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NUMERICAL ASSESSMENT OF THE OUT-OF-PLANE RESPONSE OF A BRICK MASONRY STRUCTURE WITHOUT BOX BEHAVIOUR

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Abstract *This paper presents the assessment of the out-of-plane response due to seismic loading of a masonry structure without rigid diaphragm. This structure corresponds to real scale brick masonry specimen with a main façade connected to two return walls. Two modelling approaches were defined for this evaluation. The first one consisted on macro modelling, whereas the second one on simplified micro modelling. As a first step of this study, static nonlinear analyses were conducted to the macro model aiming at evaluating the out-of-plane response and failure mechanism of the masonry structure. A sensibility analyses was performed in order to assess the mesh size and material model dependency. In addition, the macro models were subjected to dynamic nonlinear analyses with time integration in order to assess the collapse mechanism. Finally, these analyses were also applied to a simplified micro model of the masonry structure. Furthermore, these results were compared to experimental response from shaking table tests. It was observed that these numerical techniques simulate correctly the in-plane behaviour of masonry structures. However, the out-of-plane failure mechanism of brick masonry model was not accurately reproduced.*

1. INTRODUCTION

Masonry is considered as one of the oldest building materials and is the result of the

arrangement of units with mortar joints. Each of these components present their own material properties, being the mortar joints weaker and softer than the units [1]. Due to the development of advance tools for static and dynamic analyses, the structural assessment of masonry constructions has experienced a significant progress. For this purpose, two numerical approaches have been implemented corresponding to macro and micro modelling of masonry structures. These approaches consist on the modelling of masonry as an equivalent continuum homogenous material, and on the individually representation the masonry units and its interaction with the mortar joints, respectively [2].
When subjected to seismic solicitations, masonry structures experience in-plane and out-of-plane loads. During these type of solicitations, the most common collapse mechanism observed in masonry structures corresponds to the insufficient out of plane strength, the weak connection between orthogonal walls or masonry units with the mortar joints. In the last decades, there has been several experimental, analytical and numerical studies regarding the in-plane behaviour of masonry structure [3-5]. Studies on the out-of-plane response of this type of structures have also been conducted by researched [6-8]. However, the literature regarding this behaviour presents inconsistency.
This paper aims at assessing the effect of seismic solicitations on the out of plane behaviour of masonry structures. Two numerical approaches were taken into consideration for the evaluation of this type of construction namely macro and simplified micro modelling approaches. In addition, these numerical models were subjected to nonlinear static and dynamic analyses for evaluation purposes.

2. EXPERIMENTAL DESCRIPTION

An experimental campaign was conducted in order to determine the mechanical properties and to study the out-of-plane behaviour of a brick masonry structure with English bond. This experimental campaign consisted on the application of vertical and diagonal compression tests aiming at characterizing the material. These tests were conducted to quadratic walletts with 1.00 m x 1.00 m with thickness of 0.235 m as illustrated in Figure 1a. Three wallets were studied according to each test (vertical and diagonal compression), reaching a total of six samples In addition, shaking table tests, consisting on the application of incremental ground motion records, were conducted to a real scale structure. The brick masonry specimen consisted of three walls: one main gable wall with two return walls. The main gable wall had a height of 2.75 m and a length of 3.5 m, whereas the two orthogonal walls presented a height of 2.25 and a length of 2.5 m. The thickness of the three walls presented a value of 0.235 m. In addition, the main gable wall and one of the return walls presented a window opening as illustrated in Figure 1b. It is worth noting that these walls do not present a box behaviour due to the lack of a rigid diaphragm.


(a)


(b)

Figure 1. Experimental campaign: (a) walletts for compression tests, and (b) real scale construction for shaking table tests.

From the compression tests it was possible to determine the mechanical properties of the brick masonry. The Young modulus and compressive strength presented mean values of 5.17 GPa and 2.48 MPa, respectively. In the case of tensile strength and specific mass, the mean values correspond to 0.10 MPa and 1890 kg/m3, respectively. The results from the mechanical characterization are detailed in Table 1.

