Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering
Compte Rendu de la 9ième Conférence Nationale Américaine et
10ième Conférence Canadienne de Génie Parasismique
July 25-29, 2010, Toronto, Ontario, Canada • Paper No 1386

A STUDY ON THE POSSIBILITY OF ROOF ISOLATION AS A TECHNIQUE FOR UPGRADING THE SEISMIC BEHAVIOR OF MASONRY BUILDINGS

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ABSTRACT

In this paper the roof isolation technique as a simple and easily doable method is introduced for improving the seismic behavior of masonry buildings. The basic idea is letting the roof to sit simply on the walls with not structural connection, so that the horizontal seismic forces between the roof and the walls can be transferred only by friction. Therefore, the maximum force transferred to the roof is limited to $\mu \times g$, where μ and g are respectively the friction coefficient and the gravity acceleration, and this in turn leads to decrease in the seismic forces acting on the building walls. To show the efficiency of the proposed technique, some masonry buildings were considered to be modeled and analyzed subjected to simultaneous effect of horizontal and vertical components of earthquake acceleration, with various frequency contents and different PGA levels. The simplified model of any buildings consists of an upper large block, representing the roof, resting on several small blocks, each one connected to two springs and two dampers. Each of these small blocks represents one of the building's walls. The upper block is in contact with lower blocks with a friction coefficient of μ, and the two springs connected to each of the lower blocks represent the walls stiffness values, either in in-plane or out-of-plane direction. The results show that by using roof isolation if μ is not greater than 0.3, the maximum shear forces of single-story masonry buildings, subjected to strong earthquakes, can be decreased between 30% to 50% depending on the earthquake characteristics, and the maximum roof acceleration is reduced more than 50%. Maximum displacement of roof with respect to walls is just a few centimeters in each direction. The vertical ground motion is effective on maximum response values, but, its effect is mostly negligible.

Introduction

Masonry buildings are seismically weak because of their low strength and low ductility. Therefore, any provision, particularly simple ones, which can improve the seismic behavior of these buildings is desired. In some of the past earthquakes, like the 2006 Balakoot earthquake in

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Pakistan, it was observed that the roof of some brick masonry buildings had moved as a rigid body, by sliding, with respect to the supporting walls, so that at the end of earthquake the roof was off-placed from its initial location by several centimeters along with a little rotation in horizontal plane, and there were no major damage to the building's walls. On this basis, the roof isolation technique (letting the rood to slide on walls) seems to be a usable way for seismic response reduction of masonry buildings. Using the sliding concept for mitigation of earthquake disaster to masonry buildings goes back to early 80s (Arya 1984). The roof isolation idea is not also very new, and the first studies in this regard go back to late 90s (Villaverde 1998). The studies on roof isolation have continued till resent years (Ribakov and Agranovich 2008), however, almost no thorough study has been performed with regard to the use of roof isolation in masonry buildings.

In this paper the roof isolation technique as a simple and easily doable method is introduced for improving the seismic behavior of masonry buildings. The basic idea is separating structurally the roof of the masonry buildings from its walls (provided that the roof has enough integrity to move as a relatively rigid body) and letting the roof to sit simply on the walls, so that the horizontal seismic forces between the roof and the walls can be transferred only by friction. To show the efficiency of the proposed technique, some masonry buildings models were analyzed subjected to simultaneous effect of horizontal and vertical components of earthquake acceleration, with various frequency contents and different PGA levels.

The Proposed Roof Isolating System

In typical 1- or 2-story masonry buildings in open areas, built in recent decades in many parts of the world, dimensions of the roof plan are usually 2.0 to 3.0 meters larger than the dimensions of building's plan area, surrounded by external walls. Therefore, if the roof slips from its initial location up to one meter in any direction it will be still on it supporting walls, provided that it does not lose its integrity because of the motion. Even, if rotation of roof in horizontal plane occurs, it can not cause large displacement of the roof with respect to its initial location.

