

# MECHANICAL BEHAVIOR OF SIMPLE MASONRY BUILDINGS WITH LOW-COST DISSIPATORS DISTRIBUTED THROUGHOUT THE BASEMENT

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# SUMMARY

The design criteria and numerical results for a new low-cost base isolation technique for simple masonry buildings are presented. The proposed base isolator, named RCW -Reinforced Cut Wall-, is made up of a layer of weak mortar (50 mm) and an elastomer membrane sheath (4 mm) located between the foundation and the base of the bearing wall, which is reinforced by a series of vertical steel rods (8-10 or 12mm in diameter) connecting it to the foundation. A preliminary series of experimental trials have been performed on a sample set of isolators, during which specific tests have been conducted to check their mechanical properties and to define their assembly techniques. ANSYS 5.5.1. numerical simulations of the horizontal and vertical loads, consisting of non linear static incremental analysis, acting in several types of buildings (one, two or three stories high with rectangular floor plan) highlight the system's efficient performance in terms of force-displacement law. For moderate horizontal actions, the mortar and elastomer layers of the RCW do not cause any relevant foundation-base displacement. Instead, when a prescribed limit is exceeded, the weak layers of the RCW permit large inelastic deformation due to friction behavior, while the vertical steel rods ensure an elastic restoring force that provides an elastic-plastic response of the base dissipator. Design possibilities for the RCW are illustrated, in order to optimize number and size of the steel reinforcing rods as a function of the magnitude of vertical loads and seismic actions. Moreover the RCW performs advantages in terms of feasibility and cost-effectiveness: the increase in construction costs with respect to a non-isolated building is very low, due to the same technology of simple masonry buildings, and provides further benefits in terms of isolation from ground humidity.

# INTRODUCTION

Study of the damage caused to small masonry buildings (fig.1) by the earthquakes which occurred in China between 1960 and 1976 (Tqiao in 1960, Xintai in 1966, Bohai in 1969 and Tangshan in 1976) led to the finding that buildings whose bases underwent some slippage held up better than those whose foundations remained completely connected. Such conclusions, in turn, led various researchers to propose and test friction isolation systems.

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Li Li (1984) proposed [1] separating the superstructure from the foundation by two rigid stone plates, which were in turn separated by washed sand grains with diameters ranging from 1 to 1.2 mm. Experimentation on vibrating tables have demonstrated the effectiveness of such systems. A.S. Arya [2] has instead proposed setting a smooth polyethylene membrane above the foundation and then building a reinforced concrete belt course on the membrane. Under normal conditions the building will remain stable on the membrane thanks to the friction between the polyethylene and belt-course, while in the event of seismic actions the construction will tend to slide, and the reinforced concrete belt-course will have to insure that the entire building displaces as a rigid structure. Y. Lou, M. Wang and Z. Su (1992) have proposed [3] placing a layer of graphite under the bearing walls. This material is ideal for creating sliding layers since it is durable and inexpensive, has a large load capacity, can guarantee stable behavior under conditions of high or low humidity and remains effective after many cycles of sliding. In 1996 S. Nikolic-Brzev and A.S. Arya [4] performed experimental trials on a building including two different isolation systems set at two different levels: one at the base and one at the height of the second floor. The superstructure is separated from the foundation by a isolation system made up of a set of discrete Teflon and steel supports, while the second floor was fitted with a continuous sliding joint consisting of a perfectly smooth mortar belt-course covered with a thin layer of lubricant. The results show a structure on a fixed base undergoes much greater acceleration than one on an isolated base. Also worth recalling are the proposals advanced early in the 20<sup>th</sup> century by Calantarient [5] and J. Bechtold [6], the first of whom proposed inserting a layer of talcum and sand between the foundation and base belt-course, while the second conceived of buildings on a plate that could slide over rollers. The seismic isolation technique studied in the present work [7] is of the distributed type and has been denominated "reinforced cut-wall" (RCW). The main idea guiding its formulation is to achieve improvements in the seismic behavior of masonry buildings by employing low-cost devices that do not involve the need to deviate from traditional building techniques.

