A TYPE OF UPLIFT RESTRAINER FOR THE OPRCB ISOLATORS

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

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

Keywords: U-Shape Uplift Restrainers, Finite Element Analyses, Nonlinear Regression Analysis, OPRCB Isolator, Uplift Forces

ABSTRACT

Orthogonal Pairs of Rollers on Concave Beds (OPRCB) isolator is a recently introduced seismic isolating system which in their original form is weak against uplift. In this study a type of U-shape restraining system is proposed for making the OPRCB isolators resistant against uplift. At first the geometrical features of the restrainer system, which has been obtained by nonlinear regression analysis, is explained and then it mechanical resistance against the uplift forces is examined by finite element analysis. Numerical results show that the proposed restraining system can tolerate uplift forces up to 8.4 tonf in elastic range within a maximum deformation of 1 mm. This amount of uplift force is a reasonable value for 5-story buildings equipped with OPRCB isolators.

INTRODUCTION

It is well-known that most of seismic base isolation devices are weak against uplift, and this is more crucial in case of roller-based devices. Retraining seismic base isolators against uplift has been a concern for researchers since late 80s (Kelly et al., 1987), and some preliminary studies have been conducted in that time (Griffith et al., 1988). Studies in this regard have been continued in 90s (Nagarajaiah et al, 1992) and also during the last decade (Roussis and Constantinou, 2006).

Kelly et al. (1987) proposed a displacement control and uplift restraint device for base isolated structures, which can be installed within multilayer elastomeric base isolation bearings. The device acts to limit the displacement of the bearings and can also be used to take uplift tension forces if necessary. Their device was tested in earthquake simulator tests of a nine-story, 1/4scale steel frame model. Following, Griffith et al. (1988, 1988) performed some earthquake simulation tests on a 1/5-scale, 7-story reinforced concrete structure, and also a 9-story braced steel frame. One of the main objectives of those studies was to evaluate the feasibility of base isolation for medium-rise structures subject to column uplift during severe seismic loads. Those studies showed that either rubber or lead-plug bearings do not show suitable behavior subjected to uplift, even when shear keys are used. Nagarajaiah et al. (1992) conducted an experimental study to evaluate the feasibility of using a sliding isolation system with uplift restraint devices for medium-rise buildings subject to column uplift. They used a Teflon-disc sliding bearing with built-in uplift restraint devices for isolating a quarter-scale, 52-kip (231-kN) model of a six-story structure. Roussis and Constantinou (2006) proposed an uplift-restraining friction pendulum seismic isolation system, called XY-FP isolator, which consists of two orthogonal opposing concave beams interconnected through a sliding mechanism that permits tension to develop in the bearing, thereby preventing uplift.

Hosseini and Soroor (2011) introduced a kind of rolling isolators called Orthogonal Pairs of Rollers on

Concave Beds (OPRCB), and later studied on the application of OPRCB isolators in multi-story buildings up to 14 stories (Hosseini and Soroor, 2013). They have expressed that in case of relatively tall buildings, particularly when subjected to near-fault earthquakes with high vertical ground acceleration, the OPRCB isolators lose their proper function due to uplift forces which result in separation of columns bases from rollers. To prevent this phenomenon, it is necessary to add some specific parts to the isolators between the upper and lower plates to keep them and rollers all in touch together all the time during earthquake. Continuing the studies of Hosseini and Soroor (2011, 2013), Mahmoudkhani (2013) worked on the uplift restraining of OPRCB isolators, by adding some connecting parts between lower, middle, and upper plates, and creating a specific curvature on the surface of the upper plate. Details of that study are presented in the following sections of this paper.

THE FEATURES OF OPRCB ISOLATORS

A sample of the OPRCB isolator is shown in Fig. 1, which shows the isolator installed on the shake table for investigating its behavior in free vibration case as well as sinusoidal and earthquake simulated excitations. This figure also shows one pair of OPRCB isolators in a test under constant vertical force and cyclic lateral loading, applied by actuators.

