UPLIFT FORCES IN BUILDINGS EQUIPPED WITH OPRCB ISOLATORS

Sadegh MAHMOUDKHANI
Adjunct Lecturer, Islamic Azad University, Tehran, Iran
s.mahmoudkhani@srbiau.ac.ir

Mahmood HOSSEINI
Associate Professor, Structural Engineering Research Center, the International Institute of Earthquake Engineering and Seismology (IIEES), Tehran, Iran
hosseini@iiees.ac.ir

Mansour ZIYAEIFAR
Associate Professor, Structural Engineering Research Center, the International Institute of Earthquake Engineering and Seismology (IIEES), Tehran, Iran
mansour@iiees.ac.ir

Keywords: Uplift Forces, Empirical Formula, Time History Analysis, Nonlinear Regression, Near Fault Earthquakes

ABSTRACT

Recent studies on Orthogonal Pairs of Rollers on Concave Beds (OPRCB), as a somehow new isolating system, show that these isolators are weak subjected to uplift. In this paper a set of regular 3-, 6-, and 9-story steel buildings, with dual moment frames and chevron bracing system, installed on OPRCB isolators, have been considered subjected to near-fault earthquakes with moderate to high vertical accelerations. The buildings were analyzed subjected to 19 three-component records of selected near-fault earthquakes. By using nonlinear regression analysis, empirical formula was derived for predicting the uplift forces, based on six main parameters, including PGA values in three directions, the structure's volume, and its aspect ratios in two directions. To check the accuracy of the proposed formula another building with different parameters was analyzed and the values of axial forces at the level of isolators were compared to the corresponding values obtained by the proposed formula. The relatively high Index of Agreement between the predicted and observed results and low values of error indices indicate the good performance and accuracy of the proposed formulas.

INTRODUCTION

In spite of the remarkable effects of vibration isolating systems on the seismic behavior of structures, uplift (e.g. in sliding bearings) and tension forces (e.g. in bonded rubber bearings) during near-fault excitations are contingent (Roussis and Constantinou, 2006a). Based on the available references it seems that the first studies with regard to the effect of uplift on seismic isolators go back to late 80s. As one of the first studies Kelly et al. (1987) worked on the evaluation and strengthening of isolators against uplift or tensile forces. In order to resist against uplift in elastomeric bearings, an uplift restraint device has been proposed and tested (Kelly et al., 1987). The feasibility of base isolation for structures subjected to column uplift during earthquake on a reinforced concrete structure with a height-to-width ratio (r) of 1.23 and on a braced steel frame with r of 1.59 have been studied experimentally (Griffith et al., 1988; Griffith et al., 1988).

An experimental and analytical study has been performed to evaluate the feasibility of using a Teflon sliding bearing with uplift restraint devices for a six-story structure (with a *r* of 4.5) (Nagarajaiah et al., 1992). Furthermore, an analytical study on isolated structures with the friction pendulum system has been carried out by taking into account the uplift forces (Almazán et al., 1998). For preparing sufficient compressive force on the isolator for preventing uplift, pre-stressing tendons have been used (Kasalanati and Constantinou, 2005). In another study, experimental and analytical investigations have been performed on a new uplift-restraining sliding isolator (Roussis and Constantinou, 2006a) and structures equipped with this isolator (Roussis and Constantinou, 2006b). They called their proposed system 'XY-FP' and expressed that the axial compression and tension in isolator lie in the range of 2-3 times the gravity load. Roussis (2009) studied the effects of uplift-restraint on the seismic behavior of XY-FP isolated structures. Roussis (2009) reported that tension in individual XY-FP isolators does not have any significant effect on the seismic response of structure. In continuation, Tsopelas et al. (2009) developed an algorithm for seismic analysis of multi-base seismically isolated structures and Roussis et al. (2010) presented some verification examples in which the analyzed structure was excited under conditions of bearing uplift. The influence of axial loads on seismic behavior of seismic isolators was also studied by Yamamoto et al. (2009), however, their work was on elastomeric bearings.

