

MODELING THE DYNAMIC BEHAVIOR OF MASONRY WALLS AS RIGID BLOCKS

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Abstract. *This paper addresses the numerical modeling of masonry walls as rigid blocks. Models based on rigid block assemblies provide a suitable frame work for understanding their dynamic behavior under seismic actions. In this context, the problem is primarily concerned with Rocking Motion dynamics. The numerical tool is based on the Discrete Element Method (DEM) specially effective for the numerical modeling of rigid blocks. Some authors have been used successfully the DEM in the study of block structures. However, they have used experimental test to calibrate their models and to obtain the parameters used in the DEM; because these parameters cannot be obtained directly form the characteristics of the stones. In this context, a new methodology is proposed to find the parameters of the DEM by using the parameters of the classical theory. Special attention regards about the damping factor, since in the DEM a viscous damping is considered, but in reality the damping is due to impulsive forces that they can be considered as a type of Dirac- δ forces. An extensive comparison between numerical and experimental data has been carried out to verified the proposed methodology. Very good agreement between the numerical model and experimental data is achieved.*

1 INTRODUCTION

Historical constructions formed by large stone blocks (i.e. columns, sculptures, arches, Greek temples, etc.) have no tensile strength and stability is ensured if the line of pressure due to their own weight falls inside the structure. These structures are particularly vulnerable objects under lateral seismic loading. However, this behavior is typical of most masonry constructions, which often fail forming large macro-blocks under seismic loading. In this way, the study based upon the assumption of continuum structures would not be realistic for many cases. On the other hand, models based on rigid block assemblies provide a suitable framework for understanding their dynamic behavior under seismic actions. So that the problem is primarily concerned with Rocking Motion (RM) dynamics [2].

Rocking motion is defined as the oscillation of the rigid bodies (RB) present in a structure when center of rotation instantly change from one point to another one; this instantaneous change produces a loss of energy due to an impulsive force.

In this context, the study of the out-of-plane behavior of unreinforced masonry (URM) walls can be studied as an assemblage of rigid blocks. Figures 1 and 2 show two simply models of a URM wall. The first one presents the case in which the URM wall is detached from the rest of the structure. The collapse mechanism is due to overturning of the wall. This behavior can be study by a single rigid block under RM (Figure 1). The second model is made by an ensemble of two rigid blocks. Particularly, this model is useful if the wall has different width along its height or if the upper part of the wall is restrained (Figure 2).

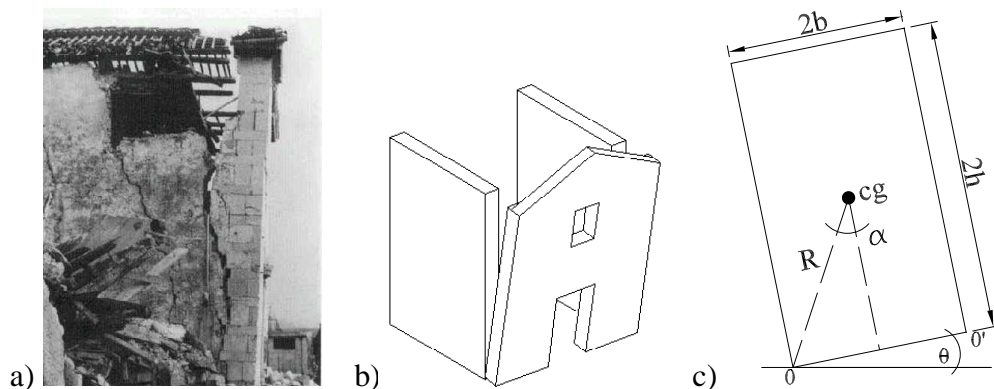


Figure 1: Modeling URM walls as single rigid block; a) real behavior, b) collapse mechanism, c) rigid block model.

The reference analytical frame for the study of RM dynamics remains based on the formulation introduced by Housner [6] (which will be referred as *classical theory* in this study). Housner obtained the equation for the period of the system, which depends on the amplitude of rocking, and the equation for the restitution coefficient.

Several authors [3, 5, 9, 16] have used the *Discrete Element Method* (DEM) to study the rocking motion of RB. Those works show that DEM is a useful tool in the study of RB in free rocking motion or subjected to base motion. However, in the referred contributions, the parameters that define the characteristics of the model (mainly stiffness and damping) are found by means of fitting numerical results to experimental test, being a major limitation of this method for engineering applications. For this reason, a methodology to find the parameters of DE model based on the parameters of the classical formulation is proposed here. An extensive comparison

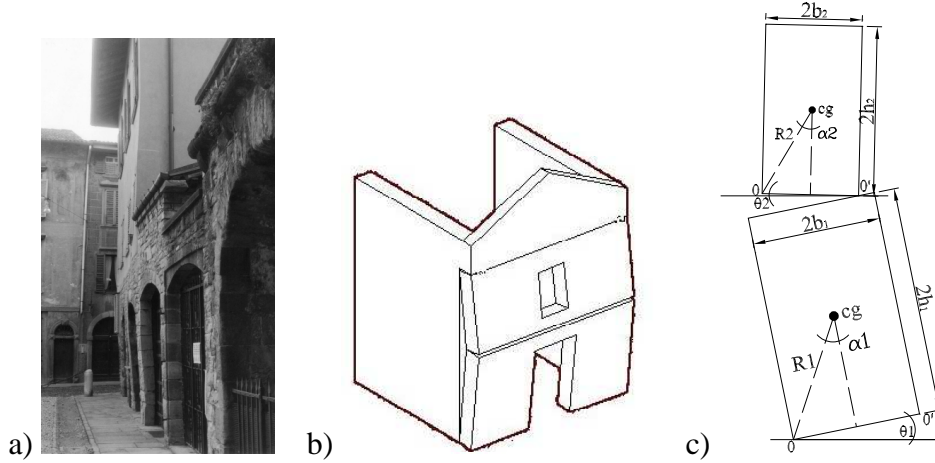


Figure 2: Modeling URM walls as ensemble of two rigid blocks; a) real behavior, b) collapse mechanism, c) rigid blocks model.

between numerical and experimental data [10] has been carried out to verified the proposed model. Very good agreement between the numerical model and experiment is achieved.