Figure 1. The proposed OPRCB base isolation system installed on shake table (left) and a pair of them under constant vertical and cyclic lateral loading (right) (Hosseini and Soroor, 2011)

More detailed information with regard to the OPRCB isolator and its dynamic and seismic behavior can be found in study of Hosseini and Soroor (2011). It is worth mentioning that because of orthogonal setting of rollers pairs, the top plate can move in all horizontal directions. The concave beds give a restoring capability to the system. Based on the response analyses of some sets of buildings, equipped with OPRCB isolators (Hosseini and Soroor, 2013), it has been observed that the OPRCB isolating system has high efficiency in case of high- and mid- and most of low frequency earthquakes, and earthquakes with strong large-amplitude pulse; however, as mentioned before, in cases of some low-frequency earthquakes and earthquakes with vertical PGA of more than 1.0 g, the performance level of the system may not be satisfactory. In the next section of the paper a solution, proposed for preventing the OPRCB isolators against uplift, is discussed.

RESTRAINING THE OPRCB ISOLATOR AGAINST UPLIFT

To prevent the OPRCB isolators against uplift a set of four U-shaped elements with some specific features has been employed between the lower and middle plates, and also another set of those elements between the middle and upper plates, as shown in Fig. 2.

As it is seen in Fig. 2, the lower part of each U-shape element is fixed to the edge of corresponding lower plate by a rigid connection, and its upper part is in contact with the top surface of the corresponding upper plate by a roller, which can move on the convex surface provided at the top surface of the upper plate near its edge. To obtain the geometric form of the convex surface it is necessary to calculate its vertical ordinate versus the horizontal displacement of the rollers in each direction, as shown in Fig. 3.

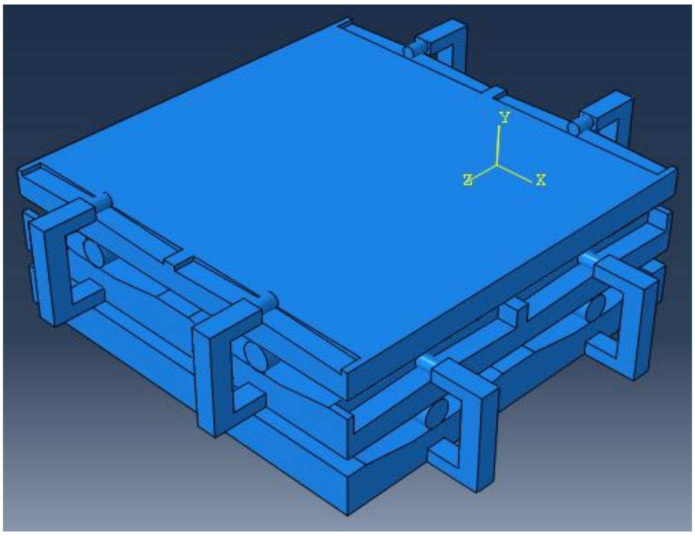

Figure 2. The use of U-shaped elements for restraining the OPRCB isolators against uplift

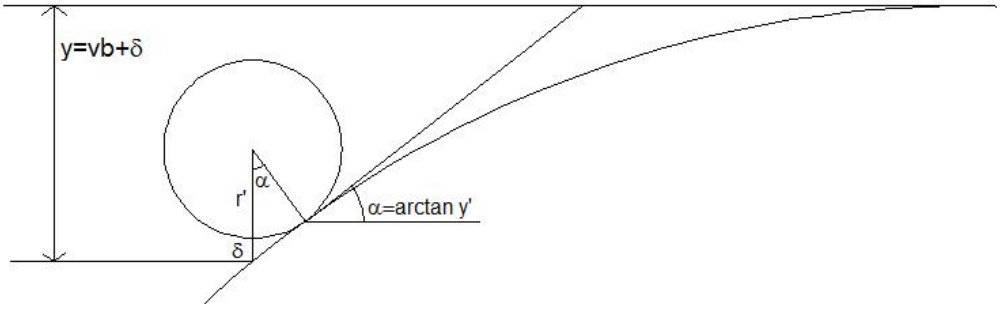

Figure 3. The convex surface provided at the top of upper plates of the OPRCB isolators

