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Modelling and Evaluation of the Seismic Capacity of Typical Brick URM Buildings of the Historical Center of Cuenca- Ecuador

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Modelling and Evaluation of the Seismic Capacity of Typical Brick URM Buildings of the Historical Center of Cuenca-Ecuador

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Abstract. The Historic Center of Cuenca (HCC) is located in the southern region of Ecuador. It is well known that our country is located on the so-called belt of fire of the Pacific Ocean, this area is characterized by having generated the most important seismic events in the history of mankind. More specifically, there are records that show that in the last 200 years the city of Cuenca has been exposed to earthquakes that have produced moderate to severe damage. These reasons make it possible to establish that the city of Cuenca and specifically its historic center could present important problems in the face of significant seismic events. Most of the buildings in the HCC date back to the middle of the 20th century and have used unreinforced brick masonry (brick-URM) to build their walls. This work is part of the Seismic Vulnerability Project: Seismic Damage Scenarios of the Built Heritage of the Historic Center of Cuenca. In the context of this vulnerability project, the objective of this work was to establish a family of pushover curves for three unreinforced brick masonry buildings typical of the HCC, based on a parametric pushover analysis. The definition of the typical buildings was based on an extensive work of architectural and geometric characterization of the traditional built heritage of HCC. On the basis of focusing the study on two-story buildings (the most common), the size of the floor area of the buildings (small, medium and large area) was assumed as a base parameter. Based on an analysis of the variability of different geometric and mechanical characteristics, and in order to study their influence on the pushover curves of the three typical brick URM buildings, the following study parameters were defined: 1) compressive strength of brick masonry, 2) lateral displacement capacity of brick-URM elements, 3) wall thickness. The pushover analysis was carried out with the Ruaumoko program. The model of the buildings responds to an equivalent portal frame macro-model scheme that has been formulated and validated by the authors of this paper. In order to consider the effects of the flexible floor on the dynamic response of this type of structures, a lateral load pattern that takes into account the contribution of higher order modes of vibration will be used in pushover analysis. The results will be discussed in terms of the incidence of the variability of the study parameters on the basic characteristics of the pushover curves. These results will be an essential input for the next stage of the project consisting of damage estimation for different levels of seismic action expected in the city.

1. Introduction

The city of Cuenca (located in southern Ecuador) has a high level of seismic hazard. Between 1999 and 2002, the *Red Sísmica del Austro* (the seismic monitoring and research center of the University of Cuenca, RSA) carried out the P-BID 400 project: Seismic Hazard in the South and seismic vulnerability in the city of Cuenca ([1], [2]), which evidenced that its historic center is the area most vulnerable to earthquakes. Almost twenty years after this project, the RSA has begun to work on a new study of seismic vulnerability study in the Historic Center of Cuenca (HCC), in order to obtain more reliable damage scenarios for its built heritage. This study, based on modeling and nonlinear seismic analysis, considers the Confidence Factor Method ([3], [4]) as a simplified alternative to account for the uncertainty.

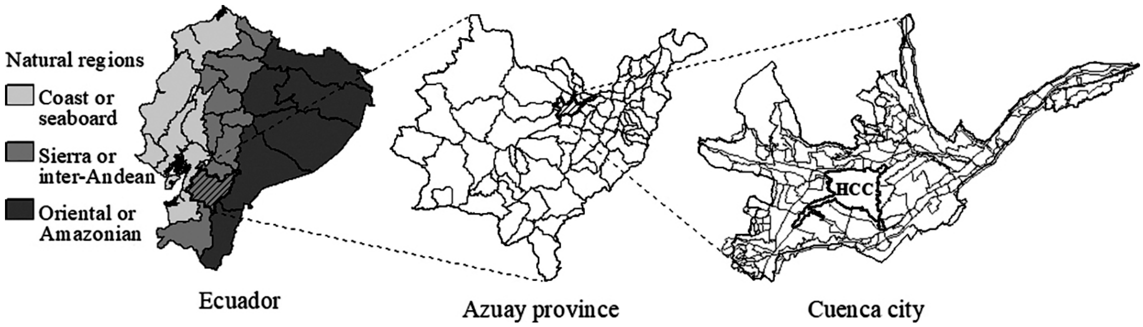

Figure 1. Location of Cuenca city, Azuay province, Ecuador.

