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An Investigation to the Seismic Performance of Base Isolator-Equipped Moment Frame Steel Structures

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ABSTRACT

Today, civil engineers employ various techniques to control the deflections induced by lateral forces, of which passive seismic isolators have attracted burgeoning attention. A rapid growth in the number of critical centers such as information storage and data processing centers (DPCs), traffic control centers (TCCs), hospitals, power plants, etc., has multiplied the need for protecting the equipment in these centers against the harmful effects of assertive seismic vibrations. The huge costs of such equipment, keeping their continued servicing during and after the earthquake, and improving their performance are factors of utmost importance. Concerning that equipment such as computers, servers, data storage systems, communication tools, etc., are prone to damage caused by earthquake horizontal accelerations, using seismic isolators can provide outstanding seismic performance for equipment in critical centers located on seismically active zones. This study sought to model and scrutinize the performance of seismic isolation systems installed in the foundation of steel buildings and isolate equipment from the floor of stories under investigation. To do so, a moment frame structure was employed to be investigated under two modes for each scenario, i.e., for the rigidity or flexibility of the joints connecting equipment to the structure and the ground. The results of all four modes were eventually compared with those obtained from control structures.
Keywords: Deformation, Seismic isolator, Modeling, Retrofitting.

Introduction

A large portion of people worldwide live in earthquake-prone areas (EPAs) with a high risk of seismic shaking of varying magnitude and frequency. Earthquakes each year cause marked deaths and inflict huge financial burdens [1]. The idea of constructing robust buildings strongly anchored to the ground for withstanding seismic vibrations seems to be extravagant and overrated, as it may cause numerous hazards. For example, ordinary construction attempts can suffer from massive acceleration in the floors of rigid buildings and enormous interplanetary drifts in the flexible structures, resulting in numerous problems for citizens and their properties. Therefore, it is crucial to explore solutions for the improvement of the flexibility of the building to relieve or neutralize the seismic vibrations and block their harmful effects on the building [2].

In Iran, many buildings are low-rise and have natural periods that are matched with the energetic periods of accelerations recorded for powerful ground motions. In addition, improper materials and unfitting design and implementation procedures have inflated the vulnerability of such buildings to seismic vibrations [3].

Geographically, and concerning the current state of buildings in the country, Iran's construction system requires deep reforms and remedies. Low-rise buildings are more prone to earthquakes in the country, principally due to improper materials utilized for construction. Recent decades have caught marked progress in the technology of constructing and designing earthquake-resistant structures with the ability to absorb and dissipate effects of seismically induced motions on buildings, bridges, and their weak extensions. For instance, seismic isolation of structures is a fairly new strategy. To reduce and dissipate stress in structural elements concerning non-standard building materials utilized in buildings, anti-seismic systems such as isolated buildings can significantly develop construction in the country [3]. Isolators eliminate and restrict the seismic forces on the structure. Vibration isolators are used in soft structural support such as springs. They cause seismic forces to be transmitted to the building merely as absorption.

Simply put, isolation resembles a ship that is not impacted by ground vibrations, as motion-less water does not transfer lateral forces to the ship. In practice, isolation is the maximum blocking of horizontal forces in seismic-prone buildings. This is while vertical isolation is much difficult and less required [4]. A retrofitting plan requires certain operations and design benchmarks to achieve predefined goals. Definition and classification of retrofitting goals are the first steps in any design. Employers accentuating functionality or retaining properties need to regard higher performance such as sustained usability. However, other goals may entail lower performance levels, such as safety [5]. Seismic isolation systems and diminished energy absorption are practical examples of seismic retrofitting buildings. These systems alter the structural elements of the buildings, such as period and damping, and thus improve their performance [6]. Such systems are typically useful for buildings with given conditions such as higher performance and numerous design levels. Seismic isolators are particularly instructed for higher performance and sustained usability [7].

