Finite Element Analyses of Seismically Isolated Buildings with Variable Geometric Configurations

Dr. Haider S. AL-Jubair, Fareed H. Majeed

Abstract— Multi-story hypothetical reinforced concrete buildings of variable geometric configurations (symmetrical, vertically irregular, horizontally irregular); with fixed base and isolated bases via high damping rubber bearing and friction pendulum systems, are analyzed by using finite element method under seismic load function (North-South component of the ground motion recorded at a site in El Centro, California in 1940). The bilinear hysteretic model of base isolation system and the Rayleigh damping framework for superstructure are adopted. It is proved that, the base isolation is very effective technique in reducing the earthquake responses and that, the friction pendulum system is more efficient in reducing the earthquake responses compared to the high damping rubber bearing isolators of the same design displacement and fundamental period. Also, the results showed that, the isolators still highly effective in reducing the earthquake responses for the horizontally and vertically irregular buildings. The twist due to the horizontal irregularity is magnified due to the presence of isolators, especially for the friction pendulum system.

Index Terms— Multi-story, vertically irregular, horizontally irregular, isolated building, friction pendulum, high damping rubber bearing, seismic, finite element

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1 INTRODUCTION

The concept of passive base isolation has two basic types of isolation systems.

1-The system that uses elastomeric bearings. In this approach, the building is decoupled from the horizontal components of the earthquake ground motion by interposing a layer with low horizontal stiffness between the structure and the foundation.

2-The system that uses sliding. In this approach, the system is limiting the transfer of shear across the isolation interface by using sliders or rollers between the structure and the foundation.

In this paper the two isolator types that are representative of sliding and elastomeric systems will represented by the Friction Pendulum System (FPS) and the High Damping Rubber Bearings (HDRB), respectively.

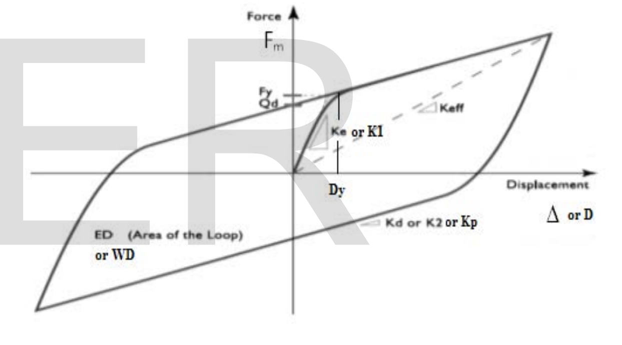

Fig. 1. Parameters of basic hysteresis loop of an isolator for bilinear modeling [1].

2 MODELING THE ISOLATED BUILDINGS

The buildings are modeled using the finite element method. The force-deformation behavior of the two systems of isolators is modeled as non-linear hysteretic represented by the bi-linear model as shown in Fig. 1. The isolator is modeled using six springs. The springs for three of the deformations: axial, shear in the x-z plane, and pure bending in the x-z plane are shown in Fig. 2. The hysteretic models for bearings is used to account for all the energy dissipation and the viscous damping using the Rayleigh damping framework is used for the superstructure.

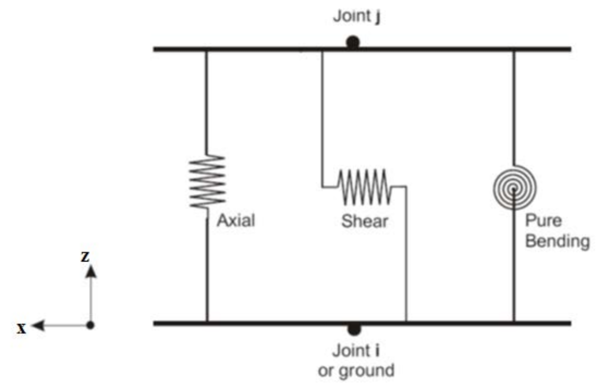

Fig. 2. Three of the six independent springs in a Link/Support element [2].

The geometric configurations of the superstructures are shown in Fig. 3. A (150 mm) thick slab is considered with (400 mm x 600 mm) beam typical sections and column size of (600 mm x 600 mm).