Four typologies of URM buildings coexist in the HCC, two traditional and two moderns: adobe-URM, brick-URM, brick-URM with tie beams and brick confined masonry (figure 2). These typologies make up a panorama of low-rise buildings (from one to three stories). The present work dealt with brick masonry buildings (BM-buildings), addressing the first two stages foreseen for the study of their seismic vulnerability: 1) geometric and mechanical characterization and 2) parametric study of seismic capacity, and limiting itself to the most typical case of two-story buildings.

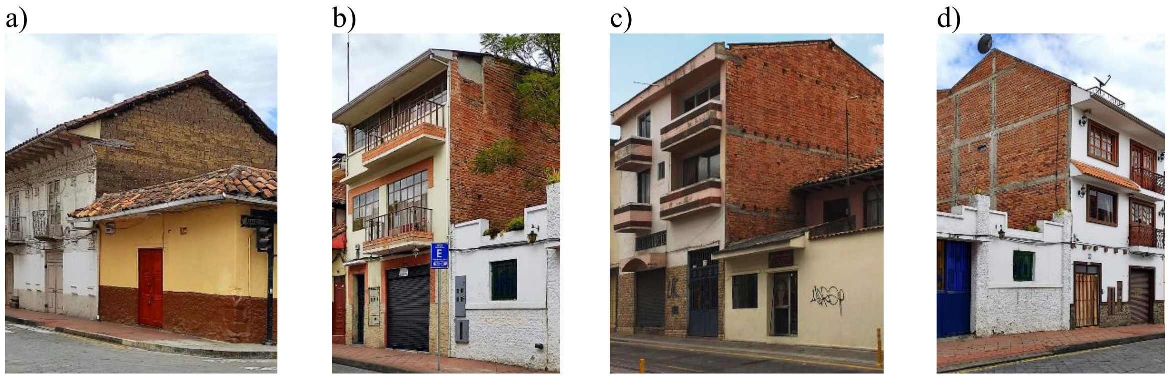

Figure 2. The four typologies of masonry buildings in the Historic Centre of Cuenca: a) unconfined adobe masonry; b) unconfined brick masonry; c) brick masonry with tie beams; d) confined brick masonry [5].

In the framework of seismic vulnerability studies at a territorial scale, characterizing a certain typology of a built heritage based on the definition of typical buildings is a very widespread strategy ([6–12]). Thus, adopting this strategy, the first objective we set ourselves was to establish a catalog of typical BM-buildings. To reach it, the floor area was assumed as the main variable, and three categories (by size) were established: small, medium and large. Based on this initial classification, the variability of different geometric parameters (e.g., floor shape, aspect ratio, interstory height, wall thickness, layout of interior walls) was studied in different ways (e.g., review of different documentary sources, consultation of databases, field work). A catalog of typical buildings was the result of the effort to capture the typicality (e.g., most frequent cases, mean values) of the geometric parameters considered. This whole process is briefly described in the section 3, and more in detail, in [5] and [13].

To capture the real seismic performance of a traditional building, it is necessary to examine the influence of certain variables (e.g. geometric, mechanical) on their seismic capacity [14]. In this regard, the second and main objective of this work is the parametric study of the seismic capacity of three typical BM-buildings of the HCC. Taking as main parameter the size of the floor area (basis for the definition of the three buildings), the effect of the variability of the parameters wall thickness and compressive strength of masonry on the lateral capacity of the established three typical BM-buildings is evaluated.

2. Description of Equivalent Frame Model used

The model for nonlinear static analysis pushover used in this work constitutes an implementation in Ruaumoko-3D ([15]), which develops the strategy of an assembly of spring-based macroelements ([16]). In [12] the kinematic and mechanical models of both the wall macroelement and the floor diaphragm macroelement are described. In addition, the assembly process is explained with two cases: first, a simple building (two stories-one span), and then a complex one; the latter was a typical building of the Eixample-Barcelona. Regarding the validation of the proposed macroelements, four walls tested under lateral load, selected from the literature, constituted the framework for the validation of the wall macroelement (in Ruaumoko-2D).The performance of the floor diaphragm macroelement was examined by comparing the results of modal analysis and pushover analysis of the two buildings modeled with Ruaumoko against the corresponding results obtained on the buildings modeled with Tremuri ([17]).

