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FINITE ELEMENT ANALYSIS OF A FRICTION PENDULUM BEARING BASE ISOLATION SYSTEM FOR EARTHQUAKE LOADS

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ABSTRACT

Base isolation systems have become a significant element of a structural system to enhance reliability during an earthquake. One type of base isolation system is Friction Pendulum Bearing in which the superstructure is isolated from the foundation using specially designed concave surface and bearing to allow sway under its own natural period during the seismic events. This study presents the finite element analysis of Friction Pendulum System (FPS) of a multi-story building and without base isolation, subjected to two real different earthquakes (El Centro & Loma Prieta) by use engineering program (ETABS Nonlinear version 9.5). Comparing with the available experimental data, the application of the current model gives close prediction. It has been shown that as a result of isolation, base shear acting are reduced considerably.

A parametric study dealing with the coefficient of friction μ (0.08,0.15 and 0.25) and radius of concave surface R (40 in, 80 in and 400 in) to study the base shear and the displacement of Friction Pendulum System. Overall the base isolated system showed a significant improvement in dynamic response of the model structure by reducing the base shear and increasing the damping of the system

التحليل بالعناصر المحددة لنظام العزل بقاعدة بندول الاحتكاك للأحمال الزلزالية

الخلاصة

أصبحت أنظمة العزل القاعدي من العناصر الهامة في تعزيز فاعلية المباني إثناء الهزات الأرضية. واحد هذه الأنظمة هو نظام العزل بقاعدة بندول الاحتكاك الذي يقوم بعزل المبنى عن أساسة ويستخدم تصميم خاص لتقعر سطح قاعدة الاستناد ويسمح بالتأرجح بفترة طبيعية أثناء حدوث الزلزال.
تقدم هذه الدراسة تحليل العناصر المحددة للمبنى متعدد الطوابق غير معزول و معزول بنظام العزل بقاعدة بندول الاحتكاك معرض لزلزالان حقيقيان مختلفين (El Centro & Loma Prieta) باستخدام برنامج هندسي (ETABS Nonlinear version 9.5) وقورنت مع النتائج العملية المتوفرة حيث أعطا النظام المستخدم نتائج متقاربة و كما لوحظ كنتيجة للعزل, انخفاض كبير بقوة قص القاعدة.
وتم أخذ ثلاث قيم مختلفة لكل من معمل الاحتكاك (0.08, 0.15 & 0.25) μ و نصف قطر التقعر(R(40 in, 80 in & 400 in لدراسة القص القاعدي وإزاحة نظام بندول الاحتكاك.

وقد أظهرت النتائج إن لنظام بندول الاحتكاك تحسين هام عنده الاستجابة الحركية لنموذج المبنـى بتقليل القص القاعدي وزيادة إخماد المبنى .

KEY WORD

Base-isolated, friction pendulum, finite element, earthquake, seismic isolation bearings

INTRODUCTION

In recent years, the Friction Pendulum System (FPS) has become a widely accepted device for seismic isolation of structures. The concept is to isolate the structure from ground shaking during strong earthquake. Seismic isolation systems like the FPS are designed to lengthen the structural period far from the dominant frequency of the ground motion and to dissipate vibration energy during an earthquake. The FPS consists of a spherical stainless steel surface and a slider, covered by a Teflon-based composite material. During severe ground motion, the slider moves on the spherical surface lifting the structure and dissipating energy by friction between the spherical surface and the slider.

The period of the Friction Pendulum System (FPS) is selected simply by choosing the radius of curvature of the concave surface. It is independent of the mass of the supported structure. The damping is selected by choosing the friction coefficient. Torsion motion of the structure are minimized because the center of stiffness of the bearing automatically coincides with the center of mass of the supported structure. The bearing's period, vertical load capacity, damping, displacement capacity, and tension capacity, can all be selected independently.

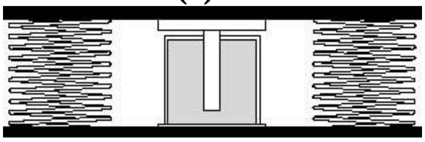
BASE ISOLATION TYPES

Base isolation systems are divided into two main groups of systems with a recentering (Restoring) mechanism and systems without this mechanism. The recentering mechanism is responsible to push the structure back to its original place to minimize the permanent displacement of the structure in its base. Regarding isolation mechanisms, base isolated systems can be divided into three main groups: elastomeric-based systems, sliding-based types, and spring type systems

1. Elastomeric-based systems
   1.1 BLow-damping rubber systems
   1.2 BHigh-damping rubber systems
2 . BSliding-based systems
   2.1 BElectricite-de-France system
   2.2 BEERC system
   2.3 BResilient-Friction based isolation system (R-FBI)
   2.4 Fiction pendulum systems
      2.4.1 Bearing F.P.S
      2.4.2 Tension F.P.S

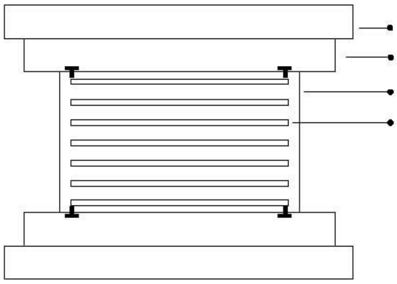
3. Spring-type systems

(a)



(b)

(c)



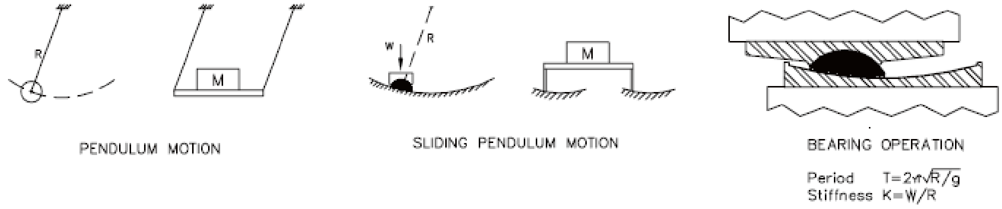
(d)

Fig.1 Most popular building isolation devices: (a)Spring-based isolator,(b) Tension F.P.S,(c) BElectricite-de-France system,(d) Bearing F.P.S

CONCEPT OF FRICTION PEMDULUM SYSTEM

Friction Pendulum Bearings work on the same principle as a simple pendulum. When activated during an earthquake, the articulated slider moves along the concave surface causing the structure to move in small simple harmonic motions, as illustrated in Fig.2 & 3 Similar to a simple pendulum, the bearings increase the structures natural period by causing the building to slide along the concave inner surface of the bearing. The bearings filter out the imparting earthquake forces through the frictional interface. This frictional interface also generates a dynamic friction force that acts as a damping system in the event of an earthquake. This lateral displacement greatly reduces the forces transmitted to the structure even during strong magnitude eight earthquakes. This type of system also possesses a re-centering capability, which allows the structure to center itself, if any displacement is occurred during a seismic event due to the concave surface of the bearings and gravity.

Fig.2 Pendulum motion



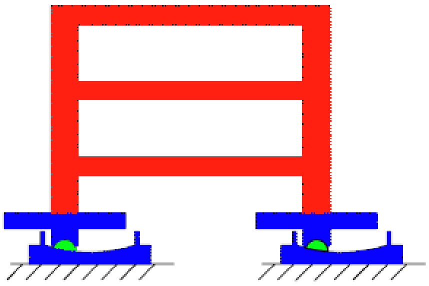


Fig.3 Basic Principles of the Friction Pendulum Bearing

EXPERIMENT STUDY OF NIKOLAG KRAVCHUK, RYAN COLQUHOUN, AND ALI PORBAHA

This model (Fig. 4) was tested by [Nikolag Kravchuk, Ryan Colquhoun, and Ali Porbaha California State University, Sacramento] to simulate the pendulum motion of a single Friction Pendulum Bearing. The springs acted as the force that centered the system when it was displaced in any direction. The preliminary model was modified slightly to improve the response of the system. The new design had four actual bearings machined to reduce the friction and better represent the response of an actual pendulum system.

Both model structures (with and without isolation system) were made from the same flexible material and mounted on the same shake table to allow comparison of the responses of the two structures during lateral loading.