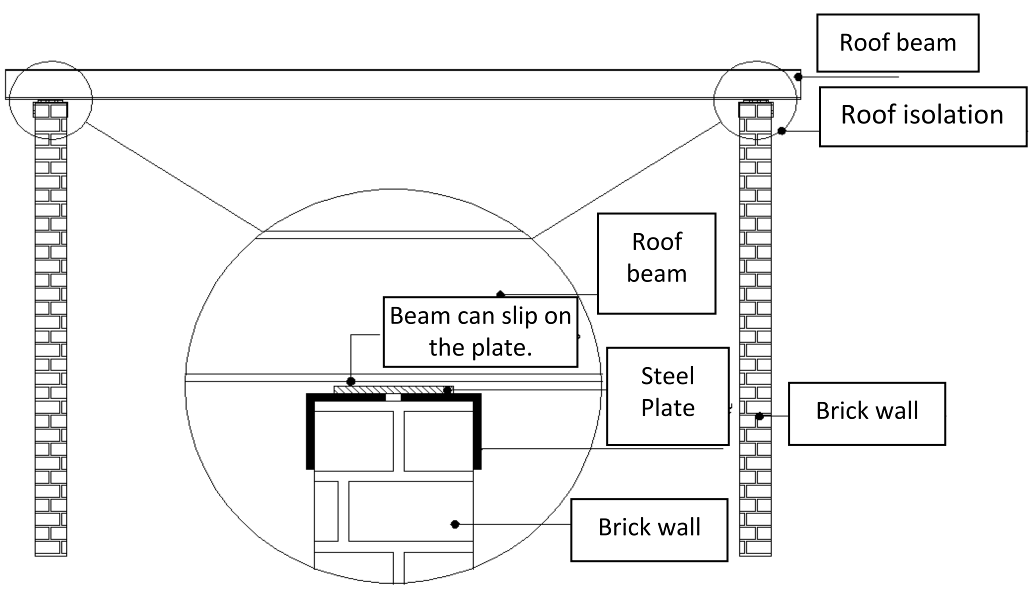


Figure 1. Detailing of the proposed roof isolation

On this basis, if the roof is permitted to slip on supporting walls, the some amount of earthquake input energy is dissipated by the work of friction forces, and the amount of roof mass contribution to the effective mass of the building subjected to earthquake decrease, and as a result, the seismic forces acting on the building walls decrease and therefore the building's seismic demands decrease as well. As the coefficient of friction between two relatively smooth steel surfaces is around 0.3, the detail shown in Fig. 1 can be suggested for roof isolation.

Sample Buildings

Two single story buildings, one a double bedroom residential suite, and one a 10-calssroon school have been considered for the study, as shown in Fig. 2.

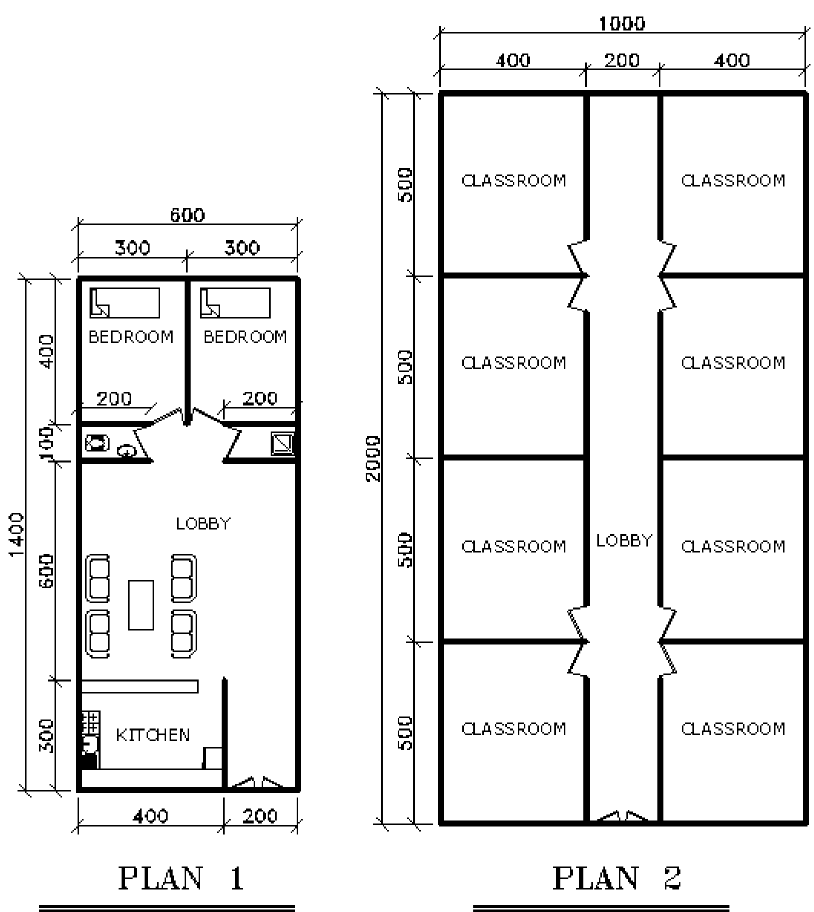


Figure 2. Architectural plans of the two considered buildings 1 and 2

Modeling and Deriving the Equations of Motion

The simplified model of any buildings consists of an upper large block, representing the roof, resting on several small blocks, each one connected to two springs and two dampers. Each of these small blocks represents one of the building's walls. The upper block is in contact with lower blocks with a friction coefficient of μ, and the two springs connected to each of the lower blocks represent the walls stiffness values, either in in-plane or out-of-plane direction (Fig. 3).