		Specific mass (kg/m^3)	Young's modulus (MPa)	Compressive strength (kPa)	Tensile strength (kPa)
Brick masonry	V1	1894	6682	2881	-
	V2	1826	3669	2237	
	V3	1821	5152	2329	
	D1	1945	-	-	79
	D2	1906			111
	D3	1974			115
Average values		**1890**	**5170**	**2480**	**100**

Table 1. Mechanical properties of brick and stone masonry under simple and diagonal compression tests

On the other hand, unidirectional seismic loading (perpendicular to the main gable wall) was applied up to collapse to the brick masonry structure in the shaking table tests. Aiming at recording the structure's response due to the dynamic loading, the specimen was instrumented with nineteen accelerometers and six LVDT as illustrated in Figure 2.

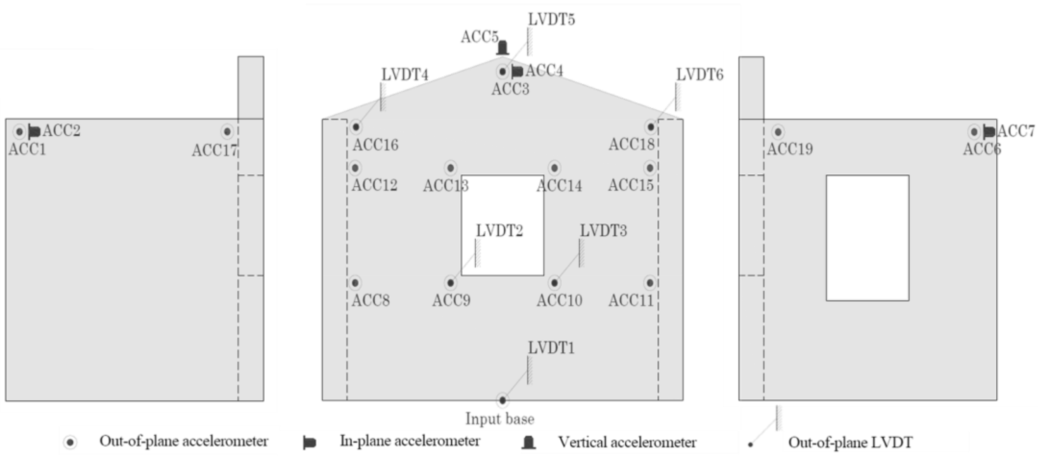


Figure 2. Instrumentation for the shaking table tests for the brick masonry specimen

Throughout the shaking table tests, the brick masonry structure was subjected to eight ground motion records reaching a maximum Peak Ground Acceleration (PGA) of 1.27 g. In the first six motions, it was not possible to identify significant damage. Nonetheless, the structure experienced accumulation of damage and micro cracks. The last two records presented a major influence on the overall stability of the structure in terms of in-plane and out-of-plane behaviour. As it is shown in Figure 3, the return wall with opening experienced an in-plane failure mechanism which consisted on the collapse of the upper part of the wall. On the other hand, the main gable wall presented the total out-of-plane collapse of the tympanum. These two wall also experienced horizontal cracks propagating from the connection until the corresponding opening. Finally, the return wall with no opening did not experienced visible damage.

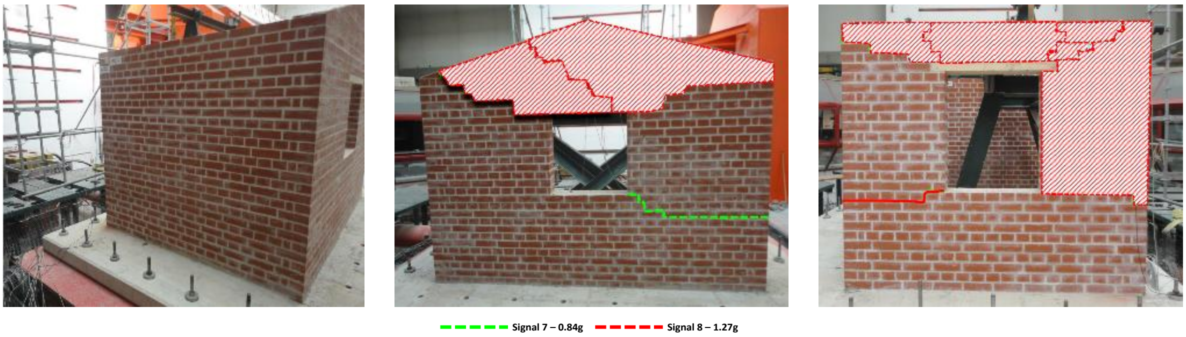


Figure 3. Failure mechanism from the shaking table tests for the brick masonry specimen