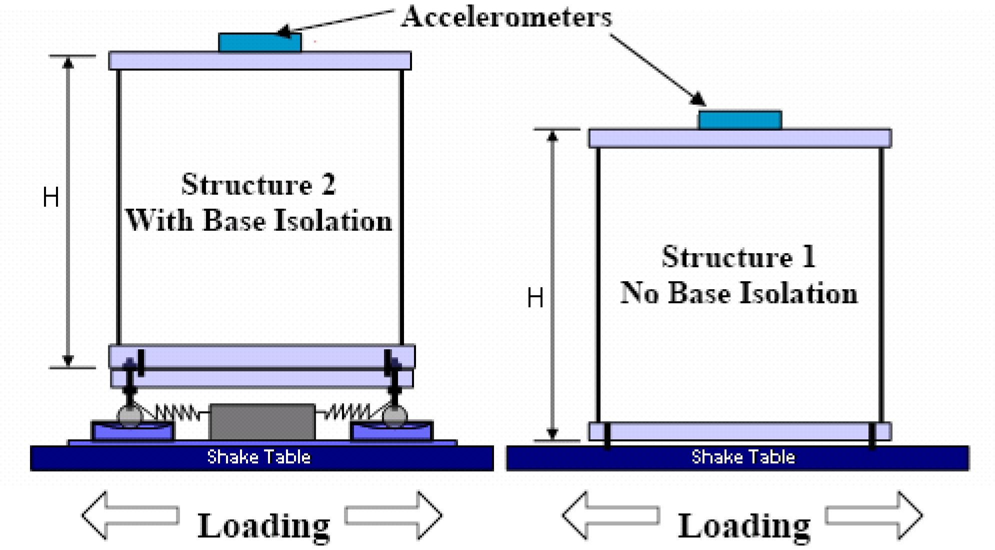


Fig.4 Experimental Setup of Nikolag Kravchuk, Ryan Colquhoun, and Ail Porbaha

TESTING AND RESULTS OF NIKOLAG KRAVCHUK, RYAN COLQUHOUN, AND ALI PORBAHA

Free Vibration

The first sequence in the experiment testing was to get the response of the structures under free vibration. An equal drift was applied to the top of both structures with and without base isolation system. The force was released and the structures allowed to oscillate until the natural damping of the structures brought the system to stop. The accelerometers recorded the acceleration that each structure experienced until they stopped oscillating. Fig. 5 shows the responses of these two structures.

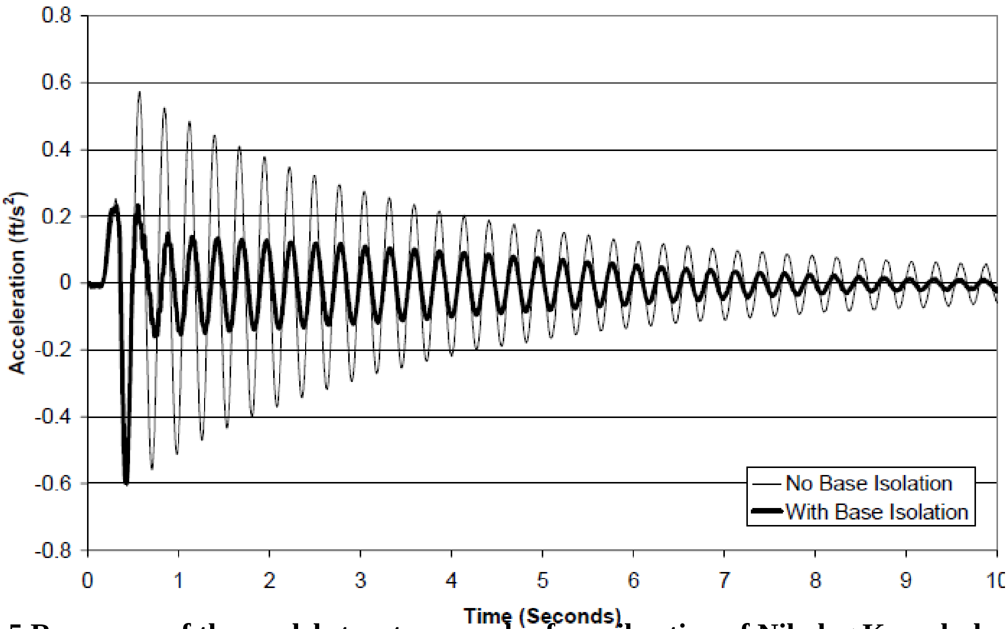


Fig.5 Responses of the model structures under free vibration of Nikolag Kravchuk, Ryan Colquhoun, and Ali Porbaha.

Forced Vibration

The second sequence of experiment was the forced vibration of the structures. The shake table was loaded with an increasing acceleration (sweep) for a period of 10 seconds. The acceleration of each structure was recorded and the responses of both structures were recorded, as shown in Fig 6.

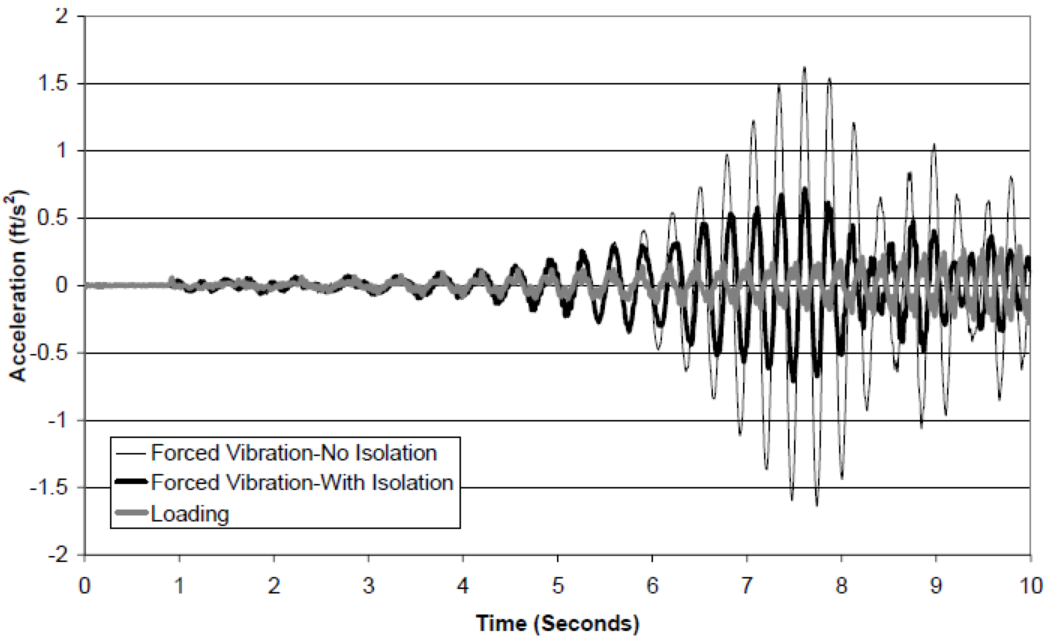


Fig.6 Responses of the model structures under forced vibration of Nikolag Kravchuk, Ryan Colquhoun, and Ali Porbaha.

Table1. Results of the shake table tests

	Free Vibration		**Forced Vibration**	
	With Base Isolation	**Without Base Isolation**	**With Base Isolation**	**Without Base Isolation**
Maximum acceleration	0.23	0.57	0.72	1.63
Damping ratio	0.085	0.016	-	-

USING OF FRICTION PENDULUM SYSTEM

Friction Pendulum may be used between components of the structures (Friction pendulum gap - element) or between structure and foundation (Friction pendulum base isolation)

San Francisco Airport International Terminal was designed by Skidmore, Owings and Merrill with Dr. Anoop Mokha as project Eng. The seismic design used friction pendulum seismic isolation to resist a magnitude 8 earthquake occurring on the San Andreas Fault, with no structural damage.

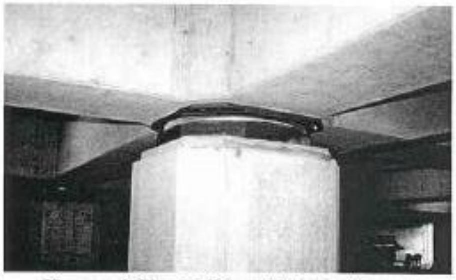
Benicia-Martinez Bridge is one of the largest bridges to date to undertake a seismic isolation retrofit, and uses the largest seismic isolation bearings ever manufactured. [Dr. Victor Zayas. Earthquake Protection Systems, Inc. 2801 Giant Hwy . Blodg. A Richmond, California 94806 . (510)232-5993. Fax 232-6577].