abstract Hosseini and Kangarloo (2007) and Kangarloo (2007) introduced a new low-cost rolling isolation system that does not need high-tech for manufacturing. The proposed system is composed of two pairs of orthogonal steel rollers that move on concave beds. This gives possibility of movement in all horizontal direction and also a re-centering capability to the system. Following the mentioned studies, the proposed isolator was called Orthogonal Pairs of Rods on Concave Beds (OPRCB) (Soroor, 2009; Hosseini and Soroor, 2011, 2013). Hosseini and Soroor (2011, 2013) performed experimental and numerical studies to investigate the seismic response of 2D structures equipped with OPRCB isolators. According to those studies suitable performance of low- and mid-rise OPRCB-isolated buildings have been confirmed. Nevertheless, Hosseini and Soroor (2013) expressed that uplift is an important problem in the case of near-fault earthquakes in which separation of rollers from their beds happens in excitations with vertical acceleration higher than 1.0g. With regard to the effect of building aspect ratio on behavior of isolators, He et al. (2013) conducted study on dynamic response of large and small aspect ratio isolated buildings. Their experimental results reveal that the aspect ratio is an important factor influencing the axial load action on isolators and the tension stress of the lead-rubber bearings. They expressed that the superstructure flexibility of the large aspect ratio building-isolation system and the effects of the axial force variation of the lead-rubber bearings should be carefully considered for design.

Regarding the importance of effect of the axial forces of columns in the behavior of OPRCB isolators, particularly their weakness against uplift, in this paper an analytical investigation is performed to find out how the columns axial forces vary with the geometrical feature of the buildings as well as the specification of earthquake ground motions. At first a brief description of the buildings considered for the study are introduced, and then their response to a selected set of accelerograms are obtained. Finally, based on numerical results, the empirical formula is presented for calculation of maximum uplift forces to be used in design of isolators.

STRUCTURAL MODELS AND SELECTED EARTHQUAKE RECORDS

In order to evaluate the uplift forces in the OPRCB bearings, a set of regular steel buildings with dual moment frames and chevron bracing system, installed on OPRCB isolators, have been considered subjected to near-fault earthquakes. Three types of plans including 2×3, 3×5 and 5×7 bays have been considered, all with span length of 5 meters. Number of stories have been 3, 6 and 9, and the story height has been considered 3.25 meters in all cases.

The dynamical specifications of the OPRCB isolators have been considered to be same as the simplified bilinear force displacement relationship, and their natural period has been assumed to be 2.0 seconds (Soroor, 2009). The Time History Analysis (THA) of the considered buildings was performed subjected to 19 three-component records of selected near-fault earthquakes (see Table 1).

As it is seen in Table 1, the PGA values of the vertical component of the selected records are relatively high, which is quite reasonable for studying the effect of vertical ground motion. Furthermore, the PGA values of the horizontal components of the selected records vary from 0.29g to 0.64g. This relatively wide range has been considered to make the use of PGA as an input variable in developing the empirical formula explained in following section.

Table 1. Seismic records used for the THA

No.	Record ID at PEER Database	PGA (g)			
		Vertical		In x direction	In y direction
		Upward	Downward		
1	NGA0180	0.54	0.42	0.52	0.38
2	NGA0183	0.40	0.44	0.60	0.45
3	NGA0184	0.71	0.49	0.48	0.35
4	NGA0189	0.38	0.26	0.29	0.51
5	NGA0230	0.39	0.35	0.44	0.42
6	NGA0540	0.47	0.36	0.61	0.49
7	NGA0569	0.48	0.27	0.61	0.41
8	NGA0741	0.51	0.39	0.53	0.48
9	NGA0752	0.54	0.53	0.53	0.44
10	NGA0753	0.46	0.30	0.64	0.48
11	NGA0766	0.29	0.21	0.37	0.32
12	NGA0802	0.35	0.39	0.51	0.32
13	NGA0959	0.49	0.37	0.42	0.36
14	NGA1044	0.55	0.39	0.59	0.58
15	NGA1045	0.29	0.20	0.45	0.33
16	NGA1082	0.31	0.29	0.30	0.44
17	NGA1111	0.37	0.37	0.51	0.50
18	NGA1505	0.49	0.33	0.57	0.46
19	NGA1507	0.45	0.35	0.66	0.57

NUMERICAL RESULTS

The axial forces in bearings of the buildings were obtained from 342 THA cases. Three samples of these time histories, related to the 9-story building subjected to Loma Prieta earthquake are shown in Figs. 1-3.