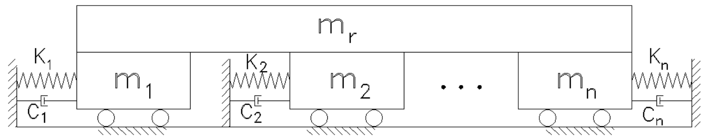


Figure 3. Simplified model of walls and roof of the masonry building with slipping roof

One of the major issues in modeling the motion of the simplified model of the building system is friction between lower masses m_1 to m_n and the upper mass m_r. To take into account the effect of friction it is necessary to consider various states which can be created as the roof slides with respect to some of walls, while is still in contact with some other ones. Before the roof start sliding, all masses moves together with the same acceleration, as shown in Fig. 4, and the of Eqs. (1) can be written for them.

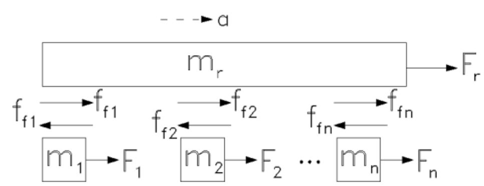


Figure 4. The free body diagrams of the masses before the roof slippage

$$\sum F_x = ma \rightarrow \begin{cases} F_1 - f_{f1} = m_1 a \\ \vdots \\ F_n - f_{fn} = m_n a \\ F_r + f_{f1} + \cdots + f_{fn} = m_r a \end{cases} \rightarrow \begin{cases} f_{f1} + m_1 a = F_1 \\ \vdots \\ f_{fn} + m_n a = F_n \\ -(f_{f1} + \cdots + f_{fn}) + m_r a = F_r \end{cases} \tag{1}$$

These equations can be written in the following matrix form:

$$\begin{bmatrix} 1 & 0 & \cdots & 0 & m_1 \\ 0 & 1 & 0 & \cdots & m_2 \\ \vdots & 0 & \ddots & \cdots & \vdots \\ 0 & \cdots & 0 & 1 & m_n \\ -1 & -1 & \cdots & -1 & m_r \end{bmatrix} \begin{Bmatrix} f_{f1} \\ \vdots \\ f_{fn} \\ a \end{Bmatrix} = \begin{Bmatrix} F_1 \\ \vdots \\ F_n \\ F_r \end{Bmatrix} \tag{2}$$

from which the following value is obtained for the friction force of mass i:

$$f_{fi} = F_i - \frac{m_i(\sum F_i + F_r)}{\sum m_i + m_r} \tag{3}$$

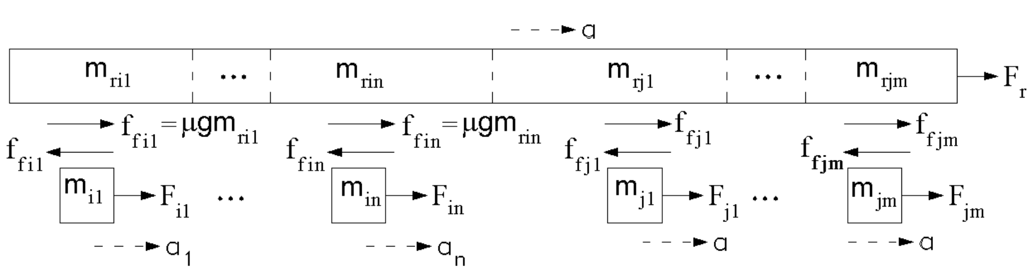


Figure 5. Free body diagram of the system model in case of slippage between roof and mass i

Regarding that each of walls carries a portion of the roof weight, the whole roof mass, m_r, can be considered as the summation of some m_{ri} masses, each corresponding to one wall with the mass m_i, as shown in Fig. 5. On this basis the maximum friction force between the roof and mass i can be considered as $\mu m_{ri} g$. If the required friction force for this mass, f_{fi}, is greater than the maximum available force, slippage will occur between the roof and mass i, and other masses, denoted by subscript j, will keep moving with the roof. Therefore, the following dynamic equilibrium equations can be written:

$$\sum F_x = ma \rightarrow \begin{cases} F_{j1} - f_{fj1} = m_1 a \\ \vdots \\ F_{jm} - f_{fjn} = m_m a \\ F_r + f_{fi1} + \cdots + f_{fin} + f_{fj1} + \cdots + f_{fjm} = m_r a \end{cases} \tag{4}$$

where the friction force of each of masses denoted by subscript i, between which and the roof slippage has occurred, is $f_{fi} = \mu m_{ri} g$, and for other masses is given by:

$$f_{fj} = F_j - \frac{m_j (F_r + \sum_{j=1}^{m} F_j + \sum_{i=1}^{n} f_{fi})}{m_r + \sum_{j=1}^{m} m_j} \tag{5}$$

On this basis the equations of motion for roof and walls can be derived by taking into account the spring and damper forces, corresponding to each wall, as shown in Figs. 6 and 7.

