Evaluation of Seismic Behavior of Friction Pendulum System on Irregular Reinforced Concrete Structures

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Abstract

The design methods and technologies of constructing earthquake-resistant buildings have recently witnessed significant improvements. Seismic separation of structures is among the methods that in most cases indicates proper resistance against seismic risks, considering the background of the method worldwide. For this reason, engineers and manufacturers of buildings are interested in this method. In Iran, due to increasing development and growing processes of construction, on the one hand, and due to the country's high seismicity and considerable hazards resulting from this issue, on the other, using this technology is crucial. In this study, separated structures of geometric irregular reinforced concrete of 4, 6, and 15 stories with frequency periods of 1.5, 2.5, and 3 seconds and friction coefficient of $\mu= 0.1$ and $\mu= 0.5$ were designed under the impact of earthquake spectrum of soil type 3 specified in Iranian Seismic Code 2800, and seismic behavior of the of structure was evaluated using linear accumulative analysis in SAP2000 software. The seismic response of structures were investigated in performance points compared to geometric irregular reinforced concrete with fixed pillars.

Keywords: Seismic separation, Friction Pendulum System (FPS), nonlinear static analysis, seismic behavior evaluation

Introduction

Seismic separation is a relatively new method for building designs resistant to earthquake. The method is based on reducing forces exerted to the structure by earthquake, instead of increasing structure capacity for enduring side loads. The basis of this method is response reduction through frequency time and mortality in structures.

The criteria for various design regulations are formed such a the way that resulted into a relatively rigid pavement design with low relative displacement which are in accordance with the purpose of uninterrupted use of topside after the earthquake. In other words, though using seismic isolation system leads to increment of frequency time of structure and thereby the demand reduction, on the other hand, uninterrupted use conditions can contribute to increment capacity of topside.

Due to the widespread use of this seismic-resistant system, it can be predicted that it will be commonly used in normal buildings with a lower performance level. [5] The analyses conducted in

(DOI: dx.doi.org/14.9831/1444-8939.2014/2-6/MAGNT.34)

this study include linear static analysis and spectral dynamics, and nonlinear statics. The studied results contain the displacement of roof centroid, relative displacement of stories and pillar shear stress.

2. The characteristics of FPS

The restoring force in these systems can be supplied through earth gravity and structure weight (figure 1). The inner part of this system is made of a steel concave surface, on which a piece of steel can move with high resistance and low friction.

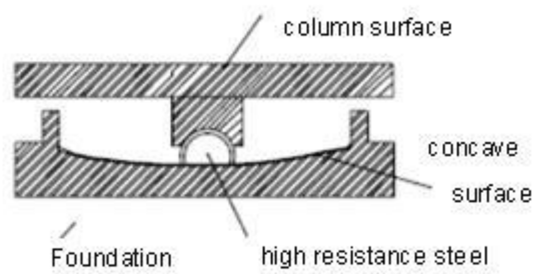

Figure1. Friction pendulum system [2]

The radius curvature of this periodical isolator specifies the frequency of isolator system. Therefore, if the weight of structure changes or the estimated amount is different, the frequency period wouldn't change. [2]

The factors considered in designing FPSs include the radius curvature of isolator surface (R_{FPS}), the friction coefficient of isolator surface (μ) and dimensions of isolator.

R_{FPS} is calculated according to desired frequency period of designing (T_D) via:

Equation 1: $R_{FPS} = g \times (\frac{T_D}{2\pi})^2$

where g is gravity. [2]

3. The characteristics of structures under study

Structures under study include structures of geometrical irregular reinforced concrete of 4, 5 and 16 stories in plan (according to Clause 1-8-2 of Iranian Seismic Code 2800) that their resistant system against earthquake is moment frame. Seismic loading was performed using Iranian Seismic Code 2800 of building design against earthquake with the assumption of soil type 3 (according to categorization of this Regulation) and 0.35 scheme based acceleration. On the basis of common values for flooring construction and loading regulation of sixth subject of building national rules, the values of dead and live gravity loads are considered 650 k/cm^2 and 200 k/cm^2, respectively, and 20% participation was assumed for live load during earthquake.

(DOI: dx.doi.org/14.9831/1444-8939.2014/2-6/MAGNT.34)

Each of these structures is FPSs with a radius of 56, 100, 156 and 224 cm and they are designed using two friction coefficients of isolator surface, μ= 0.5 and μ=0.1, for the frequency period of 1.5, 2, 2.5 and 3 seconds. All modeling and analyses is performed by SAP 2000 v14.2 software. The considered models of this study include the structures of geometric irregular concrete of 4, 6 and 15 stories in the plan and the structures of 4 and 6 stories are of similar plans (figure 2) and the 15 stories structure has a different plan comparing figure 2 (figure 3-1).

Geometrical properties of 4-story and 6-story structures

According to figure 2-1, the area of each structure is 397 m^2 and the steady height of 3 m for each story and it has totally 28 pillars. The weight of 4-story structure is estimated 1746.8 tonf and 6-story structure 2620.2 tonf.

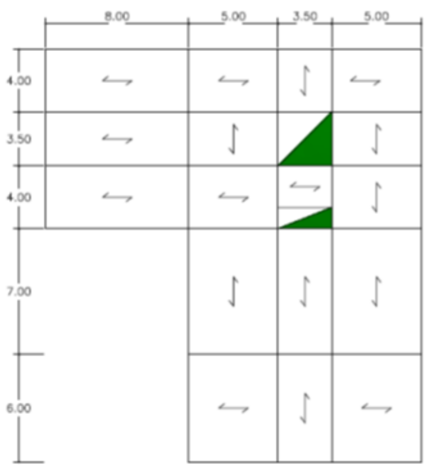

Figure2. Structure plan of 4 and 6 stories

Geometrical properties of 15-story structures

According to figure 3, the area of the structure is 239.20 m^2 and the steady height of each story is 3 m, and it has totally 27 pillars. The structure weight is estimated 3946.8 tonf.