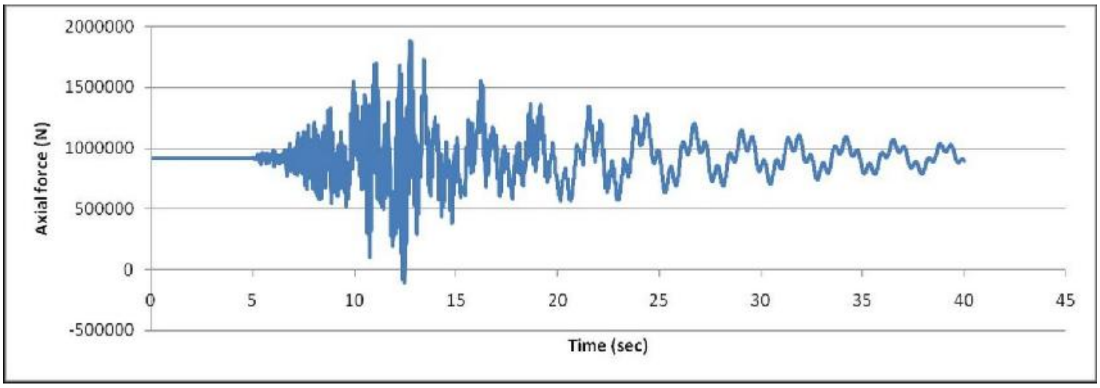

Figure 1. Time history of axial force in one of side columns of 9-story building

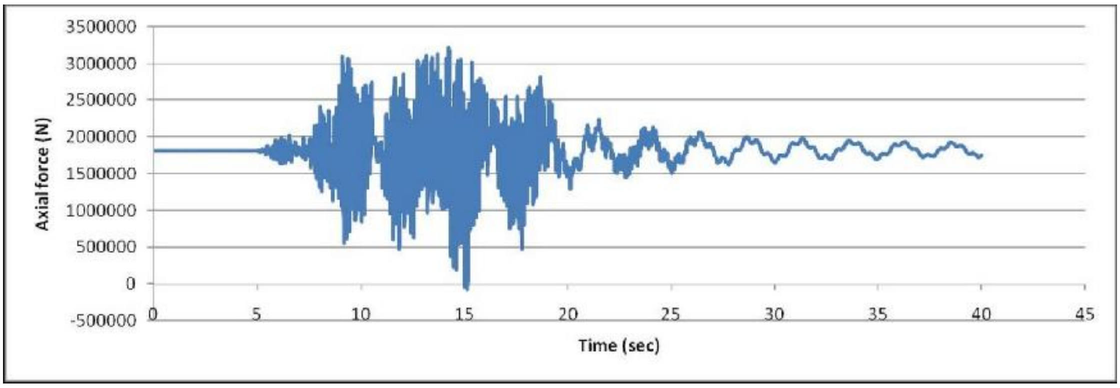

Figure 2. Time history of axial force in one of interior columns of 9-story building