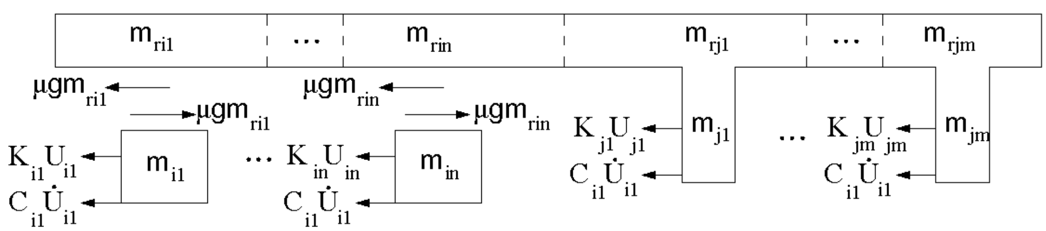


Figure 6. Free body diagram of the system model in general state of motion

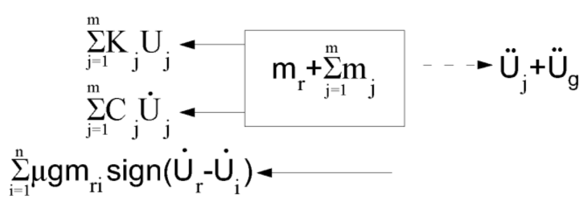


Figure 7. Free body diagram of the roof and the walls moving with it because of friction

Considering the forces shown in Figs. 6 and 7, and showing the ground horizontal acceleration by $\ddot{U}_g$ the following equation can be written for the roof:

$$-\sum_{j=1}^{m} K_j U_j - \sum_{j=1}^{m} C_j \dot{U}_j - \sum_{i=1}^{n} (\mu g m_{ri} \mathrm{sign}(\dot{U}_r - \dot{U}_i)) = (m_r + \sum_{j=1}^{m} m_j)(\ddot{U}_j + \ddot{U}_g) \tag{6}$$

in which U_i , $\dot{U}_i$ and $\ddot{U}_j$ are respectively the relative displacement, velocity and acceleration of masses between which and roof slippage has occurred, and U_i, $\dot{U}_j$ and $\ddot{U}_j$ are those of the masses which have kept moving with the roof. On this basis $\ddot{U}_j$ can be obtained as:

$$\ddot{U}_j = -\ddot{U}_g - \frac{\sum_{j=1}^{m} K_j U_j + \sum_{j=1}^{m} C_j \dot{U}_j + \sum_{i=1}^{n} (\mu g m_{ri} sign(\dot{U}_r - \dot{U}_i))}{(m_r + \sum_{j=1}^{m} m_j)} \quad (7)$$

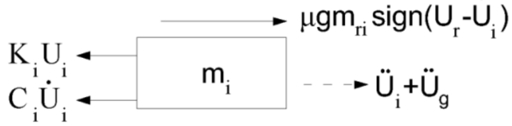


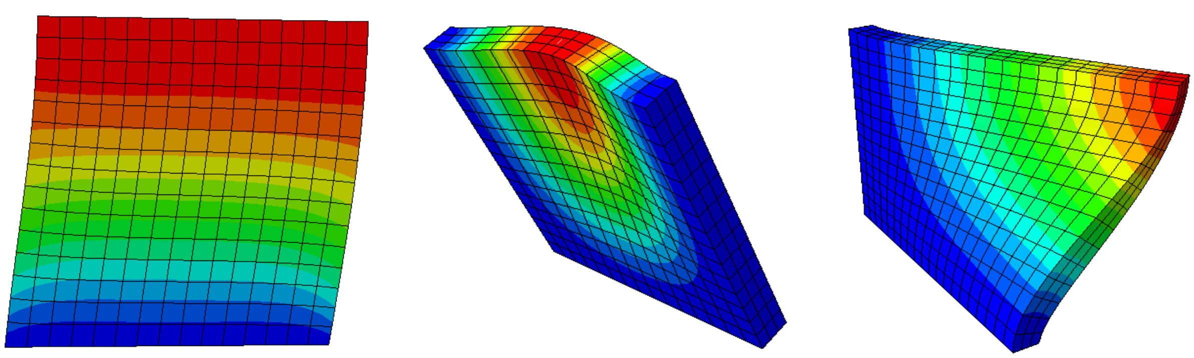
Figure 8. Free body diagram of masses *i*, between which and roof slippage has occurred