## THE DESIGN OF THE REINFORCED CUT-WALL

The innovative base-dissipation system, named RCW dissipator, consists of a single layer of mortar of modest mechanical properties, resting on a elastomer waterproofing sheath set between the foundation and the base of the masonry wall to be isolated. Both layers are fitted with a series of vertical metal rods anchored to the foundation casts and the belt-course of the wall base (figure 2). The technique results in a rigid connection between the foundation and the superstructure, which is however able to detach the structure from the ground in the even of violent quakes, like a damp-proof course reinforced by steel rods and endowed with a layer of mortar that can perform horizontal cracks at assigned levels of seismic shocks. In fact, the damp-proof course maintains its integrity in the presence of small seismic actions, while it cracks to dissipate mechanical energy in the event of high-intensity earthquakes. The displacements at the base are nevertheless limited to the vertical by reinforcing rods, which apart from guaranteeing vertical bearing capacity, prevent rigid motions that could force the building out of the foundation axis. By varying the amount of reinforcing and the type of mortar in the joint it is possible to adapt the isolator to a wide range of buildings and fix the limits of its elastic behavior. Apart from preventing the capillary rise of the water through the walls, the elastomer sheath also collaborates with the mortar layer in dissipating mechanical energy through elastic-plastic type hysteresis cycles, because it slides in its own plane. Such a dissipator design moreover allows for construction through the use of prefabricated blocks containing the reinforcing rods, the mortar layer and the water-proofing sheath.

The RCW has been subjected to series of experimental tests on a number of specimens built with varying arrangements of the reinforcement and different mechanical characteristics of the middle mortar layer [8]. Each test specimen was subjected to a constant axial load, exerted by two prestressed harmonic steel rods, and a shear load, produced by an oil-pressure jack actuated via a hydraulic pump, to simulate seismic shocks (figure 3). To better define the behavior of the isolator, the tests were performed for two different values of the vertical load: 5000 and 10000 daN. Figure 4 shows the results of testing on specimen no. 2, composed of 8 rods ( $\phi$ =10mm) and a mortar layer made up of concrete, hydraulic lime and sand in the ratio of 1:3:12, while the applied vertical load was 5000 daN. The diagram also indicates the mean horizontal displacement with varying shear on the specimen.



Figure 1: example of distributed low cost isolation systems



Figure 2: the proposed RCW base-dissipator.



Figure 3: geometry of the test block for RCW dissipator.



Figure 4: typical test result of RCW dissipator.

## ANALYTICAL MODEL AND CASE STUDIES OF SIMPLE MASONRY BUILDINGS

In 1985 Qamaruddin, Rasheeduzzafar, Arya and Chandra proposed a mathematical model for the study of masonry buildings with friction isolators [9]. The model (figure 5) is composed of the masses  $M_t$  and  $M_b$ ; where  $M_t$  is the sum total of the mass of the roofing, all the floors and walls between the second and last floors and that of half the height of the first-floor walls, while  $M_b$  is the remaining mass of the walls on the first level.  $K_s$  and  $C_s$  represent the stiffness and damping of the system, respectively. As long as the force of static friction is not overcome, mass  $M_b$  remains integral with the foundation, and it is therefore possible to distinguish three different stages of motion: a first stage in which the mass  $M_b$  moves with the foundation and the system reduces to 1 degree of freedom; a second stage, when the force at the base exceeds the maximum static friction, in which the mass  $M_b$  begins to slip along the foundation, and finally a third stage when sliding stops and the condition of non-slippage is restored. Integrating the motion equations during the second stage, when the system has two degrees of freedom, can be accomplished via the Runge-Kutta fourth-order method. In 1988 Zongjin Li, Rossow and Shah performed an analytical study using a very similar mathematical model and compared the numerical results with those obtained through a series of vibrating table tests conducted on two different model buildings: one made of aluminum and the other masonry [10].

With the aim of comparing the behavior of buildings with and without the proposed seismic isolation system, we carried out a preliminary structural analysis of the three-dimensional, non-linear static type. The ANSYS 5.5.1 computational code has been used for conducting the F.E.M analysis [11]. The masonry is modeled as a perfectly elastic-plastic, homogeneous isotropic material. The parameters identifying the material's properties are:

- elastic modulus  $E = 50000 \, daN/cm^2$ ;
- Poisson's coefficient v = 0.15;
- Compressive breaking stress  $\sigma_{rc} = 50 \, daN/cm^2$ ;
- tensile breaking stress  $\sigma_{rt} = 1.5 \, daN/cm^2$ .

