*International Balkans Conference on Challenges of Civil Engineering, BCCCE,*
*19-21 May 2011, EPOKA University, Tirana, ALBANIA.*

# Friction Pendulum Bearings for Seismic Isolation

**Muhammet Yurdakul[1], Şevket Ateş[2]**

[1]*Department of Civil Engineering, Bayburt University, Turkey*
[2]*Department of Civil Engineering, Karadeniz Technical University,Trabzon, Turkey*

## ABSTRACT

Seismic isolated building structures are examined in this study. Herein, a two dimensional and eight stories of a building with and without triple friction pendulum (TCFP) bearing is used in the time history analysis under three ground motions in order to investigate of the effectiveness of the seismic isolation systems on the building. The motions are the GBZ000 component of the 17 August 1999 Kocaeli Earthquake recorded at Gebze station, the TCU129-W component of the 1999 Chi-Chi earthquake recorded at TCU129 station and the ELC-270 component of the 1940 Imperial Valley earthquake recorded at 117 El-Centro Array #9 station available from PEER database are used as earthquake records in the time history analysis. Results are compared with each other to emphasize efficiency of the TCFP as a seismic isolation device. Additionally, the seismic behavior of structure isolated by TCFP bearing is compared with the response of the same building using the single concave friction pendulum (SCFP) and double concave friction pendulum (DCFP). Results are compared with each other to emphasize efficiency of the TCFP bearing. The results support the advantages of TCFP bearing isolation system.

TCFP bearing is used as a seismic isolation system which is easy to be manufactured and enduring more than the others. This system offers advantage to buildings which subject to severe earthquake. This is result of damping force of earthquake by means of their internal constructions, which consists of multiple surfaces. As the combinations of surfaces upon which sliding is occurring change, the stiffness and effective friction change accordingly. The TCFP bearing used in this study is not available current structural analysis program because of newly develop system. Therefore, the TCFP bearings are modeled as of a series arrangement of the three SCFP bearings. This arrangement is call series model. TCFP bearing is not exactly like a model organized as a three SCFP bearing in series model although it is similar. Therefore, rigid beam and gap elements are also used.

## INTRODUCTION

Seismic isolation systems generally make structure more resistant to earthquake ground motions. This is because of the positive effects; the seismic isolation techniques have been rapidly a widespread application. Most of the seismic isolation systems currently in use provide friction properties as their energy dissipation mechanism. Theoretical and experimental research studies [1-6] have immensely investigated frictional and rubber based seismic isolation systems. Zayas at al. [7] introduced one of the most effective isolation systems, namely single concave friction pendulum (SCFP) bearing offer developments in strength, life span, resistance of severe earthquake and easy to installation. That is why; many of studies regarding earthquake-resistant structures have been focused on developing more versatile and economic isolation systems such as friction pendulum. Hence double concave friction pendulum (DCFP) and triple concave friction pendulum (TCFP) have been come up with. The DCFP consists of two spherical stainless steel surfaces and an articulated slider covered by a Teflon-based high bearing capacity composite material. On the other hand, the TCFP is also consisted of two facing concave stainless steel surfaces, but an articulated slider is separately placed between the two spherical stainless steel surfaces. Namely, in the later system motions occur in three sliding surfaces. So the system is named as triple. The TCFP exhibits multiple changes in stiffness and damping properties during its motion. It is provided increasing amplitude of displacement. The great advantage of the TCFP bearing is that there is motion on two inner concave surfaces in small amplitude of earthquake while there is no motion on outermost surfaces. However, the motion occurs on the outermost surfaces in case of more severe earthquake. Owing to the fundamental law of the TCFP, chafing does not occur on these surfaces and the system provides long living usage of these devices than the SCFP and the DCFP bearings. Numerical investigations have been carried out on the base isolation effect of the DCFP bearings by Kim and Yun [8]. Nonlinear time history analyses have been carried out on a simplified bridge model to examine the complex behavior of the DCFP and bridge under various earthquake inputs with different intensities, as well. Especially, benefits of the tri-linear DCFP over the bi-linear DCFP are investigated.