In figures 3 and 4 the basic schematics of both the wall macroelement and the floor diaphragm macroelement are shown. Figure 5 shows the model of the simple building studied and the assembly of the macroelements. The equivalent frame model of the wall macroelement was based on that proposed by [18]. The strength capacity formulas proposed in [19] were adopted for piers. As for the spandrels, the formula proposed by FEMA 306 [20] for strength capacity against bending failure and those proposed by [21] and [22] for strength capacities against shear failure modes were adopted. The floor diaphragm macroelement, inspired by the one implemented in Tremuri ([17]), does not consider the flexural component in the deformed shape of the flexible diaphragm. Based on this simplification, its behavior was conceived as that of a thin plate with simple shear in the two orthogonal directions, with different shear stiffnesses in both directions (depending on the type of the floor system).

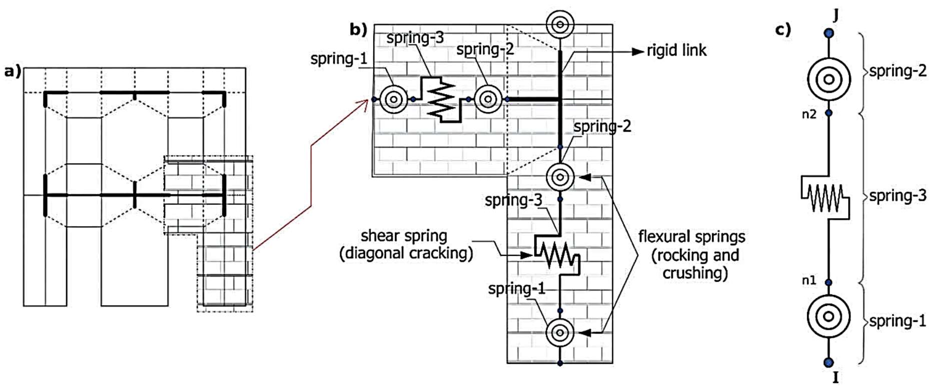

Figure 3. Proposed model for non-linear static pushover analysis of URM walls: a) identification of piers and spandrels; b) assembly of pier and spandrel macro-elements; c) conformation of the generic macro-element [12].

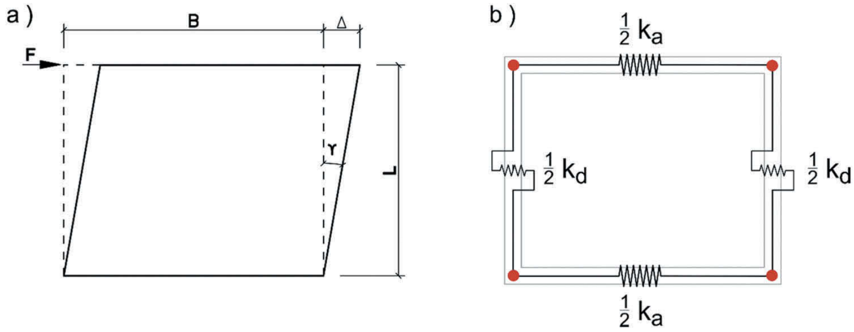

Figure 4. a) Ideal plate under simple shear; b) basic macro-element floor diaphragm to simulate the behavior of the ideal plate (for lateral load in the indicated direction) [16].