For the masses, between which and roof slippage has occurred, the equation of motion can be written, considering the forces shown in Fig. 8, as:

$$-K_i U_i - C_i \dot{U}_i + \mu g m_{ri} sign(\dot{U}_r - \dot{U}_i) = m_i(\ddot{U}_i + \ddot{U}_g) \quad (8)$$

$$\boxed{\ddot{U}_i = -\ddot{U}_g - \frac{K_i U_i + C_i \dot{U}_i - \mu g m_{ri} sign(\dot{U}_r - \dot{U}_i)}{m_i}} \quad (9)$$

If the friction force f_{fi} is larger than the threshold force $\mu m_{ri} g$ the acceleration of mass *i* will be $\ddot{U}_i$, given by Eq. (9), otherwise it will be $\ddot{U}_j$, given by Eq. (7). To model each of the walls as a SDOF system, their effective mass and stiffness should be determined. For this purpose both in-plane and out-of-plane states should be considered. In this study for in-plane state the wall was modeled by ABAQUS software and its top displacement under the effect of a unit load was obtained, form which the wall stiffness coefficient was calculated. Also the fundamental frequency of the wall model was obtained by the software. Having the values of wall stiffness coefficient and natural frequency the equivalent mass of the wall was easily calculated. For out-of-plane state, regarding the architectural features of walls in the building, three cases of end conditions, including both ends free, one end free and one end built-in, and both ends built-in, were supposed, and the same procedure of displacement and frequency calculations by ABAQUS was followed. It should be noted that in the two end conditions of one end free and one end built-in, and both ends built-in the wall top have varying displacement from one end to the other, and therefore the average displacement value of the wall top should be used in these cases. Some samples results of computer analyses in this regard are shown in Figs. 9.



(a) (b) (c)

Figure 9. Deformed shapes of walls in in-plane and out-of-plane states for calculating their stiffness coefficient: a) in-plane state, b) out-of-plane state with both ends built-in, and c) out-of-plane state with one end free one end built-in

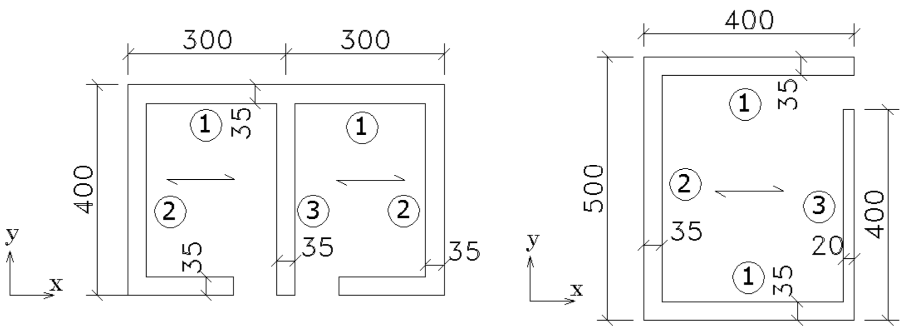


Figure 10. Wall numbering for building 1 (left) and building 2 (right)

Numbering the walls of buildings 1 and 2, as shown in Fig 10, their calculated stiffness coefficients and equivalent masses were obtained, as given in Tables 1 and 2.

Table 1. Calculation stiffness coefficient and equivalent mass of wall in building 1

wall number	direction	F (N)	d (m)	K=F/d (N/m)	f (Hz)	ω (rad/sec)	$m_e=K/\omega^2$ (kg)
1	X	1050	5.70E-06	1.84E+08	45.1	283.4	2294.0
1	Y	1050	1.00E-05	1.05E+08	42.8	268.9	1451.9
2	X	1400	2.20E-05	6.36E+07	27.3	171.5	2162.8
2	Y	1400	5.00E-06	2.80E+08	48	301.6	3078.3
3	X	1400	2.30E-04	6.09E+06	12.5	78.5	986.8
3	Y	1400	5.00E-06	2.80E+08	48	301.6	3078.3

