AN APPLICATION OF THE RCW SEISMIC DISSIPATOR ON MASONRY BUILDINGS: ON-SITE TESTING AND STRUCTURAL ANALYSIS

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ABSTRACT

An innovative reinforced damp proof course, the RCW seismic dissipator, is hereby proposed. An application has been performed in a masonry building for council housing estate with 42 flats. It consists of a course between foundation and ground floor made by 3-4 mm glued foil overlapped by 60 mm layer of weak mortar, reinforced by several couples of vertical steel bars. In case of low seismic actions, the RCW ensures a connection between basement and ground floor; in case of strong motions, the damage of weak mortar layer allows relative displacements dissipating energy by friction mechanism, while vertical steel bars furnish elastic restoring force to lead back the building to the initial position after the earthquake. Tests are performed on two couple of specimens: several series of quasi-static time histories with increasing intensity were applied in presence of different compression levels. Trials showed the self-centering performance of the RCW and the wide hysteretic behaviour. The increase of building seismic performance obtained by the RCW has been evaluated by way of numerical models: the results are presented in terms of behaviour factor *q*.

KEYWORDS: base dissipator, on-site testing, case study, RCW, seismic behaviour

INTRODUCTION

The idea of placing a vibration filter at the base of masonry buildings to reduce the effects of seismic shocks is typical of traditional housing in countries such as China and India, as studied by Buckle and Meyes [1] and Zhou et al. [2].

In this context, the application of a dissipator named RCW, consisting of a cut-wall reinforced by vertical steels, placed between foundation and ground floor, has already been studied and tested by Sassu [3], Sassu and Ricci [4], Mariani et al. [5], Sassu [6], revealing the advantage, in comparison to previous proposals, to ensure the elastic return of the building in the initial configuration at the end of the earthquake. The practical application of RCW to a set of four four-storey adjacent masonry buildings, used as council housing, is presented. The results of experimental tests on site, recently analyzed in detail by Sassu et al. [7, 8], show the positive effects of dissipation technique.

The RCW dissipator is formed by 3-4 mm glued foil overlapped by 60 mm layer of weak mortar class M2.5, reinforced by couples of vertical steel bars (diameter 16 mm, distance 200 mm), anchored to both the reinforced concrete curb and the underlying RC foundation (Figure 1).
The bearing capacity of steel bars is adequate to sustain the building load, so the collapse of the mortar layer does not affect their stability.
The operating modes of RCW are simple and intuitive: for low values of seismic action the mortar layer and the foil ensure the total connection between curb and foundation, while for high values of seismic action the mortar layer cracks, allowing relative displacements. The bars allow the elastic return of the building to the initial position at the end of the seism (*self-centering property*), while the cracked mortar layer shows an hysteretic behavior (*dissipative property*), even in presence of small relative displacements between foundation and base of the wall.

EXPERIMENTAL TESTS

Before the construction of the building, three specimens with mortar class M2.5 were prepared, adding waterproofing powder to the compound. The resistance of the mortar has been verified through drilling tests (PNT-G test). The resulting average value of the compressive strength is equal to 2.40 MPa, with a standard deviation of 0.51 MPa. After the construction of the foundation beam, a couple of identical and opposite dissipators, whose size is 40 cm × 60 cm ×30 cm, was prepared, as shown in Figure 1. An hydraulic jack with flow rate of 390 kN has been placed horizontally between the two specimens, to perform a quasi-static load process.
Vertical forces was applied by vertical steel bars *M20 cl 8.8,* passing through the specimens, horizontally released thanks to PVC pipes of 45 mm diameter and tightened by a calibrated torque wrench to induce different vertical pressures in each specimen, respectively