San Francisco Airport International Terminal

SF Airport Terminal Installed Bearing

Friction pendulum system bearing base isolation between column and separate footing

Hayward City Hall



Hayward City Hall Installed Bearing

Friction pendulum gap - element between beam and column

Benicia-Martinez Toll Bridge

Concave for Benicia-Martinez Bridge Bearing

Friction pendulum system bearing base isolation between pier and foundation

Fig.7 Using of Friction pendulum system [Dr. Victor Zayas. Earthquake Protection Systems, Inc. 2801 Giant Hwy . Blodg. A Richmond, California. www.earthquakeprotection.com].

FINITE ELEMENT ANALYSIS OF FRICTION PENDULUM SYSTEM (FPS)

The differential equation governing an FPS isolated structure is [Almazan and Llera, 2002and 2003]:

$$M\ddot{q}+C\dot{q}+Kq+Q=-ML_wW \quad (1)$$

where $\boldsymbol{q}$ is the vector of the system degrees of freedom. $\boldsymbol{M}$, $\boldsymbol{C}$, and $\boldsymbol{K}$ are mass, damping, and stiffness matrices, respectively. $\boldsymbol{W}$ is the 3-D excitation input vector, $\boldsymbol{L}_W$ the input influence matrix, and $\boldsymbol{Q}$ the vector of non-linear restoring force generated by isolators with respect to the degree-of-freedom $\boldsymbol{q}$ of the structure. To keep track of the axial force in bearings a friction pendulum element has been incorporated in the set Fig.8. The sliding displacement of the isolator is:

$$\delta_k = \overline{O_k S_k} = \{\delta_{xk}\delta_{yk}\delta_{zk}\}^T \qquad (2)$$

By imposing the kinetic constraint, i.e. spherical surface of the isolator, the three components of the deformation $\boldsymbol{\delta_k}$ and its velocity $\dot{\delta}_k$ are implicitly expressed in terms of each other as:

$$\delta_{xk}^2 + \delta_{yk}^2 + (\delta_{zk} - R_k)^2 = R_k^2 \qquad (3)$$

$$\delta_{xk}\,\dot{\delta}_{xk} + \delta_{yk}\,\dot{\delta}_{yk} + \dot{\delta}_{zk}(\delta_{zk} - R_k) = 0 \qquad (4)$$

where R_k is the radius of curvature of the spherical surface of the k^{th} isolator.

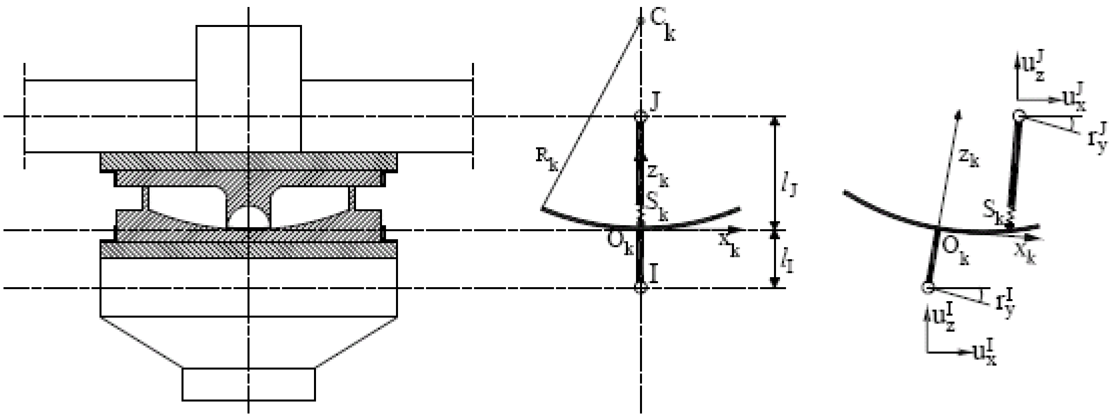


Fig.8 Friction pendulum element in downward position [Almazan and Llera, 2002and 2003]

The element demonstrated in fig. 8 has 2 nodes, I and J, and 12 degrees of freedom, which are linearly related to the global degrees-of-freedom ($\boldsymbol{q}$):

$$u_k = \{u_k^J ; u_k^I\} = P_k q \qquad (5)$$

where P_k is the nodal kinetic transformation matrix of the k^{th} isolator. u_k^J and u_k^I are nodal deformation vectors of the lower and upper element nodes.
Assuming small node rotations, it is possible to relate deformation and velocity in the isolator, δ_k and $\dot{\delta}_k$, with nodal deformations, u_k as:

$$\delta_k = \bar{S}(u_k)u_k \tag{6}$$

$$\dot{\delta} = \hat{S}(u_k)\dot{u}_k \tag{7}$$

In which

$$\bar{S}(u_k) = \begin{bmatrix} 1 & 0 & 0 & 0 & -l_j & 0 & -1 & 0 & 0 & 0 & \Delta u_z + l_I & \Delta u_y \\ 0 & 1 & 0 & -l_j & 0 & 0 & 0 & -1 & 0 & \Delta u_z + l_I & 0 & -\Delta u_x \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & -1 & \Delta u_y & \Delta u_x & 0 \end{bmatrix}$$

(8)

$$\hat{S}(u_k) = \begin{bmatrix} 1 & r_z^I & -r_y^I & 0 & -l_j & 0 & -1 & -r_z^I & r_y^I & 0 & -(\Delta u_z + l_I) & \Delta u_y \\ -r_z^I & 1 & r_x^I & l_j & 0 & 0 & r_z^I & -1 & -r_x^I & \Delta u_z + l_I & 0 & -\Delta u_x \\ r_y^I & -r_x^I & 1 & 0 & 0 & 0 & -r_y^I & r_x^I & -1 & -\Delta u_y & \Delta u_x & 0 \end{bmatrix}$$

(9)

Where $\Delta u_i = u_i^J - u_i^I$ for $i = x, y, z$ and l_J and l_I are vertical distances between nodes J and I and origin O_k in the original configuration of the fraction pendulum system, corresponding Fig. 8

In the next step the non-linear restoring force vector ***Q*** must be determined. The restoring force in an isolator of this type is composed of the two main terms of the pendulum effect, *fp*, and the frictional part, $f\mu$:

$$f_k = fp + f\mu$$

$$f_k = N_k \hat{n}_k + \bar{\eta}_k \mu_k N_k \hat{s}_k$$

$$f_k = N_k(\hat{n}_k + \bar{\eta}_k \mu_k \hat{s}_k) = N_k r_k \tag{10}$$

Where N_k is the magnitude of the normal force $\hat{n}_k$ and $\hat{s}_k$ are unit vectors in the outward normal direction and tangential to the trajectory of the isolator, respectively. μ_k is the friction coefficient. $\bar{\eta}_k$ is a positive non-dimensional variable with value one during sliding phases and less than one during sticking phases [Wen, 1976] and [Park, 1986].

In sticking phases, it is not possible to determine the magnitude and direction of the friction force, as regarding equation 10, the sliding velocity vanishes. To overcome this problem, instead of the Coulomb friction law an equivalent hysteretic model is applied.

