Performance of a distributed base isolation system for masonry buildings

S. Chiostriini, L. Galano & M. Rosi
1Department of Civil Engineering, University of Florence, Italy.
2Civil Engineer, Florence, Italy.

Abstract

The paper presents results from a research study on a new distributed base isolation system for masonry buildings. This system consists of a layer of mortar interposed between the top face of foundations and the shear walls base. The mortar layer is reinforced with vertical mild steel bars, anchored both to masonry walls and to subside concrete of foundations. The proposed system is simple and inexpensive and it is capable of high degree of protection. To demonstrate its effectiveness, the seismic response of a masonry building is investigated by simplified 2 DOFs mathematical model performing numerical analyses in the time domain. Parameters involved in this study were: the fixed-base natural period of the building, the mass ratio, the isolation degree and, the ratio between the yield level of the soft base and the ultimate strength of the shear walls. Comparisons between dynamic responses of fixed-base and isolated models are presented in the form of spectral quantities. Results show that this type of isolation is capable of significantly reducing accelerations at the floor level, with performance comparable to FSI schemes, and an additional advantage of reducing amplitude of residual displacements.

1 Introduction

Past earthquakes demonstrated that masonry buildings suffered maximum damage when compared with other types of structural systems. Therefore, several strategies have been developed to improve the seismic behaviour of these buildings. In the last twenty years, base isolation technique has emerged as an effective method for rehabilitation of existing buildings, as well as to protect new
structures against major earthquakes. A great number of base isolation systems have been developed world-wide (Kelly [1], Buckle [2]), in which the superstructure is connected to foundations through flexible elements and dissipation devices. Unfortunately, many of these systems cannot be economically applied to existing or new masonry buildings.

Friction system isolation (FSI) was initially proposed by Qamaruddin [3] for earthquake protection of single story brick buildings. In this system a continuous smoothed surface is created at foundations level on which the superstructure is free to slide and it is restrained only by frictional resistance.

The FSI concept has been extensively investigated by experimental and analytical studies performed in the last two decades (Mostaghel [4] and [5], Arya [6], Qamaruddin [7], Zongjin [8], Nikolic-Brzev [9]). These and other researches, concerning different types of masonry buildings and friction materials, demonstrated that the FSI scheme is an effective strategy in reducing floor accelerations and limiting structural damages. Despite these good performances, FSI schemes have been applied in a few cases of new buildings and their use in rehabilitation designs poses severe difficulties.

In the present paper the effectiveness of a new type of base isolation system for masonry buildings is investigated. This system belong to the distributed type and is conceptually similar to FSI scheme. Single and two degrees of freedom mathematical models are used to represent fixed-base and isolated buildings; numerical analyses in the time domain are performed to evaluate seismic response of these systems. Comparisons between fixed-base and isolated models are presented and discussed.

2 Distributed base isolation system

The system here discussed has been recently proposed (Sassu [10]) and belong to the base distributed type, called “reinforced cut-wall”. It consists of a thin layer of mortar of poor mechanical properties interposed between the foundations and the shear walls (Fig. 1).

A reinforced concrete beam stays on the mortar layer to form a stiff base for the masonry walls of the first story level. The mortar layer is reinforced by a series of vertical bars of mild steel, anchored to the cast-concrete foundation and to the building’s base walls. Finally, a further layer of elastomeric waterproof can be used in the isolation package.

Different design performances of this isolation system can be obtained varying geometrical and mechanical properties of the mortar layer and of the reinforcements. Characteristics required to the isolation layer are a suitable compressive strength to withstand the dead load and high horizontal flexibility to increase the first natural period of the building. Reinforcements furnish to the system high energy dissipation capabilities, so as to reduce the dynamic response under strong earthquakes. These bars also contribute to the vertical load-bearing capacity. A correct correlation among horizontal flexibility, energy dissipation and bearing capacity can be obtained with a proper design of the system.
3 Mathematical models

Fixed-base and base-isolated buildings have been idealised respectively as single and two degrees of freedom discrete models (Fig. 2). In these models \( m, k, \) and \( c \) denote mass, stiffness and viscous damping coefficient of the superstructure; symbols with subscript "b" represent the same properties of the base layer. If \( \ddot{u}_b \) is the horizontal component of ground acceleration at any instant of time, equations of motion of the base-isolated system are:

\[
\begin{align*}
    m_b \ddot{u}_b + (c_b + c_s) \dot{u}_b - c_s \dot{u}_s + (k_b + k_s) u_b - k_s u_s &= -m_b \ddot{u}_g \\
    m_s \ddot{u}_s + c_s \dot{u}_s - c_s \dot{u}_b + k_s u_s - k_s u_b &= -m_s \ddot{u}_g
\end{align*}
\]  

(1)

being \( u_b \) and \( u_s \) lateral displacements of \( m_b \) and \( m_s \) with respect to the ground. For the fixed-base system only the second of eqns. (1) holds, with \( u_b = \ddot{u}_b = 0 \).