The resistance criterion adopted has been drawn from Drucker-Prager and is expressed by the following relation:

$$f(j_1, j_2) = \alpha \cdot j_1 + j_2^{\frac{1}{2}} - k = 0$$
 (1)

where  $\alpha$  and k represent two positive constants, while  $j_1$  and  $j_2$  are respectively the linear invariant of the stress tensor and the second invariant of the deviatory tensor. The computational code represents the Drucker-Prager criterion through the following relation:

$$F = 3 \cdot \boldsymbol{\beta} \cdot \boldsymbol{\sigma}_{m} + \left[\frac{1}{2} \cdot \{s\}^{T} \cdot [M] \cdot \{s\}\right]^{\frac{1}{2}} = \boldsymbol{\sigma}_{y} \qquad (2)$$

where  $\sigma_m$  is the hydrostatic stress,  $\{s\}$  is the vector of the deviatory tensor components, [M] is a diagonal matrix of order 6, whose first three elements equal 1 and the remainder equal 2,  $\beta$  is a constant and  $\sigma_y$  is the yielding parameter of the material:

$$\sigma_{y} = \frac{6 \cdot c \cdot \cos \phi}{\sqrt{3} \cdot (3 - \sin \phi)} \tag{3}$$

The input data is therefore represented by the constants c and  $\phi$ , which are determined from the compressive and tensile breaking stresses by applying the breaking criterion given by (2) for the two stress states, to obtain  $c = 3.55 da / cm^2$  and  $\phi = 73^\circ.82$ . In order to provide a summary visualization of the points in the structure that have reached the state of plasticization, the computation code yields the results in terms of the ratio N between the equivalent stress  $\sigma_e$ , given by the second member of (2), and the stress parameter of the material,  $\sigma_y$ . Thus, wherever N  $\geq$  1, the material has yielded, while where N<1, it is still in the elastic phase.

The isolator has been modeled as an elastic-plastic orthotropic material with strain hardening. By averaging the results of the experimental trials in the different load cycles, it is possible to schematize the behavior of the isolator by means of a bilinear graph (figure 6) with initial stiffness E=33801 daN/cm, strain hardening coefficient,  $\eta$ =0.879, and shear strength at the elastic limit, Fe=500 daN. The orthotropic law, which expresses symmetrical behavior with respect to the three mutually orthogonal axes (x,y,z), is represented by the followings relations.

$$\varepsilon_{x} = \sigma_{x} / E_{x} - v_{yx} / E_{y} - v_{zx} \sigma_{z} / E_{z}$$

$$\varepsilon_{y} = -v_{xy} \sigma_{x} / E_{x} + \sigma_{y} / E_{y} - v_{zy} \sigma_{z} / E_{z}$$

$$\varepsilon_{z} = -v_{xz} \sigma_{x} / E_{x} - v_{yz} \sigma_{y} / E_{y} + \sigma_{z} / E_{z}$$

$$\gamma_{xy} = \gamma_{xy} / G_{xy}$$

$$\gamma_{yz} = \tau_{yz} / G_{yz}$$

$$\gamma_{zx} = \tau_{zx} / G_{zx}$$
(4)

where the nine independent constants are  $(E_x, E_y, E_z, V_{xy}, V_{xz}, V_{yz}, G_{xy}, G_{yz}$  and  $G_{zx}$ ). The normal moduli in the x, y and z directions are given by the weighted average of the stiffness values of the materials used in the respective sections, where the weighting is represented by the areas. The tangent moduli are drawn in the graph of F- $\delta$ , considering the area of the test specimen and the height of the jack, while the Poisson coefficients have all been assigned a value of 0.15. The resulting numerical values are:

$$E_{x} = E_{z} = 281067 \cdot daN / cm^{2}$$
  

$$E_{y} = 44906 \cdot daN / cm^{2}$$
  

$$G_{xy} = G_{xz} = G_{yz} = 833 \cdot daN / cm^{2}$$

The Hill resistance criterion has been used to model the isolator, while the strain hardening has been estimated to be isotropic, as the analysis is static under monotonic loads. In order to define the yield surface and its variation as a function of plastic work a total of eighteen constants must be assigned to the computational code:

- C1-C3 tensile yielding stress in directions x, y, z;
- C4-C6 corresponding tangent moduli;
- C7-C9 compressive yielding stress in directions x, y, z;
- C10-C12 corresponding tangent moduli;
- C13-C15 yielding tangential stress in the xy, yz and xz planes;
- C16-C18 corresponding tangent moduli;.

The numerical values are reported in Table 1. A value of 0.01, rather than 0, has been assigned in order to avoid numerical instability. Figure 7 represents the three types of buildings studied: building n°1 is composed of the ground floor alone, while building n°2 is made up of the ground and first floors, and building n°3 of the ground, first and second floors. For each building the vertical loads are represented by the weight of the roofing, g1=300 daN/m<sup>2</sup>, the accidental roofing load, Q=150 daN/m<sup>2</sup>, the accidental load on the various floors, Q=200 daN/m<sup>2</sup>, and the masonry's own weight, g=1700 daN/m<sup>3</sup>. The horizontal seismic load is calculated by referring to current Italian legislative standards (category 1).