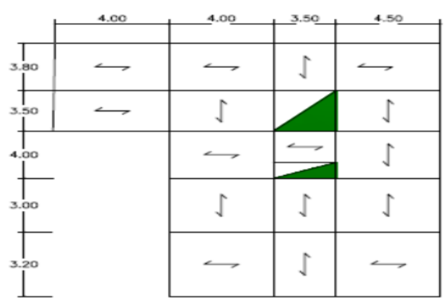

Figure3. 15-story structure plan

4. The nonlinear static analysis method (Push over)

(DOI: dx.doi.org/14.9831/1444-8939.2014/2-6/MAGNT.34)

This method is proposed by American Federal Agency. In this method, the nonlinear properties of members are directly modeled and then the structure which is under a specific gravitational loading is increasingly and step-by-step analyzed through a side load model. This analysis is continued to the point where the displacement of predetermined structure roof reaches the target displacement. In the target displacement, the structure performance can be evaluated according to the members' condition. [6]

5. The levels of structure performance

Current structures are designed for various levels. In this project, the live safety (LS) level is evaluated for normal important structure like residential houses. The LS level is the level at which no damage is predicted during earthquake, but the level of damages leading to fatality should be minimized.

The nonlinear behavior of topside elements was taken into account using modeling with force relation of member's transformation or the same method of plastic hinge allocation during element. In the model, moment hinge is allocated for two ends of bars as well as PMM to two ends of columns and it is used the curve of transformation for moment concrete frames of Regulation FEMA 356 for modeling regarding figure 4. Parameters of a, b, and c of this curve are determined according to section condition and the value of section pivotal force in columns through Regulation FEMA 356. The slope of B and C is considered about 10% of total strain hardening for steel. [3]

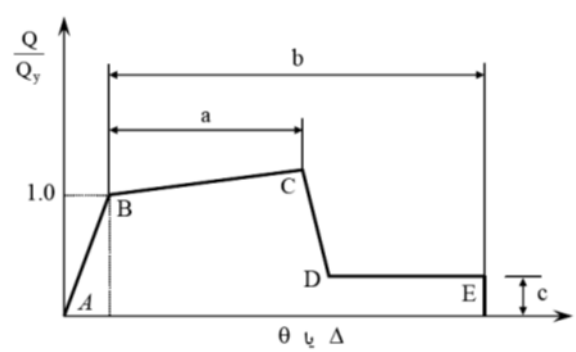

Figure4. Behavior curve of structures' member for transformable hinges [4]

3. Determination of target displacement

Building with rigid diaphragm:

Target displacement for structure with rigid diaphragms should be estimated regarding nonlinear behavior. Using an approximate method, the value of target displacement can be calculated through equation (2):

Equation (2): $\delta t= C0C1C2C3Sa \frac{Te^2}{4\pi^2} g$

(DOI: dx.doi.org/14.9831/1444-8939.2014/2-6/MAGNT.34)

where T_e is the time of major effective frequency of building according to equation (3) for desired length.

Equation (3): $Te = Ti\sqrt{\left(\frac{ki}{Ke}\right)}$

where T_e is the time of major frequency of building with assumption of linear behavior and Ki is side resilient rigidity (figure 5).

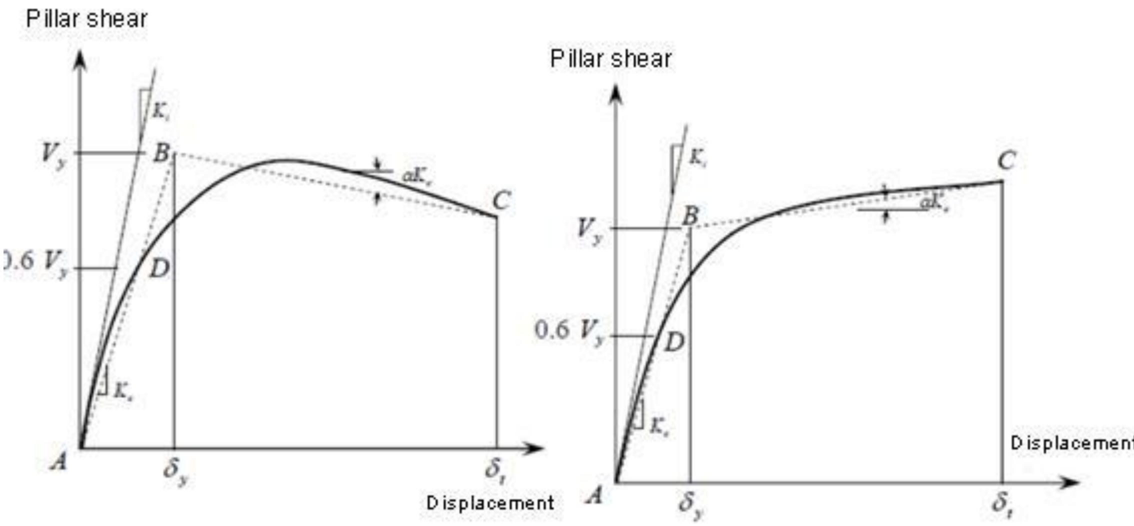

Figure5. Normalized curve of force-displacement [4]

C_0 , adjustment coefficient for relating system spectral displacement, is a freedom degree called displacement of roof system selected according to one of the below values:

- First mood participation coefficient
- Approximate values according to table 2

Table1. The value of C_0 coefficient

All buildings	Shear buildings*		The number of stories
Each kind of load distribution	Load Steady distribution	First type distribution according to clause (3-3-1-3) of 360 issue	
1.0	1.0	1.0	1
1.2	1.15	1.2	2
1.3	1.2	1.2	3
1.4	1.2	1.3	5
1.5	1.2	1.3	10 and more

* Shear building is the one that in all the stories, relative side displacement is less than beneath story.

C_1 is calculated by equation 4:

(DOI: dx.doi.org/14.9831/1444-8939.2014/2-6/MAGNT.34)

Equation 4:

$$T_e \geq T_s \rightarrow C_1 = 1.0$$

$$T_e < T_s \rightarrow C_1 = \frac{\left[1.0 + [R-1]\frac{T_s}{T_e}\right]}{R}$$

Anyhow, the value of C_1 should not be less than 1 and more than its value according to clause (3-3-1-2). In this equation, R is resistance proportion calculated through equation 5:

Elation (5):

$$R = \frac{S_a}{V_y/W} C_{m,}$$

In this equation, S_a is the spectral acceleration for main frequency of T_e and C_m is effective mass coefficient in first mood which can be determined through table 2.

Table2. The values of C_m coefficient [4]

The number of stairs	Moment concrete or steel frame	Restrained steel frame with convergent or divergent pivot	Structure with shear wall	Other structural systems
One or two	1	1	1	1
Three or more	0.9	0.9	0.8	1

The C_2 coefficient includes the impacts of rigidity reduction and the resistance of structural members on displacements due to their non-resilient behavior and it is calculated using table 3.

