Seismic Performance Improvement of Masonry Buildings by WSBI Method

M. Yekrangnia, A. Mahdizadeh, H. Seyri, M. Raessi
State Organization of Schools Renovation and Mobilization of Islamic Republic of Iran

SUMMARY:
Masonry buildings are the most abundant type of structures in Iran and many other countries as well. This structural type, however, has shown very poor performance during past earthquakes, even in moderate ones. The main weakness of these buildings is detachment of the perpendicular walls and spoiling "box-like" behavior; resulting in the collapse of the roof. The classic retrofitting techniques aim at providing the building with extra strength, while usually care less about energy dissipation capacity, failure modes, ductility and stability of the building being retrofitted. This approach towards retrofitting usually causes excessive retrofitting elements. In this article, a new approach which combines these classic methods with an innovative-while-forgotten base isolation method is utilized. The performance improvement of a typical masonry building which is retrofitted with classical and also innovative method is evaluated and compared with the common-practice state.

Keywords: Masonry Buildings, WSBI Method, Retrofitting, Seismic Performance

1. GENERAL INSTRUCTIONS

In many moderate to strong earthquakes (Xintai in 1966, Bohai in 1969, Tangshan in 1976), it has been observed that URM buildings experience extensive damages and in some cases collapse. This unacceptable seismic performance of these buildings is mainly due to lack of ductility, strength and energy dissipation capacity. Spoiling the "box-like" behavior of these buildings is one of the most common failure modes in which the perpendicular walls detach from each other. This mode is mainly due to low-quality workmanship and absence of vertical and horizontal ties. However, in some earthquakes it has been observed that while numerous number of URM buildings has collapsed, the adjacent buildings with almost the same geometrical and material mechanical characteristics, survived the earthquake without experiencing considerable damages. In the majority of these buildings, a horizontal crack occurred at the base of the buildings which usually extends in all walls, affecting the whole plan of the building. This crack acts like a base isolator which greatly reduces transferring the accelerations to the walls and hence preventing the relative displacement in the walls. This crack is mainly due to some natural unwanted phenomena like weathering and decaying at the top of the foundation, causing a neck-like section (Fig. 1 and Fig. 2). A number of base isolation techniques have been proposed during last decades concentrating on adding some flexible elements for reducing the transferred acceleration and enhancing the energy dissipation capability. However, all these methods require considerable intervention to the building which imposes great functioning halt and also financial resources. While these methods cannot be regarded as proper retrofitting solutions for URM buildings due to inherent low price of the buildings and the limited economical capability of the habitants.

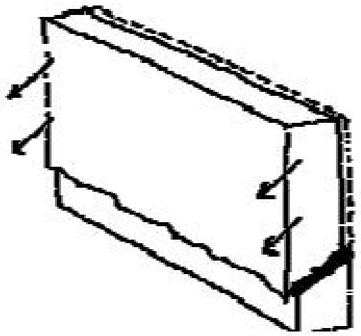


Figure 1. Weak line at the base of the walls **Figure 2**. Weathering and moistening of the base of a wall

Li performed shaking table experiments on half-scale two-story masonry specimen. The models were excited in three dimensions and the plan dimension was 5*5m. The specimen was isolated from the shaking table at the base by putting a terrazzo plates on the foundation, then spraying a layer of sand on it and then placing another terrazzo plate of the layer. Although the P.G.A. of the record excitation was greater than 1g, the peak of acceleration at top of the walls was not more than 0.5g. The sliding of the superstructure on the substructure initiated at 0.2g. Also the residual sliding of the walls was in the order of 1.5cm. However, the other un-isolated specimen was severely damaged during the same excitation and various cracks propagated through the walls. He suggested even a simpler method which consists of removing the mortar at a bed joint near the base of the building to half of the wall thickness. He claimed that this method is as effective as the other base isolation method, while cheaper and more feasible.