All the buildings have been discretized by means of a mesh composed of four-node isoparametric shell elements, with linear interpolation functions and six degrees of freedom per node, drawn from the ANSYS library (shell 43). All the elements are square, 50 cm on a side, and have same thickness as the walls (20 cm). The ceilings have been considered to be rigid, and the ground floor has been excluded from the non-isolated model, as it does not significantly alter the response of the building. The loads have been concentrated on the structural nodes.

In addition to the static analysis, a dynamic analysis has also been performed for the same buildings, the aim being to determine the principal modes of vibration in order to compare the frequencies and amplitudes of oscillation of the structures with and without seismic isolation.







Figure 6: RCW dissipator constitutive law.

$C1=50 \text{ daN/cm}^2$	C7=50 daN/cm <sup>2</sup>	C13=0.5 daN/cm <sup>2</sup>
C2=50 daN/cm <sup>2</sup>	$C8=50 \text{ daN/cm}^2$	C14=0.5 daN/cm <sup>2</sup>
$C3=50 \text{ daN/cm}^2$	C9=50 daN/cm <sup>2</sup>	C15=0.5 daN/cm <sup>2</sup>
C4= $0.01 \text{ daN/cm}^2$	$C10=0.01 \text{ daN/cm}^2$	C16=743 daN/cm <sup>2</sup>
C5= $0.01 \text{ daN/cm}^2$	C11=0.01 daN/cm <sup>2</sup>	C17=743 daN/cm <sup>2</sup>
C6=0.01 daN/cm <sup>2</sup>	C12=0.01 daN/cm <sup>2</sup>	C18=743 daN/cm <sup>2</sup>

Table 1: yield surface constants.



Figure 7: floor plan and vertical section of examined buildings.

## NUMERICAL ANALYSIS AND RESULTS.

#### Static analysis.

Three distinct models were applied in studying the various buildings: non-isolated (model *a*), isolated without a base floor (model *b*) and isolated with rigid ground floor (model *c*). Qualitative examination of the deformed shape of the building reveals that in the seismically isolated models, the greatest deformations occur in the isolators, rather than in the above-ground structures. Analyzing models b and c, it can moreover be noticed that the deformation is substantially different for each of the buildings. The presence of the rigid diaphragm at the base in model c causes the seismic load to be distributed amongst all the isolators, so that the shear actions also involve the isolators of the walls parallel to the horizontal load are affected, thereby provoking so a *corner effect* (figure 8) that modifies the pattern of horizontal displacements with respect to model *c*. In the non-isolated structures the values of the horizontal displacements are very small in comparison to the isolated structures because of the deformability furnished by the isolators. Figures 9 and 10 show the horizontal displacements in models *a* and *c* for building n°3. Regarding the stresses, we have calculated the values for the normal stresses Sz, the tangent stresses Sxz, and the ratio  $N = \sigma_e / \sigma_y$ . Figures

11 and 12 report the values of ratio N for models a and c, once again for building n°3.

It can be seen from the values of parameter N that for the loads prescribed by regulations the masonry, remains in elastic field in all the models except model *a* for building n°3. In every case, the value of N is lower in the isolated models: this indicates that the isolator reduces the degree to which the masonry must sustain the seismic actions. In fact, the highest values of N are found in correspondence to the elements represented by the isolator, as the horizontal load impinges for the most part on the isolator rather than the masonry. Comparing the results for models *b* and *c* reveals that, in the first case, ratio N is very low in the isolators set orthogonally to the seismic action, while in model *c* the ratio takes on practically the same value as with isolators parallel to the horizontal load. This phenomenon is due to the load distributing function carried out by the rigid ground floor. In order to highlight the effects of the isolator on the buildings, the seismic load was increased incrementally by a multiplying factor  $\lambda$ . Then, for models *a* and *c* for each building we calculated the mean displacement values with varying parameter  $\lambda$  at height +50 cm and at the various ceiling levels, defined as the average of the horizontal displacement for building n°3.

Then, for the non-isolated models we calculated the value of  $\lambda$  for which the ratio N is unity in at least one node (condition of incipient plasticization). For all the buildings, the transition from the non-isolated to the isolated model (with constant load factor) is accompanied by a notable reduction in parameter N in the same nodes where the condition of incipient plasticization is reached (Table 2).



Figure 8: corner effect.