$$\sigma_1 = 0.3\ MPa; \qquad \sigma_2 = 0.6\ MPa. \tag{1}$$

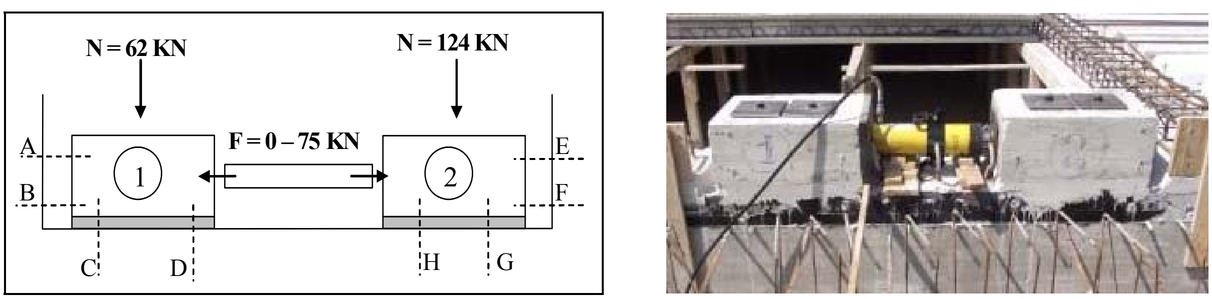

Figure 1: a) Simplified scheme of the test (A-H displacements 1/100 mm); b) Test on opposite specimens of RCW dissipator.

A unilateral quasi-static load process was applied to the two opposite specimens, increasing the horizontal force *F* up to a value of 0.60 and 1.20 times the vertical force *N* for specimen n°1 and n°2, respectively.
The relative displacements of the two specimens have been monitored by means of a mechanical gauge, equipped by a centesimal comparator and positioned between two reference points (A, B specimen n°1 - E, F specimen n°2).

The results, summarized in Figure 2, show in both specimens a strong hysteretic behavior which is higher in the earlier stages of the load process; instead, no vertical motions occurred ensuring the absence of rocking.
Once cracked, the mortar layer maintains interesting dissipative properties and still allows the self-centering at the end of the test, due to the elasticity of the vertical bars.

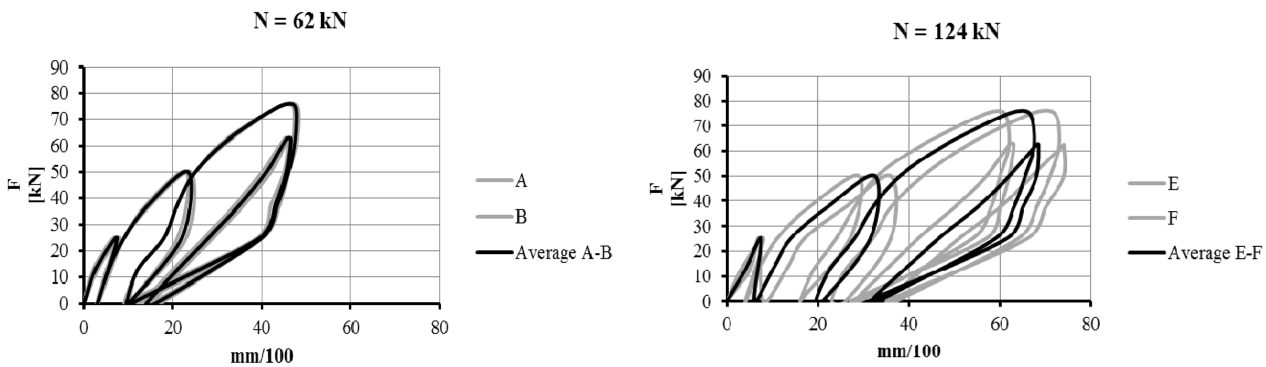

Figure 2: Horizontal force - displacements diagrams.

Due to the reduced amount of displacement, the system does not perform a complete isolation of the base of the building; however, the hysteretic behavior of the base layer can dissipate a great amount of energy.
The drilling test performed on the mortar layer underlying specimens n°1 and n°2 at the end of the load process surveyed compression strength respectively of 2.10 MPa and 1.51 MPa, lower to that measured at the beginning. Nevertheless, the reduction of the load-bearing capacity of the mortar does not affect the proper working of the dissipator: mortars of high mechanical properties are not necessarily to use. Figure 2 shows the effect induced by different vertical loads, i.e. the increase of the dissipative properties in presence of higher normal stresses, for the same horizontal action, according to the well-known "biaxiality effect" (Sassu [9]) detectable in elasto-plastic solids and in previous experimental tests on similar specimens.
The role of the base dissipator can be evaluated, in the first instance, in terms of behavior factor q defined assuming the conservation of energy between the linear elastic and the non-linear response of the structure (Frumento et al. [10]):