Qamaruddin et al. investigated the effectiveness of the Friction Seismic Isolation (FSI) on URM buildings by performing shaking table experiments on 1:4 scale single story masonry specimens. They tested four models with different scales and material properties. The materials were graphite, dry and wet sand with the friction coefficient of 0.25, 0.34 and 0.41, respectively. The ratio of the peak acceleration at the top of the walls to the peak acceleration of the excitation is 0.63 and 2.34 for the graphite isolated model and the fixed-base model, respectively. Also eight half-scale models were tested; six of which were un-isolated and different parameters like walls thickness, quality of mortar and reinforcing patterns were considered. Also they proposed a simple mathematical model for single story masonry buildings. They concluded that good agreement between the experimental and theoretical results exists. They found out that the greater the friction coefficient, the less the peak acceleration at the top of the walls would be. Also unlike the un-isolated buildings, the acceleration spectrum of the model is flat and does not have any correlation with the natural period of the system.

Mostaghel et al. developed Qamaruddin's model and concluded that for URM buildings with the natural period less than 1.8 sec, the residual sliding at the base is of 1.5 times the P.G.D. Also the more intense the excitation, the more effective the base isolation system would be. Moreover the intensity of the response is independent of the intensity of the excitation. The same observation by made by Sue et al, and Zongjin et al.

Lou et al. studied seismic performance of shaking table models which were base isolated with different materials like asphalt felt, graphite powder, screened gravel, fine sand and paraffin wax. They concluded that graphite powder is the best possible material for base isolation of URM buildings.

Bingze et al. performed shaking table tests on reduced-scale gypsum models with asphalt felt and graphite powders interposed. They excited the model with the P.G.A. ranged from 0.1g to 5g. They observed the initiation of sliding in the model in 0.25g, but no serious damage to the base-isolated models even in the last excitation were observe.

Sassu and Ricci proposed an almost the same base-isolation method for URM buildings named "reinforced cut-wall". Their method consisted of a layer of mortar of rather modest mechanical properties overlaying waterproof elastomeric sheathing laid between the foundation and base of the masonry walls to be isolated. Both layers are moreover reinforced by a series of vertical metal rods anchored to the cast concrete. The proposed retrofitting system was evaluated by performing 12 cyclic friction tests on double-block specimens. The models were different in type of mortar and the reinforcing rebars. It is noteworthy that the sheathing part provides the system with considerable displacement and the sliding of this part occurs first. The next mode of failure is the rupture of the low strength mortar which takes part in the energy dissipating phenomenon. They proposed a simple mathematical model for simulating the base isolation effect of URM buildings. In a numerical analysis, they studied three cases: the non-isolated, isolated without the rigid base beam and isolated with rigid base beam. They concluded that the isolated model without rigid base beam is susceptible to toe crushing because of the concentration of compressive stresses at the corner of the building. This phenomenon is originated from the fact that in this model, only walls parallel to the excitation direction contribute to the load bearing action and this also results in out-of-plane collapse of the walls.

2. PROPOSED SYSTEM

Li mentioned that the proposed retrofitting technique should have features below:

1) Effectiveness: The method should be effective in reducing the main modes of failure and at least postponing these modes or transferring the dangerous modes to other less threatening ones.
2) Economic: The system should be economic in order to be vastly implemented.
3) Endurance: the retrofitting system should endure the harsh environmental effects at lease for some decades.
4) Ease of construction: the system should be feasible to implement; otherwise it negatively affects the effectiveness of the system.

Fig. 3 shows the details of the proposed retrofitting system. The method consists of isolation of walls at their base and can be executed as followings:

1- One of the bed joints near the base of the building should be removed with 40cm increments. It is impossible to remove the bed joint in one step since the settlement problems.
2- Clean the dusts and remained of the bed joint.
3- Insert the steel plates cut in 40cm length to the empty bed joint. This may be done by using hammer.

Table 1 presents the cost analysis for the proposed retrofitting method. As can be seen, the proposed method is considerably more economical than other common retrofitting methods like shotcrete which for the selected plan would reach to 3670 US$ compared to 891 US$ for the proposed method.