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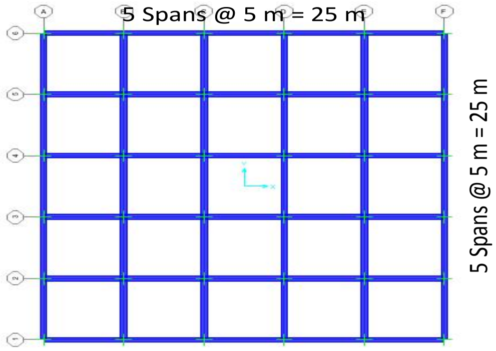
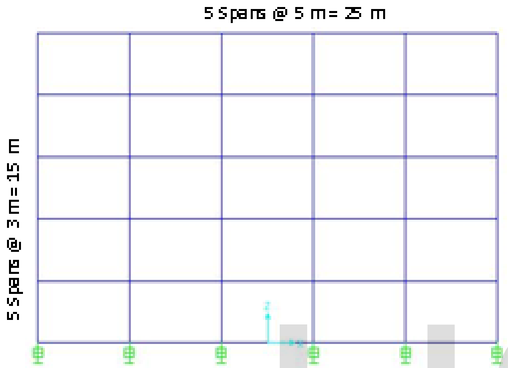
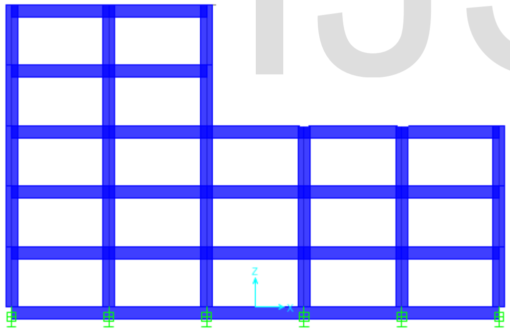


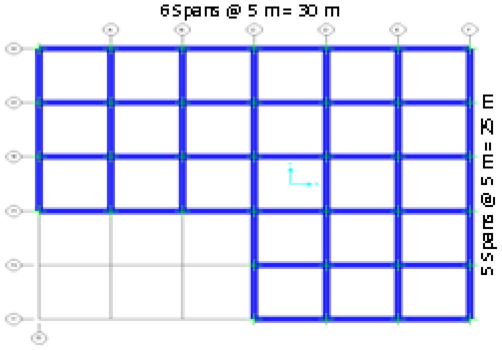
a. Plan of symmetrical building



b. Section of symmetrical building.



c. Section of the vertically irregularity building.



d. Plan of the horizontally irregularity building.

Fig. 3. The geometric configurations of the superstructures.

3 APPLIED LOADS

The reinforced concrete buildings are analyzed for dead, live and earthquake functional loads. The minimum design dead load on each floor consists of loads due to floor slab, beams, columns and portion walls. The floor live load is taken as (3 kN/m²) and the roof live load is taken as (1.5 kN/m²). The North-South component of the ground motion recorded at a site in El Centro, California in 1940, shown in Fig. 4, is applied to the building. All of the dead load and only (25%) of the live load is considered in the seismic analysis [IBC 2012] [3].

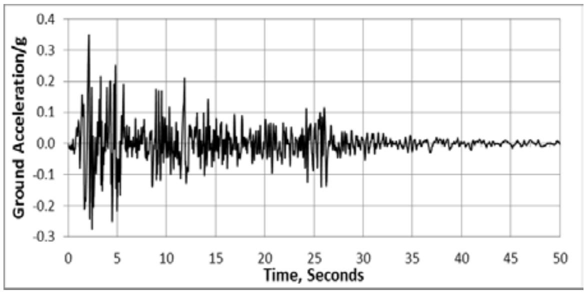


Figure 4 El Centro, California in 1940 earthquake [4].

4 Design of Base Isolators

The isolators are designed according to the procedures described in the UBC-97 [5]. The characteristics of high damping rubber bearing system are illustrated in Fig. 5 whereas, the mechanism of friction pendulum system is shown in Fig. 6.