To compute the restoring force in the global coordinate system, the restoring force computed in equation 10 is transformed as Fig.9.

$$Q_k = L_k^T f_k \tag{11}$$

Where

Q_k is local vector of non-linear restoring force for fraction pendulum element and

$$L_k = \hat{S}_k P_k \tag{12}$$

Finally adding restoring forces of all isolators in the system:

$$Q = \sum_k Q_k = \sum_k L_k^T f_k = L^T F \tag{13}$$

Where

Q the global vector of non-linear restoring force from fiction pendulum systems [Almazan and Llera, 2003]

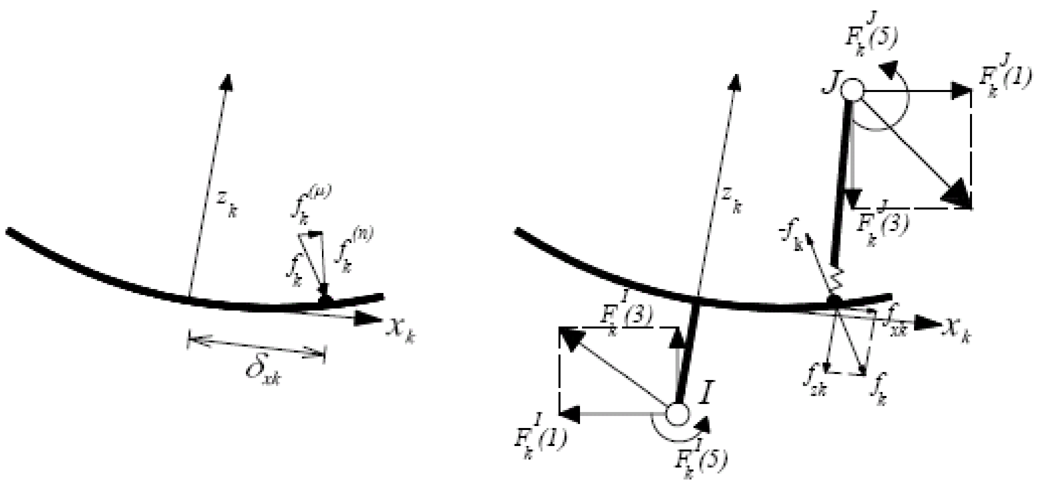


Fig.9 Forces acting on an FPS bearing (left) in local coordinates, (right)in global coordinates system [Almazan and Llera, 2002and 2003]

CASE STUDIES

The finite element mesh model of a three-story structure with two bays on the two direction by engineering programs (ETABS Nonlinear version 9.5). The columns (24 in x 24in) , beams (36 in x 24 in) and slab thickness (8 in) Fig.11. The material properties of structure (Table 3 & 4) and the linear and nonlinear properties of friction pendulum in table (Table 5 & 6). The response of the aforementioned system has been subjected to two strong earthquakes are studied. El Centro earthquake has 500 increment and 0.02 time step and Loma Prieta earthquake has 2000 increment and 0.02 time step (Table 2) and fig.10.

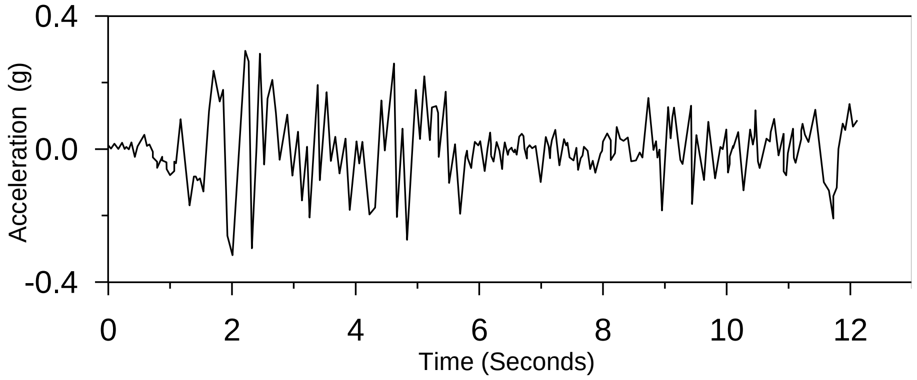
Two type of supports have been taken (fixed support and base isolation of friction pendulum) as a result of finite element analysis has been found that the friction pendulum show a significant improvement in dynamic response of structure by reducing the base shear fig. 12 & 13.

As a comparison with model of [Nikolay Kravchuk, Ryan Colquhoun, and Ali Porbaha 2008] fig. 5 & 6 there is a good agreement in the general behavior.

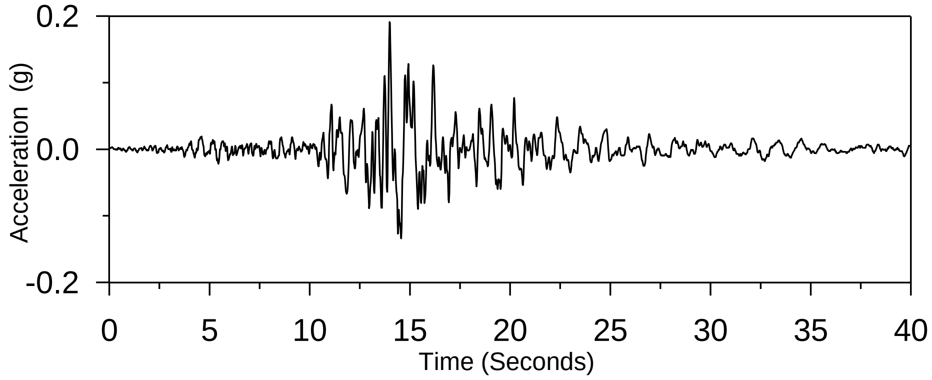
The numerical analysis show that the input energy from earthquakes (El Centro & Loma Prieta) and efficiency the FPS on dissipation of the vibration energy to keep the structure from failure fig. 14 & 15.

Table 2 Earthquake motion used in the analysis.

Excitation	Record	Duration [s]	Magnitude
El Centro	USA, Imperial Valley, May 18, 1940	10	6.7
Loma Prieta	USA, Santa Cruz, California October 17, 1989	40	7.1



(a) El Centro earthquake, 1940



(b) Loma Prieta earthquake, 1989

Fig.10 Earthquake Loads used in analysis

Table 3 Analysis Property Data.

Modulus of elasticity , (Kip-in)	3600
Mass per unit volume, (Kip-in)	2.246E-7
weight per unit volume, (Kip-in)	8.841E-5
Poisson’s ratio , ν	0.2
Coefficient of thermal expansion, (Kip-in)	5.5E-6
Shear Modules, (Kip-in)	1500

Table 4 Design Property Data.

Reinforcing Yield Stress, (Kip-in)	60
Compressive strength, (Kip-in)	4
Shear Steel Yield Stress, (Kip-in)	40
Concrete Shear Strength, (Kip-in)	4

Table 5 Linear Properties of FPS.

Direction	Effective Stiffness, (Kip-in)	Effective Damping
U_1	1000	o
U_2	4	o
U_3	4	o

Table 6 Non Linear Properties of FPS.

Direction	Stiffness, (Kip-in)	Rate parameter	μ	R (in)
U_1	1000	-------	------	------
U2	100	20	0.08	40
			0.15	80
			0.25	400
U3	100	20	0.08	40
			0.15	80
			0.25	400