$$q_{RCW} = \frac{F_y}{F_{el}} \sqrt{2\mu_s - 1}\,, \tag{2}$$

where μ_s is the ductility of the dissipator, F_y the ultimate resistance and F_{el} the resistance at the elastic limit. The test provides values of q higher than 4.0, in particular

$$\begin{aligned} &specimen\ n°1 - q_{RCW} = 2.0 \cdot \sqrt{5.2} = 4.56 \\ &specimen\ n°2 - q_{RCW} = 2.0 \cdot \sqrt{7.0} = 5.29 \end{aligned} \tag{3}$$

The same evaluations have been conducted for an identical pair of samples subjected to vertical forces of 30 kN and 90 kN, respectively.

The conventionality of the calculation in terms of behavior factor q_{RCW} and its dependence on the vertical load suggests to use, on a prudent basis, the minimum value obtained from experimental tests by applying a vertical load that represents the actual compression stress level at the base of the building.

THE CASE STUDY

As a case study (Figures 3 and 4b), a masonry building, part of the complex recently built in the district CEP of Pisa, was analyzed.

The dissipator were built following the usual procedure, in a very short time. It can be observed the substantial construction ease of the RCW technology, perfectly harmonized within the entire construction process.

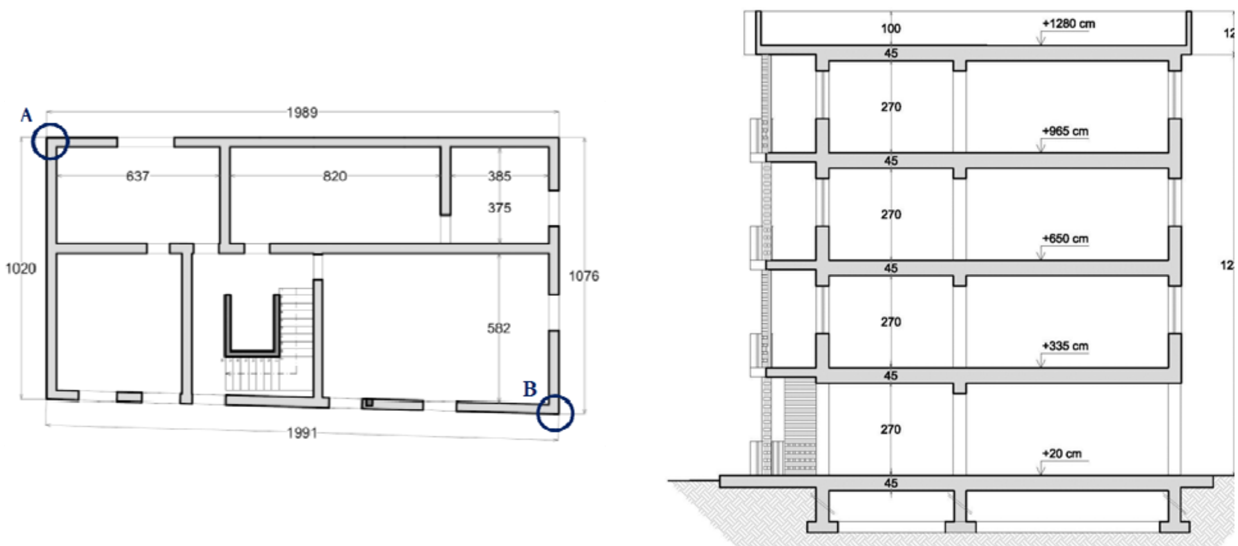

Figure 3: horizontal and vertical sections of the case study building (measurements in cm).

The wall thickness is t = 37 cm, the compressive strength of the blocks is f_{bk} = 10 MPa and the mortar class is M5. The resulting characteristic compressive strength of the masonry is f_k = 4,7 MPa. In order to evaluate the structural response of the masonry structures, the method SAM proposed by Magenes [11] has been adopted. The calculus model is shown in Figure 4a. The dissipator was modeled as a series of frame elements fixed at the base and restrained with a hinge at the top, as shown in Figure 4c.