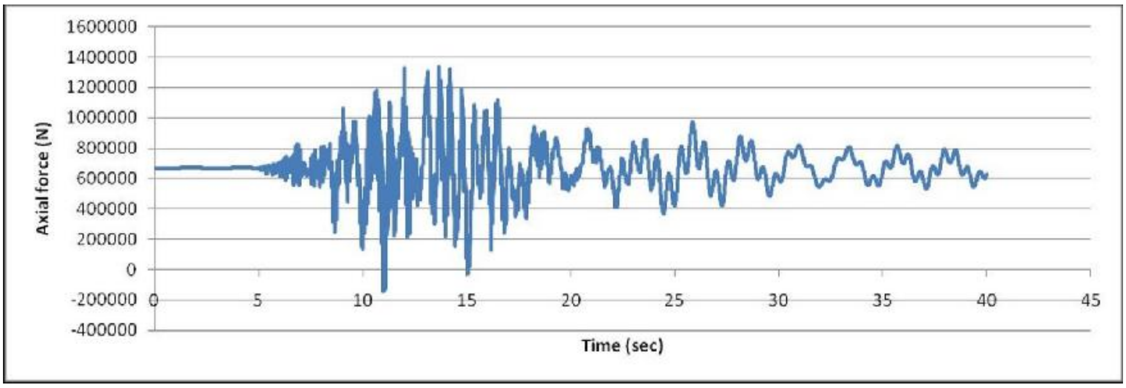

Figure 3. Time history of axial force in one of corner columns of 9-story building

As it is seen in Figs. 1-3 the ratio of tensile force in columns is quite dependent on the location of column in the building. Because of the difference between the axial gravity forces in each bearing, the following coefficient have been proposed for tensile forces:

$$\text{Tension Index} = \frac{\text{Gravity Reaction Force} - \text{Minimum Reaciton Force}}{\text{Gravity Reaction Force}} \tag{1}$$

where the upward gravity reaction forces are considered as positive. On this basis minimum the Tension Index of larger than one means the tendency of occurrence of uplift. It should be noted that in this study it has been assumed that the OPRCB isolators are restrained against uplift, and therefore, no separation can occur between the isolators and the building foundations. The Tension Index, obtained from Eq. (1), based on the THA results, ranged from 0.3676 to 2.3564 (see Table 2).

Table 2. Range of Tension Index

Building Type Number	Tension Index	
	Max	Min
1	0.9944	0.3676
2	1.2662	0.5474
3	1.6251	0.7689
4	0.9999	0.4442
5	1.5407	0.8472
6	2.3564	1.1654
7	0.9978	0.4723
8	1.6098	0.9346
9	2.2944	1.1064

Regarding that the THA is a very time-consuming process, in this study empirical formula has been proposed in order to estimate the Tension Index for studying the uplift restraining, described in the next section of the paper.

EMPIRICAL FORMULA

Empirical formula for predicting the Tension Indexes have been developed by using nonlinear regression analysis, based on six main parameters, including PGA in three perpendicular directions, the volume of structure, and r in two directions. Combining these six main parameters in the forms of squared value, products, and some other mathematical combinations have led to 22 parameters to be used in the regression analyses, as described hereinafter. By using nonlinear regression analysis, the following equation has been derived for the Tension Index.

$$Tension\ Index = -2.79500 + \sum_{i=1}^{22} b_i Z_i \tag{2}$$

The 22 parameters used for developing the empirical formula given by Eq. (2) are presented in Table 3. In Fig. 4 the predicted Tension Indexes, are compared with their observed values.

Table 3. The parameters used for developing formula for the Tension Index

Z_i		b_i		Z_i		b_i	
Z_1	r_x *	b_1	-0.25254	Z_{12}	$PGA_{up} \times PGA_x \times PGA_y$	b_{12}	29.80160
Z_2	r_y	b_2	-0.06367	Z_{13}	r_x^2	b_{13}	0.50489
Z_3	PGA_{up}	b_3	10.96594	Z_{14}	r_y^2	b_{14}	-1.00187
Z_4	PGA_x	b_4	5.84809	Z_{15}	V	b_{15}	0.00004
Z_5	PGA_y	b_5	5.50707	Z_{16}	$r_x \times PGA_x$	b_{16}	0.59549
Z_6	PGA_{up}^2	b_6	0.45102	Z_{17}	$r_y \times PGA_y$	b_{17}	-0.43820
Z_7	PGA_x^2	b_7	0.96248	Z_{18}	$r_x^{-1} \times PGA_x / \left(r_x^{-2} \times r_y^{-2}\right)$	b_{18}	-1.49299
Z_8	PGA_y^2	b_8	1.51252	Z_{19}	$r_y^{-1} \times PGA_y / \left(r_x^{-2} \times r_y^{-2}\right)$	b_{19}	1.004156
Z_9	$PGA_{up} \times PGA_x$	b_9	-17.86063	Z_{20}	PGA_{up} / r_x	b_{20}	-0.67163
Z_{10}	$PGA_{up} \times PGA_y$	b_{10}	-18.35810	Z_{21}	PGA_{up} / r_y	b_{21}	-0.16702
Z_{11}	$PGA_x \times PGA_y$	b_{11}	-11.19962	Z_{22}	$PGA_{up}^2 / \left(r_x \times r_y\right)$	b_{22}	0.25900