Generally, the structure's flexibility against harsh earthquakes is important, while, most notably, the structure's vibration in cases of weak forces such as wind or weak shakes is not a good feature. Therefore, it is usually attempted to adopt systems that merge these two goals, such as using the concept of elastic stiffness. Such deterrent systems fail at, and above, a given loading threshold. However, when these deterrent elements do not simultaneously fail or fracture, i.e., one portion is failed, and the other remains intact, the extra forces resulting from extreme asymmetry create torsional forces in the whole system. Most importantly, these elements need to be replaced if broken or damaged after each earthquake [8]. Concerning the efficiency of base isolation systems in symmetrical and asymmetric buildings under seismic forces or vibrations, the following can be useful in the optimum design of base-isolated and base-anchored structures for both symmetric and asymmetric scenarios:

1. The efficacy of base isolation in reducing the dislocation of the upper structure, perpendicular to the direction of eccentricity, is less for asymmetric structures than symmetric ones. This effect is reduced on more exiting from the eccentricity of the structure. This is likewise applied for torsional rotations of the upper structure. Therefore, if the structure's eccentricity is disregarded and the structure is modeled two-dimensionally, the impact of base isolation has been considered much more than its actual value.
2. Base isolation is more effective for torsional forces than lateral forces.
3. Inflation in the eccentricity of the upper structure reduces the lateral dislocation of the base-isolated building, perpendicular to the eccentricity, and inflates the base period [9].

Considering the above topics, this study aims to scrutinize the seismic performance of base isolator-equipped moment frame steel structures.

Methods
Geometric modeling
A four-story, 24x24 building model with three 8-meter openings on each side was studied (Figure 1).

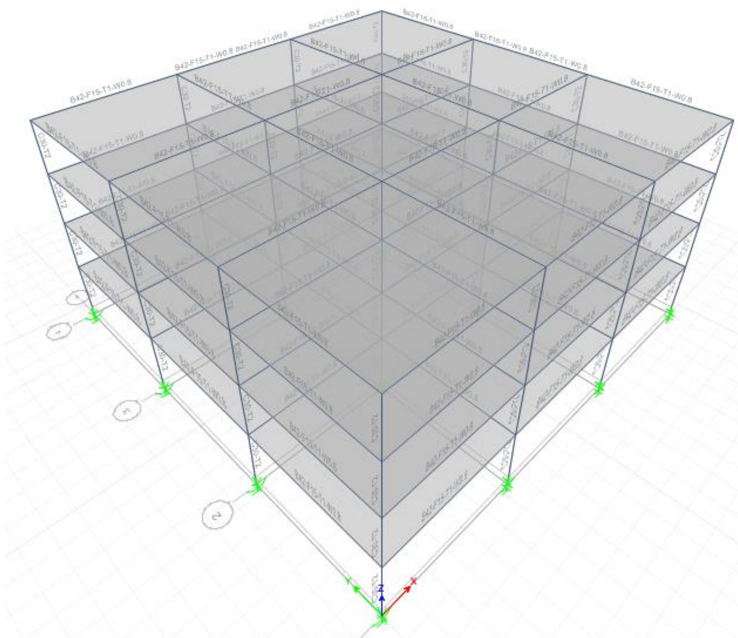


Figure 1. A three-dimensionally simulated structure

Modeling was carried out using st37 metal elements. The beams utilized were 42 cm in height and 15 cm in width, and the columns employed were square boxes with a height of 20 cm.

Loading
Loading was based on the National Building Regulations of Iran, Issue 6, and the structure was considered residential. The floor was of one-way slab type constructed of the reinforced concrete girder. The load values had no significant effect on the comparison results.

Linear static analysis
The basic hypotheses of the linear static analysis were as follows:
1. The behavior of materials is linear.
2. Seismic loads are static.
3. The total load on the structure is a factor of the weight of the building.