Table3. The values of C2 coefficient [4]

The desired level	T≤0.1		T≥Ts	
	Type 1 frame	Type 2 frame	Type 1 frame	Type 2 frame
The capability of uninterrupted use	1.0	1.0	1.0	10.
Live Safety	1.3	1.0	1.1	1.0
Breakdown threshold	1.5	1.0	1.2	1.0

In this table, type 1 frames include the structural systems in which more than 30% of side loads are carried by the members that have reduction of rigidity and resistance during earthquake. Normal moment frames are restrained frames with convergent pivots, the frames with half-rigid connection, the frames with thin restrainer designed only for tension, unequipped structural walls and unchangeable walls in shear are all of this type. Other structural systems are considered as type 2. For the values of T between 0 and 1, C_2 is calculated using linear interpolation.

(DOI: dx.doi.org/14.9831/1444-8939.2014/2-6/MAGNT.34)

C_3 coefficient is 1 for the structure that has positive rigidity after delivery (α> 0) and it is calculated through equation 6 for the structures that has negative rigidity after delivery. [4]

Equation 6:

$$C3 = 1.0 + (\frac{|\alpha|[R-1]^{1.5}}{\text{Te}})$$

7. Results

Finally, the evaluation of mentioned structure results is divided into main groups:

a. Structures in which T<Ts, No additional lateral force (4-story and 6-story structures)

Tables 4 and 5 respectively indicated the condition of frame member hinges of geometric irregular reinforced concrete with separated pillars and fixed pillar in similar loading of nonlinear static analysis. In separated frames with FPS isolators, less hinges are plasticized and minimized comparing the fixed pillar, because the performance level of these separated frames are higher.

Another criterion of seismic behavior evaluation of FPS system is comparison of relative displacement of separated structure stories with reinforced concrete frame and fixed pillar. As it can be seen in diagram 1, relative displacement of stories in separated structure of 4 and 6 stories was significantly decreased and distributed more orderly in height, which shows more plastic behavior of the structure. It is worth noting that in 4 stories structure for FPS 114 and FPS 124, the place of quake force is coincident on structure centroid and it shows that the structure has only rigid move (sweep to the original location) and it doesn't enter to plasticity.

In diagram 2, the reduced amount of pillar shear stress in separated structures is indicated comparing the structures of reinforced concrete with the fixed pillar and it is clear that energy depreciation is more in separated structures in comparison to fixed pillar ones.

Table4. Formed hinges in 4-story frame with fixed and separated pillar in similar nonlinear static analysis

TABLE: hinges in 4 story (fps in story 1th) - μ= 0.1								
name	**R**	**T**	**AtoB**	**BtoIO**	**IOtoLS**	**LStoCP**	**CPtoC**
	cm	sec						
moment frame	…..	…..	523	77	26	0	0
FPS 111	56	1.5	626	0	0	0	0
FPS 112	100	2	624	2	0	0	0
FPS 113	156	2.5	626	0	0	0	0

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FPS 114	224	3	625	1	0	0	0
TABLE: hinges in 4 story (fps in story 1th) - μ= 0.5							
FPS 121	56	1.5	626	0	0	0	0
FPS 122	100	2	626	0	0	0	0
FPS 123	156	2.5	626	0	0	0	0
FPS 124	224	3	626	0	0	0	0

Table5. Formed hinges in 6-story frame with fixed and separated pillar in similar nonlinear static analysis

TABLE: hinges in 6 story (fps in story 1th) - μ= 0.1							
name	**R**	**T**	**AtoB**	**BtoIO**	**IOtoLS**	**LStoCP**	**CPtoC**
	cm	sec					
moment frame	…..	…..	834	77	15	0	0
FPS 211	56	1.5	926	0	0	0	0
FPS 212	100	2	926	0	0	0	0
FPS 213	156	2.5	926	0	0	0	0
FPS 214	224	3	926	0	0	0	0
TABLE: hinges in 6 story (fps in story 1th) - μ= 0.5							
FPS 221	56	1.5	926	0	0	0	0
FPS 222	100	2	926	0	0	0	0
FPS 223	156	2.5	926	0	0	0	0
FPS 224	224	3	926	0	0	0	0

Diagram1. Relative displacement of stories for fixed and separated structure with 4 and 6 stories

(1-1)

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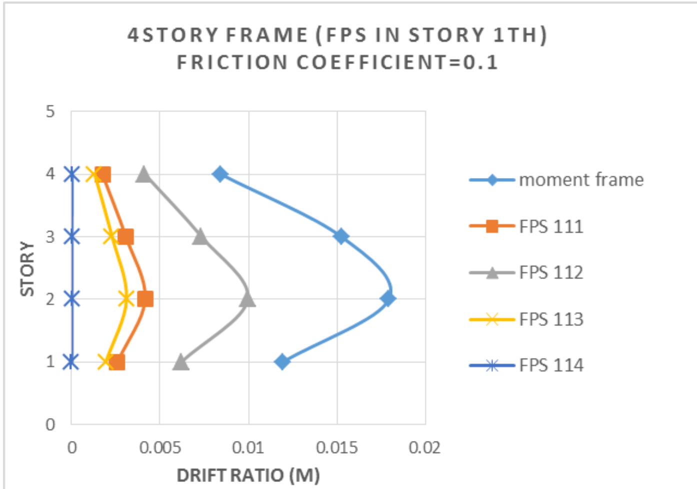

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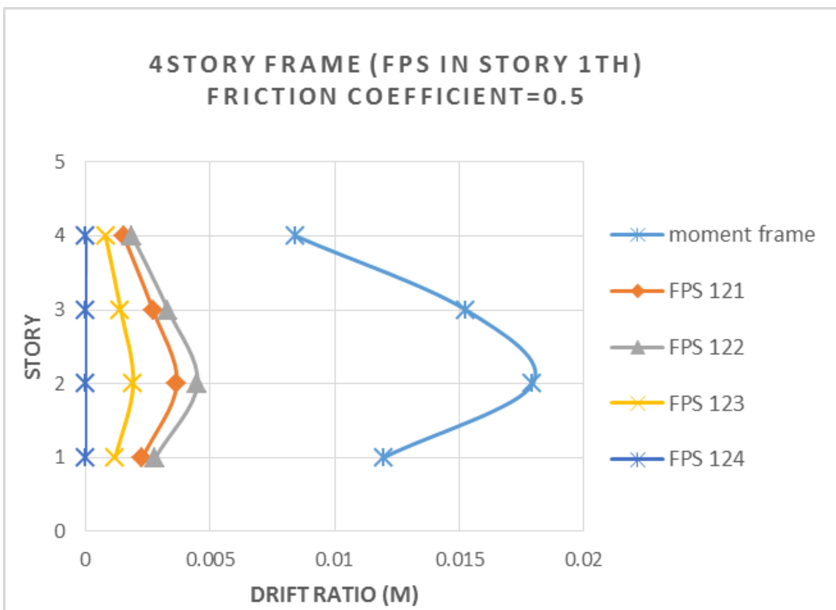