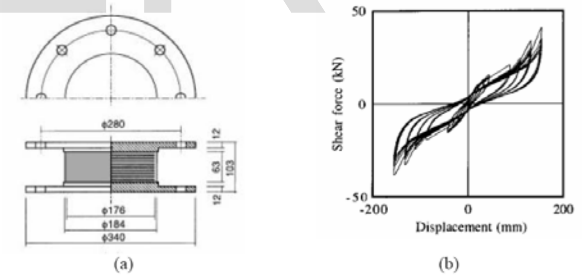


Fig. 5. The characteristics of high damping rubber bearing: a. High damping rubber bearing used in the earthquake simulator tests with dimensions in mm; b. Corresponding force-deformation hysteresis [6].

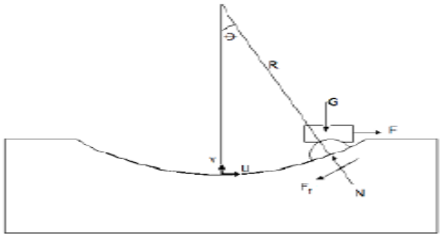


Fig. 6. Mechanism of the friction pendulum system [7].

The characteristics of superstructure materials and the design parameters of the isolation systems are summarized in Tables 1 and Table 2.

TABLE 1
THE SUPERSTRUCTURE MATERIAL PROPERTIES.

Symbol	description	unit	Value
f'_c	The cylinder ultimate compression strength of concrete	N/mm^2	25
f_y	The yield stress of steel reinforcement	N/mm^2	410
E_c	The modulus of elasticity of concrete	N/mm^2	23000
ρ_c	The concrete density	kg/m^3	2400
ν_c	Poisson's ratio of concrete	---	0.15

TABLE 2
DESIGN PARAMETERS OF ISOLATORS.

data	Parameter and unite	Value for HDRB	Value for FPS	Nomenclature
Input	T (sec)	2.5	2.5	Design period
	β (%)	20	20	Effective damping
	D (mm)	200	200	Design displacement
	W (kN)	2000	2000	maximum vertical load in service condition including seismic action
	μ	----	0.02	friction coefficient
Output	K_{eff} (kN/m)	1500	1370	Effective stiffness
	Q (kN)	88	40	Short term yield force
	K_2 (kN/m)	1200	1150	Inelastic stiffness
	K_1 (kN/m)	12000	115000	Elastic stiffness
	D_y (mm)	8.1	0.4	Yield displacement
	R (mm)	----	1700	radius of curvature

4 NONLINEAR DIRECT INTEGRATION METHOD

All buildings are solved using the nonlinear direct integration method for fixed base and isolated bases using the high damping rubber isolation and friction pendulum systems.

The modal periods and frequencies of the free vibration analyses of buildings are shown in Table 3.

TABLE 3
DESIGN PARAMETERS OF ISOLATORS.

Base condition / Case	Fixed		HDRB		FPS	
	T (Sec)	ω(rad/sec)	T (Sec)	ω(rad/sec)	T (Sec)	ω(rad/sec)
Symmetrical	0.61	10.31	2.44	2.57	2.45	2.57
Vertically Irregular	0.54	11.58	2.25	2.79	2.25	2.79
Horizontally Irregular	0.61	10.31	2.42	2.60	2.43	2.58

The responses of buildings, with different base conditions, in terms of total base shear are shown in Fig. 7, 8 and 9.

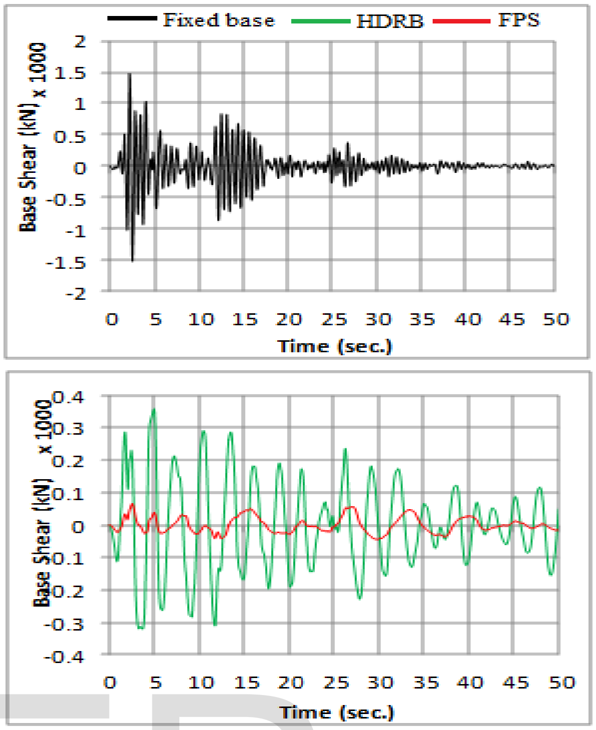


Fig. 7. Total base shear for symmetrical building.