*It is supposed, in this study, that the x direction is always parallel to the shorter side of the building plan

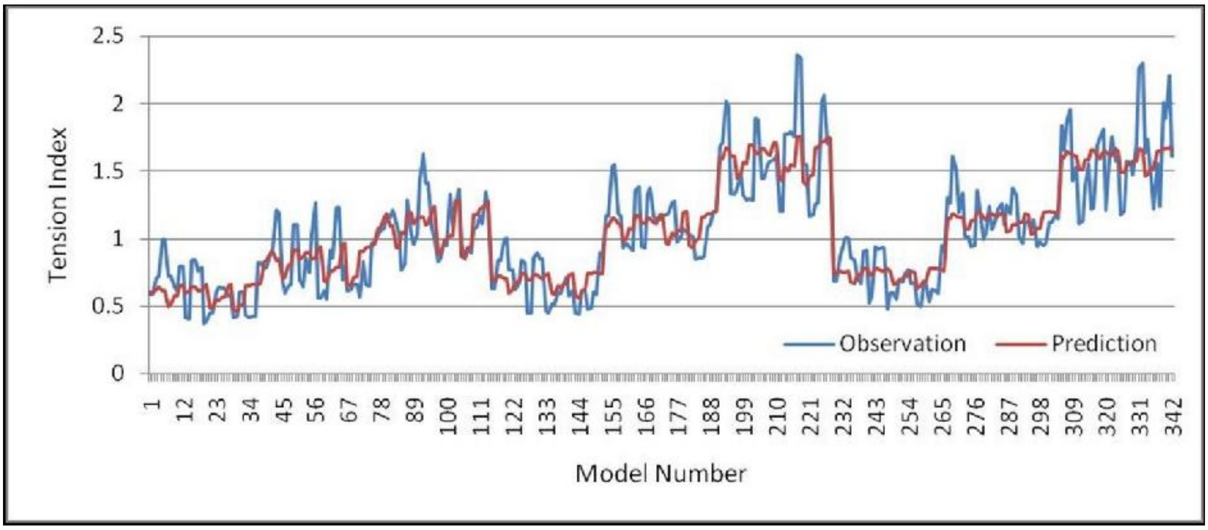

Figure 4. The predicted and observed values of the Tension Index

For evaluation of accuracy and performance of the predictions a few statistical indexes, including Standard Deviation (SD), Relative Standard Deviation (R-SD), Mean Absolute Error (MAE), Root Mean Square Error (RMSE), Relative Root Mean Square Error (R-RMSE) and finally, Index of Agreement (IOA) have been calculated as follow (Willmott, 1982):

$$SD = \left[N^{-1} \sum_{i=1}^{N} \left(P_i - \overline{P}\right)^2 \right]^{0.5} \tag{3}$$

$$R - SD = \frac{SD}{\overline{P}} \tag{4}$$

$$MAE = N^{-1} \sum_{i=1}^{N} \left| P_i - O_i \right| \tag{5}$$

$$RMSE = \left[N^{-1} \sum_{i=1}^{N} \left(P_i - O_i\right)^2 \right]^{0.5} \tag{6}$$

$$R - RMSE = \frac{RMSE}{\overline{O}} \tag{7}$$

$$IOA = 1 - \left[\sum_{i=1}^{N} (P_i - O_i)^2 \Big/ \sum_{i=1}^{N} \left(\left| P_i - \overline{O} \right| + \left(O_i - \overline{O} \right)^2 \right) \right] \tag{8}$$

where N is the number of observed or predicted cases, O_i and P_i are the observed and the predicted variables, respectively, $\overline{P}$ and $\overline{O}$ are the mean values. The statistical indicators of the mentioned index are given in Table 4 for both observed and predicted values, which again show the good performance for the proposed formula.