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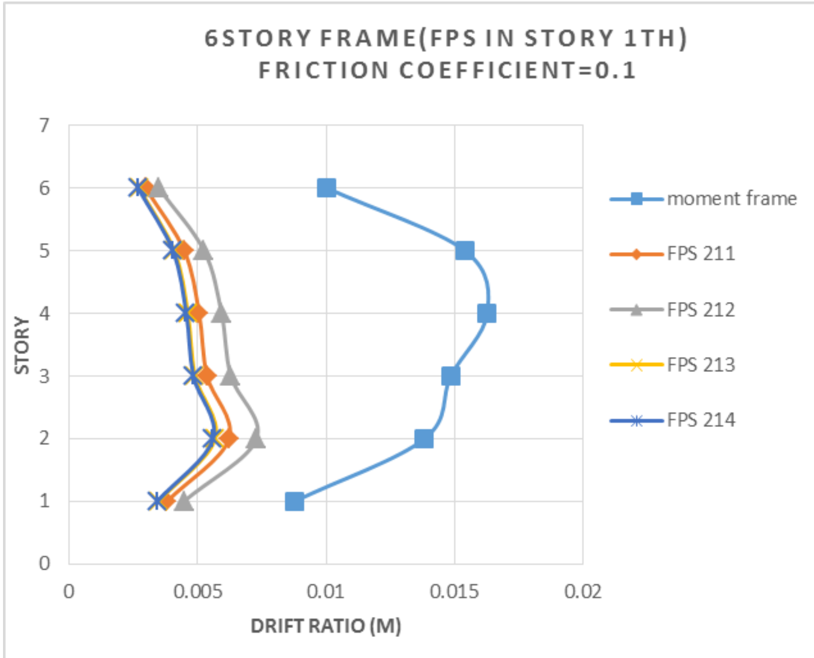

(1-4)

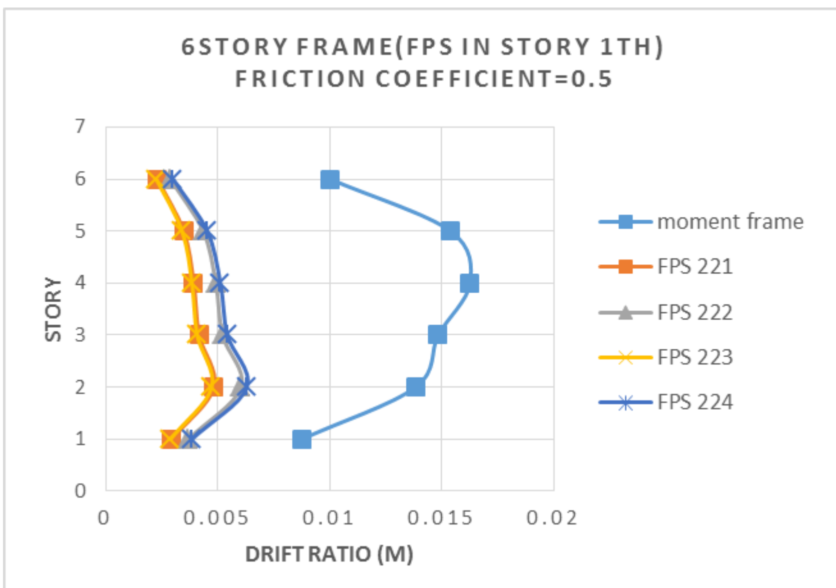

Diagram2. Roof displacement and pillar shear for structure with fixed and separated pillar

(2-1)

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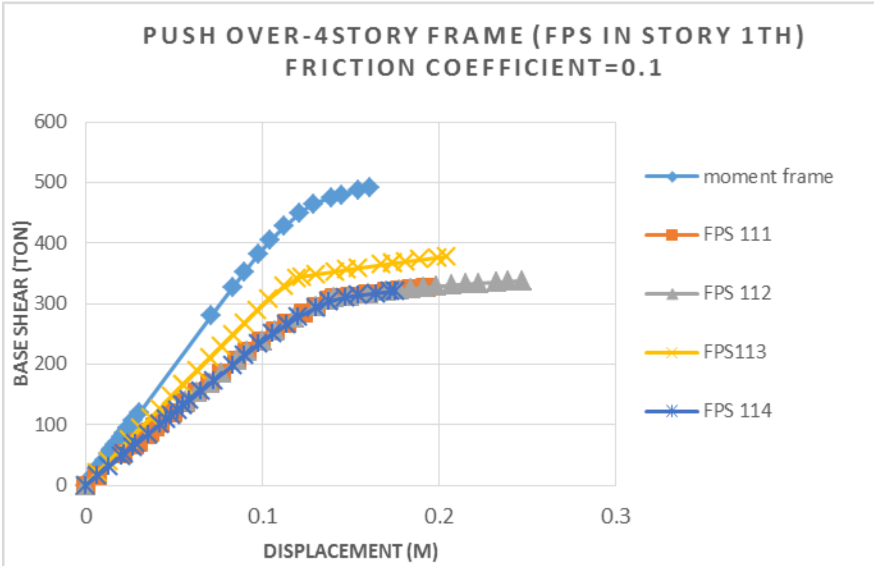