2 PARAMETERS OF THE CLASSICAL FORMULATION

It has been observed in experimental test [10, 1, 15] that there are three main parameters for the planar Rocking Motion problem. These quantities depends solely on the geometry of the specimens, as follows: α is defined as the angle at which the stone overturns due to static forces, it is called the *critical angle*; p is the frequency associated to the system due to the interaction between the block and its base and μ is the so-called *coefficient of restitution* and it is defined as the angular velocity reduction ratio, between two consecutive impacts.

These three parameters will be referenced in this work as *theoretical parameters* since they govern the differential equation of RM of a RB. For a rectangular block, with a base $2b$ and a height $2h$ the differential equation is:

$$\theta'' \pm p^2 \sin(\alpha \mp \theta) = p^2 \cos(\alpha \mp \theta) \frac{a(t)}{g} \quad (1)$$

where (') means differentiation with respect to time t , g is the acceleration of gravity, the \pm sign refers to the domains of the rocking angle $\theta > 0$ and $\theta < 0$ respectively, while α is a geometrical parameter defined as:

$$\alpha = \tan^{-1} \left(\frac{b}{h} \right) \quad (2)$$

and p is a parameter with dimensions of frequency defined as:

$$p = \sqrt{\frac{3g}{4R}} \quad (3)$$

where R is defines as: $R = \sqrt{b^2 + h^2}$ (Figure 1c).

In order to take into account the impact mechanism, it is necessary to assume a coefficient of restitution μ [6] that multiplies the angular velocity θ' when the block passes through the

equilibrium position at $\theta = 0$. By considering that angular momentum conservation exist before and after impact, the coefficient of restitution can be obtained by means of:

$$\mu = \frac{\theta'^a}{\theta'^b} = 1 - \frac{3}{2} \sin^2(\alpha) \quad (4)$$

where θ'^a and θ'^b are the angular velocities just after and before the impact, respectively.

3 EXPERIMENTAL TESTS

The numerical model proposed here has been verified by comparing its response with results obtained from an extensive experimental tests on the rocking response of RB. The tests were performed at the shaking table of the National Laboratory of Civil Engineering (LNEC) of Portugal on four single RB (blue granite stones) and one ensemble of two blocks (referred as *bi-block structure*), submitted to different types of base motion. In this section a brief review of the experimental tests is made. The complete description of the experimental tests can be found in [10, 11].

3.1 Characteristics of the specimens

The experimental tests were carried out on four single blue granite stones (Figure 3a) and an ensemble of two blue granite stones (Figure 3b). Each stone has different geometrical dimension (Tables 1 and 2). The dimensions of the single specimens 1, 2 and 3 were fixed to achieve a Height-Width ratio (h/b) of 4, 6 and 8, respectively. In addition, single specimen number 4 was specifically designed with a different geometry than the others specimens, in order to compare its performance with the rest of the stones. It has a large 45 degree cut (40 mm) at the base. Moreover, a foundation of the same material was used as the base where the blocks are free to rock. This foundation was fixed to the shaking table by means of four steel bolts.

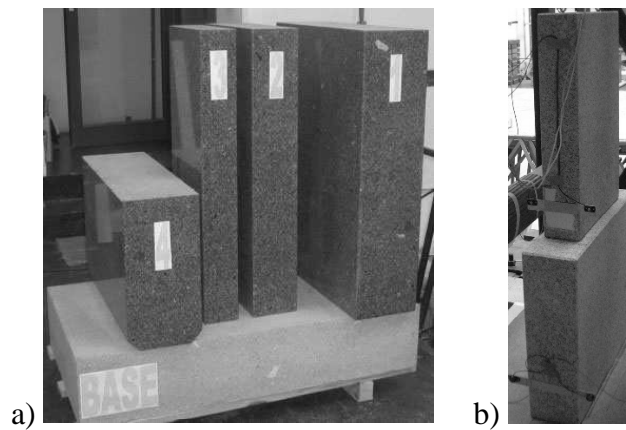


Figure 3: Test specimens, a) single blocks, b) bi-block structure.

3.2 Test set-up

The data acquisition system was designed to describe the position of the specimens at each instant of the test and, simultaneously, to avoid the possibility that the system influences the response of the specimens. In this context, the data acquisition is based upon monitoring Light

Specimen	Width $2b$ (m)	Height $2h$ (m)	Thickness $2t$ (m)	Mass M (kg)	Inertia I_0 (kg-m ²)
1	0.25	1.000	0.754	503	179
2	0.17	1.000	0.502	228	78
3	0.12	1.000	0.375	120	42
4	0.16	0.457	0.750	245	26
Base	1.00	0.250	0.750	500	–

Table 1: Test specimens dimensions.

Block	Width $2b$ (m)	Height $2h$ (m)	Thickness $2t$ (m)	Mass M (kg)	Inertia I_0 (kg-m ²)
Upper	0.15	0.60	0.40	91	5
Lower	0.20	0.60	0.55	204	15
Base	1.00	0.25	0.75	500	–

Table 2: Dimensions of the blocks used in the bi-block structure.

Emission diode Systems (LEDS) by means of high resolution cameras. This eliminates noise errors and enables accurate position measurement.