3. MACRO MODELLING APPROACH

The numerical assessment of the brick masonry structure was conducted using the software DIANA [9]. The modelling of these specimens was undertaken using brick and wedge quadratic elements (20 and 15 nodes, respectively). Aiming at obtaining a reliable out-of-plane and post peak behaviour by means of macro modelling, an assessment on the mesh size and material model dependency was conducted. For the mesh size dependency, the number of elements the numerical model presented in thickness was evaluated aiming at obtaining a consistent post peak behavior. Since the ground motions at the shaking table tests were applied in the perpendicular direction of the main gable wall, the mesh refinement was mainly focused on this element. The adopted mesh refinement varied between one, two and four elements in the thickness of the main gable wall. For the material model dependency, the total strain crack model was defined for the nonlinear behaviour of the masonry structure. For this purpose, fixed crack models with 5% and 20% of shear retention, and the rotating crack models were taken into consideration aiming at assessing the response of the material behavior. In this study, the brick masonry structure was subjected to nonlinear static (pushover) and dynamic (time history) analysis in order to assess its behaviour under incremental lateral loading and ground motion records, respectively. The mechanical properties such as Young's modulus, specific mass, compressive and tensile strength were obtained from mechanical tests, whereas values for fracture energy were defined from literature. In addition, parabolic and exponential diagrams were selected for the nonlinearity of the material in compression and traction, respectively. Table 2 presents the values used for the material properties of the brick masonry structure.

Linear parameters			Tensile parameters		Compressive parameters	
Young Modulus GPa	Poisson's ratio	Specific mass kg/m^3	Tensile strength MPa	Fracture energy N/m	Compressive strength MPa	Fracture energy kN/m
5.17	0.20	1.89	0.10	12	2.48	3.97

Table 2. Mechanical properties for brick and stone masonry specimen

3.1. Nonlinear static analysis

The nonlinear static (pushover) analysis is considered as an effective tool for the evaluation of the seismic response of civil engineering structures. This type of analysis allows the assessment of the inelastic response in terms on maximum load capacity and displacements. This last parameter presents a close relation to the ultimate limit state of the structure. In addition, this analysis aims at determining the post peak behaviour of a structure under the action of an incremental loading. Due to the advantages of its, the nonlinear static analysis has been implemented for the seismic evaluation of masonry structures [10, 11].

A mass distributed lateral force was applied to the brick masonry model in positive (pushing) and negative (pulling) directions. The response of the structure due to the pushing and pulling incremental loading for the different material models and mesh refinements is shown in Figure 4. Figure 4a-c present the behaviour of the masonry structure according to a specific material model (fixed or rotating crack model). This behaviour is represented by means of pushover curves in which the X axis correspond to the displacement in mm and the Y axis to the load factor (ratio between horizontal loads and self-weight). In addition, each figure presents three curves related to the number of elements the main gable wall have in thickness, defined as Brickx1, Brickx2, and Brickx4, respectively.

From the nonlinear static analysis it was possible to evidence the variability on the maximum load capacity of the structure depending on the number of elements in thickness (mesh size dependency). From the sensitivity analysis it could also be observed that when using two and four elements in the thickness of the main gable wall, the pushover curve presents a consistent performance. On the other hand, it was possible to determine the influence of the material model in the post peak response of the structure. In the case of the fixed model with 20% of shear retention, the structure experienced a hardening behaviour with an increase of the load capacity (see Figure 4a). The brick model with a fixed model with 5% of shear retention presented a ductile response with no significant variation on the load capacity as it is illustrated in Figure 4b. The masonry structure with rotating model presented a softening post peak behaviour which is the characteristic response of brittle materials such as masonry (see Figure 4c). The incremental lateral load was also applied in the negative direction of the brick masonry model using two elements in thickness (pulling) in order to assess its out-of-plane response. The pushover curves for this analyses according to each material model are illustrated in Figure 4d. It can be observed that the hardening/softening post peak behaviour is still governed by the type of material model used for the analyses. However, there is a significant reduction on the maximum load capacity of the structured due to the difference of strength between the main gable wall and the return walls.