Development of the friction type seismic isolation systems has still been progressed. The theoretical force–displacement relationship was verified by Fenz and Constantinou [9] through characterization testing of bearings with sliding surfaces having the same and different radii of curvature and coefficients of friction. The variable friction pendulum system (VFPS) was developed by Panchal and Jangid [10]. Soni at al. [11] presented the behavior of asymmetric building isolated by the double variable frequency pendulum isolator (DVFPI). The DVFPI is an adoption of single variable frequency pendulum isolator (VFPI). It was found that the performance of the DVFPI can be optimized by designing the top sliding surface initially softer and smoother relative to the bottom one.

The principles of operation and force–displacement relationships of the TCFP, the modified SCFP, and the DCFP with sliding surfaces of different displacement capacities are developed [12-13]. In these studies, it has been shown that when properly configured, these bearings provide stiffness and damping that change desirably with increasing displacement. Fenz and Constantinou [14] proposed series model composed of existing nonlinear elements in order to be modeled the TCFP bearing by assembling the SCFP and the gap elements in SAP2000 (1997). Fabio and Constantinou [15] reported that development of tools of simplified analysis and demonstration of their accuracy is required for the new developed TCFP bearings. So, these tools are described and validation studies based on a large number of nonlinear response history analysis results are presented in the paper. It is shown that simplified methods of analysis systematically provide good and often conservative estimates of isolator displacement demands and good estimates of isolator peak velocities. The performance-based seismic design of the Sabiha Gokcen International Airport Terminal Building in Istanbul, Turkey utilizing seismic-isolation concept with the TCFP bearings is achieved [16].

The aim of this paper is to implement the series model proposed by Fenz and Constantinou [17] on a two dimensional and eight story-building when the structure is subjected to the three different earthquake ground motions. Additionally the SCFP and the DCFP bearings are also used for comparing purpose. On account of the fact that the bearing model recently has been developed, its computer application and its behavior have not been well known. This study will serve to the researchers and engineers in field of the earthquake engineering in order to apperceive the concept of the TCFP bearings for seismically isolated buildings and other structures.

## Principles of the TCFP Bearings

The TCFP bearing shown in Figure 1 is consisted of two facing concave stainless steel surfaces coated with Teflon separated by a placed slider assembly. $R_i$ is the radius of curvature of surface i, $h_i$ is the radial distance between the pivot point and surface *i* and $\mu_i$ is the coefficient of friction at the sliding surface *i*, $d_i$ is the displacement capacity of the surface *i*. Outer concave plates have effective radii $R_{eff1}=R_1-h_1$ and $R_{eff4}=R_4-h_4$ .The articulated slider assembly consists of two concave plates separated by a rigid slider. Though the innermost slider is rigid, the assembly as a whole has the capability to rotate to accommodate differential rotations of the top and bottom plates. The friction coefficients on these concave plates are $\mu_1$ and $\mu_4$. The inner concave plates have effective radii $R_{eff2}=R_2-h_2$ and $R_{eff3}=R_3-h_3$. Additionally, these surfaces are also coated with Teflon. The friction coefficients on these concave plates are $\mu_2$ and $\mu_3$. This leads to motion of slider between up and down stainless of steel surfaces of slide plates. Unlike the SCFP and DCFP, in the TCFP bearing there is no mechanical constraint defining which defined location of pivot point [12-13].

Instead of this, pivot point corresponds to immediate center of zero velocity of slider assembly. This center is not a fixed point. It changes during sliding on the concave surfaces. Although, because the immediate center of zero velocity of up and down parts of the slider are always opposite directions, the immediate center of velocity must always be between of them. In generally, the slider height is small than radii of curvature and there is little error occurred by assuming the immediate center of velocity is fixed at middle of height of the articulated slider assembly. Like to the DCFP and the TCFP bearings enable to simultaneously sliding on multiple concave plates. Hence it is constructed smaller than the SCFP bearing using the same general displacement capacity. In case economic benefits are taken into account, there is insignificant differentiation in the cost of the SCFP and the DCFP bearings of size. However, the TCFP bearing is cost effective as per bearing size and displacement capacity.

