Experimental Evaluation of Impulsive Energy Damping in Masonry Collapse Mechanisms

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SUMMARY:
Severe earthquakes throughout the world show that existing masonry are prone to suffer out-of-plane local collapse mechanisms. In such mechanisms energy dissipation is mainly due to impacts against the remainder of the structure. Using data from an experimental campaign on free rocking walls, estimation are suggested for the coefficient of restitution in both two-sided (façade resting on a foundation) and one-sided (façade adjacent to transverse walls) rocking. Both brick and tuff masonry are considered, and the relevance of test repetition and wall height-to-thickness ratio are addressed. Additional parameters measured during the tests, such as amplitude-dependant period of vibration, are compared against analytical formulations. The importance of an accurate estimation in energy damping is highlighted through nonlinear time histories, specifying under which accelerograms the response is more sensitive to energy damping.

Keywords: unreinforced masonry, rocking, coefficient of restitution

1. INTRODUCTION

Severe earthquakes throughout the world show that existing masonry are prone to suffer out-of-plane local collapse mechanisms (e.g., refer to Decanini *et al.* 2004). Such mechanisms have been studied ultimately through non linear time history analyses (e.g., refer to Griffith *et al.* 2003; Liberatore and Spera 2003). In order to obtain good results a careful representation of the non linear mechanical behaviour of the response and of energy dissipation is necessary.

Up until now, the investigation of the estimation of energy damping and of its relevance to the response has received little attention in scientific literature. In particular, experimental tests have been very limited. Nonetheless, the energy damping that occurs during the motion, due to impacts, is a relevant parameter on the response (e.g., refer to Sorrentino *et al.* 2008).

No experimental program on unreinforced masonry wall energy damping seem to have been carried out so far. The tests (Lam *et al.* 1995; Griffith *et al.* 2004) have not been interpreted within a general theoretical framework, such as that of impulsive mechanics. Moreover, no tests whatsoever have been performed on one-sided rocking mechanisms. So far there is no mechanical model to assess energy dissipation for this kind of boundary condition, although it can be rather frequent in historical constructions. Therefore, previous investigators have assumed very small energy dissipation, usually equal to two-sided rocking (Hogan 1992), or very large energy dissipation, with no motion after impact (Liberatore and Spera 2003).

All the previous considerations suggest the advisability of an experimental program focused on energy dissipation in unreinforced masonry rocking mechanisms. Moreover, an analytical formulation of the coefficient of restitution for one-sided rocking is reported. Finally, the influence of a refined estimation of energy dissipation on non linear time history analyses of rocking mechanisms will be examined.

2. COEFFICIENT OF RESTITUTION

Housner (1963) finds an analytic velocity reduction factor, using the approach of the conservation of angular momentum, in considering two-sided rocking (2*s*), $e_{an,\,2s}$, equal to:

$$e_{an,\,2s} = \frac{\dot{\theta}^{+}}{\dot{\theta}^{-}} = 1 - 2\frac{mR^2}{I_O}\sin^2\alpha \tag{1}$$

with θ = rotation of the wall, dot indicating derivative with respect to time, superscript + (-) value after (before) impact, m = mass of the wall, R = distance of the centre of mass from the rocking hinge (Figure 1), I_o = polar moment of inertia with respect to the rocking hinge, α = angle between the vertical line through the rocking hinge and the inclined line through the rocking hinge and the centre of mass (Figure 1**,** g = gravity acceleration). The larger the coefficient of restitution, the smaller the energy dissipation. According to this approach, both material properties and size of the body are irrelevant upon damping.

Eq. (1) clearly does not apply to one-sided rocking. An analytic coefficient of restitution, $e_{an,\,tr}$, for the impact against a transverse walls has been suggested by Sorrentino *et al.* (2011):

$$e_{an,\,tr} = 1 - 2\frac{mR^2}{I_O}\cos^2\alpha \tag{2}$$

In the range of usual values of the aspect ratio, $e_{an,\,tr}$ is negative. Only for $h/b < \sqrt{2}$, does $e_{an,\,tr} > 0$ (Figure 2a). A negative value for the coefficient of restitution implies a rebound.