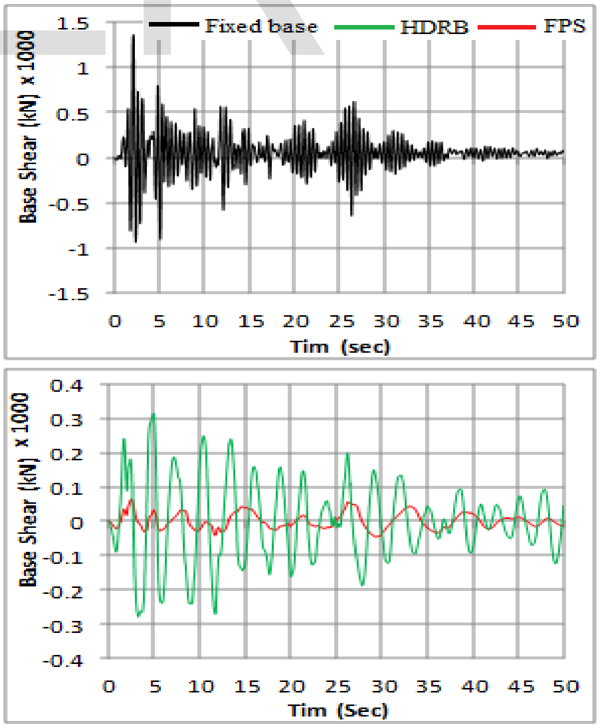


Fig. 8. Total base shear for vertically irregularity building.

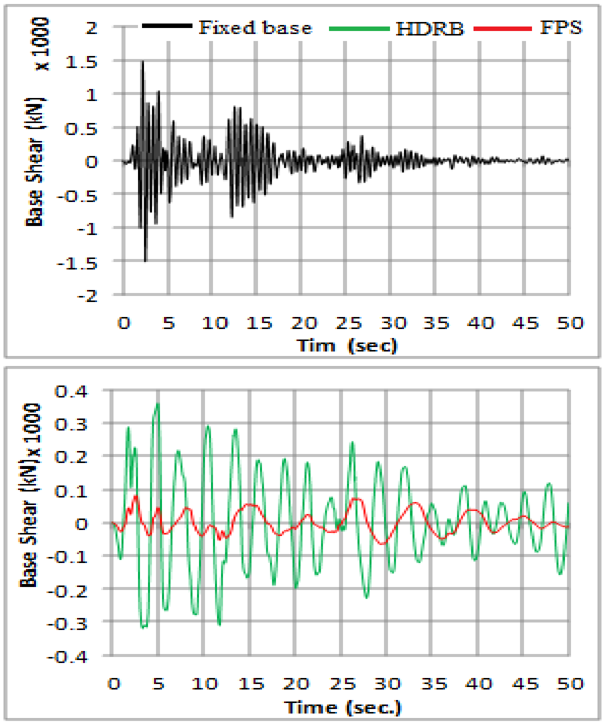


Fig. 9. Total base shear for horizontally irregularity building.

It is evident that, the total base shear is reduced in isolated buildings compared to the fixed base building. The friction pendulum system is more efficient than high damping rubber bearing base and decreases of about (95%) and (75%), respectively are recorded. This can be attributed to the geometry of friction pendulum isolator [the radius of curvature (R)], tending to restore the structure according to the gravity effect.

The maximum acceleration time histories for the fixed and isolated buildings are shown in Fig. 10, 11 and 12.