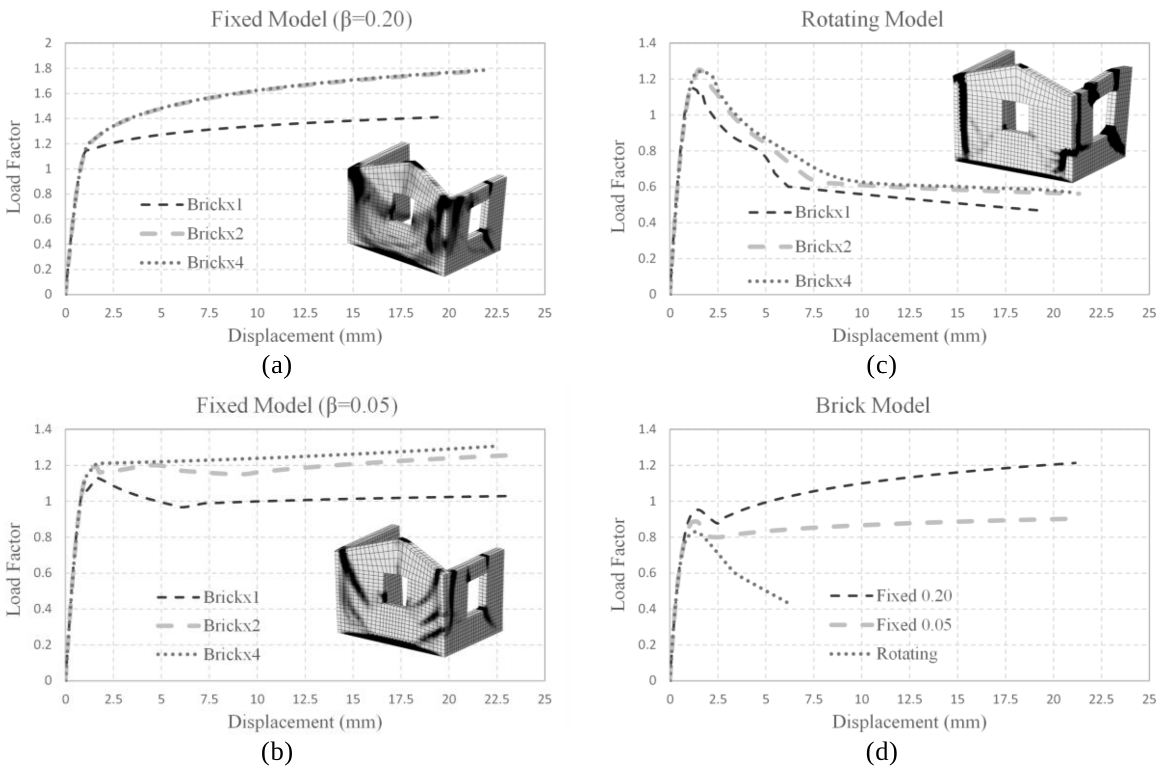


Figure 4. Pushover curves due to incremental loading: fixed crack model with (a) 20% and (b) 5% of shear retention, (c) rotating crack model, and (d) negative direction (with 2 elements in thickness)

The damage of the brick masonry model was assessed by means of principal strains and it was compared to the results from the shaking table tests. It could be observed that the concentration of damage due to the incremental loading does not completely and accurately resembles the experimental dynamic response. There is accumulation of damage in the connection between walls, in the centre part of the tympanum, and at the base of the structure of the main gable wall. In addition, the return wall with opening presented diagonal and vertical strains originating from the opening. It could be observed that the in-plane response of the return wall presented some similarities with the experimental results. However, it was not possible to reproduce the out-of-plane behaviour, which consisted on total collapse of the tympanum.

3.2. Nonlinear dynamic analysis

In addition to the pushover analyses, time history analyses were performed aiming at studying the out-of-plane behaviour of the masonry structure due to ground accelerations and identifying critical damage zones. The ground motion records used for these analyses correspond to the ones from the experimental campaign and were applied in a perpendicular direction to the main gable wall. The brick masonry model was subjected to the last ground motion data from the shaking table, illustrated in Figure 5, presenting a Peak Ground Acceleration (PGA) of 1.27 g (12.46 m/s^2). The values for the mechanical properties of the brick masonry structure as well as the material models correspond to the ones used in the pushover analysis. The influence of the material nonlinearity was assessed by means of hysteretic response and collapse mechanisms.