Referring to Fig. 3, the algebraic equation of the convex surface can be obtained as follow:

$$\delta = \frac{r'}{\cos\alpha} - r' \tag{1}$$

$$\cos\alpha = \sqrt{\frac{1}{1+\tan^2\alpha}} = \sqrt{\frac{1}{1+y'^2}} \tag{2}$$

$$y = v_b + r'\left(\sqrt{1+y'^2} - 1\right) \tag{3}$$

Regarding that solving the differential Eq. (3) is very difficult by analytical method, it was tried to substitute the desired function y by an approximate function numerically as follow:

$$C_{upper} = \left(R^2 - u_b^2\right)^{0.5} - R + v_b - \delta \tag{4}$$

where C_{upper} is the approximate function and u_b and v_b are, respectively, horizontal and vertical displacement of the top plate of each set of rollers of the OPRCB isolator (see Fig. 4), given by the following equations (Hosseini and Soroor, 2011):

$$u_b = (R-r)(\theta + \sin\theta) \tag{5}$$

$$v_b = (R-r)(1-\cos\theta) \tag{6}$$

In above equations R and r are respectively the radius of the concave bed and rollers of the OPRCB device, and the value of δ is given by:

$$\delta = bu^2 \tag{7}$$

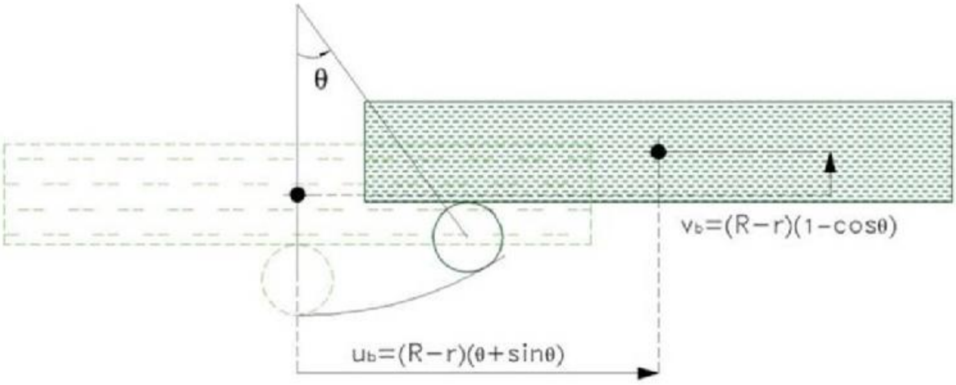

Figure 4. Horizontal and vertical displacements of the top plate of a roller of the OPRCB isolator (Hosseini and Soroor, 2011)

Parameter b in Eq. (7) was obtained numerically by second order regression analysis with respect to R values, varying between 20 and 40 cm, with 0.5 cm increment, r values varying between 1 and 3 cm, with 0.1 cm increment, and θ values varying between -5 and 5 degrees, with 0.01 degrees increment, and then a nonlinear regression analysis with respect to u^2, resulting in the following equation, whose precision has been shown by appropriate statistical indices (Mahmoudkhani, 2013):

$$b = (-3.8200E-02) + (1.4681E-03)R - (1.9085E-04)(R-r) - (1.4180E-05)R^2 \tag{8}$$

In the following section of the paper the numerical modeling of the uplift-restrained OPRCB isolator is presented.

DEVELOPING THE NUMERICAL MODEL OF UPLIFT-RESTRAINERS OF OPRCB ISOLATOR

To make sure that value of parameter b, which appears in calculation of parameter α, is obtained by regression analysis, has enough precision, a finite element analysis were conducted as shows in Fig. 5, which indicates that the upper roller keeps in touch with the upper curved surface all the time during the lateral movement of the rollers.