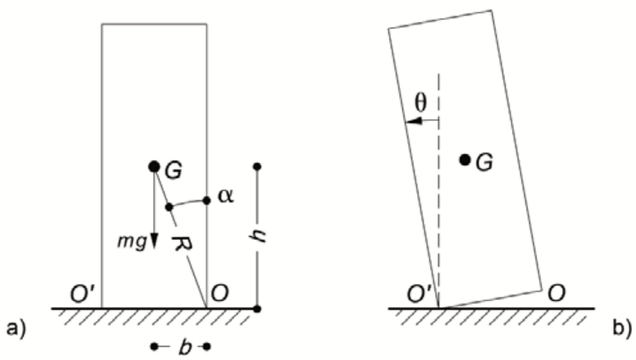


Figure 1. Parapet wall: geometrical parameters and displaced configuration.

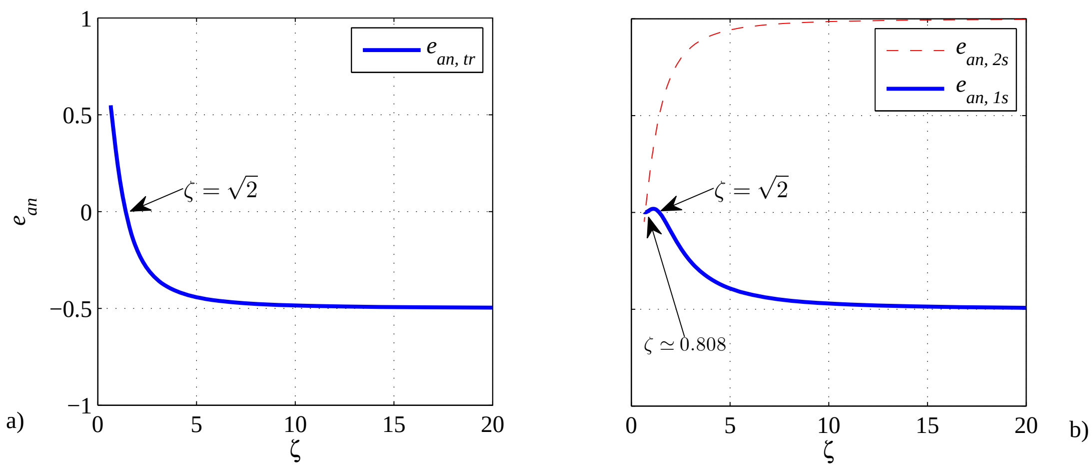


Figure 2. Coefficients of restitution as function of ς = height-to-thickness ratio of the wall. a) $e_{an,\,tr}$; b) $e_{an,\,1s}$, $e_{an,\,2s}$. An homogenous, parallelepiped wall has been assumed.

The one-sided rocking analytical coefficient of restitution, $e_{an,\,1s}$, can be obtained as the product $e_{an,\,1s} = e_{an,\,2s}$ x $e_{an,\,tr}$ x $e_{an,\,2s}$. It is evident that $|e_{an,\,1s}| << e_{an,\,2s}$, and this is mainly due to $e_{an,\,tr}$. (Figure 2b). According to this approach the coefficient is not dependant on the size of the contact surface between façade and transverse walls.

3. EXPERIMENTAL TESTS (TEST SETUP)

The experimental campaign described here investigates rocking energy dissipation with the variation of: 1) boundary condition, 2) wall height-to-thickness ratio, 3) contact depth between façade and transverse walls (one-sided rocking only), 4) unit material, 5) effect of test repetition.

Two boundary conditions are taken into account: a) wall resting on a foundation (undergoing two-sided rocking, Figure 3a); b) wall resting on a foundation and adjacent to two transverse walls (undergoing one-sided rocking, Figure 3b). The rocking walls are meant to model unreinforced masonry façades moved out-of-plane by earthquake-induced inertia forces. The condition of a two-sided rocking wall is typical of parapet, boundary walls. The condition of a one-sided rocking wall is peculiar to façades built without an efficient interlocking with transverse walls, either due to poor construction, or to building readjustments or inadequately repaired seismic damage.

The walls tested have characteristics which are common in Mediterranean existing buildings in terms of aspect ratios (height/thickness and length/thickness ratios) and materials (Table 1).
In order to increase the number of tests and because of the very limited damage accumulation observed, the walls were fractured at an intermediate bed joint, thus obtaining a shorter specimen (Figure 3c). Height/thickness ratio varies between 6.5 and 14.6 (Table 2). In one-sided rocking tests, the ratio between contact depth and wall length was varied as well. This makes it possible to simulate different transverse-wall densities and their influence on energy dissipation.