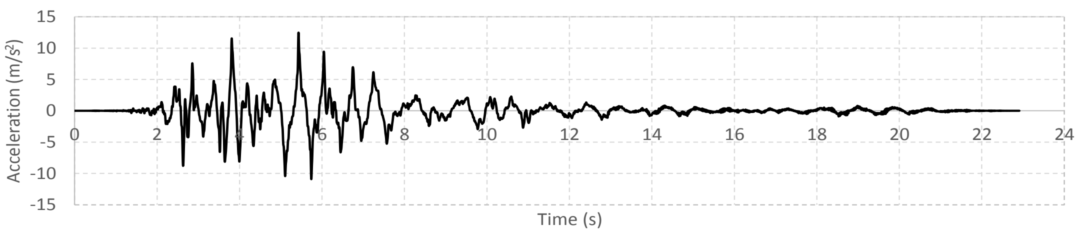


Figure 5. Ground motion record applied to the brick masonry model for the nonlinear dynamic analysis

The response of the brick masonry structure due to the dynamic loading is illustrated in Figure 6. The influence of each material model is represented by means of hysteretic response and principal strains. From the fixed model with 20% of shear retention it was possible to observe accumulated damage in the centre of the tympanum and in the lower part of the window opening of the main gable wall. In the return wall, the damage is located in the corners of the window opening (see Figure 6a). The structure reached a maximum displacement of 5 mm at the top of the tympanum. The fixed model with 5% of shear retention (see Figure 6b) presented a similar behaviour as the one with 20% in terms of damage concentration. However, in this case, the principal strains presented a higher value caused by the reduction of the shear retention factor. In addition, it could be observed from the hysteretic response that the maximum displacement corresponded to 8 mm. Figure 6c illustrates the hysteretic response and the principal strains of the rotating model due to the dynamic loading. It could be observed that there is a significant accumulation of strains in the main gable wall and the return one with opening. The main gable wall presented additional concentration of damage propagating diagonally from the window opening to the return wall without opening. In addition, the vertical strains in the connection of the two walls with opening are more predominant than the ones from the fixed models. In this case, the maximum displacement corresponds approximately to 17.5 mm. Finally, an envelope of the hysteretic response of all the material model is shown in Figure 6d. From this figure it could be observed the influence of the material nonlinearity occurs mainly in terms of deformation of the structure.