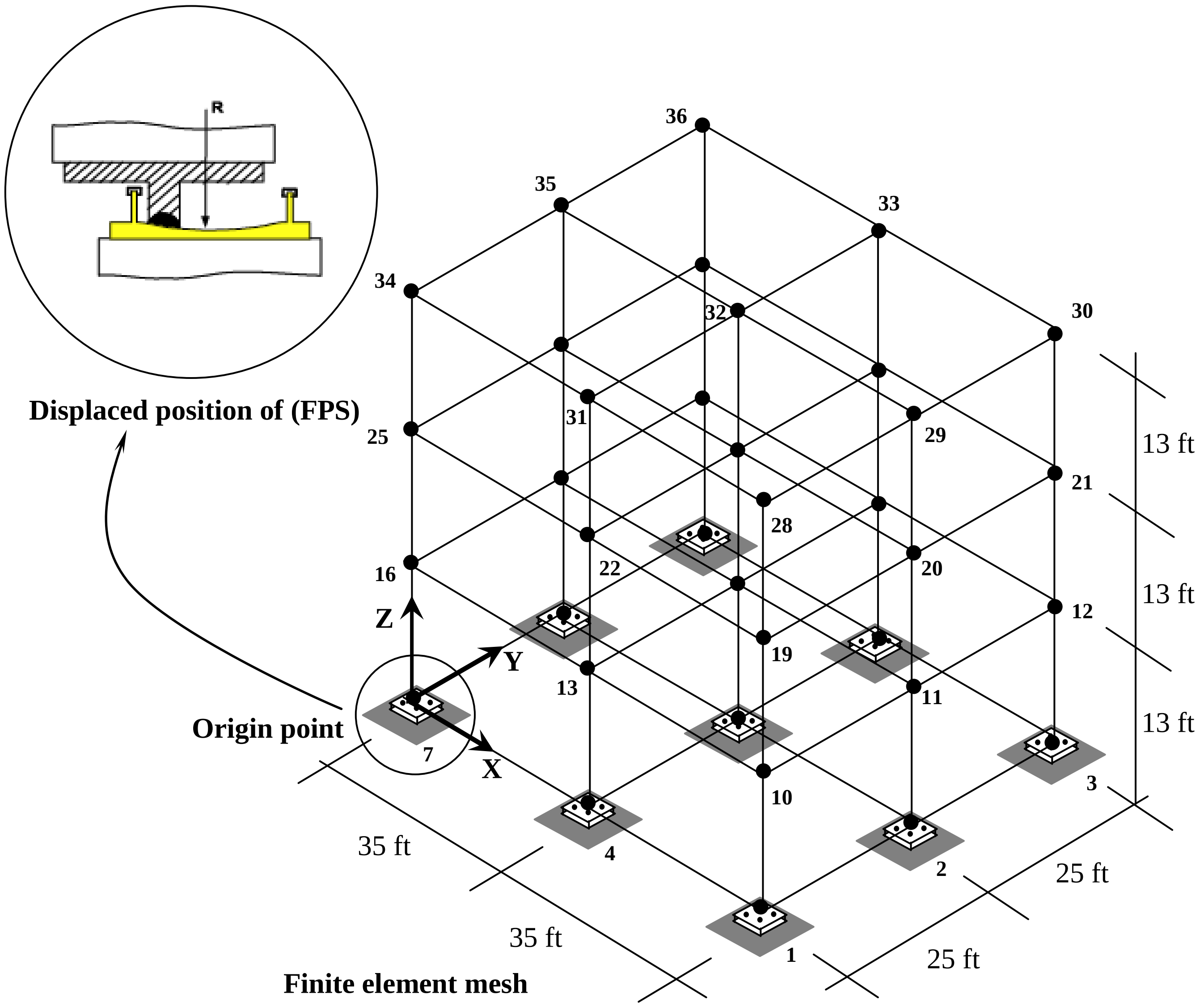


Fig.11 Finite element mesh of three-story building with friction pendulum system

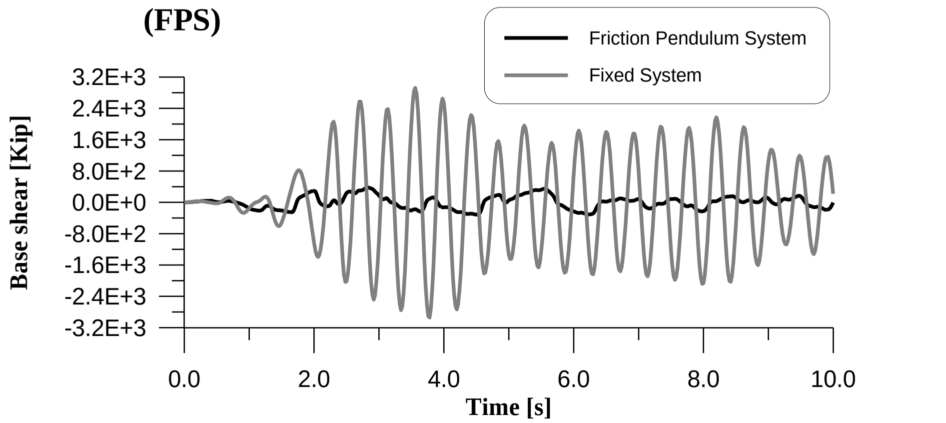


Fig.12 Comparison of the base shear in an isolated system with the one in a fixed-base structure to El Centro, R=40 in , μ =0.08

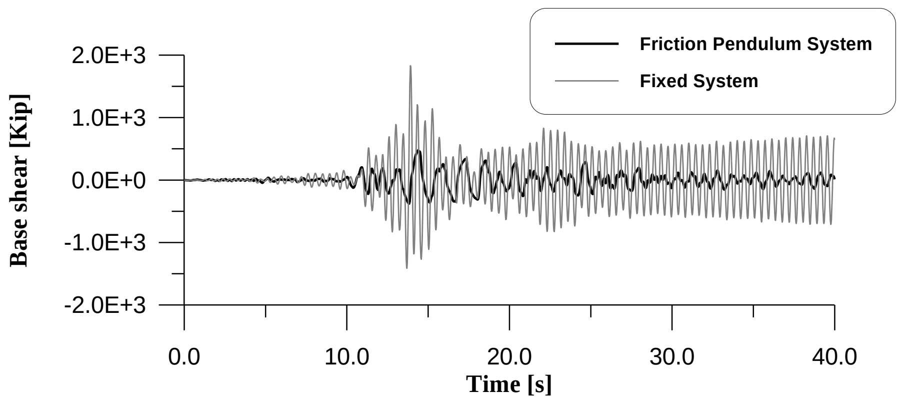


Fig.13 Comparison of the base shear in an isolated system with the one in a fixed-base structure to Loma Prieta, R=40 in , μ =0.08

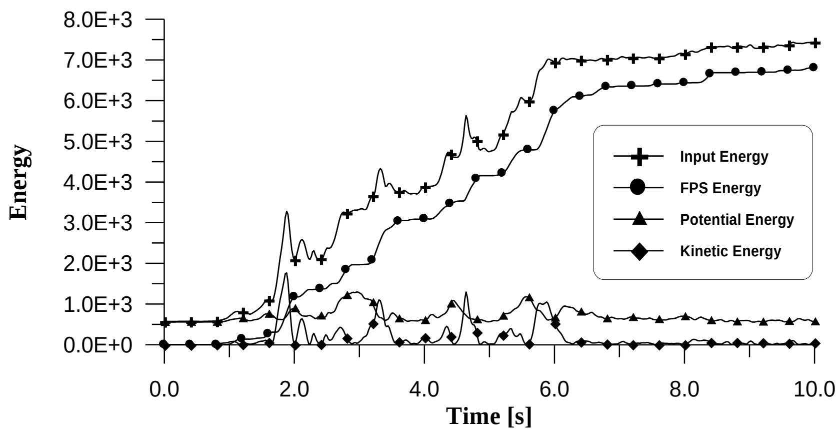


Fig.14 Energy with time in an isolated system to El Centro, R=40 in , μ =0.08

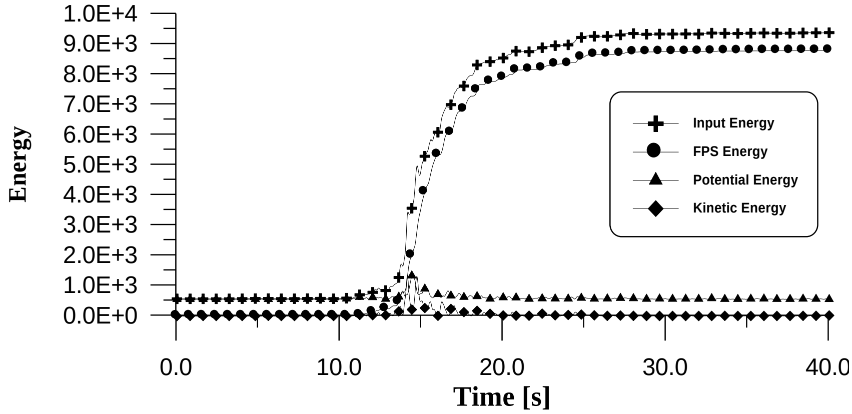


Fig.15 Energy with time in an isolated system to Loma Prieta, R=40 in , μ =0.08

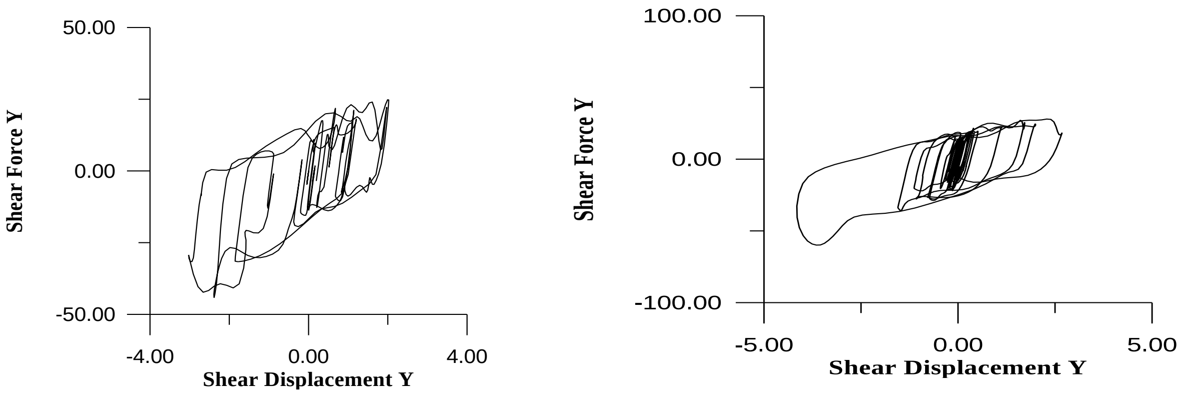


Fig.16 Shear force with displacement in Y direction to El Centro & Loma Prieta earthquake respectively ,R=40 in , μ =0.08