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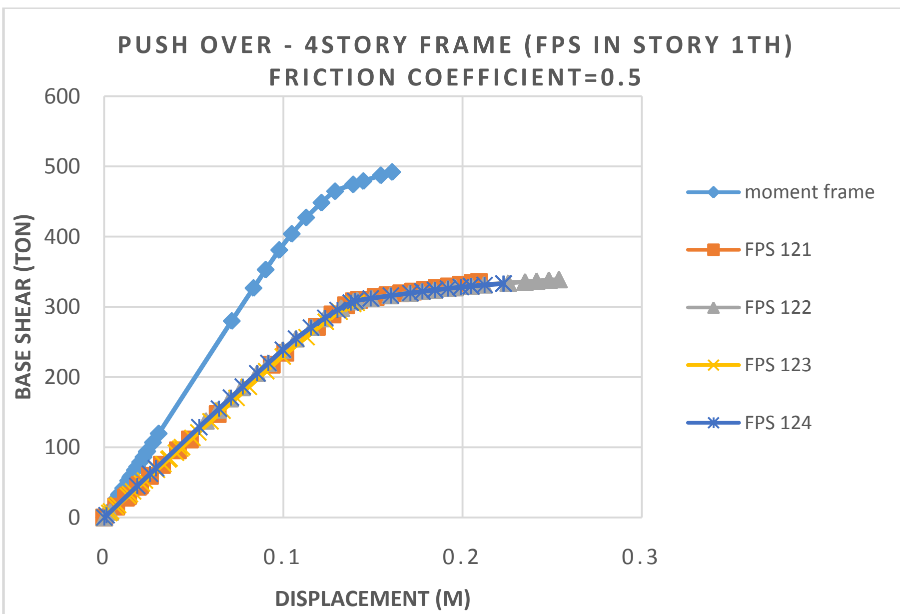

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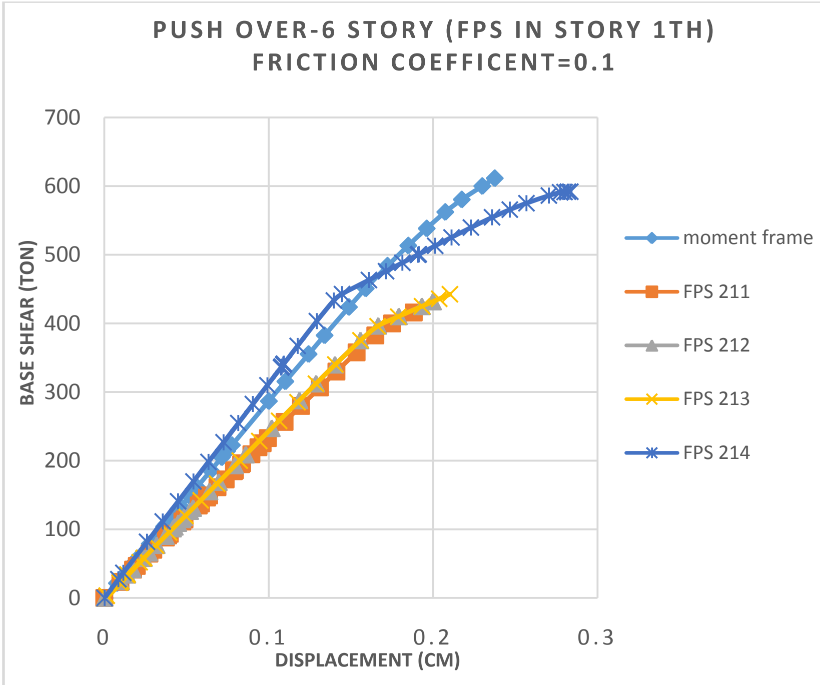
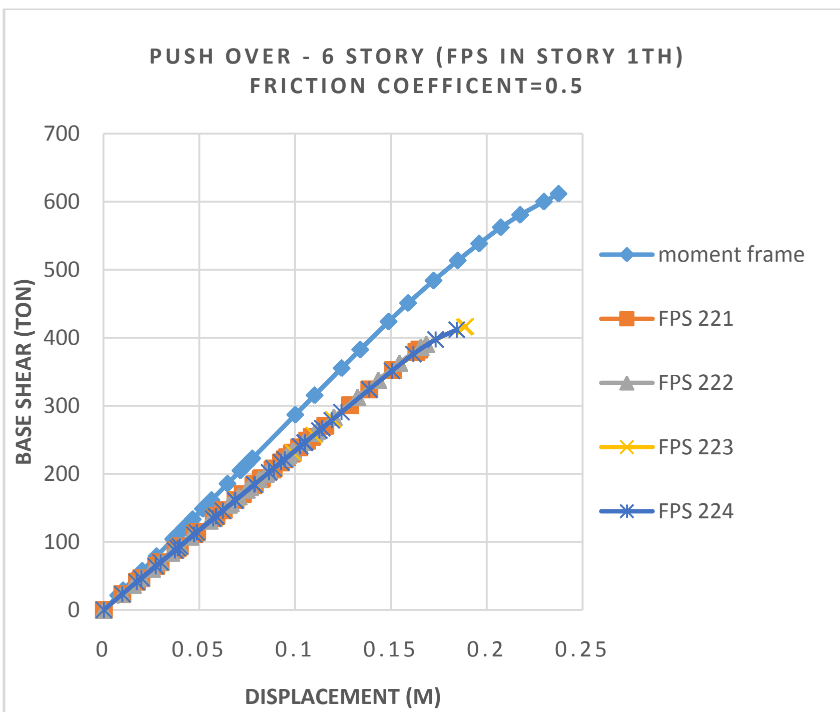


(2-4)



b. Structures in which T>Ts , Additional lateral force (15-story structures)

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In this section, first the pillar separator is placed in the first story and then it is moved to third story of structure regarding the extracted results of pillar separator. The results are given below.

According to table 6, plastic hinges are related to FPS 323 and FPS 324 (in first story) and FPS 313, FPS 314, FPS 323 and FPS 324 (in third story).

Diagrams 3-1 and 3-2 indicate inadequacy of separator systems of FPS 311, FPS 312, FPS 313, FPS 314, FPS 321 and FPS 322 which are placed in the first story; in other words, they contribute to reduction of structure plasticity. It means that separator system in such structures should be placed in structures' stories (therefore, suitable story is selected with test and error for placing isolator system at third story). According to these diagrams, it can be seen that significant increase of structure plasticity can be inferred using FPS 323 and making movement of sweep to original place through FPS 324.

Regarding the diagrams of 3-3 and 3-4, inefficiency of isolator systems of FPS 312, FPS 321 and FPS 322 is again indicated. Further, in mentioned diagrams, the significant increase of plasticity can be observed in FPS 311, FPS 313, FPS 314, FPS 323 and FPS 324 and the best performance is related to FPS 314 system in which structure performs the rigid sweep to original place.

Finally, it can be concluded that FPS systems involve the function of friction coefficient and curvature radius. Moreover, in isolator systems of FPS 311, FPS 313, FPS 314, FPS 323 and FPS 324 placed in the third story, the stories can be increased with the same mean moment frame and regulation limit can be prevented.