Table 1 : Cost analysis for the proposed retrofitting method

Item	Unit	Unit cost (US$)
grooving the wall	length (m)	0.5
holing the masonry wall	length (m)	1.7
cleaning the groove	length (m)	0.5
preparation and implementation of the steel parts	mass (kg)	24.3
Sum	27	
Sum for the considered plan	891	
Sum for a typical Iranian school	6750	

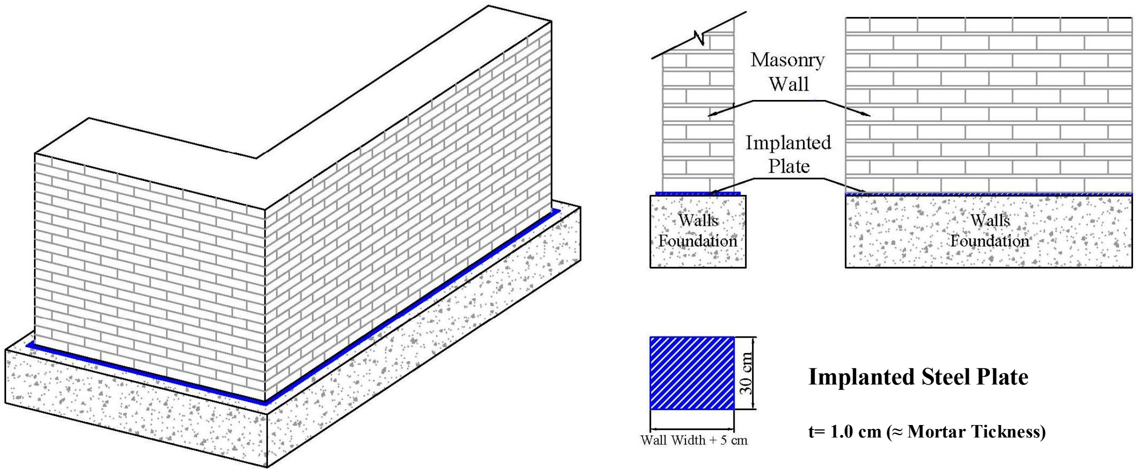


Figure 3. Details of the proposed retrofitting system

2.1. Analytical Model

For simplicity purposes, an analytical model is proposed for determination of base-isolated buildings. The model is based on the following assumptions:

- The building is an SDOF system. So for multi-story buildings, the model is expected to yield results with some approximation.
- The model does not take into account the damping of the building. So it gives conservative results.
- The building is assumed to behave in linear-elastic manner.
- The model is introduced in two phases; the building is assumed to be rigid and flexible.

Phase 1: Rigid-while-sliding building:

The equation of motion of the system is:

- If $|\ddot{u}_g| > \mu g \qquad M\ddot{u} - \mu M g = -M\ddot{u}_g$ (2.1)
- Else $M\ddot{u} + ku = -M\ddot{u}_g$ (2.2)

Phase 2: Deformable building:

The equation of motion of the system is:

- If $|\ddot{u}_g| > \mu g \qquad M(\ddot{u}_b + \ddot{u}_s) + ku - \mu M g = -M\ddot{u}_g$ (2.3)
- Else $M\ddot{u} + ku = -M\ddot{u}_g$ (2.4)

where $\ddot{u}_g$ is the total ground acceleration, $\ddot{u}$ and u are structure's relative acceleration and displacement, respectively. “M” and “K” are the mass and stiffness of the structure. μ is the frictional coefficient and “g” is the gravitational acceleration. $\ddot{u}_b$ and $\ddot{u}_s$ are the absolute acceleration of base and sliding structure, respectively.

2.2. Numerical Model

In order to investigate more sophisticated systems, a representative model is analyzed by numerical method. It is noteworthy that the main goal of this study is to investigate the effectiveness of the proposed retrofitting technique on performance improvement of URM school buildings. Since the plan of school buildings is larger than a typical residential building, analyzing the whole plan of the representative school is computationally expensive. So it is necessary to reduce the plan to an acceptable number of classrooms. This “reduced plan” should contain the main features of the real adjacent classrooms and have the same characteristics in terms of failure modes. In an experimental study, Mosalam concluded that the in-plane stiffness and strength of 2-bay URM systems is 1.7 and 2 times the same parameters of a single-bay systems, respectively. So by determining the characteristics of the “reduced plan”, the characteristics of the “real plan” can be assessed. The main concern about the reduced plan is that this plan cannot observe the irregularity in plan and height. By studying 126 URM school buildings, it is shown that most of the buildings plans are symmetric. The plan and other geometrical characteristics of the representative model are based on statistical studies on 348 plans of URM school buildings in provinces with high seismicity which is shown in Fig. 4.