In this technique, the lateral seismic force was chosen to allow the resulting base shear to match the base shear force specified in regulations. Likewise, the base shear value was chosen to allow matching the maximum structure's deflection with that anticipated in an earthquake with an expected hazard level. When the structure's behavior is linear under the applied load, the forces obtained for the structure's elements will be near the predicted values during the earthquake. Otherwise, the forces obtained will exceed the values of the material flow. Therefore, the linear analysis results are corrected for structures with non-linear behavior during an earthquake when assessing the approval criteria. The linear static analysis was done based on Standard 2800, 4^{th} edition, and the seismic factor was calculated for a moderate moment frame and included in the software.

Dynamic analysis
Linear dynamic analysis can be done into response-spectrum or time-history analysis. Hypotheses for dynamic analysis for the linear behavior include the following:

1. The structure's behavior can be calculated into a linear combination of various independent vibration modes.
2. The structure's period of vibrations is constant during an earthquake for each mode.

Like the linear static analysis, the structure's response during an earthquake with dedicated risk levels is multiplied in coefficients to allow matching the maximum structure's deflection with what is anticipated from the earthquake. For this reason, the inner forces in ductile structures with non-linear behavior during an earthquake are greater than the endurable forces in the structure. Therefore, when assessing the acceptance criteria, the linear analysis results are corrected for structures with non-linear behavior during an earthquake.

Response-spectrum dynamic analysis

Values of vibration modes in the response-spectrum analysis shall be chosen to achieve the sum of the effective mass participation for each extension of the earthquake excitation of at least 90%. At least the first three oscillation modes and all modes with a duration of over 0.4 seconds shall be considered in each extension. The spectrum should be based on the regulations. The results of each oscillation mode shall be analyzed by well-established statistical methods, such as Square Root of Sum of the Squares (SRSS), complete quadratic combination (CQC) method, or other exact methods that precisely consider the interaction between modes. The seismic effects perpendicular to the desired length shall be considered if required. In the response-spectrum dynamic analysis, the basic spectrum needs to follow Standard 2800. This spectrum reflects the impact of ground motion for the seismic plan in the standard and is calculated by multiplying the values of the building's reflection coefficient (B) in the base acceleration ratio (A), importance coefficient (I), and inverse coefficient of behavior. In this spectrum, a damping ratio is considered equal to 5%.

Time-history dynamic analysis

In time-history analysis, the structure's response is calculated using dynamic equations in short time steps. Considering at least three accelerograms, the structure's response should be calculated under the ground acceleration excitation. When less than seven accelerograms are chosen for analysis, it is crucial to consider the maximum effect to control deflections and internal forces. In the case of more than seven accelerograms, the average effect can be considered to control deflections and internal forces. In the dynamic analysis of the study models, we employed records of Tabas and Bam earthquakes in Iran and the 1940 El Centro earthquake for international earthquakes.

Seismic isolator design

The seismic isolator was designed according to equations in the Guidance on the Design and Implementation of Seismic Isolation Systems in Buildings, Issue 523. The flowchart in Figure (....) shows the design process given in the guidance.

Flowchart 1

Instructions for use, structure performance requirements
Architectural design, structural design, environmental conditions
Determination of parameters A, T, S, and R_I
Measurement of damping values of B_D and B_M
Determination of T_D
Calculation of K_{eff} based on weight and T_D
Estimation of D_D
Calculation of V_s and V_b
Initial loading design
Isolation units' configuration design – initial isolation units' design
Creating a precise model – choosing an analysis method
The final design dislocation value