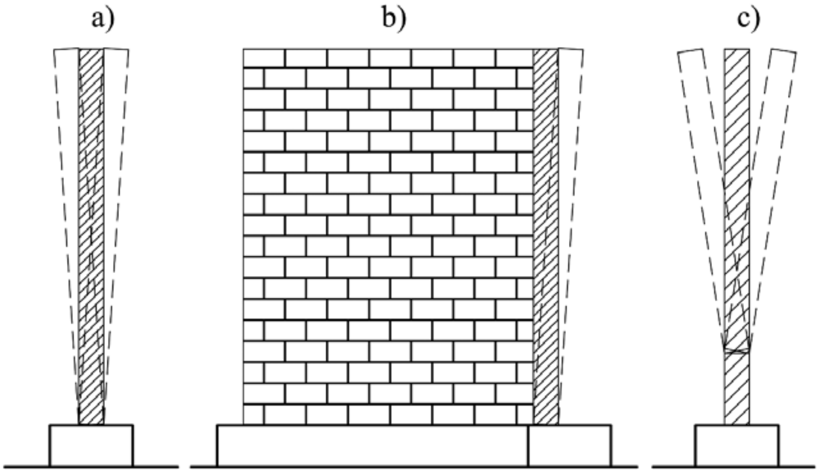


Figure 3. a) Two-sided rocking, b) one-sided rocking, c) wall fractured above the base in order to get a different height-to-thickness ratio

Table 1. Walls' main features

Wall	Size (length × height × thickness) (mm×mm×mm)	Unit
1	1420 × 1090 × 113	Solid clay brick
2	1440 × 1630 × 113	Solid clay brick
3	1500 × 1780 × 123	Tuff
4	1030 × 1630 × 113	Solid clay brick
5	1130 × 1800 × 123	Tuff
6-7[a]	1490 × 1820 × 260	Tuff

[a] used as transverse walls in one-sided rocking tests

Table 2. Height of specimens obtained from walls of Table 1, by means of fracturing at an intermediate bed joint.

Specimen	Height (mm)	Height/ Thickness	Number of valid tests performed:			
			two-sided	one-sided		
				CD = 260 (mm)	CD = 120 (mm)	CD = 60 (mm)
1a	1090	9.6	10	0	0	0
1b	800	7.1	9	9	10	0
1c	820	7.3	0	16	21	17
2a	1630	14.4	15	29	16	29
2b	1360	12.0	19	13	14	14
3a	1630	13.3	5	29	26	18
3b	1280	10.4	8	17	20	0
4a	1560	13.8	0	-	-	-
4b	1170	10.4	19	-	-	-
5a	1790	14.6	28	-	-	-
5b	1190	9.7	20	-	-	-
5c	800	6.5	21	-	-	-

Results of tests performed on materials are reported elsewhere (Sorrentino *et al.* 2011). Test repetition was examined in terms of variation of energy dissipation and variation of displacement capacity. Both proved to be limited. The total number of tests performed is 614. However, only 452 were considered valid, due to instrument malfunction, disturbed initial conditions and so on. Moreover, tests with a residual top out-of-plumb larger than 1.5 mm were also excluded.

During each test only displacements are measured, because the accelerations undergo a sudden reduction of velocity upon impact. Six inductive displacement transducers are used, in order to evaluate the activation of degrees of freedom, other than the expected out-of-plane rotation (Sorrentino *et al.* 2011). Four degrees of freedom are contemplated, with reference to the centre of the base: v, $w = x$, y displacement, ϕ = rotation around the z axis; additionally: θ = rotation around the x axis passing through the relevant base corner. Considering the walls' geometric characteristics and the absence of any stress, it has been postulated that complete uplift and rotation around y axis do not occur. The four kinematic unknowns v, w, θ, and ϕ are determined by numerically solving, for each time step, four non linear equations obtained considering four instruments. Only the out-of-plane rotation θ assumes significant values. Nonetheless, the maximum value of rotation, ϕ, around the vertical axis is non zero, as observed also by Peña *et al.* (2007).

In the range of the h/b ratios examined in this experimental campaign, rotation θ determined by solving the system of four nonlinear equations is very similar to that determined using the following simplified expression:

$$\theta \cong \arctan\left(\frac{\Delta l_i}{h_i}\right) \tag{3}$$

with h_i = height of the i-th transducer above the rocking hinge level.

4. EXPERIMENTAL ESTIMATION OF ENERGY DISSIPATION

The experimental coefficient of restitution, e_{exp}, was estimated for each time history. The application of the initial displacement by means of the screw device has shown that the experimental instability displacement is usually smaller than the nominal instability displacement. This phenomenon can be explained in terms of the local rounding of the rocking hinge, the indenting of the mortar with respect to the unit face, and the building tolerances of the wall along the height.