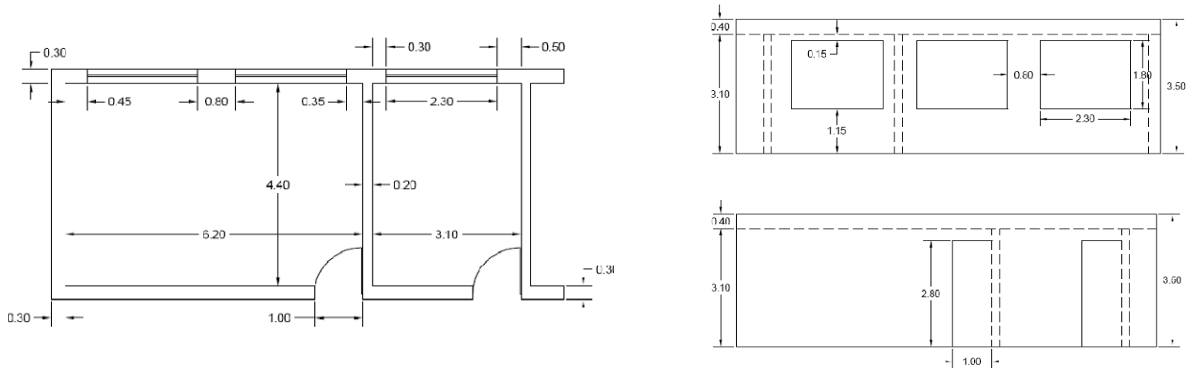


Figure 4. Geometrical characteristics of the representative model (Reduced plan)

Table 2 presents the mechanical characteristics of the materials and other numerical parameters. It is worth mentioning that the modeling approach is macro. The roof system is jack-arch with the thickness of 0.4m and the mass per area of 500 $\frac{kg}{m^2}$. The homogenized masonry can experience compressive and tensile damages with stiffness and strength degradation taking into account the cyclic weakening.

Table 2 : Materials mechanical characteristics and other numerical parameters

Brick-to-brick Frictional Coefficient	Mortar Shear Strength (MPa)	Mortar Compressive Strength (MPa)	Brick Compressive Strength (MPa)	Masonry Prism Compressive Strength (MPa)	Young’s Modulus of Masonry Prism (MPa)	Density of Masonry Prism ($\frac{kg}{m^3}$)
0.8	0.2	8	8.5	6.5	2200	1800

In order to investigate the efficiency of the proposed system with respect to the ground motion characteristics, it is preferred to implement simplified dynamic excitations. In doing so, three linearly-increasing harmonic excitations with different frequencies simulating the dominant frequencies of a typical earthquake records in low, moderate and high frequencies (5, 10 and 20 Hz) were considered. These excitations are depicted in 0Fig. 5. It is noteworthy that the excitations were scaled to impose a unique acceleration and hence base shear to the model. Also the total duration of the excitations is 10sec, representing an acceptable strong duration of earthquake records. Also three frictional coefficients were considered in this study: 0.2, 0.5 and 0.8, representing the low, moderate and high (brick-to-brick) friction. It is obvious that by reducing the frictional coefficient, the period of the building would decrease dramatically at the beginning of the earthquake excitations and hence, reducing the base shear of the building.