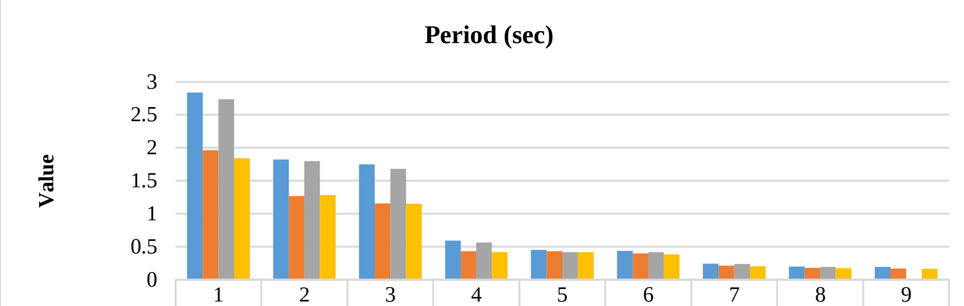
The final value for the natural period of the isolated structure
Control of the design results – negative – positive
Calculation of the final effective stiffness
Control of environmental conditions and general executive considerations
No
Matching experimental results with the numerical model
Fabrication of sample isolators
Yes
Termination

Results and discussion

According to the analysis results, deflections in the lower floor where the isolator is installed are significant in the isolated state. Such deflection reduces the effect of lateral forces on the structure. Therefore, we investigate periods 1 to 9 of the structures and the total and relative dislocations.

Structure's periods

The modal analysis of the structure's periods, which largely covers seismic mass, can compare the isolated and anchored structures with flexible and rigid foundations.



	1	2	3	4	5	6	7	8	9
ISO-RIGID	2.836	1.823	1.749	0.589	0.452	0.435	0.241	0.199	0.194
ISO-FLEX	1.962	1.265	1.155	0.429	0.432	0.398	0.211	0.178	0.169
FIX-RIGID	2.736	1.795	1.678	0.563	0.418	0.417	0.235	0.192	
FIX-FLEX	1.839	1.28	1.15	0.414	0.415	0.384	0.203	0.171	0.161

Figure 2.

As shown in Figure 2, the first period has a higher value than other modes. In comparison, structures with rigid foundations have more extended periods than flexible structures. This trend is seen in all modes.

Total dislocation

Control over the structure's dislocation is among the structure's seismic function control indicators. In this section, the structure's dislocation is investigated. Besides the parameters restricted in the standard, evaluating the total structure's dislocation is also crucial to consider the separation joint. Figure 1 illustrates dislocation in various floors of the structure.