The main data obtained were: rotations around Y and Z axes, and linear displacements X and Y (see Figure 4 for the system coordinate). Rotations Y and Z were directly measured by means of a mirror linked to the blocks surface on the West face of the specimens. Two accelerometers were placed at the top of each block. One triaxial accelerometer was located in the North face and one biaxial accelerometer was located in the South face. The displacements and accelerations of the shaking table were also measured.

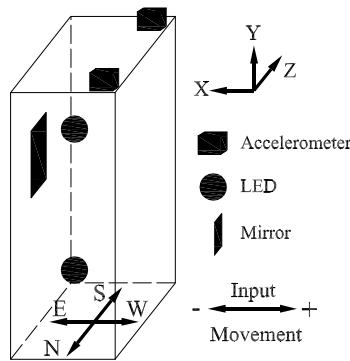


Figure 4: Reference system of the data acquisition system and typical location of LEDs in the RB.

3.3 Types of base motion

In order to study the dynamic behavior of the RB, three different test were made: a) Free rocking motion, b) Harmonic motion, and c) Random motion. The first type of test allows to identify the parameters used in the classical theory and at the same time to calibrate the analytical models. On one hand, the harmonic tests allow to study, in a simple way, the dynamic

behavior of single blocks undergoing RM regime; while on the other hand, the behavior of the RB under earthquake conditions was studied with the random test.

Thirty synthetic earthquakes compatibles with the design spectrum proposed by the Eurocode 8 [4] were generated. In order to identify them, they were named consecutively with the number of generating. Figure 5 shows a typical synthetic record and the response spectrum of four different records. The constant branch of the spectrum is located between 0.1 and 0.3 seconds, with a spectral acceleration of 7 m/s^2 while the maximum ground acceleration is 2.8 m/s^2 . The main aim of the study is to address stability of RM under random motion.

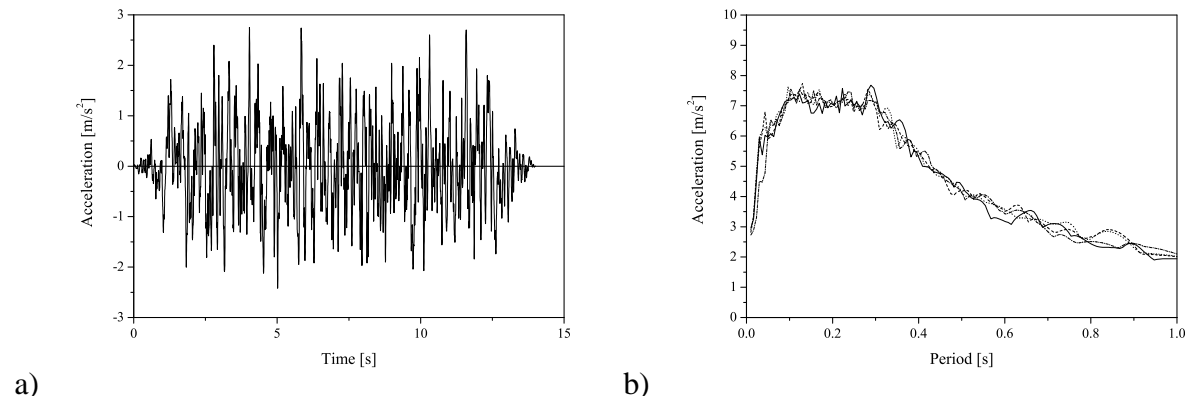


Figure 5: Generation of synthetic earthquakes; a) typical accelerogram, b) response spectra of four different records.

3.4 Theoretical and experimental parameters

The theoretical parameters give useful information about the characteristics of the RM. They can be obtained by Equations 2 to 4 or by means of free rocking motion tests. It is well known that the experimental values of these parameters are not equal to the theoretical values, because the hypotheses assumed by the classical theory are not fully fulfilled. So that, the experimental parameters are adjusted by means of a minimized error surface [10]. In general, the experimental value of α is lower than theoretical while the restitution coefficient (μ) is larger. Parameter p does not have a defined pattern.

Tables 3 and 4 show the theoretical and experimental values of these parameters. Experimental parameters for specimens 1 and 2 are similar to the theoretical values, with differences smaller than 3%. On the other hand, specimens 3 and 4, as well as the blocks of the bi-block structure, present significant differences in their parameters, see [10, 11] for a detail discussion.

It must be highlighted that the calibration of the numerical models (see section 6) were made by using the experimental parameters. The theoretical values were discarded because they do not represent the real parameters of the specimens.

4 NUMERICAL MODEL

The Discrete Element Method (DEM) can be considered as a method for modeling discontinuous media. This analysis technique allows relative motion between elements, which is especially suitable for problems in which the relative motion between blocks is a significant part of the deformation, as in the RM. A brief review of the formulation of the DEM is presented

Specimen	α (rad)			μ			p (1/s)		
	T	E	%	T	E	%	T	E	%
1	0.242	0.235	-2.9	0.914	0.936	2.4	3.78	3.84	1.6
2	0.168	0.163	-3.0	0.958	0.973	1.6	3.81	4.05	6.3
3	0.119	0.154	29.4	0.978	0.978	0.0	3.82	3.61	-5.5
4	0.310	0.268	-13.5	0.860	0.927	7.8	5.16	5.02	-2.7

T = Theoretical, E = Experimental, % = Error (in percentage)

Table 3: Theoretical and experimental classic parameters of single blocks.

Block	α (rad)			μ			p (1/s)		
	T	E	%	T	E	%	T	E	%
Upper	0.245	0.229	-6.5	0.912	0.955	4.7	4.88	5.00	2.5
Lower	0.322	0.366	13.7	0.850	0.948	11.5	4.82	4.50	-6.6

T = Theoretical, E = Experimental, % = Error (in percentage)

Table 4: Theoretical and experimental classic parameters of bi-block structure.

and was taken from [7, 13]. The commercial UDEC code, based on the DEM, has been used to perform the numerical analyses.