As another criterion regarding diagram 4, it contributes to reduction in shear stress and energy depreciate in two phases (pillar isolator in the first and third story) and this is more ordered and steady in the structure which has pillar isolator in the third story.

The important conclusion is that in irregular and divergent structures through selecting the proper FPS system (with proper curvature radius and friction coefficient), it can be prevented from stories limit and making curvature of centroid distance and rigidity center in these kind of structures.

Table6. Formed hinges in 15-story frame with fixed and separated pillar in similar nonlinear static analysis

(6-1)

TABLE: hinges in 15 story (fps in story 1th) - μ= 0.1							
name	R	T	AtoB	BtoIO	IOtoLS	LStoCP	CPtoC
	cm	sec					
moment frame	…..	…..	1735	131	107	86	0
FPS	56	1.5	1771	56	56	36	0

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311							
FPS 312	100	2	1769	52	49	35	0
FPS 313	156	2.5	1772	66	57	28	0
FPS 314	224	3	1770	53	46	36	0
TABLE: hinges in 15 story (fps in story 1th) - μ= 0.5							
FPS 321	56	1.5	1770	54	49	40	0
FPS 322	100	2	1769	51	50	33	0
FPS 323	156	2.5	2186	0	0	0	0
FPS 324	224	3	2186	0	0	0	0

(6-2)

TABLE: hinges in 15 story (fps in story 3th) μ= 0.							
name	R	T	AtoB	BtoIO	IOtoLS	LStoCP	CPtoC
	cm	sec					
moment frame	…..	…..	1735	131	107	86	0
FPS 311	56	1.5	1800	107	106	53	0
FPS 312	100	2	1833	119	103	74	0
FPS 313	156	2.5	2186	0	0	0	0
FPS 314	224	3	2186	0	0	0	0
TABLE: hinges in 15 story (fps in story 3th) - μ= 0							
FPS 321	56	1.5	1796	98	110	50	0
FPS 322	100	2	1798	102	108	53	0
FPS 323	156	2.5	2186	0	0	0	0
FPS 324	224	3	2186	0	0	0	0

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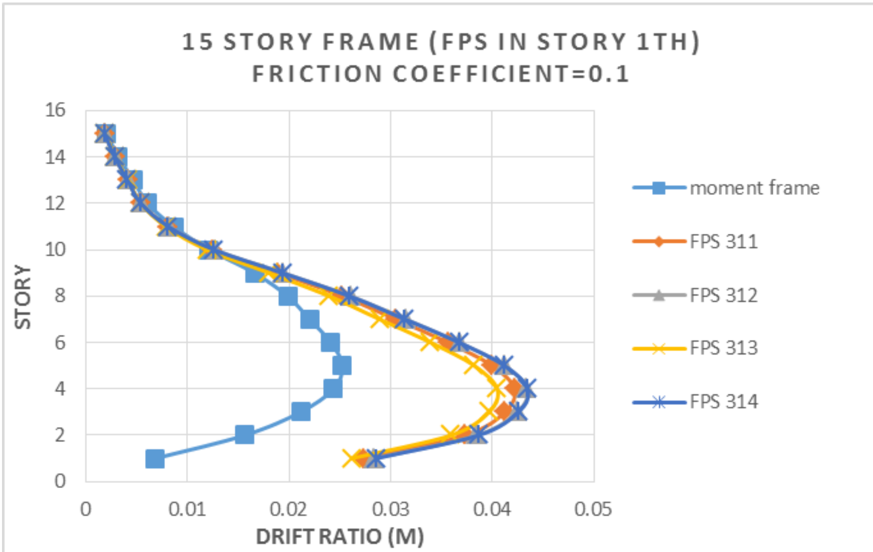
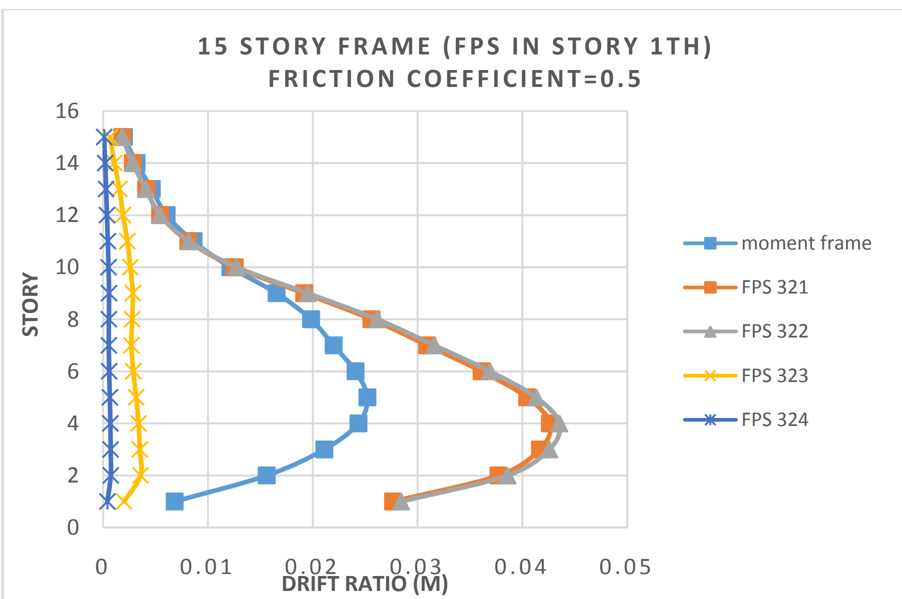
Diagram3. Relative displacement of stories for structures with fixed and separated pillar of 15 stories structure

(3-1)



(3-2)