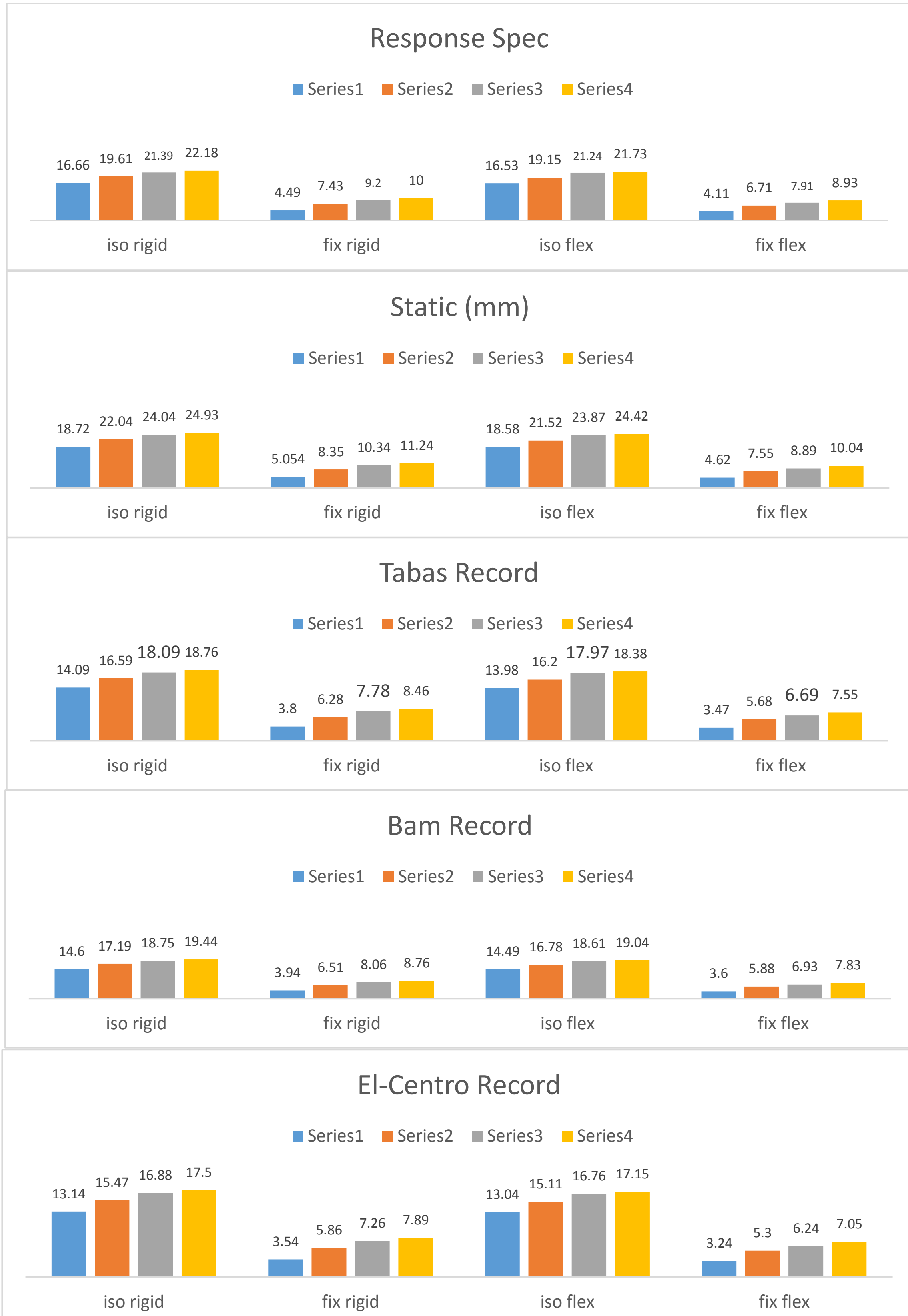
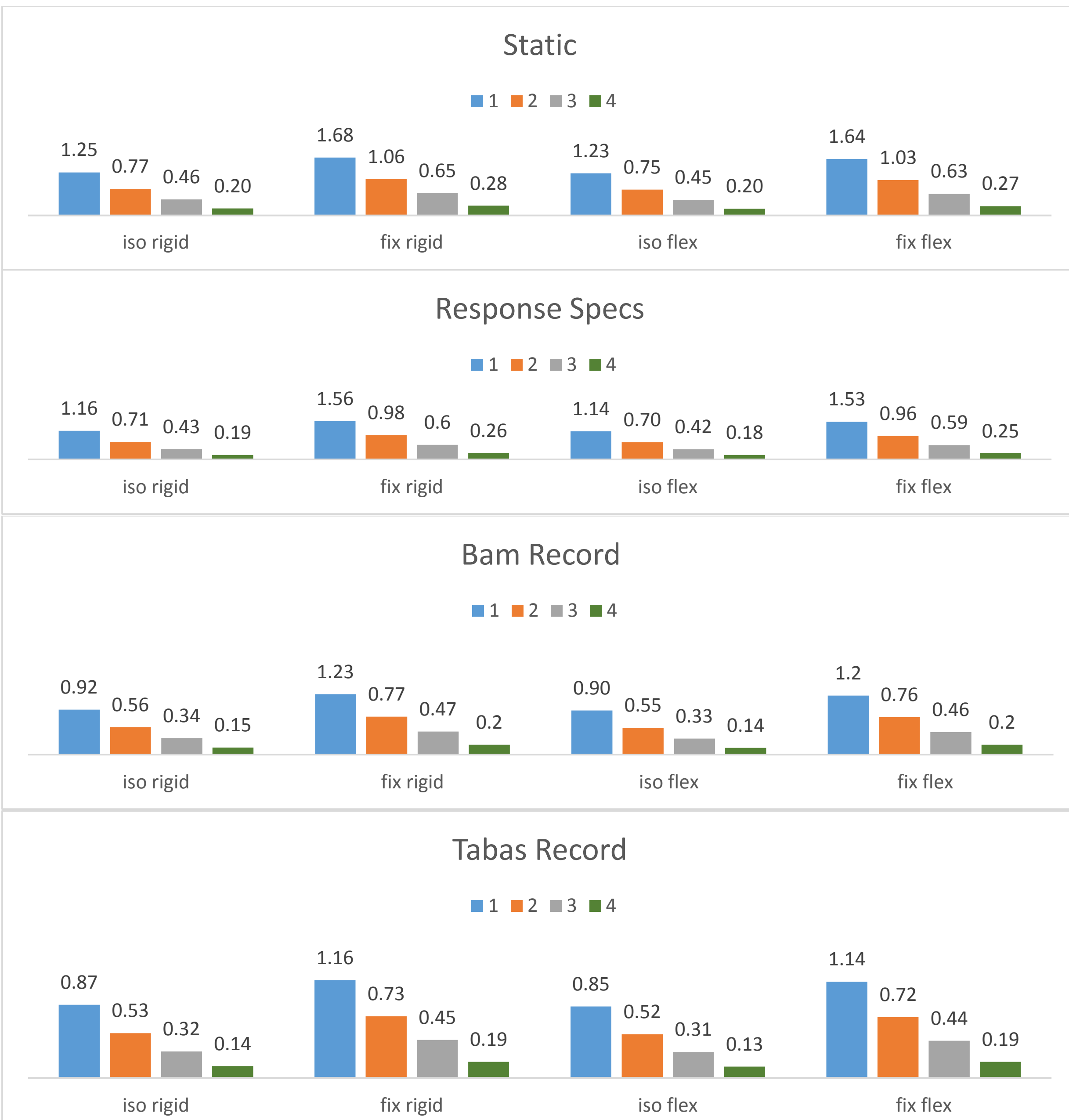