To give more significance to the investigation, a non-linear behaviour of masonry shear walls have been considered. For monotonic increasing load the relation shear \( V \) versus drift \( \delta = u_s - u_b \) has been idealised by a piece-wise model (Fig. 3) in which \( V_c \) is the cracking load level, \( V_u \) the ultimate load and \( V_r \) the residual load corresponding to the ductility capacity of the masonry. For random reversal loading a focal point model represents a good approximation of the true response of a brick masonry wall; this behaviour is also represented in Fig. 3.

The response of the base distributed layer has been idealised by the superposition of steel bars and mortar properties, neglecting interaction phenomena. The mild steel bars act as beams subjected to horizontal displacements with rotations of the end sections restrained by the surrounding concrete (Fig. 4). An elastoplastic behaviour is assumed for steel, as shown in Fig. 4 in terms of shear \( V_s \) versus drift \( \delta_b = u_b \), being \( V_{sc} \) and \( V_{su} \) the elastic and
the ultimate load levels. Idealisation of the shear-drift response of the mortar layer is more difficult due to the lack of experimental tests on this subject and to the strong variability of the mortar characteristics. In the present work the approximate model represented in Fig. 4 has been used, where $V_{Mu}$ denote the ultimate shear load carried out by the layer; this value depends on referential shear strength of material $\tau$, average vertical stress $\sigma_0$ and area $A$ of the horizontal section of the layer. For reversal loading, linear branches passing through the origin of the shear-drift diagram have been considered.

Given the non-linear response of the walls and the base isolation layer, $k_b$ and $k_s$ in eqns. (1) represent secant stiffnesses, functions of the actual displacement histories of $u_b$ and $u_s$. Finally, a linear damping behaviour of the systems was used; damping ratios equal to 0.03 and 0.05 on the two modal shapes were selected.

4 Parametric analyses

To arrive at generalised results, a wide range of parametric values representing characteristics of masonry buildings have been selected. For fixed-base system 11 different cases have been considered, in which the undamped natural time period $T$ varies from 0.10 to 0.60 s with equal spaced increments of 0.05 s.

![Mathematical models for fixed-base and base-isolated systems.](image)

![Shear load V versus lateral displacement $\delta$ of masonry walls.](image)
The building shear walls have been represented by an equivalent wall with dimensions shown in Fig. 2. Mechanical characteristics of this equivalent shear wall were: masonry referential shear strength $\tau_k = 0.11 \text{ N/mm}^2$, masonry tensile strength $f_{\text{mt}} = 0.075 \text{ N/mm}^2$, masonry compressive strength $f_{\text{mc}} = 5 \text{ N/mm}^2$, shear modulus variable from 264 to 44 N/mm² and mass $m_s$ variable from 10 to 60 kNs²/m. The selected values correspond to brick masonry walls with poor-to-medium mortar quality. Further characteristics introduced in the mathematical model were $\delta_u/\delta_c=2$, $\delta_s/\delta_c=5$, $V_r/V_u$ variable in the range 0.80 – 0.40, $V_r/V_u=0.80$ (definition of the focal point F, Fig. 3). 

The two main parameters that affect the dynamic response of base-isolated systems are expressed by:

$$R_{is} = \frac{T_{is}}{T}; \quad R_{st} = \frac{V_{Se} + V_{Mu}}{V_u}; \quad T_{is} = 2\pi \sqrt{\frac{m_T}{k_{is}}}; \quad k_{is} = k_{St} + k_M$$  \hspace{1cm} (2)

in which $R_{is}$ represents the ratio between the fundamental period of the base-isolated system $T_{is}$ and $T$; secant stiffnesses $k_{St}$ and $k_M$ as defined in Fig. 4 and the total mass $m_T = m_s + m_b$ have been used for computation of $T_{is}$. The significance of symbols $V_{Se}$ and $V_{Mu}$ is also explained in Fig. 4. In the present study, different types of isolation layer were designed in order to obtain values of $R_{is}$ equal to 2.0, 3.0 and 4.0 and $R_{st}$ equal to 0.10, 0.15, 0.20 and 0.35. Therefore, 7 different isolation hypotheses were considered. The assumed $R_{is}$ range allows to consider two limit conditions: the first represented by a low degree of uncoupling of the
building from ground motion \( (R_{st}=2) \); the second representing an effective base isolation case \( (R_{st}=4) \). At the same way, \( R_{st}=0.10 \) has been assumed as lower limit of the isolation yield threshold to prevent undesirable effects under wind, whereas for values of \( R_{st} \) greater than 0.35 no yielding occurs in most real earthquake and the system acts as a fixed-base system. Finally, a constant value \( m_b = 2.5 \text{ kN} \text{s}^2/\text{m} \) was used, which corresponded to ratios \( m_a m_b \) in the range 4 – 24 for the 11 systems analysed.