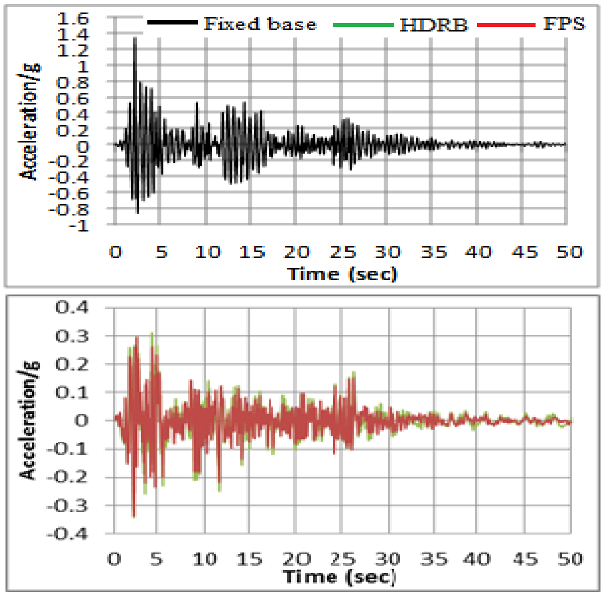


Fig. 10. Maximum acceleration for symmetrical building.

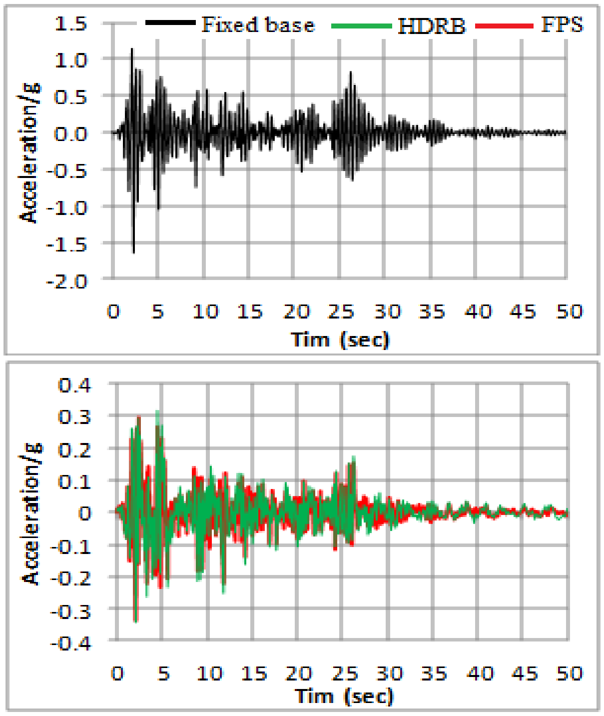


Fig. 11. Maximum acceleration for vertically irregularity building.

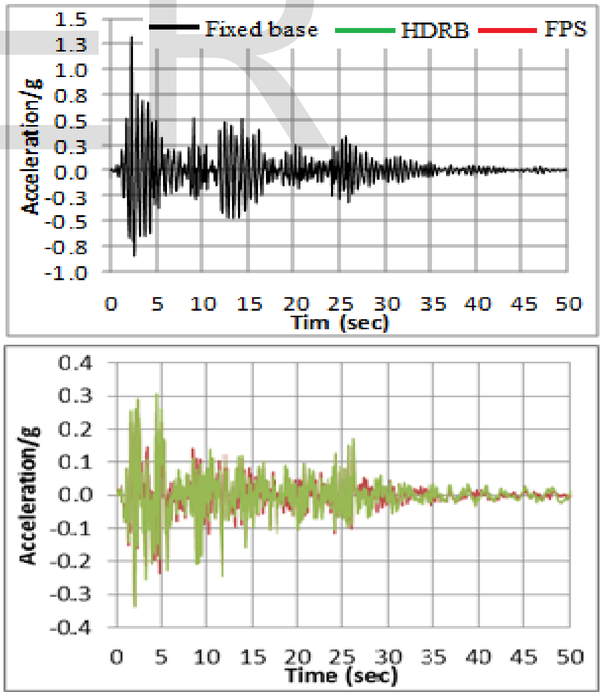


Fig. 12. Maximum acceleration for horizontally irregularity building.

It is clear that, the values are magnified for the fixed base building compared to the input earthquake. The maximum acceleration responses for both isolated buildings are nearly identical and a decrease of about (62%-80%) is recorded compared to the fixed base building.