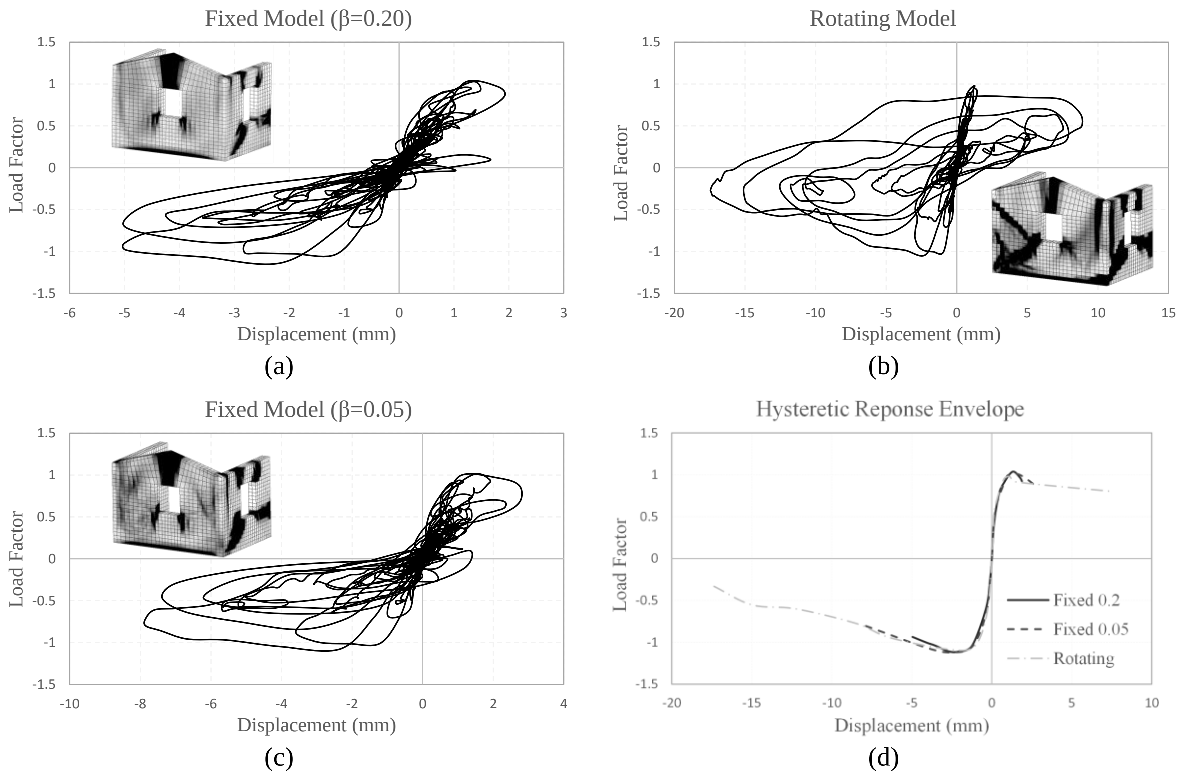


Figure 6. Hysteretic response of the brick macro model: (a) fixed model with 20% of shear retention, (b) fixed model with 5% of shear retention, (c) rotating crack model., (d) envelope

When comparing the numerical response with the experimental one, it was evidenced that the in-plane failure mechanism of the numerical model presented some similarities namely horizontal and vertical cracks from the opening. However, the out-of-plane response of the main gable wall presents significant lack of resemblance, since it was not possible to reproduce the experimental collapse mechanism.

4. SIMPLIED MICRO MODELLING APPROACH

Another alternative for the representation of masonry structures consists on the simplified micro-modelling approach. In this approach, the masonry units are modelled as continuum elements and the interaction between the mortar joints and the masonry units are represented by means of interface elements [12-15]. The simplified micro-modelling approach aims at concentration the damage at the joints as well as potential pure tensile cracks in the masonry units. In addition, the simplified micro-modelling approach is considered to be a reliable tool for the study and understanding of the behaviour of masonry structures since it is possible to take into consideration different failure mechanisms [2]. In this study, the representation of the mortar-unit interaction and masonry units, 8+8 nodes plane quadrilateral and 20 nodes brick together with 15 nodes wedge solid elements were used, respectively. The numerical model of the brick masonry structure is shown in Figure 7.

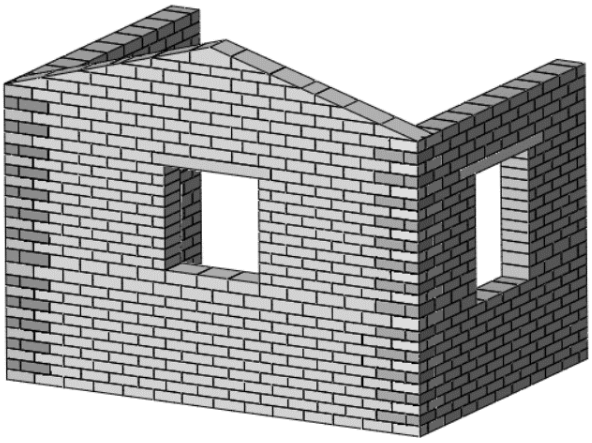


Figure 7. Simplified micro model of brick masonry structure

The mechanical properties of the masonry units presented a linear behaviour, whereas for the interface elements a Combined Cracking-Shearing-Crushing model was defined since it is able to simulate fracture, frictional slip and crushing along the elements (more details in [14, 16]). The mechanical properties used for the simplified micro model of the brick masonry structure are presented in Table 3 and Table 4.

* This element is only considered for the brick masonry model

	Young’s modulus (GPa)	Poisson’s ratio	Specific mass (kg/m^3)
Brick units	20	0.2	1890
Timber lintel*	10		1200

Table 3. Mechanical properties for masonry units and timber lintel

Linear parameters	Normal stiffness	k_n	N/m^3	7.2E+10
	Shear stiffness	k_t		3.0E+10
Tensile parameters	Tensile strength	f_t	kPa	70
	Fracture energy (mode I)	G_f^I	N/m	12
Shear parameters	Cohesion	c	kPa	105
	Friction coefficient	tan φ		0.75
	Dilatancy coefficient	tan ψ		0
	Fracture energy (mode II)	G_f^{II}	N/m	50
Compressive parameters	Compressive strength	f_c	MPa	2.84
	Shear traction contribution to compressive failure	C_{ss}		9
	Fracture energy	G_{fc}	kN/m	3.97
	Equivalent plastic relative displacement	k_p	m	0.01