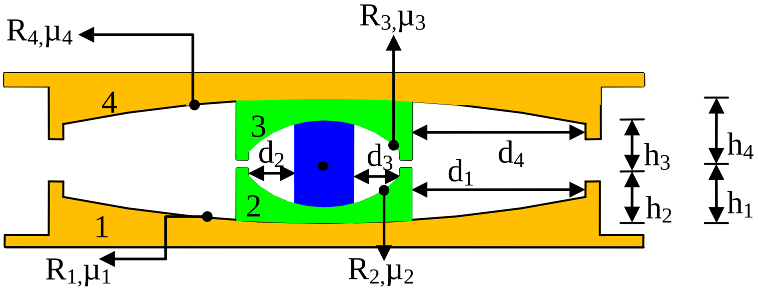
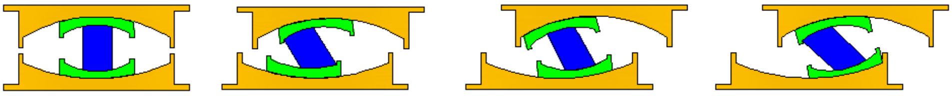


Figure 1 The cross-section of the TCFP bearing and its definition of dimensions

## Series Model of the TCFP Bearing

There are practicable no hysteresis rules or nonlinear elements present in structural program that can be used triple friction model in series model for response history analysis. Series model consist of linear element which can be used in present software structural analysis program. But, the TCFP bearing is not exactly like a model organized as a three SCFP bearing in series model although it is similar. Series models are favored because of their implementation in available commercial structural analysis program such as Sap2000 (2007). It has nonlinear elements modeling rigid linear behavior of the SCFP bearings. However, one behavioral event is preventing correctly modeling the TCFP bearing as a three SCFP bearing. This event is there is no sliding simultaneous on spherical concave surfaces 1 and 2. This observation is experimentally and analytically achieved by Fenz and Constantinou [14]. At first, sliding occurs on spherical innermost concave surfaces 2 and 3 then stops when sliding starts on outermost spherical concave surfaces 1 and 4. Then sliding starts on innermost surfaces 2 and 3 again when the outer concave plates contacts restrainer displacement. The mentioned possible motions are depicted in Figure 2. In the series modeling scheme proposed by Fenz and Constantinou [14], the FP1 link element represents the combined behavior of inner surfaces 2 and 3, the FP2 link element represents the behavior of outer surface 1 and the FP3 link represents outer surface 4.



Centre Position

Inner Pendulum Position

Lower Pendulum Position

Upper Pendulum Position

Figure 2 The possible positions of the TCFP bearing

## NUMERICAL COMPUTATIONS

Nonlinear time history analysis of the isolated and non-isolated reinforced concrete building structure is performed. A two dimensional- and eight story-building is selected as an analytical model in order to execute the analysis. The TCFP bearings are to be opted for the isolation devices and placed between the bottom of the columns and the foundation. The TCFP bearings are modeled as the series model of the TCFP bearing in SAP2000 (2007) by assembling of three friction pendulum (FP) link elements, four gap link elements and five rigid beam elements (RBE). A schematic model of the structure mentioned above is shown in Figure 3. The cross sectional properties of the column and beam elements of the structure are given in Table 1. Damping ratio is specified as 5%. Effective radius of curvature, $R_{eff1}$=$R_{eff4}$= 1200, $R_{eff2}$=$R_{eff3}$ =200, frictional coefficients, $\mu_1$=$\mu_4$=0.04, $\mu_2$=$\mu_3$=0.01, and displacement capacities, $d_1$=$d_4$=200, $d_2$=$d_3$=80 are actual properties of TCFP bearing. Input parameters in series model calculated by equations in [15].