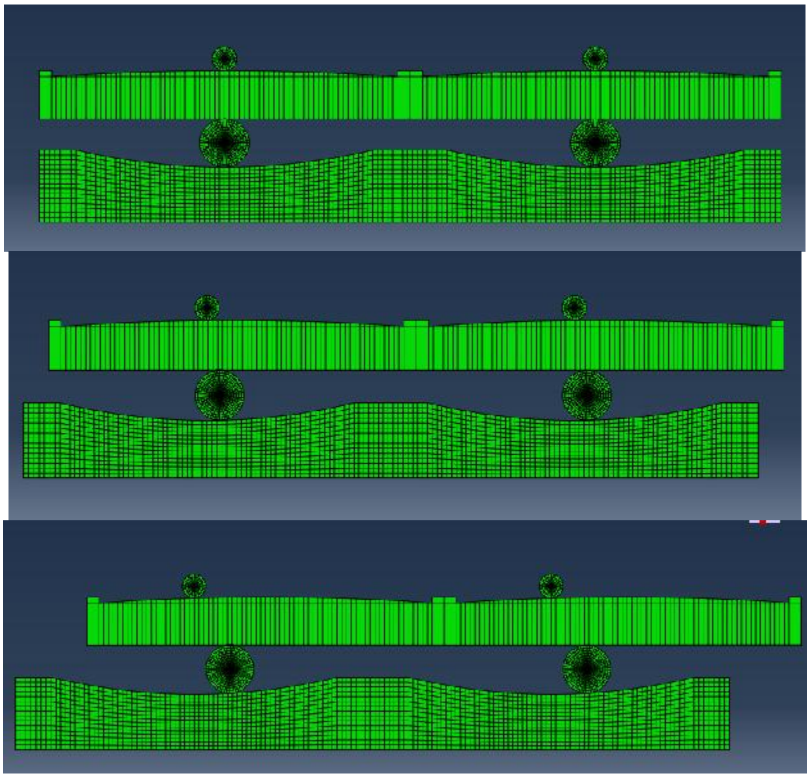

Figure 5. Applying a lateral movement of one pair of rollers of the OPRCB isolator and their corresponding upper plate, showing that the upper roller keeps in touch with the upper curved surface during lateral movement

Fig. 6 shows the geometrical dimensions of the U-shape uplift restrainer element (URE) on its side and front views.

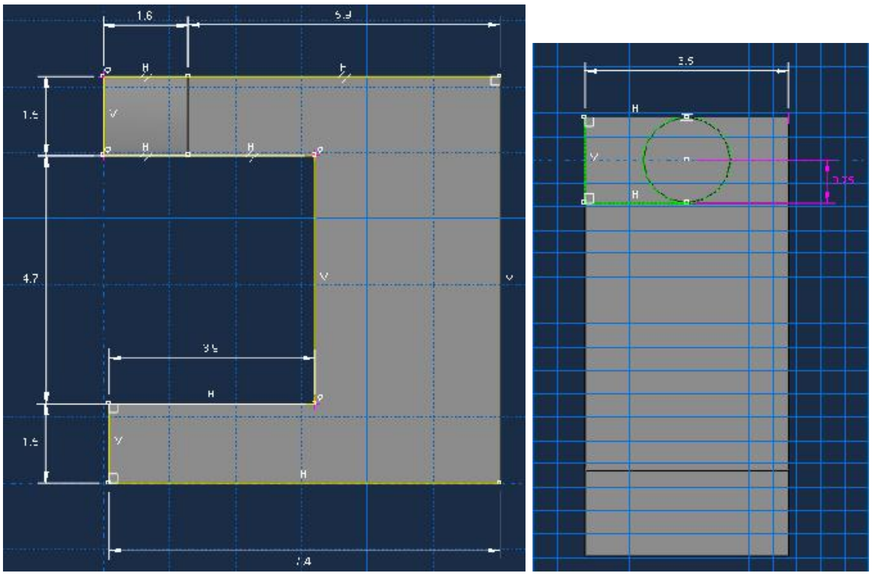

Figure 6. Dimensions of the U-shape uplift restrainer element on its side and front views

For developing the numerical model of UREs a powerful finite element (FE) computer program was employed, and 8-node solid elements were used for meshing. At first the numerical modeling approach was verified base on modeling Bernoulli and Timoshenko beams by SOLID elements (Mahmoudkhani, 2013). Then by assuming a bilinear stress-strain behavior for the material of UREs, which are made of MO40 steel alloy, their 3-D numerical models were developed. To have a symmetrical meshing in each URE its body was symmetrically partitioned as shown in Fig. 7.