Once rotation θ was determined as explained in the previous section, and if the initial rotation had been applied with the screw device up to the instability threshold, rotation θ was normalised with respect to a reduced value of the angle α, $\alpha_{ind} = \theta_0$, with θ_0 = initial rotation. Based on the piece-wise linear formulation by Housner (1963), acceptable for slender rocking elements, e_{exp} after n impacts can be estimated according to the following equation:

$$e_{exp} = \sqrt[2n]{1-\left(1-\frac{|\theta_n|}{\alpha_{ind}}\right)^2 \Big/ 1-\left(1-\frac{|\theta_0|}{\alpha_{ind}}\right)^2} \tag{4}$$

with $|\theta_n|$ = maximum absolute rotation after the n-th impact. If α is used, instead of α_{ind}, e_{exp} is in average larger by 5 % in one-sided rocking, while in two-sided rocking it is less than 0.5 %. The values of e_{exp} obtained by applying Eq. (4) to the tests here described are coincide substantially with those obtained using the expression proposed by Peña *et al.* (2007), valid irrespective of the h/b ratio.

As shown by Eqs. (4), the value of e_{exp} can be affected by the number of impacts considered (*n)*. In two-sided rocking, energy dissipation remains constant to a large extent throughout the time history. In one-sided rocking energy, on the other hand, dissipation is more markedly amplitude-dependent. Correspondingly, if the initial rotation is disregarded, the value of e_{exp} does not change sensibly in two-sided rocking, while it is usually larger in one-sided rocking.

In Table 3, the value of e_{exp}, of a two-sided rocking test has been divided by $e_{an,\,2s}$ of Eq. (1), in order to obtain a comparison with a parameter which can be calculated for any given wall, even one that has not been tested. In calculating $e_{an,\,2s}$ a nominal value of α has been assumed. In this way $e_{an,\,2s}$ can be readily calculated, even if the rounding of the corner or the indenting of the mortar joint is not known. Moreover, even for the stockiest wall tested here, a 20% difference between α and α_{ind} yields a 1% difference in the value of e_{an}. In two-sided rocking, the value of the ratio between experimental and analytic coefficients of restitution, e_{exp} / $e_{an,\,2s}$, is less than one (Table 3). As already observed, the results do not markedly depend on amplitude and they appear stable both within each test series and moving from one specimen to another. This is probably due to the presence of the mortar in the rocking hinge layer, which makes contact condition similar in all tests. Only one test series shows much smaller values for the ratio compared to all the others. If the entire time history is taken into consideration, and if this series is disregarded, the mean value of e_{exp} / $e_{an,\,2s}$ is approximately 0.95. If all series are considered, the ratio is smaller, being equal on average to 0.93. e_{exp} / $e_{an,\,2s}$ = 0.95 can probably be taken as an approximate estimation of the coefficient of restitution in a parapet wall whose rocking stability has to be assessed by means of non-linear time history analyses. The ratio e_{exp} / $e_{an,\,2s}$ is close to one, irrespective of the aspect ratio of the wall. This means that Housner formulation of the coefficient of restitution, Eq. (1), shows the right trend with h/b, but underestimates energy damping. In § 6 the influence of higher energy damping will be investigated.

In one sided rocking, the results are more scattered compared to two-sided rocking (Table 3). Unlike two-sided rocking, energy dissipation is amplitude-dependant: the larger the velocity, the larger the dissipation (and the smaller e). As a rule of thumb, if we suppose that damping remains constant with amplitude, a coefficient of restitution of 1.05 $e_{an,\,1s}$ may be assumed. An improvement is obtained if a linear relationship between non dimensional peak rotation before impact, $|\theta^-|$ / α, is assumed. The experimental coefficient of restitution remains stable test after test, within a test series. The unit material has no effect on the ratio e_{exp} / $e_{an,\,1s}$, and the ratio shows no clear trend with h/b.

The size of the contact surfaces between façade and transverse walls, measured by contact depth, CD, has no systematic influence on energy damping. Therefore, it may be assumed that the analytic model of Eq. (2) is qualitatively correct. However, it is reasonable to assume that a minimum amount of contact depth is necessary in order to avoid material failure at impacts.

It is worth noting that the experimental coefficient of restitution in one-sided rocking, although much lower than in two-sided rocking, is not zero as tentatively suggested by Liberatore and Spera (2003).