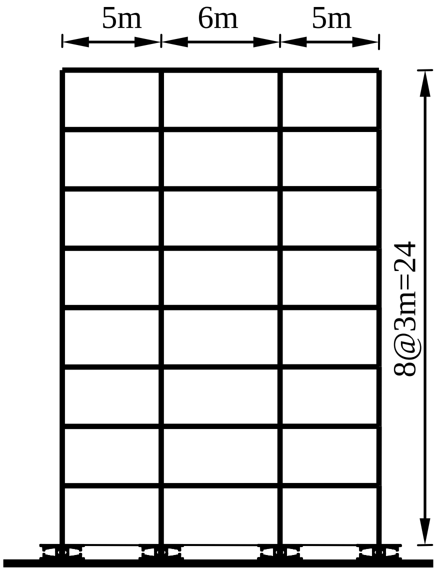


Figure 3 2D mathematical modeling of the structure

Table 1 Cross-sectional property of the buildings

| **Section name** | **Cross-section** *(mm/mm)* | **Inertia moment** *(mm$^4$)* | **Unit volume weight** *(kN/mm$^3$)* | **Modulus of elasticity** *(kN/mm$^2$)* |
|---|---|---|---|---|
| Columns | 300/800 *(1th to 2nd stories)*<br>300/700 *(3th to 5th stories)*<br>300/500 *(6th to 8th stories)* | $12.800x10^{9}$<br>$8.575x10^{9}$<br>$3.125x10^{9}$ | $2.5x10^{-8}$ | 28.5 |
| Beams | 300/600 *(all floors)* | $5.400x10^{9}$ | $2.5x10^{-8}$ | 28.5 |

Unidirectional excitation along the X-axis of the building is applied using the GBZ000 component of the 1999 Kocaeli earthquake recorded at Gebze station, the TCU129-W component of the 1999 Chi-Chi earthquake recorded at TCU129 station, and the ELC-270 component of the 1940 Imperial Valley earthquake recorded at 117 El-Centro Array #9 station, separately. The peak acceleration and displacement of the ground motions are 0.244g and 424.70mm for the Kocaeli earthquake, 1.01g and 501.50mm for the Chi-Chi earthquake, and 0.215g and 239.10mm for the Imperial Valley earthquake, respectively. The motions are scaled by a factor of 2 in order to show all possible sliding positions of the TCFP bearing. The TCFP bearing is modeled using the SCFP and the gap link elements having nonlinear properties. Time history analysis is carried out for the isolated and non-isolated buildings. The first five periods of vibration of the isolated with different type friction pendulum bearings and the non-isolated buildings obtained from the analysis are given in Table 2. Acceleration and displacement response values of the isolated building using the SCFP, the DCFP and the TCFP bearings are compared in Table 3 when the building subjected to the Kocaeli earthquake. The probability of exceedance curves of acceleration, floor displacement and isolator displacement is compared for three types of isolation system. The result supports the advantages of the TCFP bearings. Comprising of floor acceleration and displacement of three different ground motions are given in Table 4.

Table 2 Periods for the isolated and non-isolated buildings for friction pendulums

| **Mode Number** | **Period (sec)** | | | |
|---|---|---|---|---|
| | **Isolated Building** | | | **Non-Isolated Building** |
| | **with SCFP** | **with DCFP** | **with TCFP** | |
| 1 | 2.286 | 2.986 | 3.219 | 0.885 |
| 2 | 0.464 | 0.473 | 0.482 | 0.306 |
| 3 | 0.224 | 0.225 | 0.228 | 0.169 |
| 4 | 0.140 | 0.141 | 0.159 | 0.119 |
| 5 | 0.112 | 0.112 | 0.158 | 0.106 |