Response Spec
Series1 Series2 Series3 Series4
16.66 19.61 21.39 22.18
4.49 7.43 9.2 10
16.53 19.15 21.24 21.73
4.11 6.71 7.91 8.93
iso rigid fix rigid iso flex fix flex
Static (mm)
Series1 Series2 Series3 Series4
18.72 22.04 24.04 24.93
5.054 8.35 10.34 11.24
18.58 21.52 23.87 24.42
4.62 7.55 8.89 10.04
iso rigid fix rigid iso flex fix flex
Tabas Record
Series1 Series2 Series3 Series4
14.09 16.59 18.09 18.76
3.8 6.28 7.78 8.46
13.98 16.2 17.97 18.38
3.47 5.68 6.69 7.55
iso rigid fix rigid iso flex fix flex
Bam Record
Series1 Series2 Series3 Series4
14.6 17.19 18.75 19.44
3.94 6.51 8.06 8.76
14.49 16.78 18.61 19.04
3.6 5.88 6.93 7.83
iso rigid fix rigid iso flex fix flex
El-Centro Record
Series1 Series2 Series3 Series4
13.14 15.47 16.88 17.5
3.54 5.86 7.26 7.89
13.04 15.11 16.76 17.15
3.24 5.3 6.24 7.05
iso rigid fix rigid iso flex fix flex

Figure 3

As demonstrated in Figure 3, dislocation in isolated models is higher than in non-isolated models. When the system undergoes dislocation loads, the isolator absorbs a large portion of the applied load to prevent considerable damage to the structure's floors. This is why a severe dislocation is observed on the first floor.

Relative dislocation

Relative dislocation of the structure is also of utmost importance in the guidance on the seismic design of the building. As described earlier, the isolator remarkably downsizes the relative dislocation of floors. Figure 4 shows the relative dislocation of floors under varying loading.