As a matter of fact, the two researchers themselves regarded this assumption as probably being over-optimistic. On the basis of the tests presented here (§ 6), it may be stated that numerical analyses performed assuming $e_{an,\,1s} = 0$ are unsafe.

If the analytic coefficient of restitution for two-sided rocking (Eq. (1)) is used to reproduce experimental time histories, poor results are obtained (Figure 4a). On the other hand, an experimentally calibrated coefficient of restitution markedly enhances agreement. The still-not-perfect match may be partially due to the amplitude dependency of the e_{exp} / $e_{an,\,2s}$ ratio, which is present, albeit weak, and to the lack of symmetry of the actual wall.

The same comparison was performed for one-sided rocking (Figure 4b). The analytic coefficient of restitution presented in § 2 (not shown in the plot) is a marked improvement on the ones proposed in the literature, which either underestimate (Hogan 1992) or overestimate (Liberatore and Spera 2003) energy damping.

The agreement between experimental and analytic time histories is improved if the analytic coefficient of restitution is experimentally calibrated. The still not perfect match may be related to the presence of negative rotations, due to the gap existing between façade and transverse walls. Therefore, the last portion of the experimental time history shows small-amplitude two-sided rocking, which the analytical model of one-sided rocking is not able to reproduce.

Table 3. Ratio between experimental and analytic coefficients of restitution, e_{exp} / e_{an}, in each test series

Specimen	Height/ Thickness	Two-sided rocking (2s)	One-sided rocking (1s)		
			CD = 260 (mm)	CD = 120 (mm)	CD = 60 (mm)
1a	9.6	0.96	-	-	-
1b	7.1	0.95	0.90	1.09	-
1c	7.3	-	1.28	1.00	1.13
2a	14.4	0.79	0.78	0.96	1.13
2b	12.0	0.95	1.04	1.27	1.27
3a	13.3	0.95	0.48	0.69	0.64
3b	10.4	0.88	0.96	1.16	-
4a	13.8	-	-	-	-
4b	10.4	0.93	-	-	-
5a	14.6	0.96	-	-	-
5b	9.7	0.95	-	-	-
5c	6.5	0.97	-	-	-

CD is the contact depth between façade and each of the transverse walls

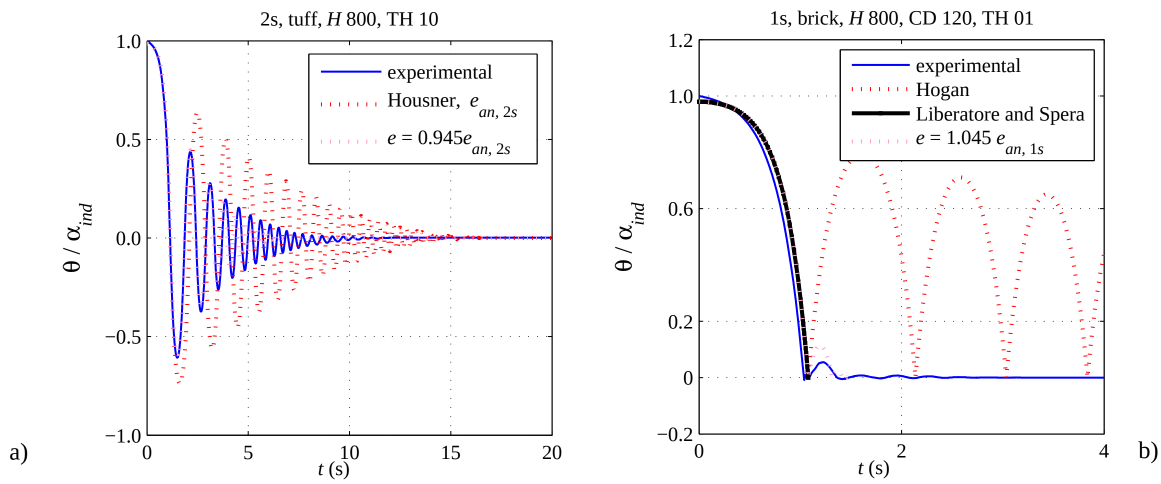


Figure 4. Comparison between experimental and analytic time histories. a) Two-sided rocking, b) One-sided rocking. Due to numerical sensitivity issues, all analytic models assume θ_0 / α = 0.985