Table 4. Statistical indicators for the Eq. (2)

Statistical Indexes	Observation		Prediction					
	SD	R-SD	SD	R-SD	MAE	RMSE	R-RMSE	IOA
Tension index	0.409	0.392	0.361	0.346	0.152	0.191	0.183	0.923

VALIDATION ANALYSES

The satisfactory accuracy of the proposed formula was confirmed by statistical indicators, as discussed in previous section. Furthermore, in this section validation of the proposed formula is investigated by using a new structural model. For this purpose, a series of THA were performed on a 7-story building with 4- by 6-bay plan, having 5.0 meters span length, subjected to all three-component records given in Table 1. The results of THA were compared with those obtained from the empirical formula. Fig. 5 shows this comparison, and the statistical indicators of the formulas are presented in Table 5. Bases on Fig. 5, and also Table 5 it can be claimed that the proposed empirical formula has satisfactory accuracy.

Table 5 Statistical indicators for the proposed empirical formula in case of the 7-story building used for validation

Statistical Indexes	Observation		Prediction					
	SD	R-SD	SD	R-SD	MAE	RMSE	R-RMSE	IOA
Tension index	0.158	0.129	0.080	0.068	0.121	0.154	0.125	0.767

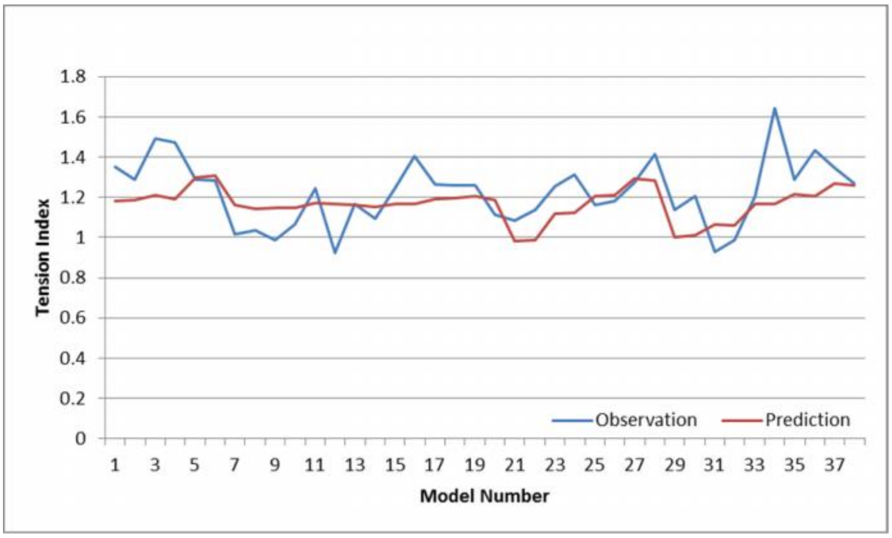

Figure 5. The predicted and observed values of the Tension Index of the 7-story building used for validation

CONCLUSIONS

Based on the numerical calculations performed in this study on the multi-story buildings, isolated by OPRCB devices, it can be concluded that the uplift may happen with vertical PGA of as low as 0.5g, and this means that the uplift cannot be controlled by only the vertical ground motion, and the combination of horizontal and vertical PGA, and also the geometric features of the building should be taken into account for this purpose. The proposed empirical formula for prediction of tensile forces in OPRCB isolators have relatively high precision (maximum RMSE around 0.2), and can be used with high level of confidence for this purpose.

It should be mentioned that the above conclusions are limited to regular buildings, and for irregular buildings more research is required. Furthermore, the effect of tensile forces on behavior of OPRCB isolators needs to be investigated in more details.