The geometrical and mechanical characteristics of the frame elements were deduced from the experimental results. Indeed, the experimental envelopes of semi - cyclical curves of the RCW specimens, obtained for different values of the vertical load and shown in Figure 5, exhibit a common initial linear elastic branch ending at the point with F = 30 kN and δ = 0.1 mm. So, once the modulus of elasticity E of the frame element was fixed (E = 210000 MPa), the dimensions of the equivalent rectangular section (31.7 mm × 123.2 mm) was determined on the base of the initial stiffness of the dissipator.

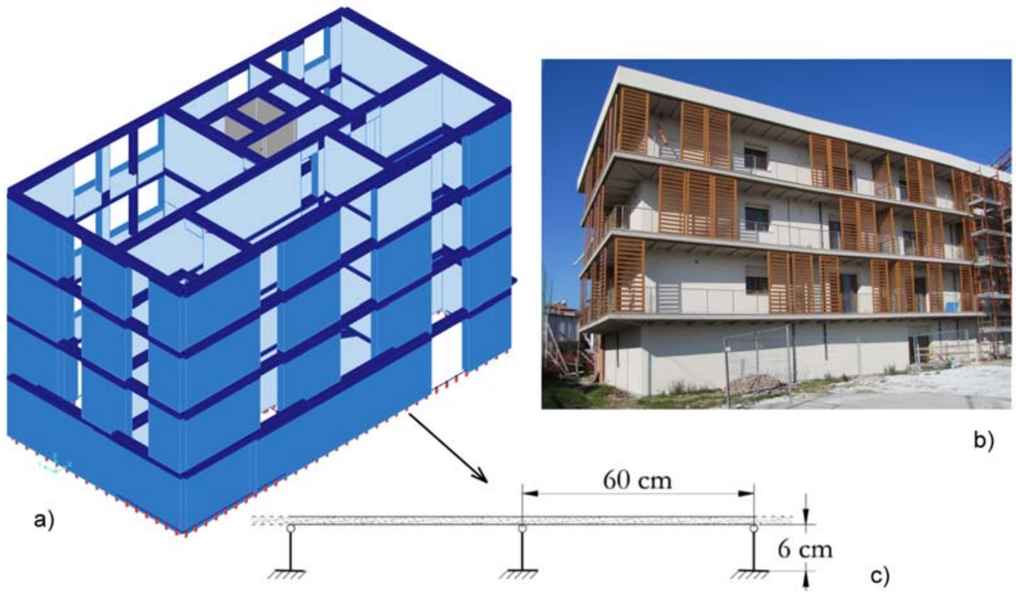

Figure 4: a) the calculus model of the masonry building
b) the masonry building
c) the scheme adopted for the RCW.

The nonlinear behavior of the dissipator has been represented by a plastic hinge, type *N-M*, placed at the base of the RCW. The input data to be assigned to the hinge are the following:

- Elastic domain *N-M* (normal load-bending moment);
- $M(\theta,N)$ (bending moment in function of the hinge rotation and of the vertical load).

The Moment-Rotation relationship M-θ for the elasto-plastic hinge was obtained starting from the envelope of the Force-Displacement curves of Figure 5b. Therefore, the relationship is easily given by:

$$M = F \cdot h$$
$$\theta = \frac{\delta_{\lim} - \delta_{el}}{h}, \qquad (4)$$

where θ is the rotation of the cantilevered beam, δ_{lim} is equal to 0.6 mm, $\delta_{el} = F/k$ and h is 60 mm. On the basis of the experimental data, four relations M-θ were obtained, for each value of the vertical force respectively, So, it is possible to take into account the “biaxiality effect” in a rough way, assigning a specific constitutive law to the plastic hinge for each vertical force.
The *N-M* domain was calculated from the *N-F* domain using relation (4). In order to create the *N-F* domain, the points corresponding to fixed displacement values were inserted in a *N-F* diagram, as shown in Figure 6. Subsequently, the points corresponding to 10 mm /100 displacement (curve 10 in Figure 6), assumed as elastic limit, was interpolated by a second order polynomial regression.