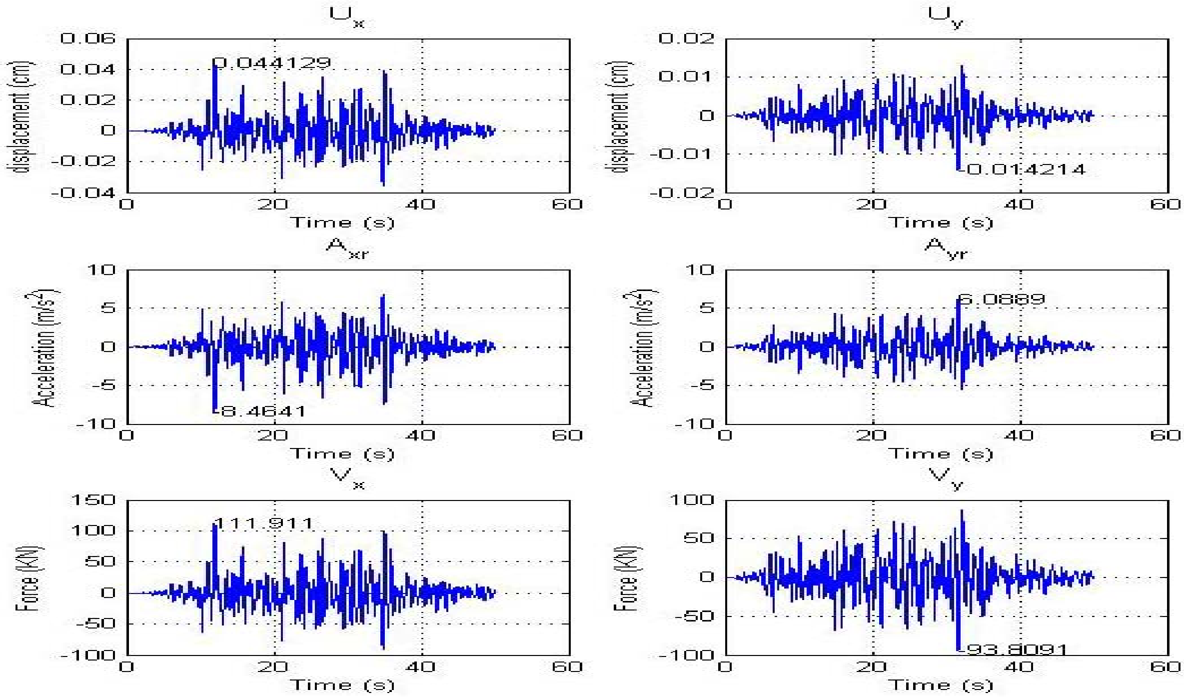
Table 2. Calculation stiffness coefficient and equivalent mass of wall in building 2

wall number	direction	F (N)	d (m)	K=F/d (N/m)	f (Hz)	ω (rad/sec)	$m_e=K/\omega^2$ (kg)
1	X	1400	5.00E-06	2.80E+08	48	301.6	3078.3
1	Y	1400	2.20E-05	6.36E+07	27.3	171.5	2162.8
2	X	1750	3.80E-05	4.61E+07	20.2	126.9	2858.9
2	Y	1750	4.70E-06	3.72E+08	49.7	312.3	3818.3
3	X	800	6.90E-04	1.16E+06	7.3	45.9	551.1
3	Y	800	5.00E-06	1.60E+08	48	301.6	1759.0