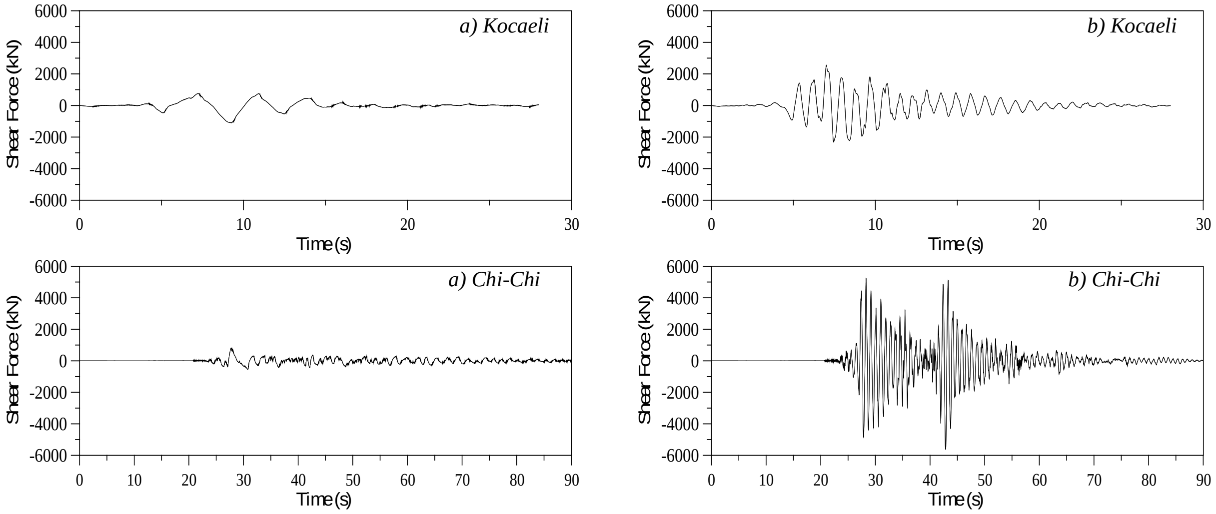
The displacements of the TCFP bearings obtained from analyses reach to 410.80mm, 290.10mm and 291.40mm in case of the Kocaeli, the Chi-Chi and The Imperial Valley earthquakes, respectively. Displacement capacity of the TCFP bearings is intended as 413.80mm. The peak displacement of the ground motions as mentioned above are 424.70mm, 501.50mm and 239.10mm for the Kocaeli, Chi-Chi and Imperial Valley earthquakes, respectively. These values show that the motion firstly starts inner surfaces 2 and 3 only. At the position of the bearing uses own approximately 13.80mm displacement capacity. Base shear forces for the isolated and non-isolated building are also plotted in Figure 4. The base shear force at the bearing level is approximately obtained as 0.646W, 0.480W and 0.493W for the Kocaeli, the Chi-Chi and the Imperial Valley earthquakes, respectively. Moreover, the base shear force of the non-isolated building is 1.498W, 3.308W and 1.631W for the Kocaeli, the Chi-Chi and the Imperial Valley earthquakes, respectively. The results show that the TCFP bearings significantly reduce the base shear forces. The decrement values are ranging from 57% to 85% in case of the usage of the three earthquake records.

Table 3 Comprising of friction pendulum bearing types

| **Level** | **SCFP** | | **DCFP** | | **TCFP** | |
|---|---|---|---|---|---|---|
| | **Acceleration ($m/sec^2$)** | **Displacement (mm)** | **Acceleration ($m/sec^2$)** | **Displacement (mm)** | **Acceleration ($m/sec^2$)** | **Displacement (mm)** |
| 1. floor | 4.406 | 106.30 | 3.715 | 139.50 | 3.713 | 416.10 |
| 2. floor | 4.824 | 117.30 | 3.696 | 146.80 | 3.719 | 424.90 |
| 3. floor | 4.374 | 129.80 | 4.158 | 154.60 | 3.771 | 434.10 |
| 4. floor | 4.293 | 141.60 | 4.139 | 161.90 | 3.670 | 441.90 |
| 5. floor | 4.228 | 152.20 | 3.870 | 168.50 | 3.638 | 448.30 |
| 6. floor | 4.949 | 163.80 | 4.360 | 175.40 | 3.812 | 454.60 |
| 7. floor | 5.757 | 172.30 | 4.378 | 180.40 | 3.920 | 458.80 |
| 8. floor | 6.099 | 177.40 | 4.356 | 183.30 | 4.091 | 461.20 |