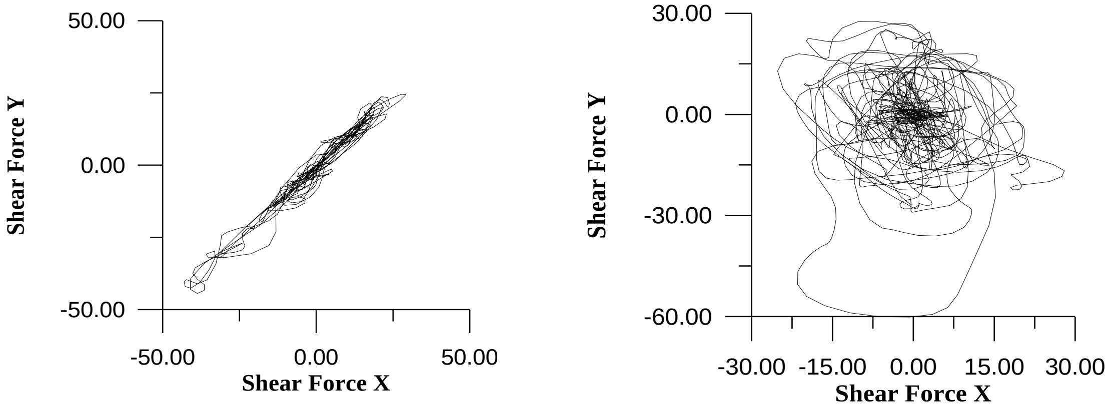


Fig.17 Shear force in Y direction. With Shear force in Y direction. To El Centro & Loma Prieta earthquake respectively ,R=40 in , μ =0.08

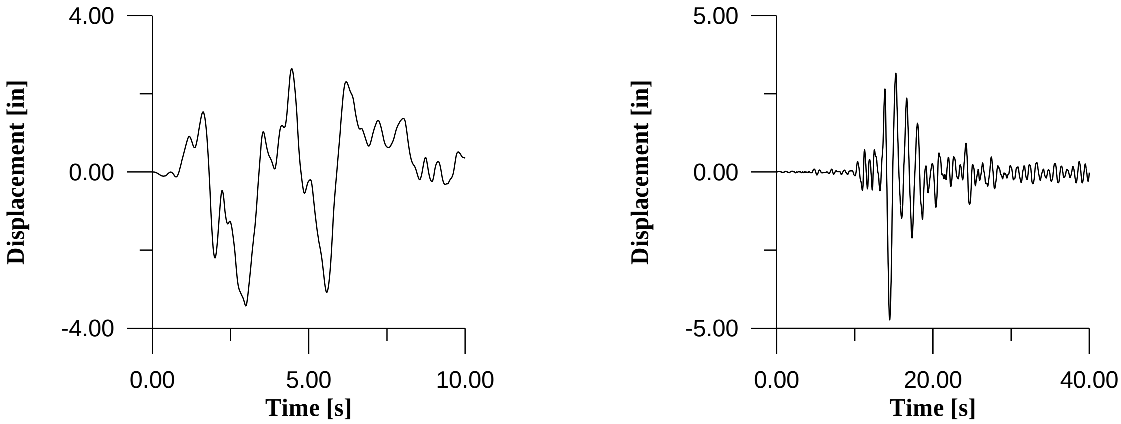


Fig.18 Drift at the top the structure (third floor) to El Centro & Loma Prieta earthquake respectively ,R=40 in , μ =0.08

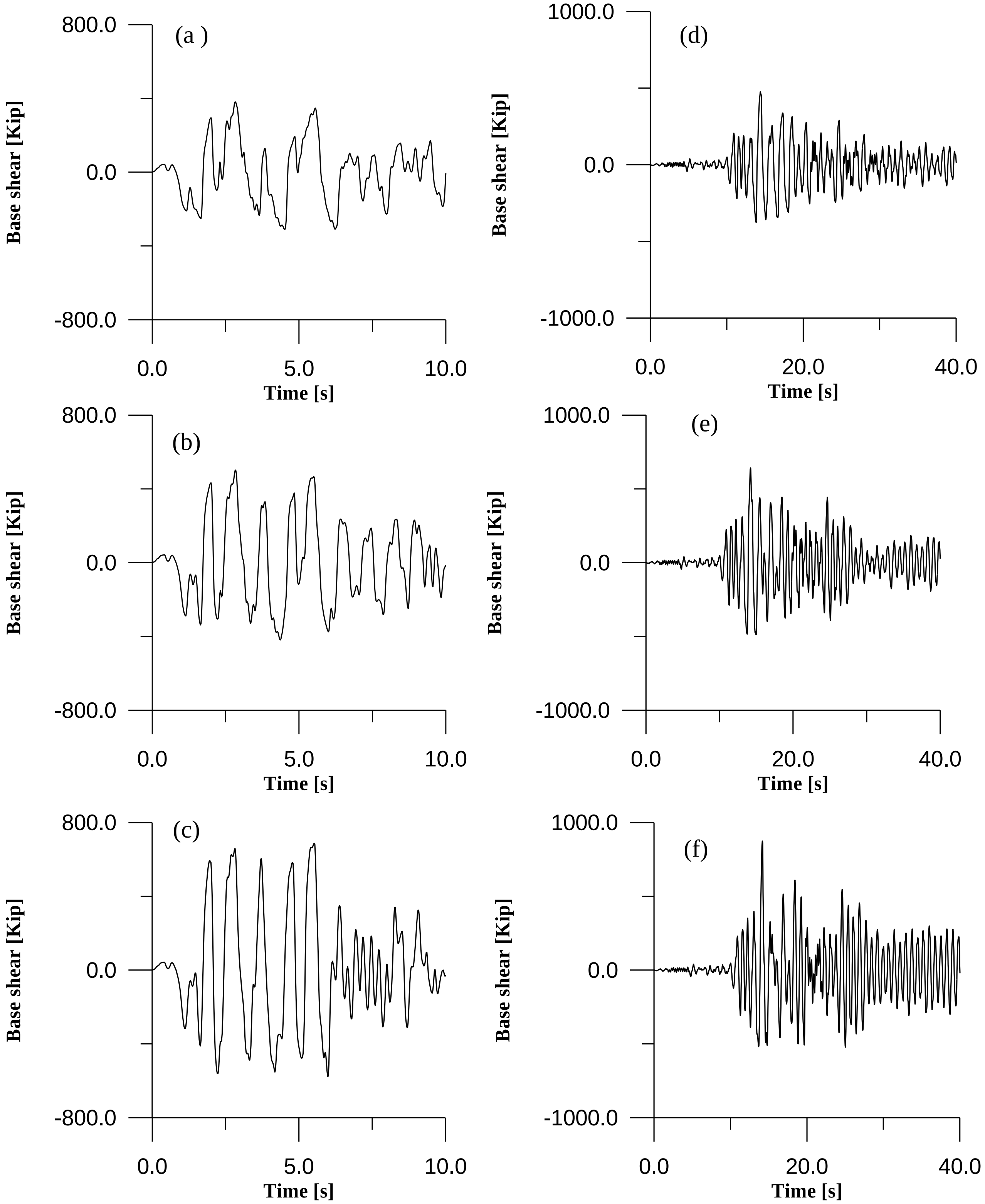


Fig.19 Base shear Y for 3 story building isolated by FPS with deferent coefficient of friction (a) 0.08 (b) 0.15 (c) 0.25 El centro and (d) 0.08 (e) 0.15 (f) 0.25 Loma Prieta