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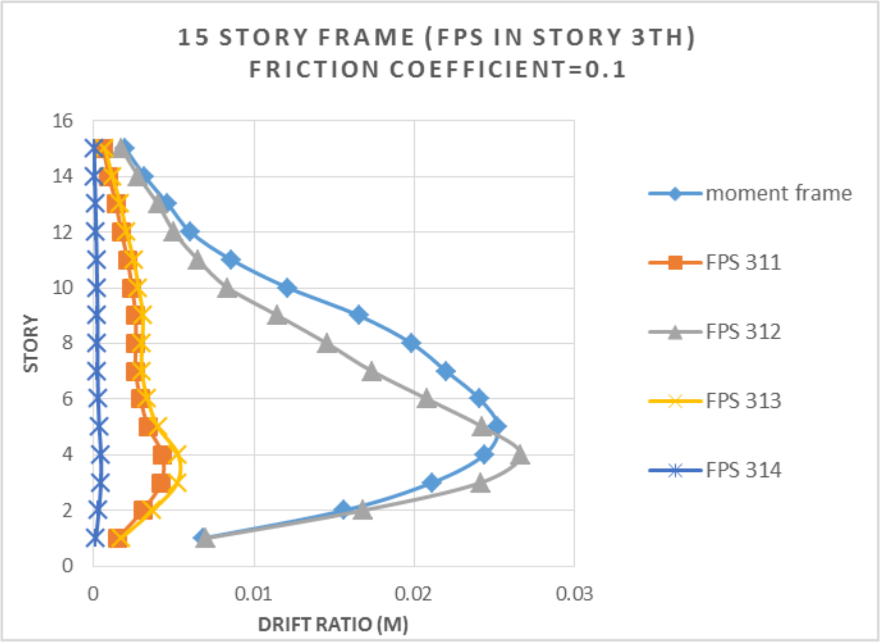

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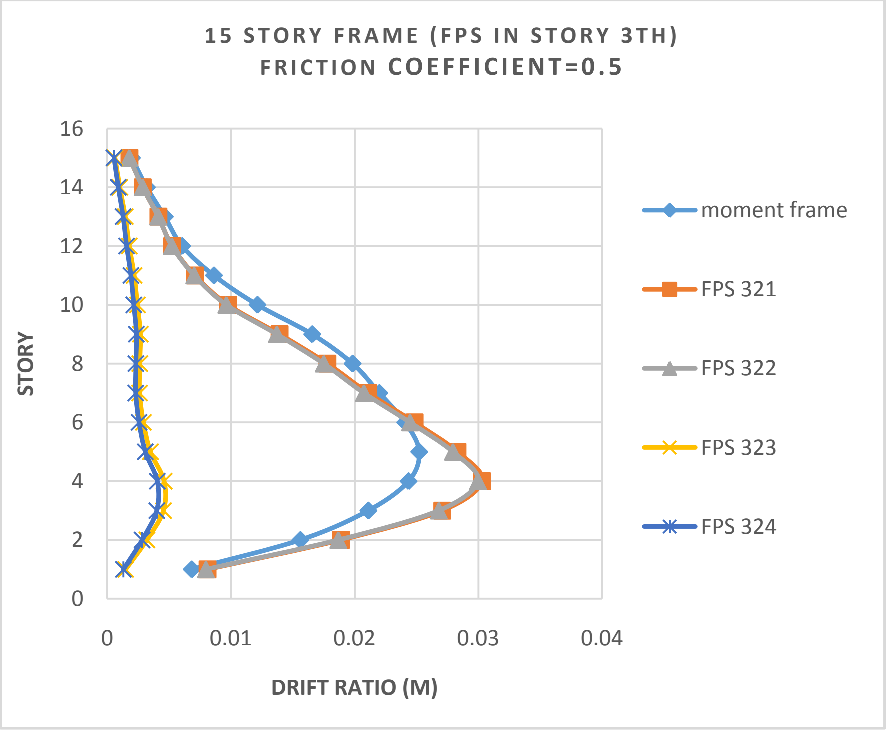

Diagram4. Room displacement and pillar shear for the structure with fixed and separated pillars

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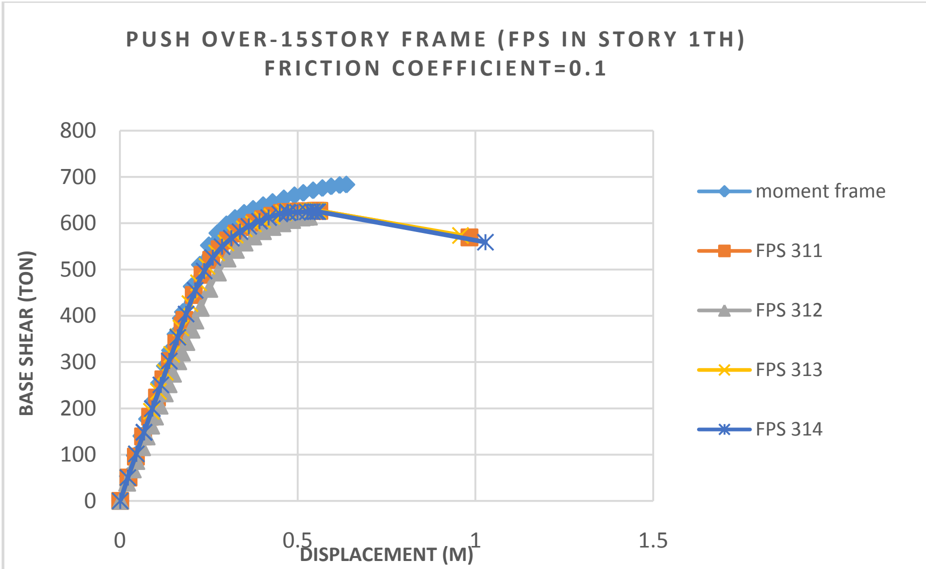
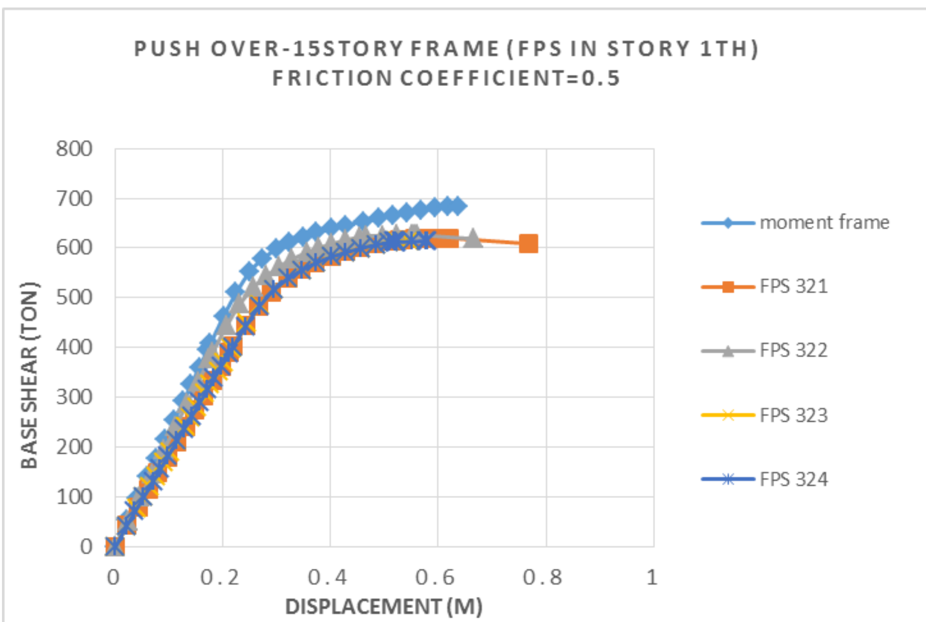
(4-1)