REFERENCES

Almazán JL, De La Llera JC and Inaudi JA (1998) Modelling Aspects of Structures Isolated with the Frictional Pendulum System, *Earthquake Engineering & Structural Dynamics*, 27(8): 845-867

Griffith MC, Aiken ID and Kelly JM (1988) Experimental evaluation of seismic isolation of a 9-story braced steel frame subject to uplift, Technical Report, University of California, UCB/EERC-88/05, Berkeley, USA

Griffith MC, Kelly JM, Coveney VA, Koh CG (1988) Experimental evaluation of seismic isolation of medium-rise structures subject to uplift, Technical Report, University of California, UCB/EERC-88/02, Berkeley, USA

He WF, Liu WG, Yang QR and Qin C (2013) Study on Dynamic Response of Large and Small Aspect Ratio Isolated Buildings, *The Structural Design of Tall and Special Buildings*, 23(17): 1329-1344

Hosseini M and Kangarloo K (2007) Introducing Orthogonal Roller Pairs as an Effective Isolating System for Low Rise Buildings, *Proceedings of the 6th International Conference on Earthquake Resistant Engineering Structures (ERES 2007)*, Bologna, Italy

Hosseini M and Soroor A (2011) Using Orthogonal Pairs of Rollers on Concave Beds (OPRCB) as a Base Isolation System—Part I: Analytical, Experimental and Numerical Studies af OPRCB Isolators, The *Structural Design of Tall and Special Buildings*, 20(8): 928-950

Hosseini M and Soroor A (2013) Using Orthogonal Pairs of Rollers on Concave Beds (OPRCB) as a Base Isolation System—Part II: Application to Multi-Story and Tall Buildings, *The Structural Design of Tall and Special Buildings*, 22(2): 192-216

Kangarloo K (2007) Experimental studies on orthogonal rollers pairs as an isolating system for low- to mid-rise buildings, M.Sc. Thesis, South Tehran branch of Islamic Azad University, Tehran, Iran

Kasalanati A and Constantinou M (2005) Testing and Modeling of Prestressed Isolators, *Journal of Structural Engineering*, 131(6): 857-866

Kelly JM, Griffith MC and Aiken ID (1987) A displacement control and uplift restraint device for base isolated structures, Technical Report, University of California, UCB/EERC-87/03, Berkeley, USA

Nagarajaia S, Reinhorn A and Constantinou M (1992) Experimental Study of Sliding Isolated Structures with Uplift Restraint, *Journal of Structural Engineering*, 118(6): 1666-1682

Roussis P (2009) Study on the Effect of Uplift-Restraint on the Seismic Response of Base-Isolated Structures, *Journal of Structural Engineering*, 135(12): 1462-1471

Roussis PC and Constantinou MC (2006a) Uplift-Restraining Friction Pendulum Seismic Isolation System, *Earthquake Engineering & Structural Dynamics*, 35(5): 577-593

Roussis PC and Constantinou MC (2006b) Experimental and Analytical Studies of Structures Seismically Isolated with an Uplift-Restraining Friction Pendulum System, *Earthquake Engineering & Structural Dynamics*, 35(5): 595-611

Roussis PC, Tsopelas PC and Constantinou MC (2010) Nonlinear Dynamic Analysis of Multi-Base Seismically Isolated Structures with Uplift Potential II: Verification Examples, *Earthquake Engineering and Engineering Vibration*, 9(1): 83-91

Soroor A (2009) Analytical study of effectiveness of orthogonal rolling rods isolation system in mid-rise regular buildings, M.Sc. Thesis, Science and Research branch of Islamic Azad University, Tehran, Iran

Tsopelas PC, Roussis PC and Constantinou MC (2009) Nonlinear Dynamic Analysis of Multi-Base Seismically Isolated Structures with Uplift Potential I: Formulation, *Earthquake Engineering and Engineering Vibration*, 8(3): 421-431

Willmott CJ (1982) Some Comments on the Evaluation of Model Performance, *Bulletin of the American Meteorological Society*, 63(11): 1309-1313

Yamamoto S, Kikuchi M, Ueda M, Aiken ID (2009) A Mechanical Model for Elastomeric Seismic Isolation Bearings Including the Influence of Axial Load, *Earthquake Engineering & Structural Dynamics*, 38(2): 157-180