5. ADDITIONAL EXPERIMENTAL PARAMETERS

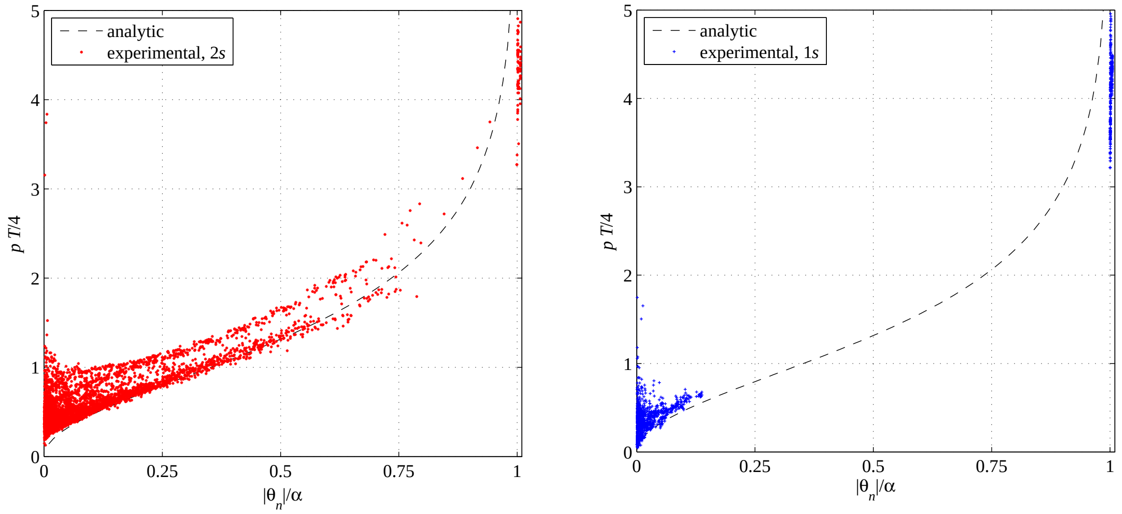
In addition to the experimental coefficient of restitution, the response of the walls tested was investigated by observing some other parameters. Here only two aspects are discussed, a few more are presented elsewhere (Sorrentino *et al.* 2011).

The non-dimensional initial rotation is rather stable in a single test series, even in the case of the heaviest walls tested. However, it can be significantly scattered from wall to wall, and from test series to test series (Table 4). This is true for both two-sided and one-sided rocking experiments, although the initial rotation is usually larger in two-sided rocking than in one-sided rocking. Such behaviour is probably due to mortar debris accumulation in the rocking hinge layer, not only during rocking but also when changing test setup.

As a matter of fact, when the hinge layer was cleaned between two test series, the initial rotation increased (Sorrentino *et al.* 2011). Mean non-dimensional initial rotation θ_0 / α is 0.91 in two-sided rocking and 0.73 in one-sided rocking.

Table 4. Ratio between initial rotation θ_0 and nominal value of α (= arctan (b/h), refer to Figure 1)

Specimen	Height/ Thickness	Two-sided rocking (2s)	One-sided rocking (1s)		
			CD = 260 (mm)	CD = 120 (mm)	CD = 60 (mm)
1a	9.6	0.83	-	-	-
1b	7.1	0.93	0.84	0.85	-
1c	7.3	-	0.81	0.83	0.87
2a	14.4	0.89	0.70	0.66	0.54
2b	12.0	0.91	0.74	0.65	0.51
3a	13.3	0.88	0.77	0.71	0.66
3b	10.4	0.89	0.73	0.74	-
4a	13.8	-	-	-	-
4b	10.4	0.96	-	-	-
5a	14.6	0.94	-	-	-
5b	9.7	0.99	-	-	-
5c	6.5	0.97	-	-	-



a) b)

Figure 5. Non-dimensional period of the wall, T, multiplied by the frequency parameter $p = \sqrt{m\,g\,R/I_O}$. Comparison between experimental data and analytical formulation (Housner 1963).

The non-dimensional period of the wall, with reference to the first quarter of the first cycle, is usually close to or larger than 4 (Figure 5), indicating a non-dimensional initial rotation close to one (Housner 1963). Figure 5 shows a reasonable agreement with the analytical formulation proposed by Housner (1963), which highlights that the period is amplitude-dependant. These results are similar to those experimentally obtained by ElGawady *et al.* (2011). As already observed in the case of non-dimensional initial rotation, the non-dimensional period of the first quarter of the first cycle is usually stable in each test series.