The following two main characteristics of the DEM make it suitable for the analysis of RM [13]: a) it allows large displacements and rotations between blocks, including complete detachment of the blocks and, b) it automatically detects new contacts as the calculation progresses.

It is possible to represent the material as rigid or deformable. The first option is used here because in the rocking motion, most of displacements are due to the relative motion between elements and not due to the deformation of the materials. However, the contact between elements (joint) has not been considered as completely rigid because the energy dissipation at each impact depends on the material of the block and its base [17].

The contact between elements is defined as sets of contact points located at the corner of the elements. No special joint element or interface element needs to be defined [13]. The contact point is defined by two linear springs, one axial and one shear, and a viscous damper (Figure 6). The axial spring is linear-elastic in compression, while zero tensile strength is assumed for tension. The shear spring is defined as linear-elastic-perfectly plastic and a Coulomb-type behavior is assumed (Figure 7). Therefore, four parameters are needed to define the mechanical behavior of the contact: axial stiffness K , shear stiffness K_s , friction angle ϕ and cohesion c . The viscous damping C is regarded as a mass M and stiffness K dependent quantity by means of the Rayleigh formulation:

$$C = aM + bK \quad (5)$$

where a is the mass proportional damping constant and b is the stiffness proportional damping constant. These quantities are defined as:

$$a = \xi_{min}\omega_{min}; \quad b = \frac{\xi_{min}}{\omega_{min}}; \quad \omega_{min} = 2\pi f_{min} \quad (6)$$

being ξ_{min} the fraction of the critical damping associated to the frequency f_{min} .

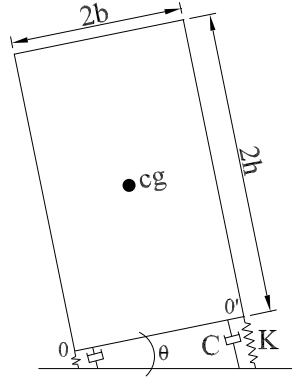


Figure 6: Discrete Element Model.

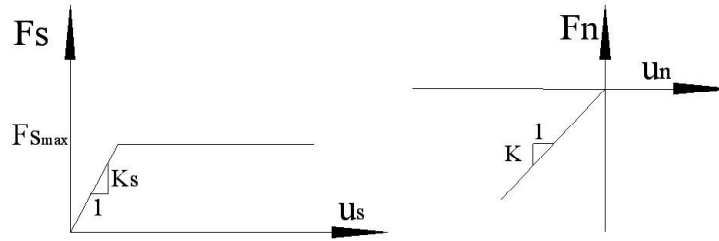


Figure 7: Joint constitutive laws, shear (left) and axial (right).

The stability of the solution algorithm used in the DEM (central difference algorithm) is related to the time step Δt . The stability criteria for inter-block relative displacement must be satisfied and it can be calculated as:

$$\Delta t = (frac)2\sqrt{\frac{M_{min}}{K_{max}}} \quad (7)$$

where M_{min} is the mass of the smallest block in the system, K_{max} is the maximum contact stiffness and the factor $frac$ takes into account the fact that a single block may be in contact with several blocks at the same time. The default value is 0.1 that is usually sufficient to guarantee a numerical stability [7].

5 DERIVATION OF THE JOINT CONTACT PARAMETERS

The parameters required in the DE model are: axial K and shear K_s stiffness, cohesion c and friction angle ϕ , as well as the damping parameters ξ_{min} and f_{min} .

The parameter p can be defined as the frequency associated with the system due to the interaction of the block with its base. Therefore, it can be associated with the frequency of the joint. In this context, it is possible to define the axial stiffness K as:

$$K = Mp^2 = K_1 \quad (8)$$

By taking into account the theoretical value of p (Equation 3), K takes the following value:

$$K = M\frac{3g}{4R} = K_2 \quad (9)$$

It is clear that K_1 will be equal to K_2 if theoretical parameters are used; however if the fitting parameters [10] are used then K_1 will be different than K_2 . For this reason, K is defined as:

$$K = \frac{K_1 + K_2}{2} = \frac{M}{2} \left(p^2 + \frac{3g}{4R} \right) \quad (10)$$

Shear stiffness K_s is considered equal to axial stiffness K [9, 16], while the cohesion c is considered null, as typical of dry joints.

The α parameter can be defined as the relationship between the rotation points of the base (0-0') and the position of the gravity center (cg) of the block. In theory these rotation points are located at the corners of the block; however this is true only if the block and its base are completely rigid. In practice, the rotation points are not located at the corners of the block, because the material is not perfectly rigid. In the DE model, the rotation points are located at the corners of the blocks. Thus it is necessary to consider an equivalent base (b_{eq}), in order to take into account the real value of the α parameter, defined as:

$$b_{eq} = h \tan(\alpha) \quad (11)$$

6 CALIBRATION OF THE MODELS

6.1 Single block model

The free rocking motion tests were used to calibrate the DE model. Table 1 shows the geometrical characteristics of the four specimens used in the experimental testing program; while Figure 8 depicts typical DE models during free rocking motion.

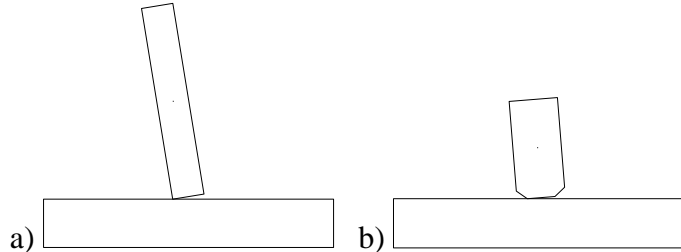


Figure 8: Typical DE models in free rocking motion; a) specimen 2, b) specimen 4.