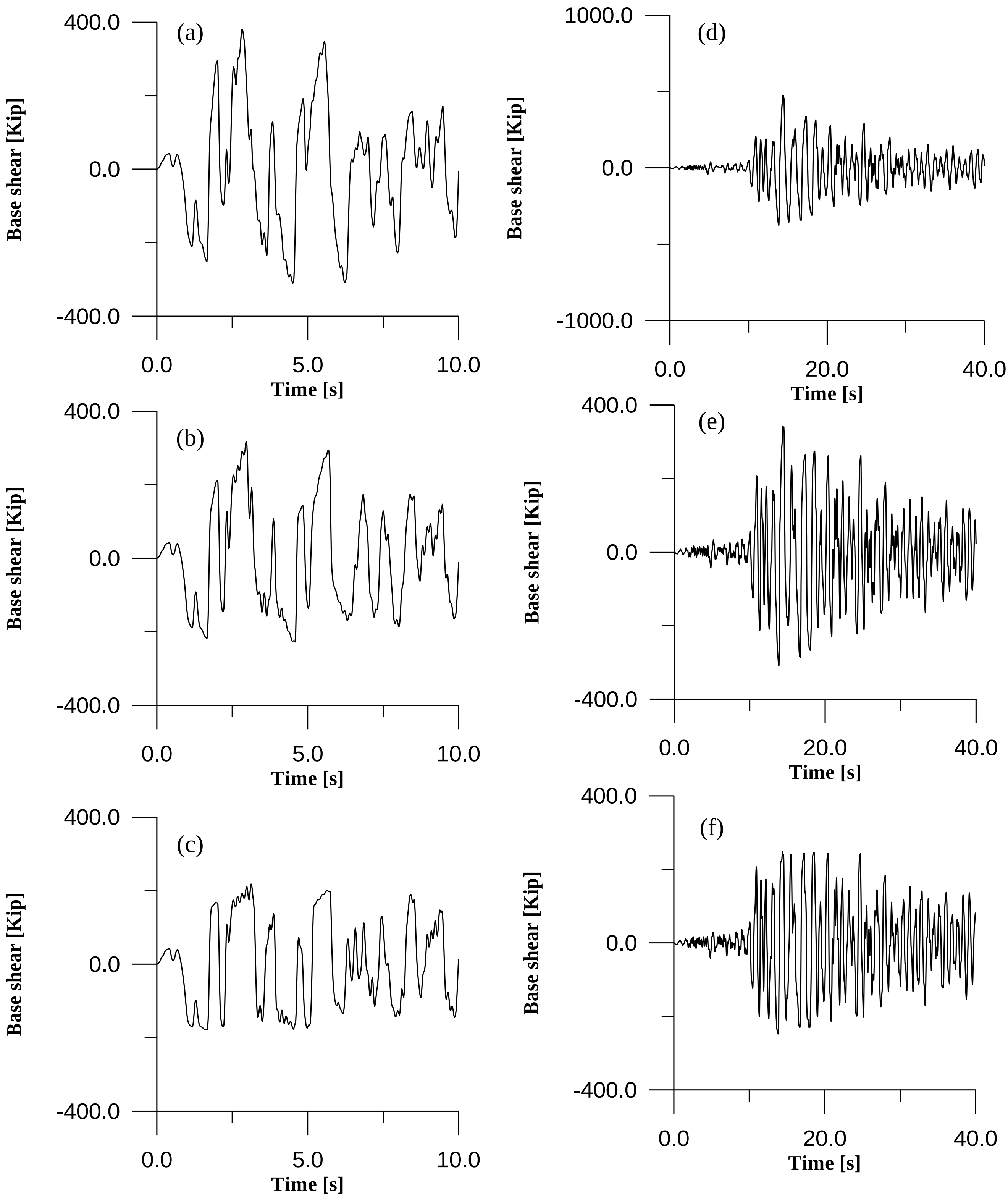


Fig. 20 Base shear Y for 3 story building isolated by FPS with deferent radiuses of concave surface (a) 40 in (b) 80 in (c) 400 in El centro and (d) 40 in (e) 80 in (f) 400 in Loma Prieta

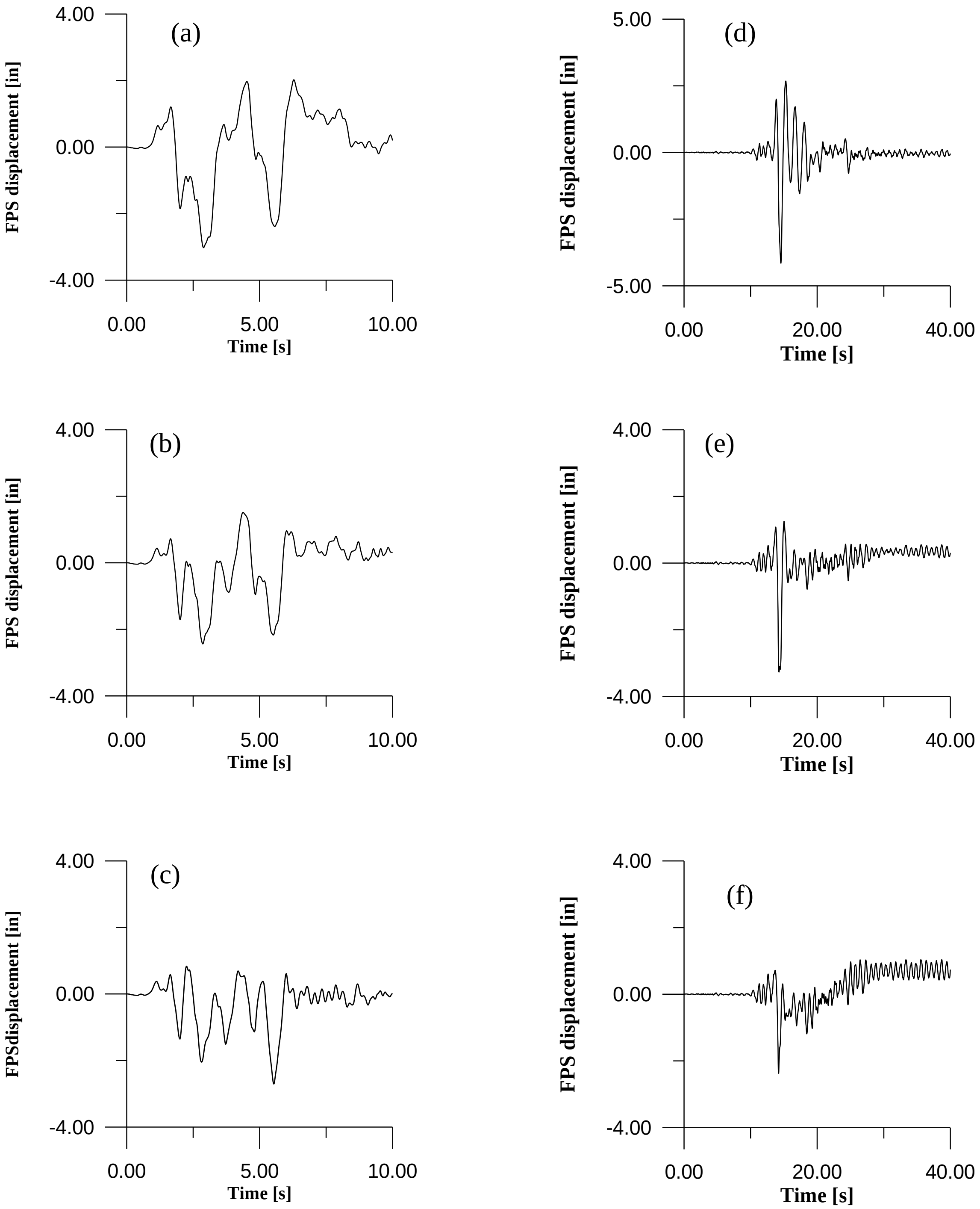


Fig. 21 FPS displacement Y (in) with deferent coefficient of friction (a) 0.08 (b) 0.15 (c) 0.25 El centro and (d) 0.08 (e) 0.15 (f) 0.25 Loma Prieta