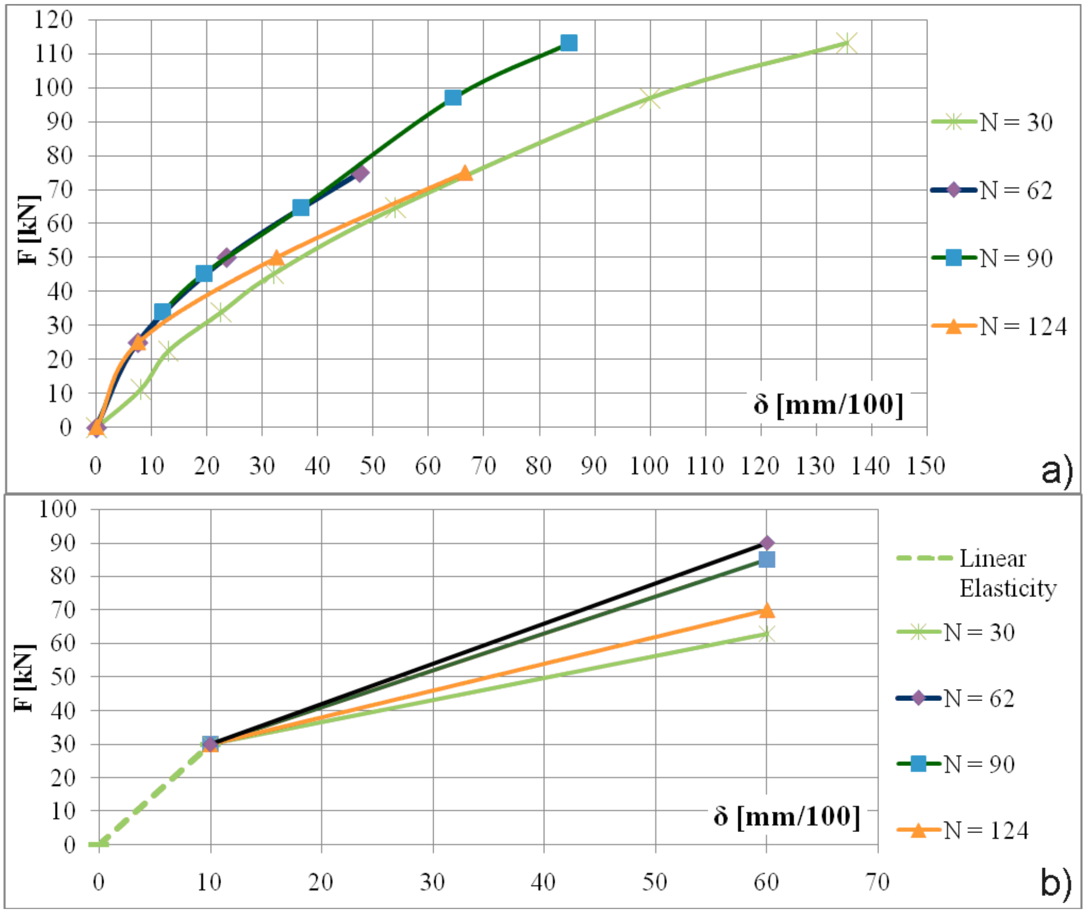

**Figure 5: a) Experimental envelope of semi-cyclical curves;
b) Schematic curves used for the analyses.**

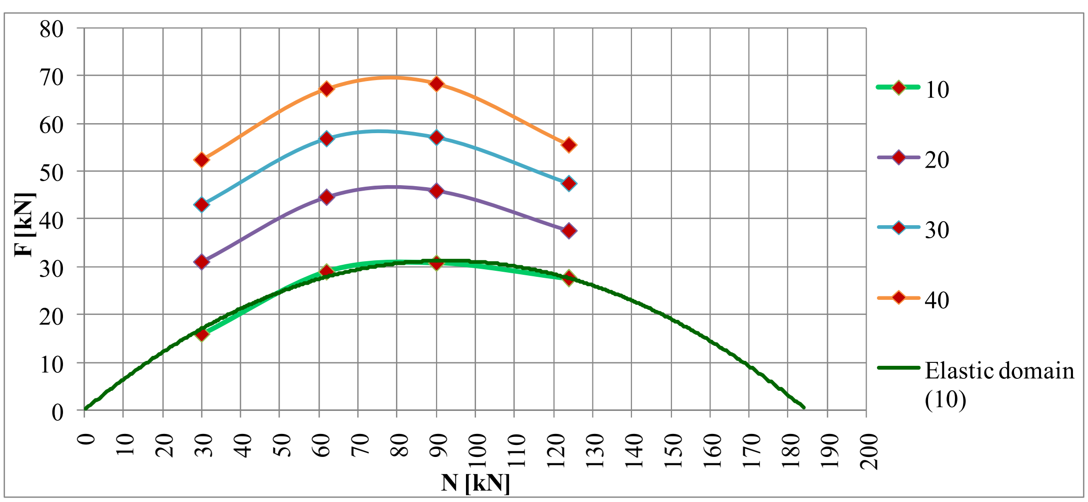

Figure 6: F-N domains of RCW.

ANALYSIS RESULTS

Two models of the building were created: the first one equipped with dissipator and the second one fixed at the base. Non-linear static analysis (*pushover analysis*) were performed in both cases, in order to draw the capacity curves (Figure 7) and to evaluate the behavior factors q of the masonry structure. A uniform distribution of incremental forces acting along the main directions of the building were adopted (*uniform shape*) and it were scaled in order to increase monotonously up collapse condition. The monitored point was initially coincident with the center of mass of the last storey of the model. The capacity curves are shown in Figure 7.

Figure 8 shows the displacement of the center of every storey, calculated at the last step of the pushover analysis. In this way, the impact of the RCW on the ductility of the entire structure can be assessed.

Observing the capacity curves, we may deduce that the RCW provides an increase in terms of ultimate displacement and in terms of base shear. This result shows an increase of seismic capacity of the structure with RCW in terms of resistance and ductility which can be appreciated in terms of behavior factor q, as follows:

$$q = q^{*} \cdot OSR \quad (5)$$

where q^* is the base value that takes into account the passive capacity of the structure and OSR is the overstrength ratio, equal to F_y / F_{el}. For masonry buildings F_{el} corresponds to the total base shear at the attainment of the ultimate strength/displacement of a single wall. The values of q for the various lateral force distributions are reported in Table 1. The average value of the behaviour factor obtained in the models without RCW turns out to be equal to 3.58: it is perfectly in accordance with the value indicated by the Italian standard NTC08 [12] for the same building typology, q = 3.60. From the model with RCW, an average value of the behavior factor equal to 5.16 was obtained, whereby an increase of q equal to 44% is found.

Table 1: Values of the behaviour factor q for the various force distributions considered

	Accel +X	RCW Accel +X	Rel. Increment	Accel -X	RCW Accel -X	Rel. Increment
q*	1.78	2.10	18%	1.86	2.21	19%
OSR	1.77	2.15	22%	1.90	2.05	8%
q	**3.14**	**4.53**	**44%**	**3.52**	**4.52**	**28%**
	Accel +Y	RCW Accel +Y	Rel. Increment	Accel -Y	RCW Accel -Y	Rel. Increment
q*	1.59	2.18	37%	1.78	2.18	22%
OSR	2.37	2.71	14%	2.18	2.62	20%
q	**3.75**	**5.90**	**57%**	**3.89**	**5.69**	**46%**
q	**3.58**	**Average Value without RCW**				
q	**5.16**	**Average Value with RCW**				
	44%	**Increment [%]**				