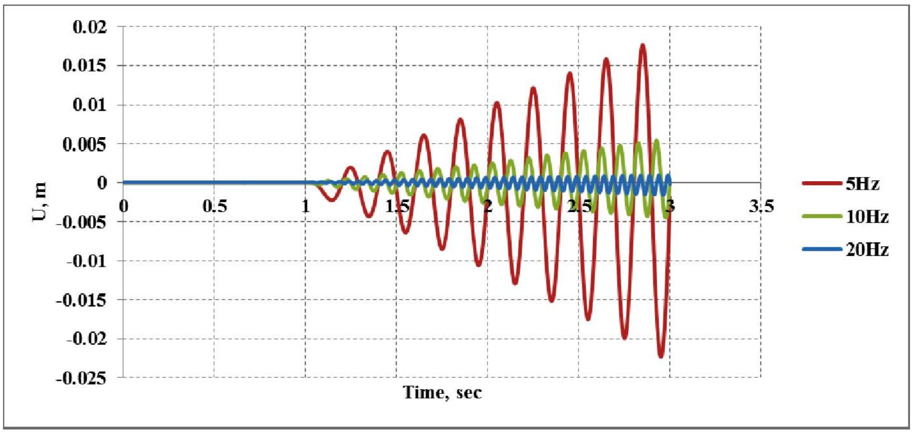


Figure 5. Time history of excitation acceleration

3. NUMERICAL RESULTS

Fig. 6 to Fig. 8 depict seismic performance and damages of the common practice model under excitations with different frequencies. One of the most important criteria for evaluation of the severity of the damages and their location is the cumulative equivalent plastic strain (PEEQ):

$$\mathrm{PEEQ} = \int_0^T \frac{2}{3}\sqrt{\dot{\varepsilon}_{ij}^{p}\dot{\varepsilon}_{ij}^{p}}dt \tag{3.1}$$

where $\dot{\varepsilon}_{ij}^{p}$ is the plastic strain rate with i,j conjugate. This parameter is suitable when the nature of the damages is not of impotence and since it has no component and sign, its magnitude can be interpreted as the severity of the damages. As can be seen, the model is more vulnerable against excitations with low frequency content and tolerate less excitations time.

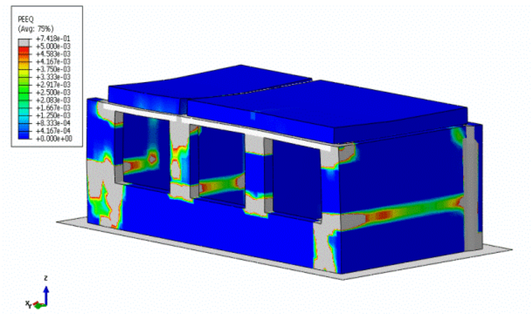


Figure 6. PEEQ (μ=0.8, f=5Hz) @ 3sec

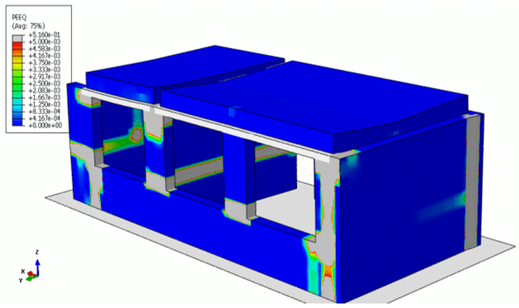


Figure 7. PEEQ (μ=0.8, f=10Hz) @ 3.5sec

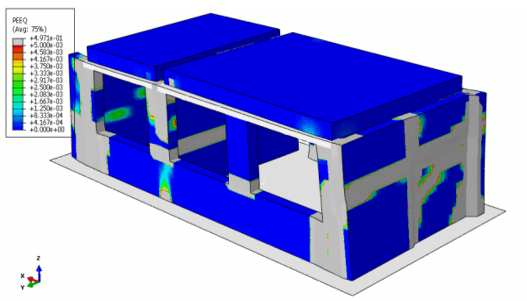


Figure 8. PEEQ (μ=0.8, f=20Hz) @ 8.5sec

The sensitivity of the model to the frictional coefficient at the base of the structure is presented in Fig. 9 to Fig. 11. As observed, the severity of damages in the model is greatly dependent on this parameter.