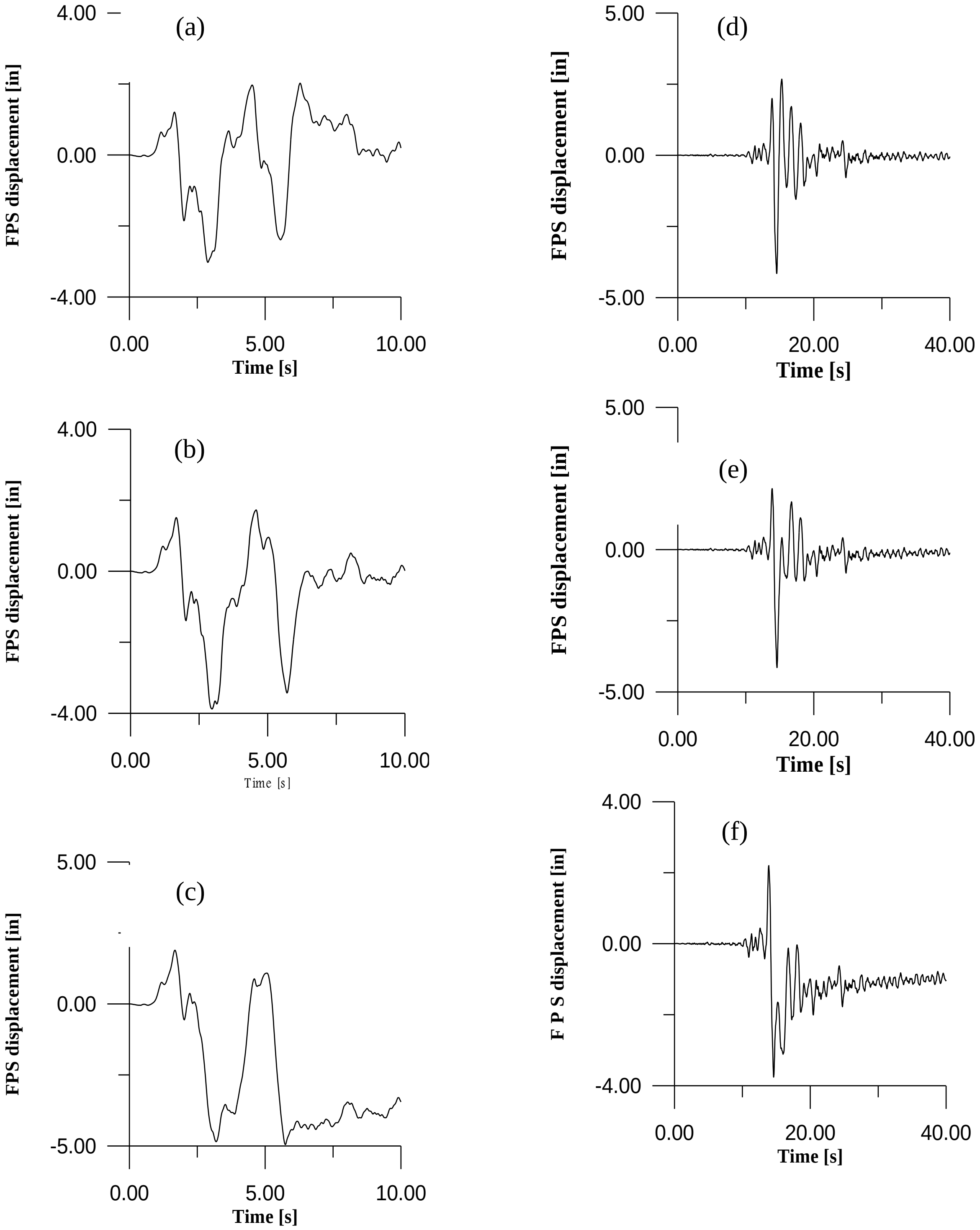


Fig. 22 FPS displacement Y (in) with deferent radiuses of concave surface (a) 40 in (b) 80 in (c) 400 in El centro and (d) 40 in (e) 80 in (f) 400 in Loma Prieta

PARAMETRIC STUDY

The Effect of Coefficients of Friction

In order to study this effect a three different coefficient of friction (0.08), (0.15) and (0.25) have been carried out with radius of concave 40 in for each type of earthquake. As a result of comparison between curves, it has been shown that the larger the friction coefficient the later the isolation mechanism is activated. In an extreme cases the base shear force does not overcome the friction force. In such a case, an isolated system responds the same as a classical fixed-base system. Fig.19

The displacement of friction pendulum system decreases with the increase in the coefficient of friction due to increased the damping of the system. Fig. 21

The Effect of the Radius of Concave Surface

To study this effect, the same model as before with a friction coefficient of 0.08 is analyzed for three different radius of concave (40 in), (80 in) and (400 in) for each type of earthquake fig 20 & 22. The base shear decreases with the increase in the radius In such a case, when the radius approach to infinity an isolated system responds the same as a classical roller support. a more concaved sliding surface with accordingly larger geometrical stiffness, reduces the permanent displacement of the bearing.

CONCLUSIONS

It has been shown that base shear in a sliding-based isolated system is 88.2 % for El Centro earthquake & 73.7 % for Loma Prieta smaller than the one in a fixed-base structure. This can be achieved at the cost of a sliding displacement in bearings.

As the magnitude of an earthquake increases, the sliding displacement becomes larger. For near source cases, to restrict the maximum sliding displacement, a higher amount of friction coefficient or an extra damping source is required. The sliding displacement anticipated by simulation matches the result reported by the experiment very well.

As a result of concavity of sliding plates in all investigated cases, bearings return back to their original configurations with a good degree of precision. This complies with results of shaking table tests done by [Nikolay Kravchuk, Ryan Colquhoun, and Ali Porbaha 2008].

Permitting a structure sliding over its foundation distracts earthquake-induced forces from the structural system. In this way, drift in isolated systems is much smaller in comparison with the classical fixed-base systems.

REFERENCES

- AL-Hussaini TM, Zayas VA, Constantinou MC.(1994),"Seismic isolation of multi-storey frame structures using spherical sliding isolation system". Technical Report No. NCEER-0007, National Center for Earthquake Eng. Research, State University of New York at Buffalo, New York.

- Almazan, J. L., Llera, J. C. (2002),’’Analytical model of structures with frictional pendulum isolators’’, Earthquake engineering and structural dynamics, 31, 305-322.

- Almazan, J. L., Llera, J. C. (2003), ’’Physical model for dynamic analysis of structures
- isolated with FPS isolators’’, Earthquake engineering and structural dynamics, 32, 1157-1184.

- Derjaguin, B.V. and Toporov, Y.P. (1982), "Influence of Adhesion on the Sliding and Rolling Friction," in Microscopic Aspects of Adhesion and Lubrication, edited by J.M. Georges, Tribology Series 7, Elsevier Scientific Publishing Co.

- Kelly JM.(1986),"A seismic base isolation: review and bibliography. Soil Dynamics and Earthquake Eng."

- Naeim, F., Kelly, J. M. (1999), "Design of Seismic Isolated Structures from Theory to Practice", John Wiley & Sons, New York.

- Nikolay Kravchuk, Ryan Colquhoun, and Ali Porbaha California State University, Sacramento (2008), "Development of a Friction Pendulum Bearing Base Isolation System for Earthquake Eng. Education", proceedings of the 2008 American Society for Eng. Education.

- Roussis, P. C., Constantinou, M. C. (2006), ’’Uplift-restraining friction pendulum seismic isolation system’’, Earthquake engineering and structural dynamics, 35, 577-594.

- Zayas, V.A., Low, S.S., and Mahin S.A.,(1989),"Shake Table Testing of a Friction Pendulum Seismic Isolation System." Seismic Engineering: Research and Practice, The American Society of Civil Engineering, Structural Congress, San Francisco.

- Zayas, V., Piepenbrock, T. and Al-Hussaini, T.(1993),"Summary of Testing of the Friction Pendulum Seismic Isolation System: 1986-1993", Proc., ATC-17-1 Seminar on Seismic Isolation, Passive Energy Dissipation and Active Control, Applied Technology Council, San Francisco.

- Charles K. Erdey (2007) "Earthquake Engineering Application to Design" book, published by John Wiley & Sons, Inc., Hoboken, New Jersey.

- M. A. Crisfield (1997)"Non-liner Finite Element Analysis of Solids and Structures " book, published by John Wiley & Sons, Inc., Hoboken, New Jersey.

- Earthquake protection systems (EPS) "Friction pendulum seismic isolation bearing " www.earthquakeprotection.com last accessed December 1, 2007.