6. INFLUENCE OF THE COEFFICIENT OF RESTITUTION UPON EARTHQUAKE PERFORMANCE OF ROCKING WALLS.

The influence of a more accurate estimation of energy dissipation upon the earthquake performance of rocking walls was appraised by means of numerical analyses.

First of all, the response of a two-sided rocking façade was studied in terms of overturning maps (Sorrentino *et al.* 2006). Each overturning map plots the response of a wall subjected to a recorded accelerogram. Each point of a map represents the overturning or non overturning of the wall for the selected accelerogram whose amplitude and duration have been scaled. The scaling of the signal can be interpreted as a scaling of the wall. The response of the selected wall to a signal with amplitude scaled by a given factor, is equal, according to Housner's (1963) piece-wise linear model, to the response of wall whose α is scaled by the same factor. This is to say that increasing the amplitude of the record is equivalent to increasing the geometric slenderness of the wall. The response of the selected wall to a signal with duration scaled by a given factor, is equal to the response of a wall whose R is scaled by the square of the same factor. Therefore, an increased duration of the accelerogram is equivalent to reducing the size of the wall in a non-linear fashion. 201 discrete values of amplitude and duration are considered, scaled to between 50 % and 150 % of natural values. Thus, each map is the result of 40401 time histories. 20 accelerograms were used.

Results obtained are qualitatively similar to that in Sorrentino *et al.* (2006), where $e = e_{an,\ 2s}$ (Eq. (1)). The boundary between overturning and non overturning domains has a non-smooth, non-connected shape. Computing the same maps for $e = 0.95\ e_{an,\ 2s}$, as could have been expected, the number of overturnings, N_O, decreases (Table 5). However, the reduction of the coefficient of restitution can have a varying effect on the number of overturnings. This phenomenon may be related to the time of occurrence of the overturning. If such critical response is obtained due to an initial excitation pulse, an increase in the energy dissipated through impact is irrelevant, because no impact has occurred. However, if the overturning occurs after a few impacts, a reduced value of e plays a role, because the wall will have a smaller velocity after hitting the base. On average, in the 20 maps computed, the reduction in the number of overturnings was equal to 25%.

Another aspect that Table 5 reveals is that the reduction of e reduces the scatter of the response as well. In order to measure the scatter of the response in each map, two numerical indexes were defined: N_D and N_A. These are the number of changes (overturning-no overturning, scaling up the duration and the amplitude respectively) normalised by the number of overturnings (in order to take into account how many changes were actually possible). In Table 5 the average of N_D and N_A is presented for both the analytic (a) and the experimentally calibrated (b) coefficient of restitution. The response appears more ordered in the second case. On average, in the 20 maps computed, the reduction of scatter (as previously defined) was equal to 43%. Therefore, increased energy dissipation not only reduces the overturning rate of a wall, but also makes its assessment more robust.

With reference to the same set of 20 natural accelerograms, overturning maps of a one-sided rocking wall were computed. Such maps have a shape similar to that already observed for two-sided rocking. In this case the comparison is performed between a zero coefficient of restitution, as tentatively assumed by Liberatore and Spera (2003), and an experimentally calibrated coefficient of restitution. From such comparison it is clear that the first assumption is unsafe (Table 6). Table 6 has been obtained considering positive rotations. However, in one-sided rocking, a reduction of e might be relevant in one direction of rotation, but not in the other (as shown by the results obtained for negative rotations and here not presented for the sake of brevity). The explanation of this performance is similar to that given for the different overturning rates observed in two-sided rocking. In one direction an initial pulse of the excitation might push the façade against the transverse walls, whereas in the other it might induce an overturning without previous significant impacts.

Table 5. Number of overturnings and scatter in overturning maps computed for 20 natural signals, varying the coefficient of restitution ($e_{an,\,2s}$ and e = 0.95 $e_{an,\,2s}$). Two-sided rocking.