Table 4 Comprising of floor acceleration and displacement of three ground motions

| | | **Kocaeli** | | **Chi- Chi** | | **Imperial Valley** | |
|---|---|---|---|---|---|---|---|
| **Floor** | | **Isolated** | **Non-isolated** | **Isolated** | **Non-isolated** | **Isolated** | **Non-isolated** |
| First | Acceleration ($m/sec^2$) | 3.713 | 1.975 | 12.403 | 5.551 | 4.120 | 1.983 |
| | Displacement (mm) | 416.10 | 12.98 | 294.16 | 29.07 | 295.73 | 14.08 |
| Middle | Acceleration ($m/sec^2$) | 3.670 | 7.461 | 13.525 | 22.524 | 4.249 | 6.548 |
| | Displacement (mm) | 441.90 | 91.29 | 313.76 | 199.19 | 317.34 | 93.70 |
| Top | Acceleration ($m/sec^2$) | 4.091 | 11.690 | 12.219 | 26.017 | 5.954 | 10.138 |
| | Displacement (mm) | 461.20 | 179.40 | 329.09 | 356.15 | 334.34 | 176.17 |



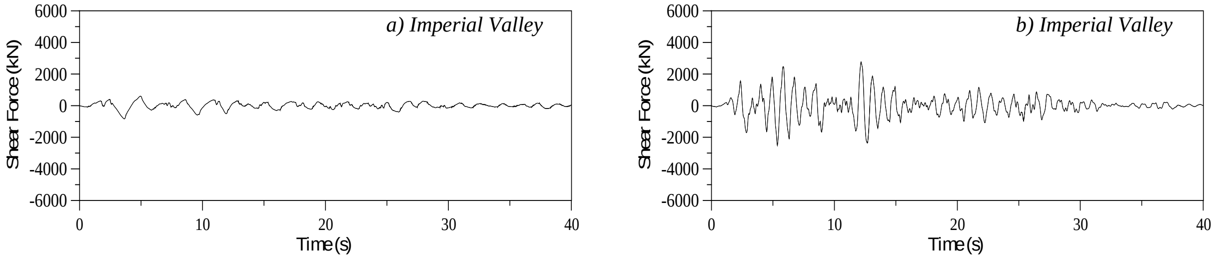


Figure 4 Base shear force histories of (a) the isolated and (b) the non-isolated buildings

## CONCLUSION

A two dimensional-and eight-story of a building isolated by the TCFP bearing is subjected to three different ground motions. Time history analysis in order to investigate of the effectiveness of the seismic isolation systems on the buildings is performed. The ground motion of the Kocaeli earthquake is used to compare isolated buildings with different friction type isolation bearings, that is, the SCFP, the DCFP and the TCFP bearing system.

Analyses are performed for the isolated and non-isolated building subjected to different ground motions. And then results obtained from time history analysis were compared. The study demonstrated that relative displacement at the floor is approximately zero at isolated building with the TCFP bearing subjected to different ground motions. The relative structural displacements as expected are increased when comparing with these of non-isolated building. This is because of the demand displacement capacity of the TCFP bearings. Provide that the displacement capacity at the TCFP bearing level is considered, it is seen that displacement for the isolated building is smaller than these of non-isolated building. In the TCFP bearing, peak accelerations at floor level are smaller than SCFP and DCFP. To the contrary displacement capacity of the TCFP is bigger than the other. Usage of the TCFP bearings to isolate structures against severe earthquakes provides more major benefits than the SCFP and DCFP in order protect the structures and then living in them. The probability of exceedance curves of acceleration, floor displacement and isolator displacement is compared for three types of isolation system. The result supports the advantages of the TCFP bearings.