The numerical models are very sensitive to variations on classical parameters particularly parameter α . The fitting parameters obtained according to the minimization procedure [10] (Table 3) have variations smaller than 5%. However, these small variations induce large differences in the response of the numerical models.

Figure 9 shows the comparison on a typical free rocking test with the response obtained from the DE model using the theoretical and fitted parameters. The friction angle ϕ is considered equal to 30° [8] for the four specimens. It is worth to note that stiffness for each model was calculated with equation 10, while the damping ξ_{min} was fitted in order to obtain the best correlation with the experimental test data. Frequency f_{min} was considered equal to p (Table 5; see next subsection). It can be seen that the response obtained with the theoretical parameters do not fully agree with the experimental data. In particular, the differences lie inside the period and amplitude range of each cycle. On the other hand, good agreement has been achieved between numerical and experimental results when fitted parameters are used.

Specimen	K (N/m)		ξ ($\times 10^{-3}$)		f_{min} (Hz)		$2b_{eq}$ (m)	
	T	E	T	E	T	E	T	E
1	7233	6560	2.92	4.33	3.78	3.84	0.25	0.24
2	3302	3449	1.75	2.34	3.81	4.05	0.17	0.16
3	1174	2168	5.00	0.73	3.82	3.61	0.12	0.15
4	6454	6471	1.50	3.09	5.16	5.02	0.16	0.14

T = Theoretical, E = Experimental, % = Error (in percentage)

Table 5: Parameters used in the definition of the DE models.

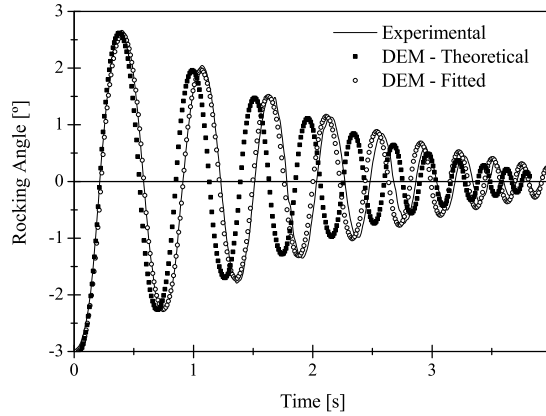


Figure 9: Typical free rocking motion response of DE model using theoretical and fitting parameters (Specimen 1).

The comparison between the acceleration measured at the top of the block and acceleration calculated by the DE model using the fitted parameters is shown in Figure 10 for the horizontal and vertical acceleration. Good agreement between experimental results and numerical model can be again observed. The DE model presents higher values of the acceleration at the impact. Nevertheless, this fact has no physical meaning since it is associated with the higher frequencies obtained during the integration algorithm. In fact, it is possible to filtrate the output in order to cancel the higher numerical frequencies without loosing accuracy.

6.2 Impact and equivalent viscous damping

The damping force appears only in the system during the impact as a Dirac- δ force [10]. As the damping in the DE model is considered viscous and the Rayleigh formulation is used, some considerations must be done in order to take into account the damping in the real system due to the impact. The damping in the DE model is related to each contact point. Thus, when the contact point is detached from the base, the damping must be zero. Therefore, both terms of Equation 5 (damping proportional to the mass and stiffness) must be zero. On the one hand, the damping proportional to the mass will be zero only if $a = 0$. On the other hand, the proportional stiffness damping factor b will be the responsible for introducing the impulsive damping force. This is possible because the stiffness is zero for tensile strength whereas the stiffness will reach a finite value when contact takes place.

With the damping factors obtained with the calibration of the DE model by inverse fitting (Table 5), it is possible to obtain an empirical formula for the equivalent viscous damping. This

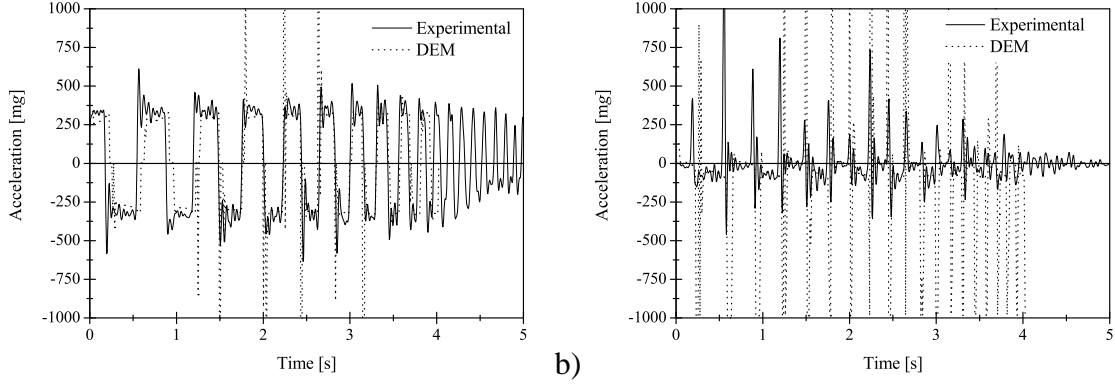


Figure 10: Typical free rocking motion response of DE model using fitting parameters (Specimen 1, with initial conditions from Figure 9); a) Horizontal acceleration, b) Vertical acceleration.