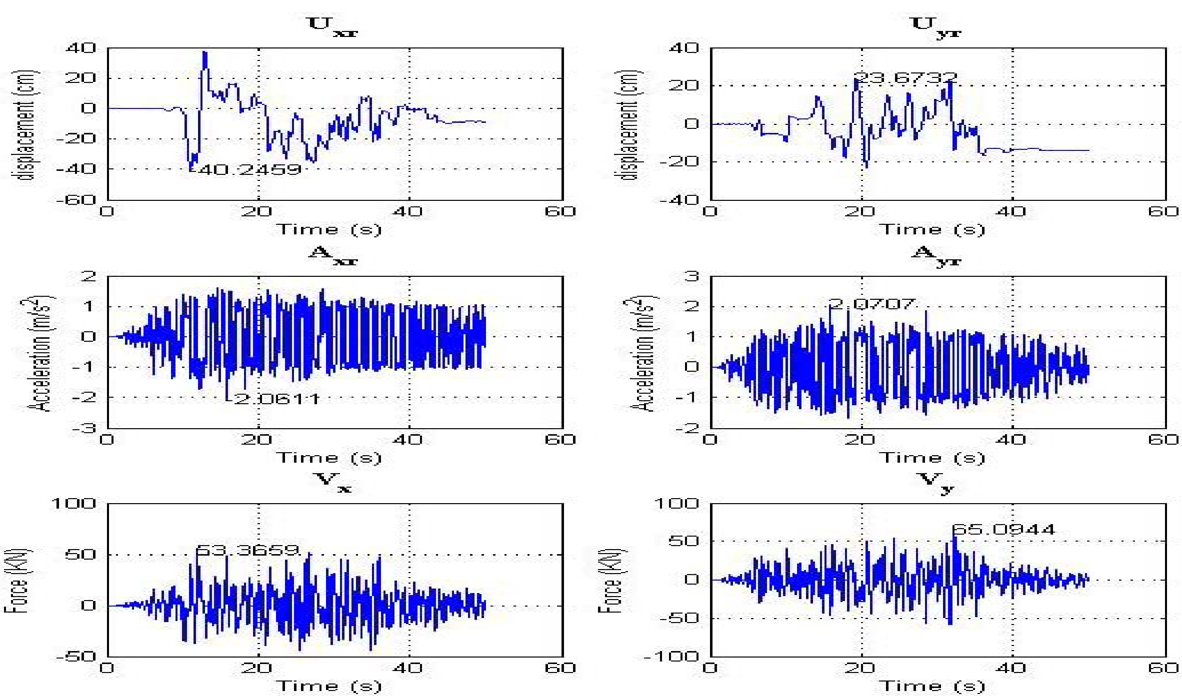
Numerical Results of Seismic Responses

To solve the governing equations, which are highly nonlinear because of effects of frictional forces, the 4th order Runge-Kutta-Nystrom method (Kreyszig 2006) was employed, and a computer program was developed in MATLAB environment for this purpose. Several 3-dimensional accelerograms with various frequency content and PGA values, including some near-fault records having high vertical accelerations, were used for time history analyses.

Response time histories of building 1 subjected to Bam earthquake (PGA=0.74g) for friction coefficient value of 0.1 are shown in Fig. 11, as a sample. More results cannot be presented here because of lack of space, and can be found in the main report of the study (Yousefi 2009).



a) Without roof isolation



b) With roof isolation

Figure 11. Response time histories of building 1 subjected to Bam earthquake for friction coefficient value of 0.1

Remarkable effect of roof isolation in reduction of roof acceleration and base shear force can be clearly seen in Fig. 11. As expected, the roof relative displacement has increased, however, even with the low assumed value of friction coefficient of 0.1 in this case the roof displacement value does not go beyond 0.5 m. It should be mentioned that in typical buildings, whose plans are shown in Figure 2, usually the roof is larger than the building plan, so that it creates a cantilever of around 1.00 m length all around the building. This amount is quite enough to facilitate the maximum displacement of roof relative to walls. To find out how the value of friction coefficient, affects the amount of response reduction, response calculations were repeated for various μ values, from 0.0 to 0.7, and the maximum shear force as well as the maximum absolute roof acceleration and displacement values were obtained. Figs. 12 and 13 show samples of these results for Bam, Landers, Tabas, San Fernando, and Northridge earthquakes with PGA values of, respectively, 0.74, 0.8, 0.85, 1.4 and 1.75g.

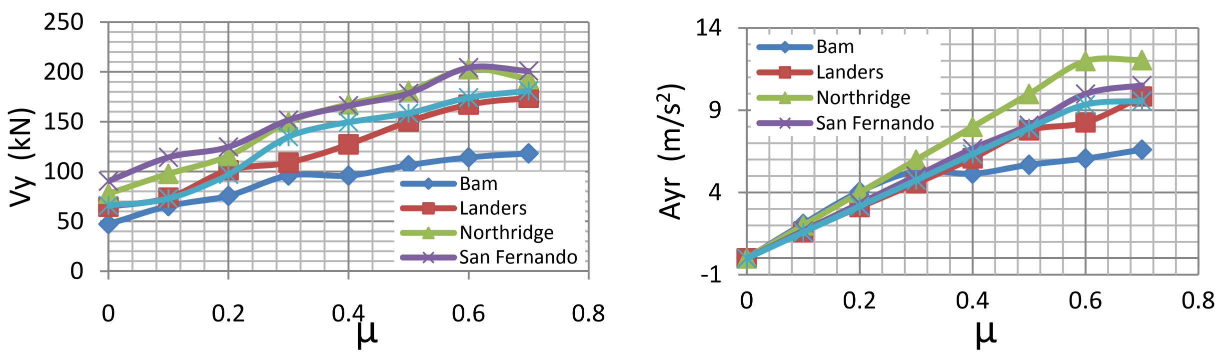


Figure 12. Variation of maximum values of shear force (left) and roof absolute acceleration (right) of building 2 in y direction with respect to friction coefficient value

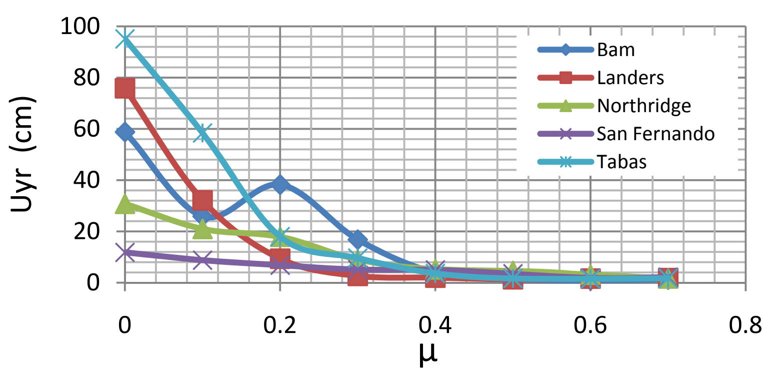


Figure 13. Variation of maximum values of roof displacement of building 2 in y direction with respect to friction coefficient value