Finally, it should be noted that isolation system such as the TCFP bearing is effective when the structures are subjected to severe earthquakes.

## REFERENCES

[1] Mostaghel, N. and Tanbakuchi, J. (1983), Response of sliding structures to earthquake support motion, *Earthquake Engineering and Structural Dynamics* 11, 729–748.

[2] Lin, B. C. and Tadjbakhsh, I. G. (1986), Effect of vertical motion on friction driven systems, Earthquake Engineering and Structural Dynamics 14, 609–622.

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

[4] Tsai, C. S., Chiang, T. C., and Chen, B. J. (2003), Finite element formulations and theoretical study for variable curvature friction pendulum system, *Engineering Structures* 25, 1719–1730.

[5] Panchal, V. R. Jangid, R. S. Soni, D. P. and Mistry B. B.(2010), Response of the Double Variable Frequency Pendulum Isolator under Triaxial Ground ExcitationsJournal of Earthquake Engineering, 14, 527–558.

[6] Khoshnoudian F. and Rabiei M., (2010), Seismic response of double concave friction pendulum base-isolated structures considering vertical component of earthquake, Advances in structural engineering, 13(1), 1-14.

[7] Zayas, V., Low, S. ve Mahin, S.A., 1987. The FPS Earthquake Resisting System Experimental Report, EERC Technical Report, UBC/EERC, 87-01.

[8] Kim Y. S. and Yun (2007). Seismic response characteristics of bridges using double concave friction pendulum bearings with tri-linear behaviour. Engineering Structures, Vol. 29, pp. 3082–3093.

[9] Fenz, D. M. and Constantinou, M. C. (2006) ‘Behaviour of the double concave friction pendulum bearing, Earthquake Engineering and Structural Dynamics 35, 1403–1424.

[10] Panchal, V. R. and Jangid, R. S.(2008), Seismic Isolation Of Bridge Using Variable Curvature Friction Pendulum System**,** The 14th World Conference on Earthquake Engineering, October 12-17, 2008, Beijing, China

[11] Soni D.P., Mistry B.B. and Panchal V.R. (2010), Behaviour of asymmetric building with double variable frequency pendulum isolator, *Structural Engineering and Mechanics*, Vol. 34, No. 1 61-84.

[12] Fenz D.M. and Constantinou M. C. (2008a). Development, implementation and verification of dynamic analysis models for multi-spherical sliding bearings. Technical Report MCEER-08-0018, Multidisciplinary Center for Earthquake Engineering Research, University at Buffalo, State University of New York, Buffalo, NY.

[13] Fenz D. M. and Constantinou M. C. (2008b). Spherical sliding isolation bearings with adaptive behavior: theory. *Earthquake Engineering and Structural Dynamics*. Vol. 37, pp. 163–183.

[14] Fenz D. M. and Constantinou M. C. (2008c). Modeling triple friction pendulum bearings for response history analysis. *Earthquake Spectra*. Vol. 24, pp. 1011–1028.

[15] Fabio F. and Constantinou M. C. (2010). Evaluation of simplified methods of analysis for structures with triple friction pendulum isolators, *Earthquake Engineering and Structural Dynamics*, Vol. 39, pp.5-22.

[16] Zekioglu A., Darama H. and Erkus B. (2009). Performance-Based Seismic Design of a Large Seismically Isolated Structure: Istanbul Sabiha Gokcen International Airport Terminal Building, Structural Engineering Association of California Convention Proceedings, 409-427.

[17] Fenz D. M. and Constantinou M. C. (2008c). Modeling triple friction pendulum bearings for response history analysis. *Earthquake Spectra*. Vol. 24, pp. 1011–1028.