Seismic response has been computed for the first 40 s of El-Centro shock of May 1940 (N-S component) scaled to three different peak ground acceleration values: \( pga = 0.14, 0.35 \) and 0.52 g. A step-by-step procedure in the time domain derived from the implicit-explicit \( \alpha \) method proposed in (Miranda [11]) was used for numerical computations; accuracy of the solution was obtained varying the time step from 0.005 to 0.01 s for different models.

To estimate realistic forces and displacements of the buildings the following quantities of the dynamic response have been considered: (1) absolute acceleration, which defines forces acting on the shear walls, (2) ductility demanded to the walls, (3) energy dissipated by masonry walls and isolation system and, (4) residual relative displacement of the base to the ground.

5 Discussion of results

Absolute acceleration spectral curves plotted against undamped natural period of the fixed-base system are presented in Fig. 5. The influence of the parameters \( R_{st} \) and \( R_{is} \) is explained in the graphs on the left and the right sides of the figure, respectively. It can be observed that increasing \( R_{is} \) values produces decreasing acceleration spectral values for all the fixed-base system frequencies, as a general trend of these curves. This trend is valid both for linear response of the fixed-base system (El-Centro with \( pga = 0.14g \)) and non-linear response (El-Centro with \( pga = 0.35 \) and 0.52g).

Despite these results, from a quantitative point of view little benefits were obtained when passing from \( R_{is} = 2 \) to \( R_{is} = 4 \). As an example, for the system with \( T = 0.25 \) s and the shock with \( pga = 0.35 \) g spectral values of the isolated system were reduced by factors equal to 0.55 and 0.48 \( (R_{is} = 2 \) and \( R_{is} = 4 \)).

Average reductions of spectral acceleration response with \( R_{is} = 4 \) compared to the fixed-base models were approximately equal to 0.40, 0.53 and 0.55 for the three levels of ground shock. As highlighted by curves of Fig. 5, the seismic response is strongly affected by the yield threshold of the isolation layer, herein represented with \( R_{st} \) parameter. The influence of \( R_{st} \) tends to decrease when the ductility demanded to the fixed-base system increases. This result is well understood considering that under the stronger shocks the fixed-base system dissipate by hysteresis a big fraction of earthquake input energy; hence, a relatively low benefit can be expected with base isolation. Results show that an effective protection of the building is achieved only with the two lower values of \( R_{st} \) \( (R_{st} = 0.10 \) and 0.15); as an example, average spectral reduction equal to 0.52 was obtained with \( R_{st} = 0.10 \) and \( pga = 0.35g \).
Figure 5: Acceleration response spectra for different values of parameters $R_{ls}$ (graphs on the left side) and $R_{us}$ (graphs on the right side).
Ductility factors demanded to the equivalent shear wall in fixed-base and isolated conditions are compared in Fig. 6a ($R_{st} = 0.2$ and 0.35, $pga = 0.52g$). As it can be seen, this isolation technique is effective in reducing plastic deformations of shear walls even for relatively high ratios $R_{st}$. The maximum value of required ductility equal to 1.48 was obtained for $T = 0.60$ s and $R_{st} = 0.35$. This general behaviour is well represented in Fig. 6b, in which hysteretic
energies dissipated during the entire shock by shear walls and isolation layer are presented. The fraction of energy dissipated by the base soft layer is largely prevailing.

The effectiveness of this isolation technique is well represented in Fig. 7, in which comparisons with the FSI are shown. Spectral acceleration curves obtained in this study are similar to those produced by FSI when the coefficient of friction varied from 0.20 to 0.30; FSI produce an higher degree of protection only if a very low friction coefficient is used ($f = 0.1$, Fig. 7a). However, an advantage of the technique here investigated is represented by the low values of base residual displacements after the shock (Fig. 7b); as observed in literature isolation techniques based on pure friction sliding phenomena produce high residual displacements that may seriously impair the building's functions.

6 Concluding remarks

Influence of a new type of distributed base isolation system on the seismic response of masonry buildings was analysed. The main outcome of the analyses carried out in the present study leads to following conclusions:

(1) - this isolation technique determines average reduction of the maximum superstructure response of approximately 50 % when compared with fixed-base structures; (2) - the yield threshold of the base soft layer is a critical parameter that strongly affects the behaviour of these systems; (3) - results demonstrated that $R_u$ values in the range 0.10 – 0.15 are more appropriate to provide an effective protection from earthquakes; (4) - from comparisons with pure friction sliding systems emerged that comparable performances were achieved in reducing the seismic forces with lower residual base displacements obtained with the technique here investigated.

Given the low cost and the relative feasibility in construction, this isolation technique is worthy of further research effort, especially devoted to investigate the experimental behaviour of the steel-mortar package.

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