formula is a function of the coefficient of restitution μ and the *generalized damping factor* Γ that relates the generalized damping force Q^d [12] with the viscous damping C . As C depends only on the stiffness K (Equation 5) and Q^d depends on the geometry of the block, Γ can be defined as:

$$\Gamma = KR = \frac{M}{2} \left(Rp^2 + \frac{3}{4}g \right) \quad (12)$$

In Figure 11, the values of factor b versus the ratio Γ/μ^2 for the four specimens are plotted. The best curve fitting is logarithmic and can be calculated as:

$$\sqrt{b} = 0.0057 \ln \left(\frac{\Gamma}{\mu^2} \right) - 0.0336 \quad (13)$$

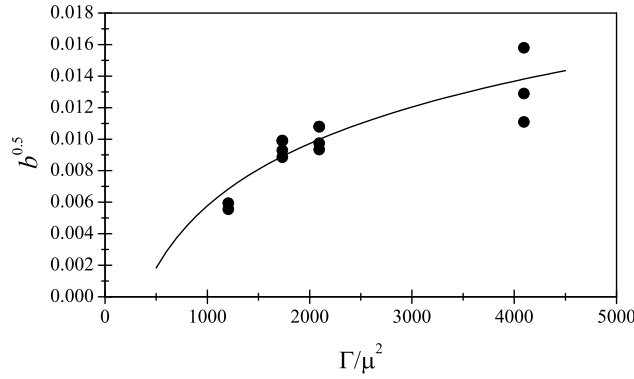


Figure 11: Fitting curve for empirical formulation of equivalent damping.

As p can be considered as the associated frequency of the system due to the interaction of the block and its base, the frequency f_{min} associated with the damping ξ_{min} can be calculated as:

$$f_{min} = p \quad (14)$$

Finally, the damping ξ_{min} is obtained by means of:

$$\xi_{min} = 2\pi b f_{min} \quad (15)$$

6.3 Bi-block model

The free rocking motion tests for each block of the bi-block structure were used to calibrate the DE model. It is worth to note that stiffness for each block was calculated with equation 10, while the stiffness proportional damping constant b was obtained with equation 13. The fitting parameters were used (Table 4). Table 6 shows the parameters used in the definition of the bi-block model, while Figure 12 depicts typical DE model during free rocking motion.

Block	K (N/m)	ξ ($\times 10^{-3}$)	f_{min} (Hz)	$2b_{eq}$ (m)
Upper	2166	0.50	5.00	0.14
Lower	4516	1.50	4.50	0.23

Table 6: Parameters used in the definition of the bi-block models.

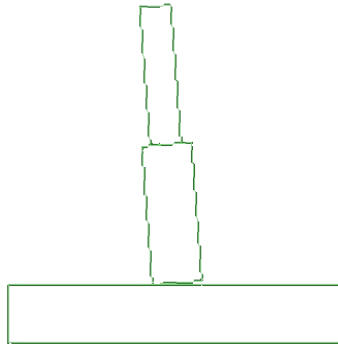


Figure 12: Typical bi-block model in free rocking motion.

Figure 13 shows the comparison between experimental data and DE models of the free rocking tests for each block, considering them as single blocks. Good agreement between experimental results and DE model can be again observed.

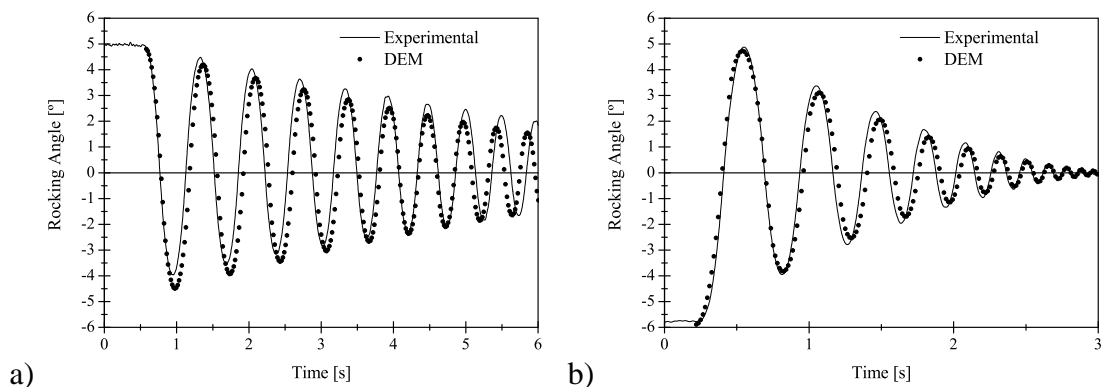


Figure 13: Typical free rocking motion response of DE model using fitting parameters (bi-block structure); a) Upper block, b) Lower block.

7 NUMERICAL SIMULATIONS

The numerical simulations were carried out with the DE models for the single blocks and for the bi-block structure. These models use the parameter values obtained from free rocking test defined in Section 6. Their values remain unchanged for all the harmonic and random simulations.

7.1 Single blocks

Figure 14 shows a typical response of RB under constant sine base motion. For clarity of the figure, there is a gap in the time axis that corresponds to the first part of the stationary state. The response of the model is almost the same as the experimental test even during the last cycles. The three states of the harmonic motions (transient, stationary and free rocking) are well reproduced by the model.