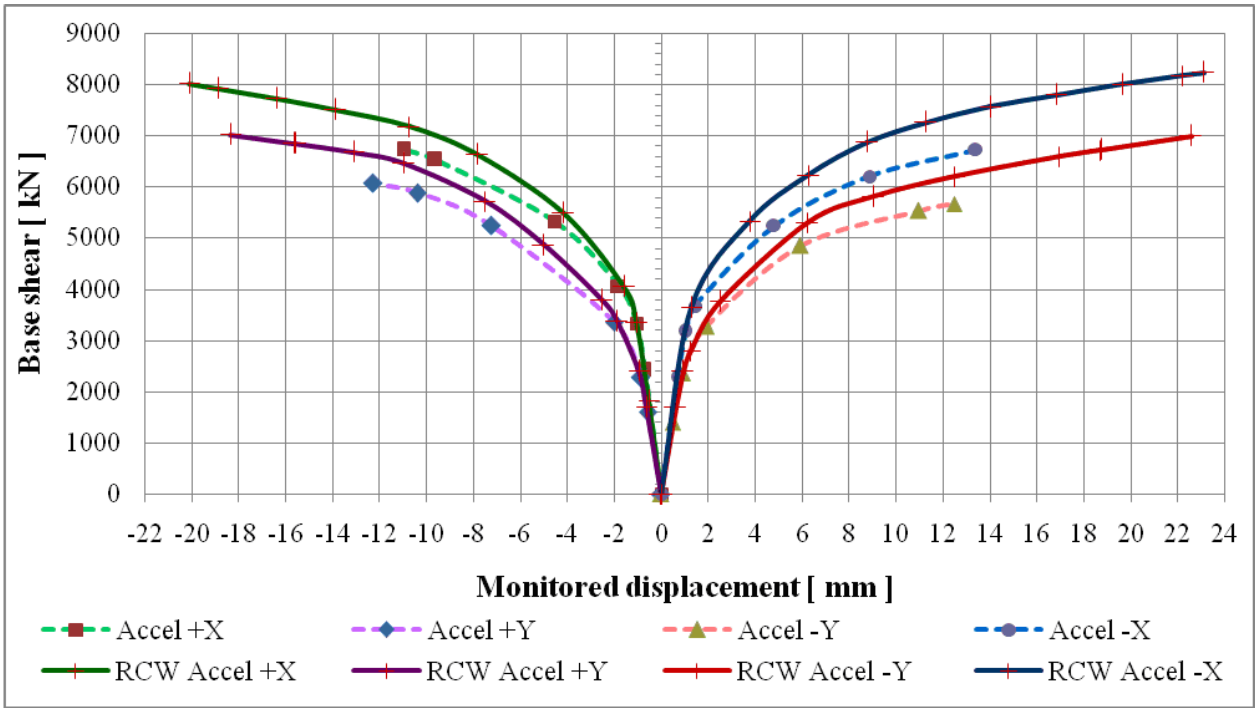

Figure 7: Capacity curves obtained from pushover analysis (uniform shape) on models with and without RCW dissipator.

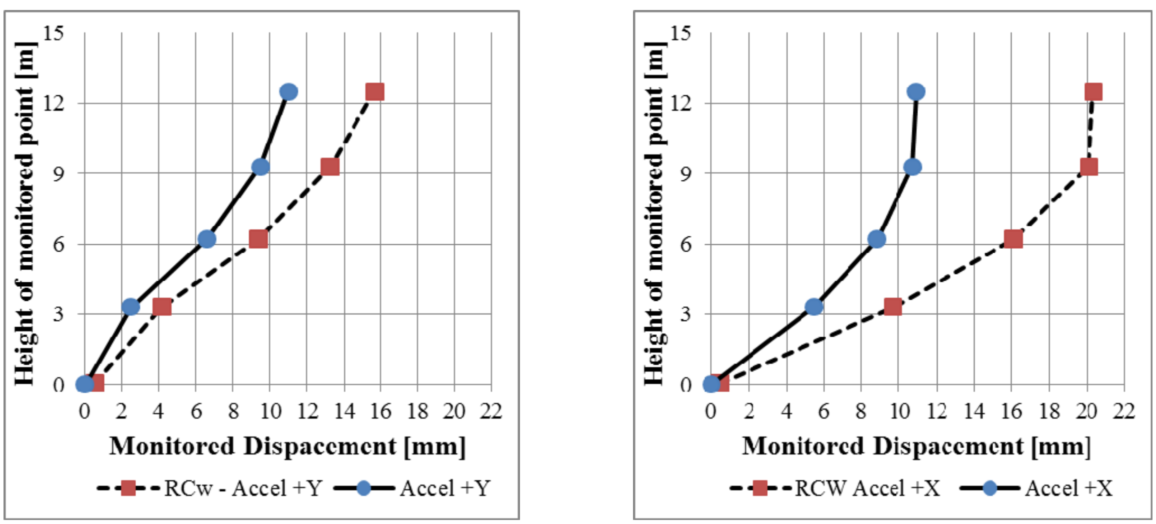

Figure 8: Displacements of the centers of mass at the various storey elevations obtained at the last load-step of the pushover analysis.