Figure 9: horizontal displacement (model without RCW).







Figure 10: horizontal displacement (model with RCW)



Figure 12: values of parameter N isolated model.



Figure 13: load factor- mean displacement at level +50cm.



Figure 14: load factor- mean displacement at the first floor.



Figure 15: load factor- mean displacement at roof plane.

Building	λ	Node	Ratio N	
Dunung	Plasticization idx.		non iso	iso
1	1 3.25	356	1.024	0.744
1		376	1.025	0.742
2	1.35	157	1.006	0.644
3	0.9	157	1.040	0.660
		341	1.040	0.660

 Table 2: Variations in the load factor.

## Dynamic analysis.

Unlike static analysis, dynamic analysis is linear. The isolator and masonry are consistently modeled as an orthotropic and isotropic material, respectively. As in the static analysis, determinations of the principal modes and frequencies of oscillation were made by means of the computational code ANSYS 5.5.1. The method of subspace iteration [11] was used for calculation of the eigenvalues and eigenvectors.

The masses considered in the analysis of each model are the mass of the vertical walls and the ceilings, including accidental overloads. All the ceilings are rigid and only the ground floor is lacking mass. The first three oscillation modes have been calculated for both the isolated and non-isolated models of each building. From the values of the eigenfrequencies it can be seen that the transition from the non-isolated to the isolated model is accompanied by a decrease in frequency (Table 3) and therefore an increase in the period of oscillation. The increase in period that the structure undergoes due to the seismic isolators is however not so great that the building shifts to the areas of the response spectrum where maximum amplification of the acceleration occurs. In essence, the building remains in the spectrum zone typical of masonry buildings. Building n°3 represents the least rigid of the three studied: the frequency reduction is less pronounced and the period of oscillation comes closer to the risk zones of the response spectrum.

Qualitative analysis of the principal vibrations modes reveals that the superstructure in the isolated models appears more rigid than in the non-isolated models. In order to highlight this phenomenon, for both models we calculated the relative amplitudes of oscillation for the first and the second oscillation modes in the direction of the earthquake between the various levels and height +50 cm (table 4). The amplitude of oscillation is to be considered a mean, in the same way as described for the displacement in the foregoing section. The first and second modes of oscillation represent the vibrations in the x and y directions, respectively.

Building	Mode of	Frequency (Hz)	
2 411 411 8	oscillation	No iso	iso
	1°	26.69	17.30
1	2°	29.58	17.96
	3°	33.13	20.42
	1°	13.76	10.42
2	2°	17.33	11.68
	3°	24.71	14.40
	1°	8.98	7.46
3	2°	11.59	8.70
	3°	17.42	11.23

## **Table 3: Principal oscillation frequencies.**

## CONCLUSIONS

Both the non-linear static analysis and the linear dynamic analysis conducted on the three building types studied have revealed clear improvements in the seismic behavior of buildings when they are fitted with the proposed isolation system. The improvement is moreover heightened by the presence of a rigid ground floor. Overall, the benefits consequent to adopting the cut reinforced wall system are:

- reduction of the relative displacements between points in the superstructure;
- increased horizontal forces needed to produce plasticization in the above-ground masonry;
- moderate alteration of the building's oscillation frequencies;
- limited absolute displacements.

Apart from such technical characteristics, the considered isolation system also offers considerable advantages from the perspective of construction methods. In fact, unlike the majority of isolators currently employed in buildings (elastomer isolators), the cut reinforced wall is perfectly compatible with today's construction techniques in terms of both cost and ease of application. It moreover offers the added benefits of water-proofing the building by blocking capillarity and the ability to prefabricate the isolator in blocks.

Lastly, designers enjoy great freedom in managing the system's precise characteristics, as they can control the dissipator's elastic load limit and thereby avoid relative displacements of the base consequent to earthquakes of moderate intensity. Thus, the isolator's dissipative capacity may be reserved for those cases in which an earthquake represents a true hazard to the overlying masonry structure.

Building	Mode of oscillation	Mean relativ of oscilla No iso	ve amplitude tion (cm) iso
1	1°	0.08616	0.02999
	2°	0.08823	0.02976
2	1°	0.11530	0.06178
		0.06956	0.03811
	2°	0.11290	0.04676
		0.07215	0.03061
3	1°	0.10440	0.06857
		0.07643	0.05083
		0.03871	0.02617
	2°	0.10130	0.05337
		0.07669	0.04089
		0.04147	0.02257

Table 4: Mean relative oscillation amplitudes	Table	e oscillation am	plitudes
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