The maximum relative displacements (displacement with respect to displacement of base) for the fixed and isolated base buildings are shown in Fig. 13, 14 and 15.

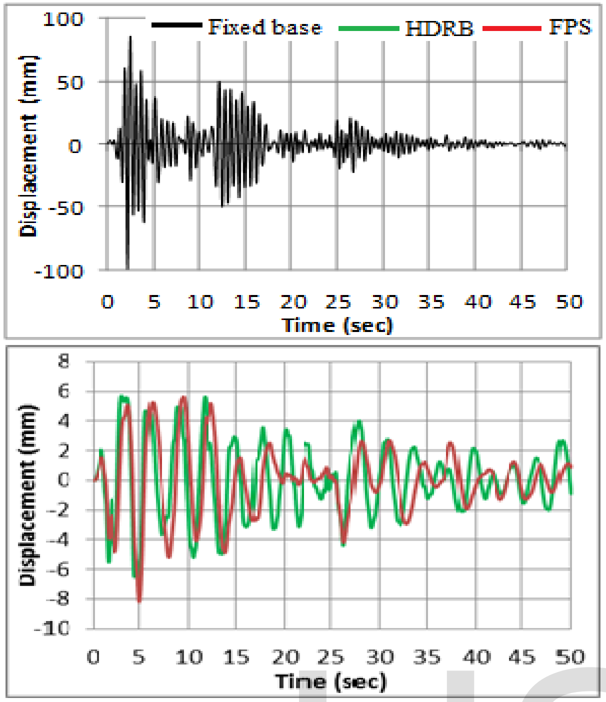


Fig. 13. Maximum relative displacement for symmetrical building.

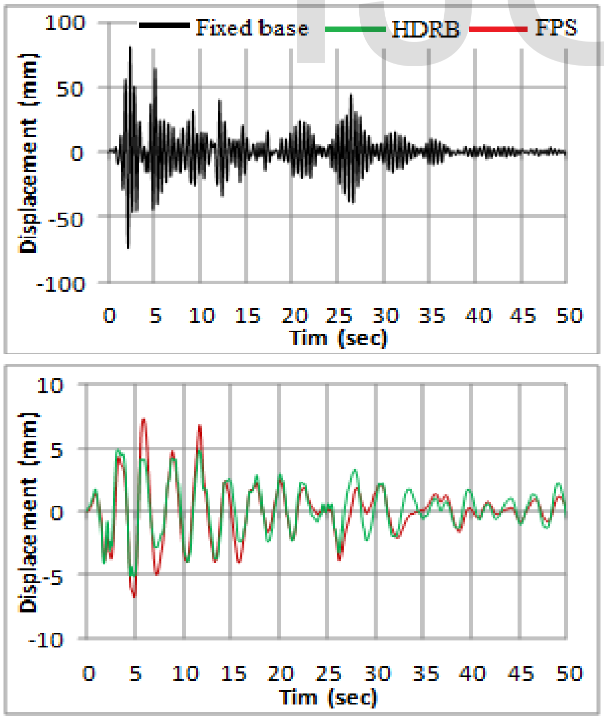


Fig. 14. Maximum relative displacement for vertically irregularity building.

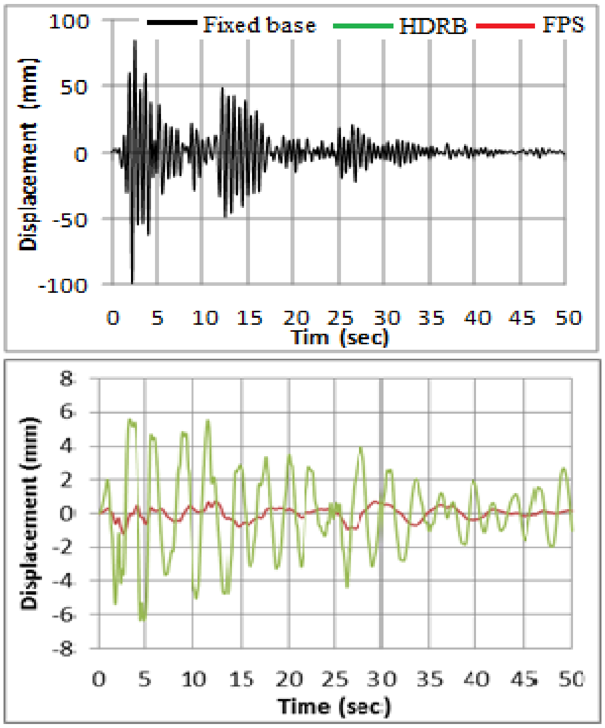


Fig. 14. Maximum relative displacement for horizontally irregularity building.