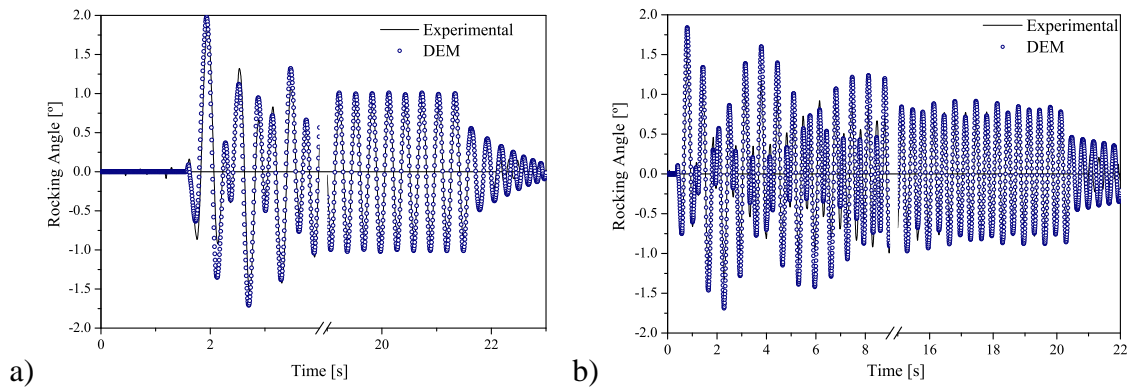


Figure 14: Typical results of harmonic motion simulation with a constant sine excitation; a) specimen 1, constant sine with frequency of 3.3 Hz and amplitude of 6 mm, b) specimen 3, constant sine with frequency of 3.0 Hz and amplitude of 4 mm.

It has been found that under random motion regime the response is very sensitive to perturbations in the boundary conditions as well as impact and base motion characteristics (frequency and amplitude). In particular, small changes in the initial conditions or geometrical variations due to the continuous degradation of the material at impact have shown to cause large differences in the experimental response. Thus, they will be a limitation of the analytical models in the study of the random motion.

Figure 15 shows a typical result of random motion with specimens 2 and 3. The numerical model is again in good agreement with the experimental test. As well as it is successful in predicting the collapse of the specimens.

7.2 Bi-block model

In this section preliminary results from the bi-block model are presented. Figure 16 shows the four possible *patterns* of rocking motion that the bi-block model may exhibit [14]. They can be divided in two main groups. The first one includes the patterns 1 and 2 and they are equivalent to a two degree of freedom system response, in which the two blocks rotate in the same or opposite direction. The second group (patterns 3 and 4) corresponds a single degree of freedom system response. In particular, pattern 3 is equivalent to one rigid structure, while pattern 4 is the case where only the top block experiences rotation [14].

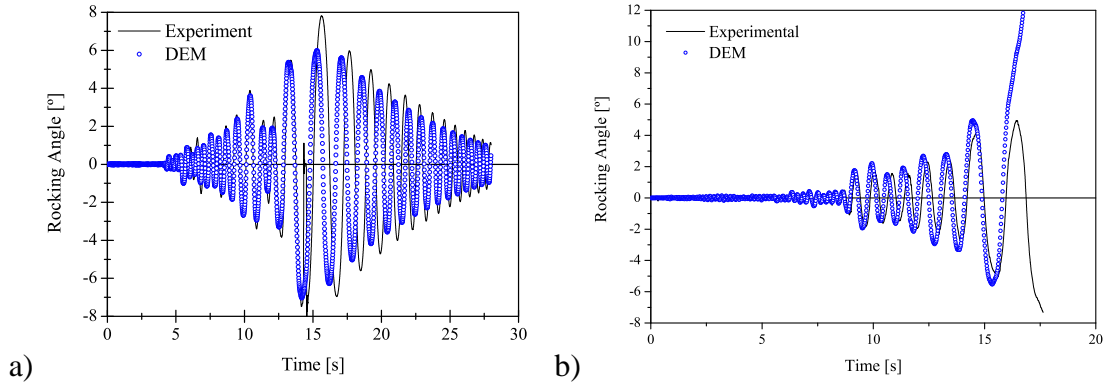


Figure 15: Typical results of random motion test; a) specimen 2, earthquake record 21 and load factor of 0.6, b) specimen 3, earthquake record 18 and load factor of 0.5.

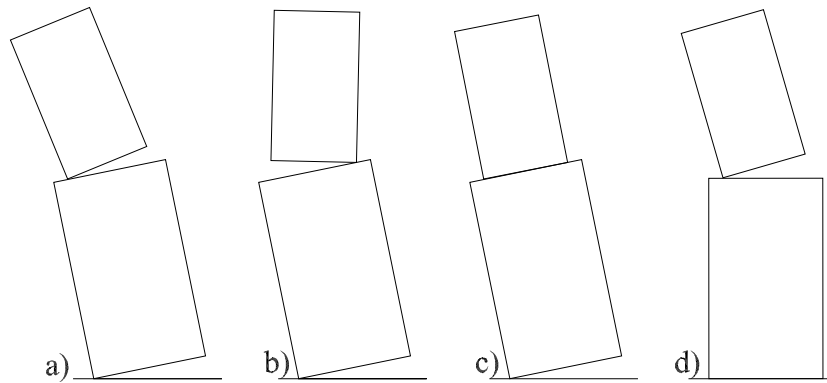


Figure 16: Classification of rocking patterns for a bi-block structure; a) Pattern 1, b) Pattern 2, c) Pattern 3, d) Pattern 4 [14].

From the experimental test first and corroborated by the numerical model, the principal patterns that the bi-block structure tested exhibit are 2 and 3 (Figure 17). These patterns are associated with the amplitude and frequency of the loads. The pattern 2 was recorded with constant sine base motion with frequencies between 4 and 5 Hz and amplitudes greater than 4 mm, with frequency of 6 Hz and amplitudes greater than 3 mm and frequency 7 Hz with amplitudes greater than 1 mm. The pattern 3 was recorded with constant sine base motions with frequencies between 1 and 5 Hz with amplitudes lesser than 4 mm.