Moreover, the return period T_R of the limit seismic action has been calculated starting from the capacity curves; in particular, it can be obtained by equating the requested displacement d^*_{max} to that offered by the structure d^*_u. In practical terms, following the instructions provided by NTC08 [12], if the system has natural periods really small, as in our case, the displacement response d^*_{max} of the inelastic system is greater than the corresponding $d_{e,max}$ of the elastic one and it is given by

$$d^*_{max} = \frac{d_{e,max}}{q^*}\left[1+\left(q^*-1\right)\frac{T_c}{T^*}\right] \geq d_{e,max} \qquad \left(if\ T^* < T_c\right), \tag{6}$$

where T^* is the natural period of the equivalent 1-dof system, T_c is the threshold between the constant acceleration and the constant velocity regions of the response spectrum,

$$q^* = \frac{S_{Ae}\left(T^*\right)m^*}{F_y^*} \tag{7}$$

where m^* is the mass, $S_{Ae}(T^*)$ is the related spectral acceleration and F_y^* is the yielding strength of the equivalent 1-dof system. q^* represents the ratio between the force of the elastic response and the yield strength of the equivalent system. By putting

$$d^*_{max} = d^*_u, \tag{8}$$

the return period T_R of the limit seismic action is assessed. The obtained results are reported in Table 2. It is easy to recognize significant increments of the return period in presence of RCW (the value at the Life Safety Limit State of Italian Standards is 2475 years).

Table 2: Maximum values of T_R for the various force distributions considered

Analysis type / Presence of RCW / Direction Analyzed	d^*_u [mm]	$S_{De}(T^*)$ [mm]	T_R [years]
Uniform Acceleration / without RCW / +X	10.8	4.6	1330
Uniform Acceleration / with RCW / +X	20.1		2475
Uniform Acceleration / without RCW - -X	13.4	5.9	710
Uniform Acceleration / with RCW / -X	23.1		2475
Uniform Acceleration / without RCW / +Y	10.9	5.9	711
Uniform Acceleration / with RCW / +Y	20.4		2475
Uniform Acceleration / without RCW / -Y	12.1	5.9	870
Uniform Acceleration / with RCW / -Y	22.6		2475

Finally, the effects of the choice of the monitoring point in a different position in respect to the center of mass of the storey were also checked. The nodes A and B, at the ends of the main diagonal of the building plant (Figure 3), were examined: the capacity curves obtained by monitoring the nodes A, B and the center of mass of the last storey are very close together.

As shown by Sassu et al. [8], in presence of earthquakes of low magnitude, the base-dissipator remains integer, whereas, when the intensity of the seismic shaking is high, it increases the global ductility of the building and, consequently, its behavior factor q.

CONCLUSIONS

The experimental tests and the illustrated analysis reveal the RCW advantages: dissipative and self-centering properties, construction ease (use of common materials and constructive procedures) with no significant increase in execution time. Moreover property of post-seismic integrity can be observed, due to the elasticity of the vertical bars. The increase of the structural ductility has been easily evaluated for the case study through the behavior factor q. In the present case, the behavior factor q calculated for the model with RCW is greater of about 44% in respect to the model fixed at the base. Thus, the RCW allows a notable increase of the return period (T_R) of the limit seismic action for the masonry building.
Micro FEM modeling of the RCW specimen is being studied; it will allow us to optimize the performances of the device for different types of buildings.

ACKNOLEDGEMENTS

The authors wish to thank the public agency APES SpA Pisa and the Consortium RELUIS through the 3-year the Italian Civil Defense Project–Line AT1-Task 1.1 (2010–2013), for their assistance and sponsorship.

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