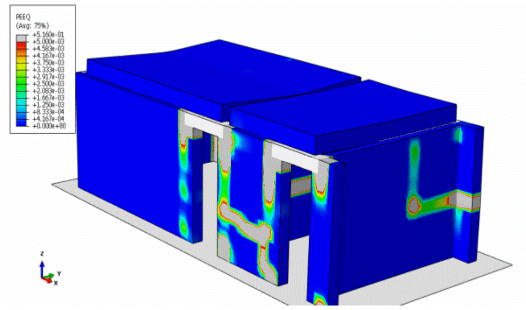


Figure 9. PEEQ (μ=0.8, f=10Hz) @ 3.5sec

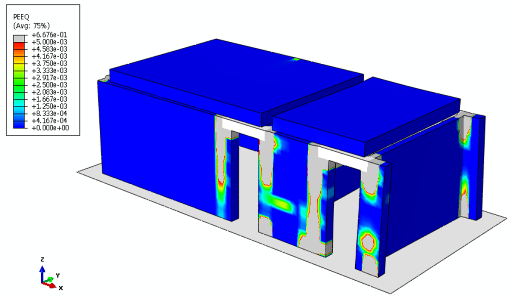


Figure 10. PEEQ (μ=0.5, f=10Hz) @ 5.0sec

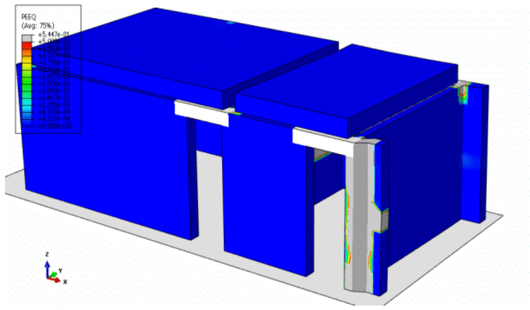
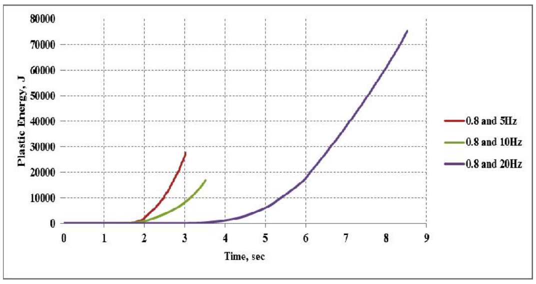
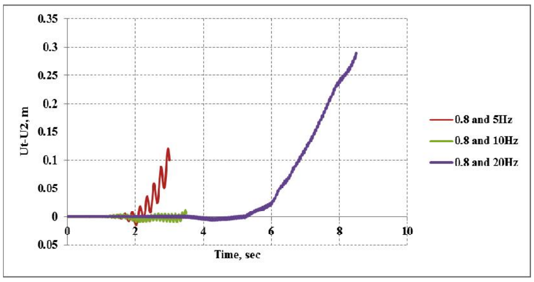


Figure 11. PEEQ (μ=0.2, f=10Hz) @ 11.0sec

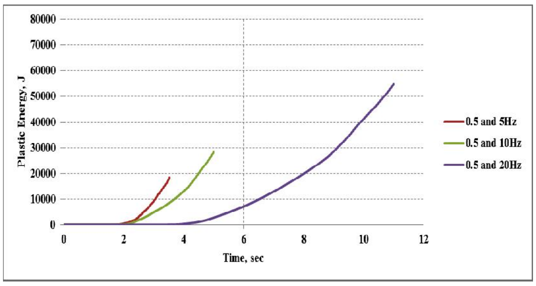
In general, masonry buildings are sensitive and vulnerable against both accelerations and hence base shear and also relative displacement of the walls and Fig. 12 to Fig. 14 show these parameters for different models. As can be seen in these figures, the proposed retrofitting technique can successfully reduce plastic energy, base shear and wall drifts and hence reducing the damages to the model building. It is worth mentioning that the curves are plotted up to the collapse of the model. Also it was observed the falling of the roof is more sensitive to low frequency excitations. This can be explained from the fact that due to low frequency nature of walls in out-of-plane motions, only low frequency excitations can be passed and amplified; causing excessive movements of top of the walls and therefore collapse of the roof. The main drawback of the proposed retrofitting method is that with lowering the frictional coefficient and hence the structural seismic vulnerability, sliding of the structure would amplify. This fact indicates considerable damages to the mechanical and electrical equipment of the building; however, these kinds of damages are more tolerable compared to structural damages considering the life safety and financial issues.