Figure 18 shows a typical response of the bi-block structure under constant sine excitation following Pattern 2 (Figure 17a). The maximum response of the lower block is only half degree but the numerical model can reproduce satisfactory the rocking motion of both blocks. On the other hand, Figure 19 shows typical responses with constant sine excitations, following Pattern 4 (Figure 17b). The response of the upper block is only shown because the lower block did not present rocking motion. The numerical model is in good agreement with the experimental data.

8 CONCLUSIONS

- This paper proposed a numerical model to study the out-of-plane behavior of unreinforced masonry (URM) walls, by means of the Discrete Element Method.

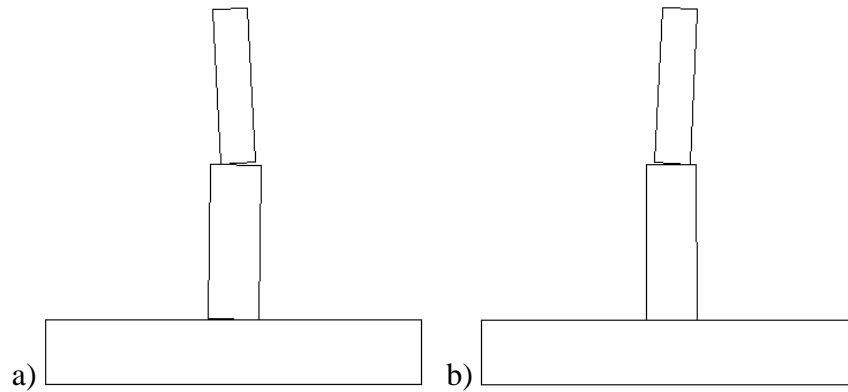


Figure 17: Typical rocking patterns for a bi-block structure found experimentally and numerically; a) Pattern 2, b) Pattern 4.

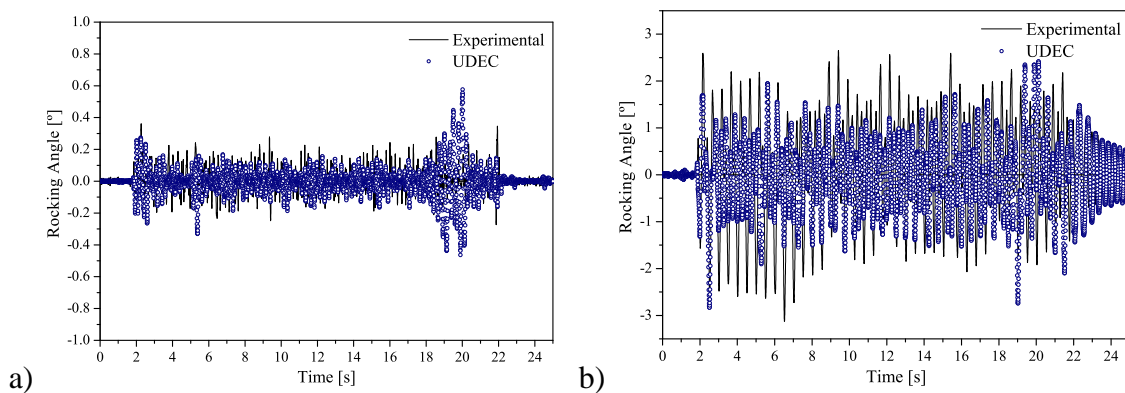


Figure 18: Typical result of harmonic motion simulation with a constant sine excitation with frequency of 4.0 Hz and amplitude of 3 mm; a) Lower block, b) Upper block.

- The Discrete Element Method (DEM) was successfully calibrated and validated with experimental results.
- A new methodology has been proposed to find the parameters of the DE model by using the parameters of the *classical theory*.
- An empirical formula to obtain the equivalent viscous damping necessary to define the DE model has also been proposed.
- The models are extremely sensitive to the *classical parameters* and small variations in their values produce large differences in the response.
- Fitting parameters obtained from experimental data were used in order to obtain good agreement between numerical models and experimental results.
- The equivalent viscous damping is a function of the geometry of the block, the stiffness of the joint and the coefficient of restitution μ .
- Despite the limitations and difficulties to reproduce the initial and boundary conditions, good agreement has been found between numerical and experimental responses.

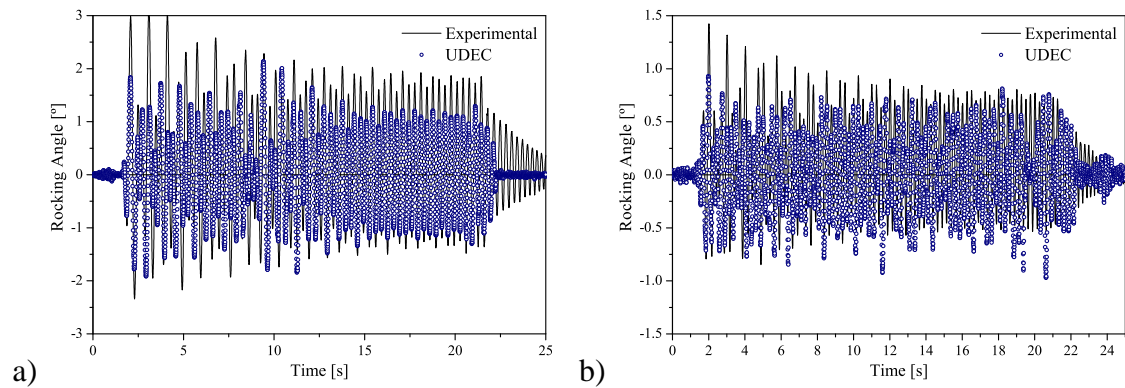


Figure 19: Typical result of harmonic motion simulation with a constant sine excitation (Upper block); a) frequency of 3.0 Hz and amplitude of 3 mm, b) frequency of 4.0 Hz and amplitude of 1 mm.

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