(4-2)



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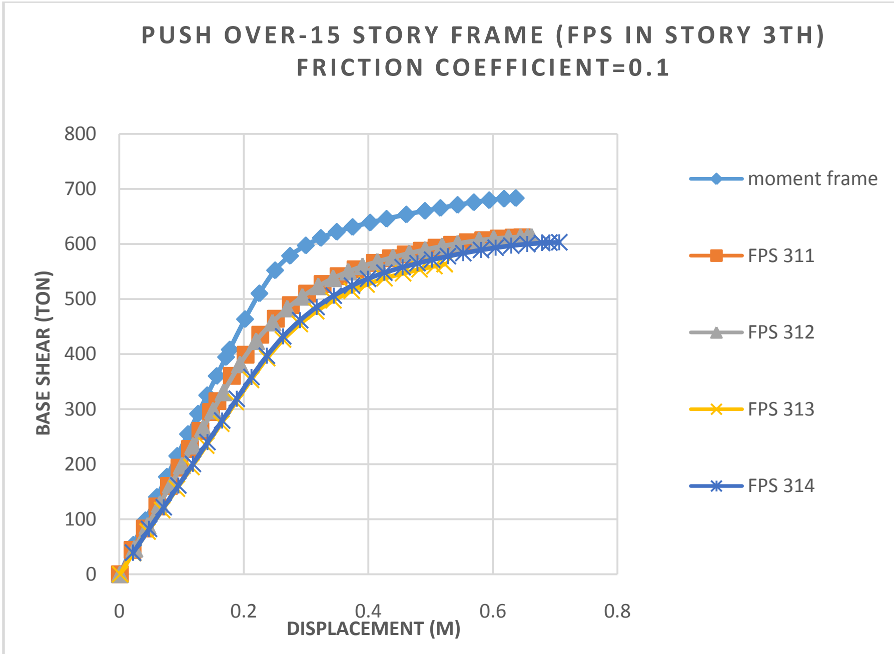
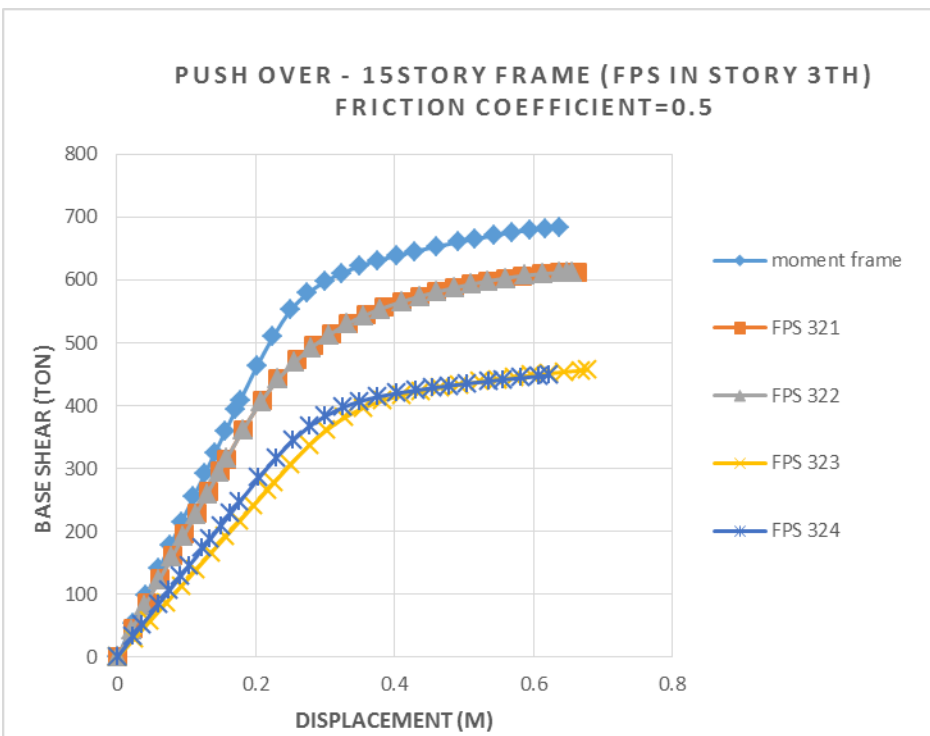


(4-4)



8. Conclusion

(DOI: dx.doi.org/14.9831/1444-8939.2014/2-6/MAGNT.34)

According to the results of all types of regular and irregular reinforced concrete equipped with FPS, a FPS system can be designed through the selection of proper curvature and friction coefficient in FPS systems, which yields a type that not only increases the structure plasticity, but also leads to rigid movement of the structure (sweep movement and structure return to the source point). This indicates that the place of earthquake force effect is coincident on structure centroid; in other words, earthquake curvature component resulting from centroid distance and structure rigidity center will be totally eliminated. It can be argued that FPS systems significantly prevent curvature force which results from earthquake curvature.

9. Reference

1. Booth, E. Design and Analysis of Concrete Structures in Seismic Places. Translated by Moradi Shaghaghi, T. & Nateghi Elahi, chapter 10.

2. Design guidance and performing seismic isolator systems in buildings.

3. Taghinejad, R. Seismic Design and Reforming of Structures on the Basis of Performance Using push-over Analysis.

6. Guideline of seismic reforming in existing buildings.

4. Naiem, F & Kelly, J.M. (1999). Design of Seismic Isolated Structures from Theory to Practice. John. Wiley & sons, Inc. 2nd edition.

5. Federal Emergency Management Agency, FEMA 356 report, Washington, DC.

6. Kelly, J.M. (1990). Base isolation: linear theory and design, John Wiley & sons, Inc.

7. International Building Code 2006 (IBC 20006).

(DOI: dx.doi.org/14.9831/1444-8939.2014/2-6/MAGNT.34)