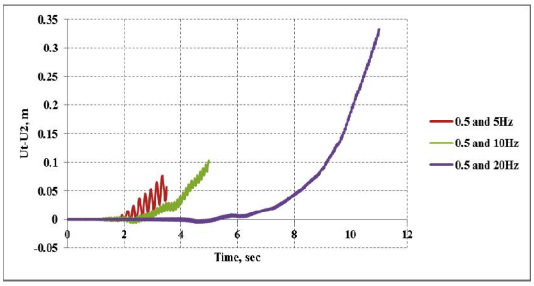
μ=0.8



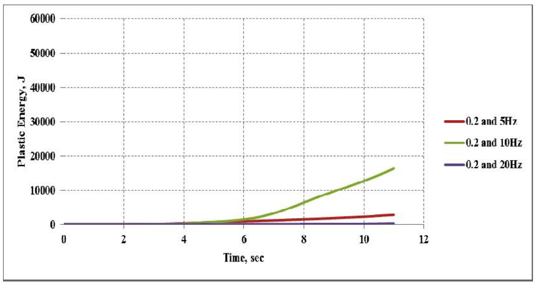


μ=0.5





μ=0.2



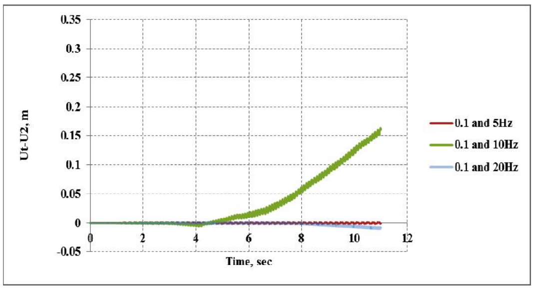
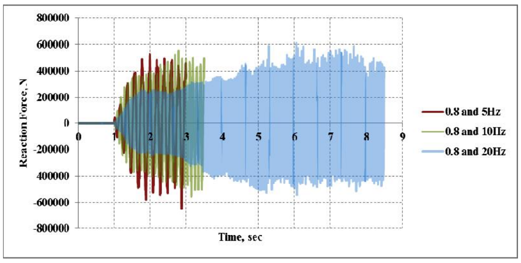
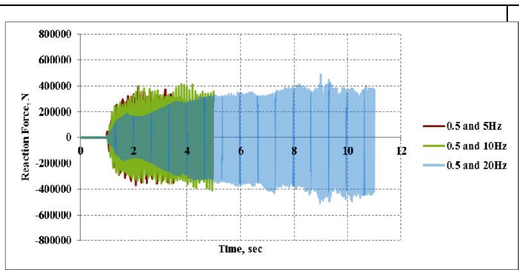


Figure 12. Plastic Energy (J)

Figure 13. Critical Wall Drift (m)

μ=0.8





μ=0.5

μ=0.2

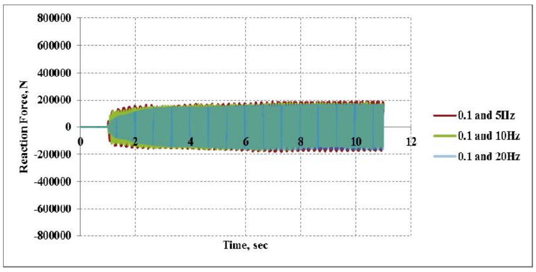


Figure 14. Base Shear (N)

4. CONCLUSIONS

The results of this study show that the proposed retrofitting technique which includes detachment of the base of the masonry buildings from the ground is an effective way in reducing the structural seismic demands. Another advantage of the system is that compared to other retrofitting techniques which are expensive and disturbing, this method is economical and feasible. The presented details of the proposed base isolation method make it possible to be implemented in the existing buildings, adding more advantage to its feasibility.

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