For the symmetrical building, the maximum relative displacements of both isolated buildings are almost the same and a reduction of about (90%) is observed compared to the fixed base building.

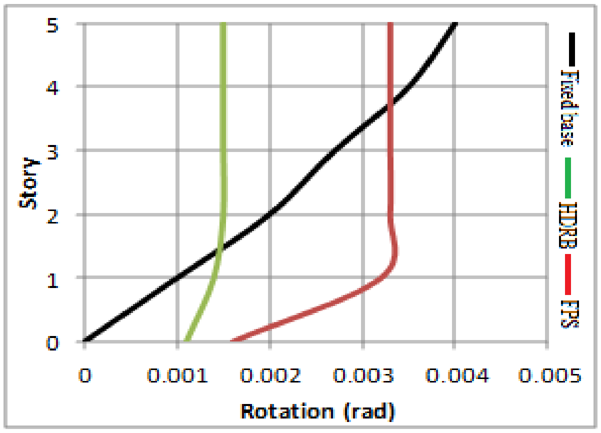
The maximum relative displacements are almost unaffected by the vertical irregularity, for the fixed base and rubber bearing base buildings. A slight asymmetric (positive increase and negative decrease) behavior is recorded regarding the friction pendulum isolated base building.

The horizontal irregularity, produced no effect on the relative displacement, for the fixed base building and minor a effect on the high damping rubber bearing isolated base building. The displacement is greatly reduced, for the friction pendulum isolated base building, due to the horizontal irregularity.

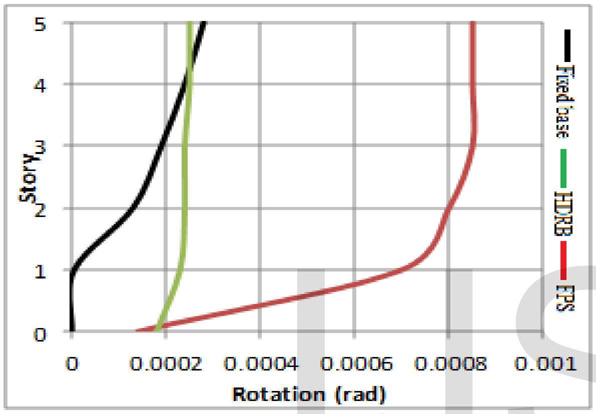
Fig. 15 shows the rotation of the center of mass about z- axis in the five stories due to the building irregularities for the various base conditions.

For the vertically irregular building, inclusion of high damping rubber bearing reduced the rotation above the first story. The friction pendulum isolators reduced the rotation at the top story only. The increase in rotation is ceased beyond the second story for the isolated buildings.

For the horizontally irregular building, inclusion of base isolators increased the rotation especially for the friction pendulum type. The increase in rotation is ceased beyond the first floor for the high damping rubber bearing and the third floor for the friction pendulum isolators.



a. Vertically irregular



b. Horizontally irregular

Fig. 15. Maximum rotation of the center of mass in the isolated building stories.

6 CONCLUSIONS

1. Base isolation is very effective technique in reducing the earthquake responses represented by the base shear, maximum acceleration, and maximum relative displacement.
2. The friction pendulum system is more efficient in reducing the earthquake responses compared to the high damping rubber bearing isolators of the same design displacement and fundamental period.
3. Vertical irregularity has minor effects on the efficiency for the base shear, maximum acceleration, and maximum relative displacement for the isolated buildings. Unlike the friction pendulum, the high damping rubber bearing isolator reduced the twist compared to the fixed-base.
4. The isolators have high efficiency in reducing the base shear and the maximum acceleration for the building with horizontal and vertical irregularity. It produces considerable decrease in the maximum relative displacement for the friction pendulum base isolated structure. The twist is magnified due to the presence of isolators, especially the friction pendulum system.

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