It can be seen in Fig. 12 that both the building maximum shear force as well as the roof maximum acceleration vary almost linearly with increase in friction coefficient value. However, in case of some earthquakes like Bam, which have high vertical acceleration, the aforementioned linear trends are disturbed somehow. Fig. 13 shows that for μ values of 0.4 or more the relative displacement of roof with respect to wall is almost zero, which means that in these cases the roof isolation is almost ineffective. To see the effect of roof isolation in decreasing the maximum values of shear force and roof absolute acceleration these values for building 2 in y direction (as a sample) in both non-isolated and isolated with μ=0.1 have been compared.

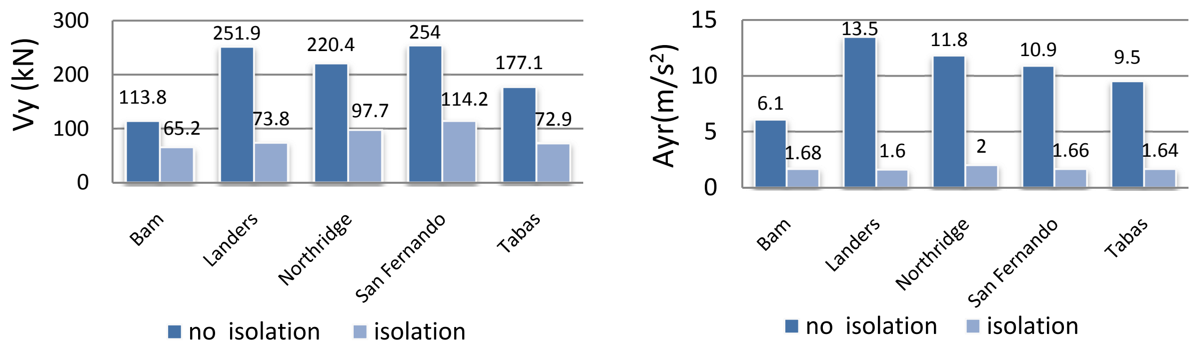


Figure 14. Maximum values of shear force (left) and roof absolute acceleration (right) of building 2 in y direction for friction coefficient value of 0.1 and without roof isolation

It can be seen in Fig. 14 that for μ values less than 0.3, the maximum base shear force of the single-story masonry buildings subjected to strong earthquakes (with PGA more than 0.4g), can be decreased more than 30% to 50%, depending on the earthquake characteristics, and therefore the building will have less damage.

Conclusions

The results show that by using roof isolation in single-story masonry buildings subjected to strong earthquakes, the maximum base shear force can be decreased more than 30%, and the maximum roof absolute acceleration more than 50%. It should be noted that the friction coefficient is usually more than 0.3 for masonry materials, and even steel on steel. However, if by using some specific materials such as very fine sand between roof and walls achieving a friction coefficient of less than 0.3 seems to be possible. Considering that using this isolation actually does needs any specific technology, using it is strongly recommended, since even with a friction coefficient between 0.3 and 0.4, the seismic response of masonry buildings subjected to strong earthquakes, are reduced remarkably, and even though the building may get damage, it will be most probably protected against collapse.

References

Arya A. S. 1984. Sliding Concept for Mitigation of Earthquake Disaster to Masonry Buildings, Proc. 8th World Conf. Earthquake Eng., Vol. 5, pp051-958, San Francisco, CA.

Kreyszig, Erwin, 2006. *Advanced Engineering Mathematics*, 9th edition, John Wiley & Sons, p904.

Ribakov Y. and Agranovich G. 2008. Design of Roof Isolation Systems with Variable Friction Dampers, Proc. 14th World Conf. Earthquake Eng., Beijing, China.

Villaverde R. and Eeri M. 1998. Roof Isolation System to Reduce the Seismic Response of Buildings: A Preliminary Assessment, *Earthquake Spectra*, 14 (3), 521-532.

Yousefi, Saeed, 2009. Upgrading the Seismic Behavior of Masonry Buildings by Roof Isolation, *Master Thesis* under supervision of Dr. Mahmood Hosseini, submitted to Earthquake Engineering Department, School of Engineering, Science and Research Branch of the Islamic Azad University (IAU), Tehran, Iran.