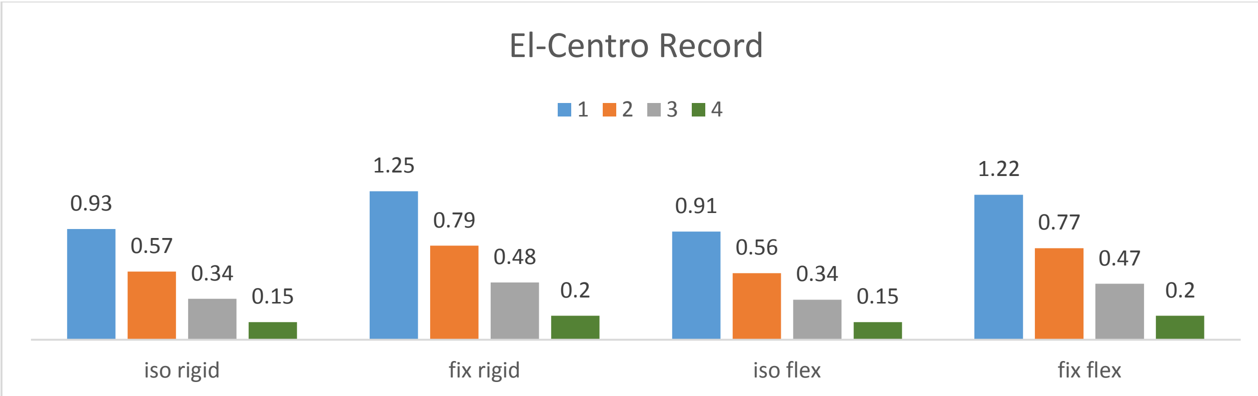


Figure 4.

Figure 4 shows that dislocation of the floors has been diminished significantly when using the seismic isolator system.

Conclusion

Every year thousands of people lose their life, depending on the number and magnitude of earthquakes that occur in the world. A subject of concern for structural engineers is to design structures with the extended capacity to withstand lateral loads. In this context, numerous techniques have been developed to retrofit the structures against the harmful effects of seismic vibrations. For this purpose, brace-reinforced frames, moment frames, shear walls, and a combination of them are more popular due to the ease and simplicity of implementation. The rationale for most of these techniques is that the seismic force is distributed and dissipated between the bearing elements intended for lateral forces in the structure. In these systems, the structure has undergone seismic forces, and vibrations and all elements contribute to withstand applied loads.

Seismic isolator systems are among popular structure control systems. The seismic performance of this system is better than the non-isolated system.

Typical construction techniques can inflict massive acceleration in the floors of rigid buildings and enormous interplanetary drifts in flexible structures. These factors push uncertainty on the security of the structure's elements and components. To avoid this, constructing the building on an isolator system blocks the large portion of horizontal movements from being transmitted to the structure. This significantly reduces acceleration in the floors and interplanetary drifts and thus protects the structure's elements and components. The next advantage of seismic isolators is that they extend the structure's main period and transfer vibrations to the low-energy areas of the earthquake in the response spectrum, culminating in a remarkable decline in elastic forces.

This study was aimed to scrutinize and compare the performance of a typical structure and a seismically isolated structure using seismic isolators for two rigid and flexible foundations. To do so, analyses were carried out in ETABS, for which four modes were analyzed in a residential building under loading using static analysis and response-spectrum and time-history dynamic analyses employing records from three major earthquakes.

This study investigated the system's performance for two flexible and flexible foundations. It was found that the relative dislocation in the system has been decreased by 25 to 37%, indicating the superior performance of the system investigated.

Future trials are recommended to cover the following subjects:

1. To investigate the effect of seismic isolators on the performance of irregular structures with an incremental irregularity
2. To compare the isolated and non-isolated in different structural systems.

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