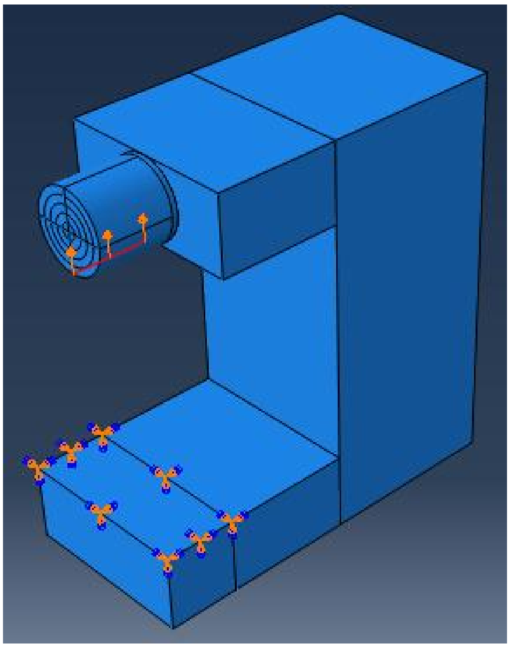

Figure 7. The partitioned URE for achieving the symmetrical FE meshing

In Fig. 7 that part of the URE body which has been assumed to be glued to the corresponding lower plate, is indicated by eight restrained nodes, and the forces which have been applied for obtaining the force-displacement behavior of the URE are also shown. By applying the upward load at the location shown in Fig. 7, the force-displacement behavior of the URE was obtained as shown in Fig. 8.

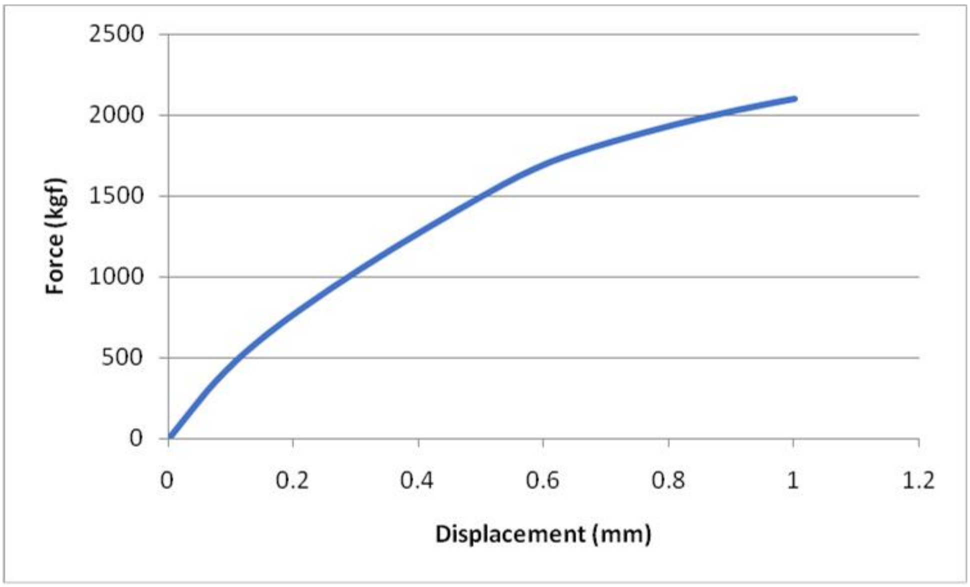

Figure 8. Upward force-displacement of the URE

As it is seen in Fig. 8, up to 1 mm upward displacement, corresponding to around 2100 kgf, at the cylindrical part of the URE its behavior is elastic. This means that an OPRCB isolator set, can confidently tolerate around 8400 kgf uplift force in elastic range. Regarding that uplift causes separation between the pair of rollers and their corresponding upper plate, the time intervals during which the rollers remain separated can affect the seismic behavior of the OPRCB isolator. The average value of these time intervals is around 0.01 sec (Mahmoudkhani, 2013), and considering the average velocities of the rollers in horizontal and vertical directions, the 1 mm is an upper bound for the distance between the rollers and their corresponding upper plates for being separated.

CONCLUSIONS

Based on the numerical results of this study, obtained from FEA of the uplift restrainers' parts, it can be concluded that:

- Using the proposed uplift restrainers can effectively prevent the OPRCB isolators from uplift.
- The proposed restrainers in this research can tolerate up to around 8.4 tonf upward forces, however, by using stronger parts it is possible to easily bear higher values.

Finally, as this study has been only based on the numerical modeling and analyses, it is recommended to conduct some experimental research on the proposed restraining system to get more reliable conclusions.

REFERENCES

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 and 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

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 of 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

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

Mahmoudkhani S (2013) Protection of the Orthogonal Pairs of Rollers in Concave Beds (OPRCB) Isolation System against Uplift Forces, M.Sc. Thesis, Earthquake Engineering Department, Science and Research Branch of the Islamic Azad University, Tehran, Iran

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