Record[a]	N_O[b] (%)		$(N_D+N_A)/2$[c] (%)		Record[a]	N_O[b] (%)		$(N_D+N_A)/2$[c] (%)	
	$e_{an,\,2s}$[a]	e	$e_{an,\,2s}$[a]	e		$e_{an,\,2s}$[a]	e	$e_{an,\,2s}$[a]	e
40ElC180	49.6	34.0	32.1	14.4	Joshua90	61.6	45.8	64.2	47.6
Taft111	5.2	0.6	6.9	0.7	LucN80W	95.4	90.9	8.7	5.9
Pac164	82.9	78.7	14.0	8.2	RRS228	72.8	66.2	27.5	22.6
TolmezWE	8.8	3.7	5.3	1.3	Syl360ff	75.9	70.4	15.5	11.1
Bucar0	66.2	58.7	13.4	7.1	Syl360VI	73.4	66.5	29.7	9.0
BCr230	31.3	17.4	48.2	14.2	LAHol0ff	7.6	0.8	21.6	1.6
IVC230	92.8	90.3	6.8	2.5	LAHol0IV	24.6	10.1	27.4	9.6
SecreN27	75.7	66.6	9.5	19.0	KJM000	70.8	62.4	20.9	15.5
1St280	40.6	31.9	27.8	21.0	Tak000	85.0	81.6	21.6	9.5
LGPC000	90.6	86.6	13.3	6.9	YPT330	89.8	84.0	16.2	10.9

[a] (Sorrentino *et al.* 2006); [b] N_O: Normalised number of overturning; [c] $(N_D+N_A)/2$: Average normalised number of changes overturning – no overturning scaling duration and amplitude

Table 6. Number of overturnings and scatter in overtunring maps computed for 20 natural signals, varying the coefficient of restitution (0 and e = 1.05 $e_{an,\,1s}$). One-sided rocking (positive rotations).

Record[a]	N_O[b] (%)		$(N_D+N_A)/2$[c] (%)		Record[a]	N_O[b] (%)		$(N_D+N_A)/2$[c] (%)	
	0	e	0	e		0	e	0	e
40ElC180	0.0	16.5	0.0	4.3	Joshua90	0.0	0.6	0.0	0.5
Taft111	0.0	0.0	0.0	0.0	LucN80W	78.4	78.8	1.3	1.0
Pac164	45.1	55.2	1.5	25.8	RRS228	96.2	96.2	0.3	0.3
TolmezWE	0.0	0.0	0.0	0.1	Syl360ff	25.0	57.9	0.9	5.4
Bucar0	39.7	39.7	1.3	1.3	Syl360VI	13.0	32.4	0.5	9.0
BCr230	3.1	22.7	0.2	27.9	LAHol0ff	0.0	0.1	0.0	0.4
IVC230	71.0	71.0	1.2	1.2	LAHol0IV	0.0	6.8	0.0	5.5
SecreN27	25.0	43.0	0.8	6.7	KJM000	41.6	69.0	2.9	18.5
1St280	0.0	1.1	0.0	1.2	Tak000	86.6	91.8	0.7	7.0
LGPC000	65.8	75.7	2.0	17.2	YPT330	10.7	14.2	0.5	2.1

[a] (Sorrentino *et al.* 2006); [b] N_O: Normalised number of overturning; [c] $(N_D+N_A)/2$: Average normalised number of changes overturning – no overturning scaling duration and amplitude

7. CONCLUSIONS

In this paper the role of energy damping on the earthquake performance of unreinforced-masonry rocking mechanisms has been evaluated. An experimental campaign considered the influence of several parameters on energy dissipation, measured by means of the so-called coefficient of restitution. Two boundary conditions have been taken into account: two-sided rocking (typical of a parapet wall) and one-sided rocking (façade adjacent to transverse walls). The experimental estimation of the coefficient of restitution was compared to the analytical coefficient of restitution.

In the case of two-sided rocking this coefficient is well known in the literature. The ratio between experimental and analytic coefficients is approximately 0.95. This 5% difference markedly increase the accuracy of the reproduction of experimental time histories, reduces the rate of overturnings and the scatter of the response.

In the case of one-sided rocking the analytic coefficient is not dependant on the size of the contact surface between façade and transverse walls, The tests confirmed this somewhat unexpected behaviour. The average ratio between experimental and analytical coefficients is approximately 1.05.

In both two-sided and one-sided rocking, neither the material of the units nor the height-to-thickness ratio play any systematic role. The behaviour of the specimens is rather stable when the tests are repeated. Displacement capacity is always smaller than what might be estimated based on geometry alone, and it is sensitive to imperfection in the rocking hinge. With reference to the tests performed, experimental displacement capacity is equal on average to 91% of geometrical value in two-sided rocking, and 73% in one-sided rocking. However, such capacity remains fairly stable within a single test series. The same happens to the period of the first quarter of cycle.

Finally, the numerical analyses performed have shown the importance of an accurate estimation of energy dissipation in order to take advantage of time history analyses in the seismic assessment of local collapse mechanisms in unreinforced masonry structures. Such refined estimation of energy dissipation shall also be considered when calibrating equivalent static procedures based on non-linear time history analysis.

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