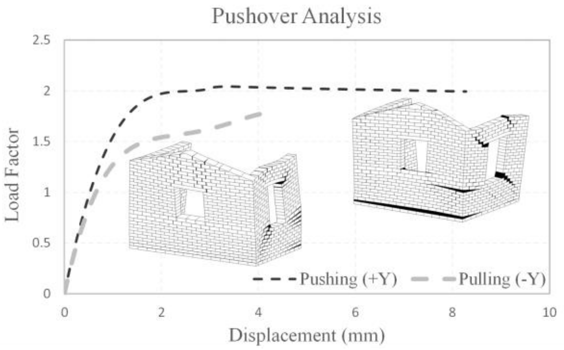
Table 4. Mechanical properties for interface elements

4.1. Nonlinear static analysis

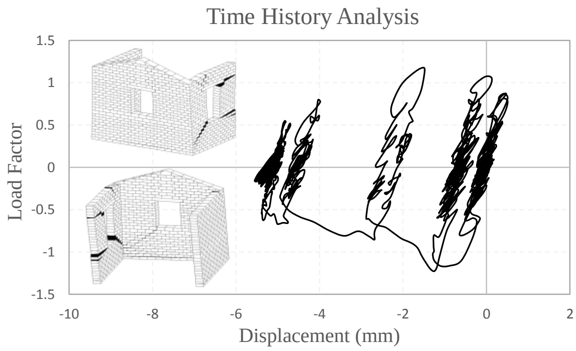
The pushover analysis for the micro model of the brick masonry structure was conducted with the same procedure as for the macro model. An incremental lateral load proportional to the mass was applied perpendicular to the main gable wall in order to assess the out-of-plane behaviour of this type of structures. This behaviour in terms of pushover curves in the positive (pushing) and negative (pulling) directions are shown in Figure 8a. It could be observed that when applying the load in a positive direction the structure presents a ductile behavior with no significant variation of the load capacity. The collapse mechanism of the micro model consisted on diagonal cracks originating from the window opening in the return wall, and a horizontal crack in the connection of the main gable wall with the return wall. On the other hand, the load capacity of the micro model presented a slight increment when applying the load in the negative direction. In this case, the failure mechanism also consisted on diagonal cracks at the window opening, and horizontal cracks at the pier of the return wall. These results presented some similarities with the experimental response in terms of diagonal and horizontal cracks. However, the total out-of-plane collapse of the tympanum was not reproduced.

4.2. Nonlinear dynamic analysis

An initial assessment on the out-of-plane behaviour and collapse mechanism of the brick masonry micro model was conducted by means of dynamic nonlinear analysis. The hysteretic response and the principal tensile strains at the interface elements due to this type of solicitation are shown in Figure 8b. It could be observed that the maximum displacement at the top of the tympanum corresponded to approximately 6 mm. On the other hand, there are two significant horizontal detachments of masonry courses at the pier of the return wall with window opening. This failure mechanism is in good agreement with the experimental response. In addition, there is a stepped detachment of the lower part of the return wall which leads to the out-of-plane collapse mechanism of the main gable wall. However, this crack pattern does not resembles the experimental response of the masonry structure.



(a)



(b)

Figure 8. Micro model of brick masonry structure: (a) pushover analysis in positive and negative directions, and (b) hysteretic response and principal strains

5. CONCLUSIONS

This paper presents the first stage of the evaluation of the out-of-plane behaviour of masonry structures without box behaviour. For this purpose, two modelling approaches were adopted: macro modelling, which consists on representing the structure as a single material, and simplified micro modelling, which consists on the individual representation of masonry units and the interaction between them and mortar joints. In addition, two different numerical techniques were performed in order to evaluate the out of plane behaviour of masonry structures corresponding to pushover and time history analysis, respectively. The results obtained from these analyses were compared with the ones from an experimental campaign that consisted on shaking table tests.

The pushover analysis comes out as a reliable tool for the assessment of the in-plane response of masonry structure when using macro modelling approach. However, this approach is not suitable enough to capture the out-of-plane behaviour of masonry structures. The experimental in-plane collapse mechanism was also reproduced by means of the simplified micro modelling approach. It was also possible to observe the horizontal cracks in the main gable wall and the return wall. However, the overall out-of-plane collapse mechanism from the experimental campaign was not fully replicated. Regarding the nonlinear dynamic analysis, the in-plane response is in good agreement with the experimental response. However, the out-of-plane failure mechanism, namely the total collapse of the tympanum, was not successfully reproduced.

6. ACKNOWLEDGE

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