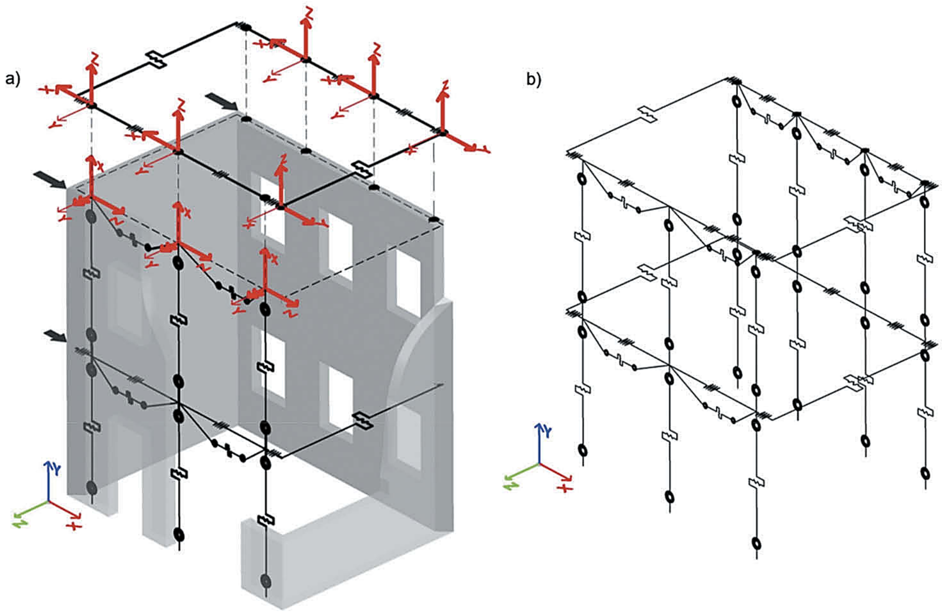

Figure 5. a) Assembly of the macro-element floor diaphragm on the system of equivalent frames, b) 3D-model implemented on Pavia prototype building [12].

It is pertinent to point out that although the equivalent portal frame model was validated in [11] and [17], the behaviour of the numerical models proposed in this work was analyzed by comparing results obtained in Ruaumoko and Tremuri (section 4.4).

3. Geometric properties of typical brick masonry buildings of the Historic Center of Cuenca

The primary sources of information for the global geometric characterization were the Cadastral Database of the City of Cuenca (CDCC), and the works of [2] and [23]. Regarding the distribution of interior walls, the work of [24] was an important contribution. However, given the great difficulty of carrying out inspections inside the buildings, a major effort of archival review was required.

On the basis of consultations in the CDCC on the territorial area of study, once the typological recognition of the buildings (from the wall material) has been carried out, a range of variation of their floor areas and three sub-ranges based on their size were established: Small-Area, Medium-Area and Large-Area. In addition, typical aspect ratios in the buildings were determined for each of these area sub-ranges. The global geometric characteristics (e.g., interstory heights, wall thicknesses) were established, in terms of variation ranges, from the review of the works [2] and [23] and several theses of Architecture (University of Cuenca). The establishment of typical distributions of interior walls and

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patterns of openings in façade walls were among the objectives of the characterization. The patterns of openings in the façade walls were studied from 75 photographic records made in several tours through typical streets of the HCC.

The study of the distribution consisted of a review of part of the physical and digital archive of intervention proposals in the buildings of the HCC. A survey formulary was implemented in a database and included four information blocks: 1) identification and general information, 2) typological characteristics, 3) architectural characteristics, 4) floors and roof. Although the focus was on the architectural characteristics block. Finally, in the case of traditional brick buildings, the synthesis of these results with those of an architectural nature made it possible to obtain a catalogue of typical buildings (figure 6).

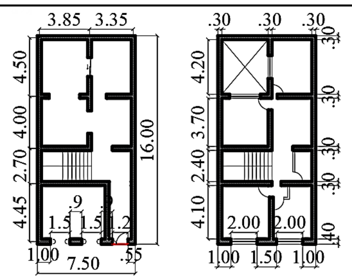
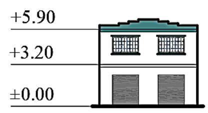
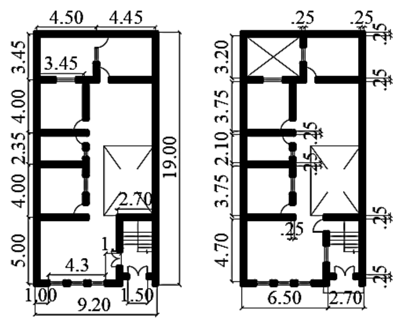
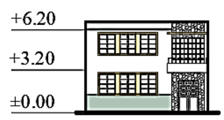
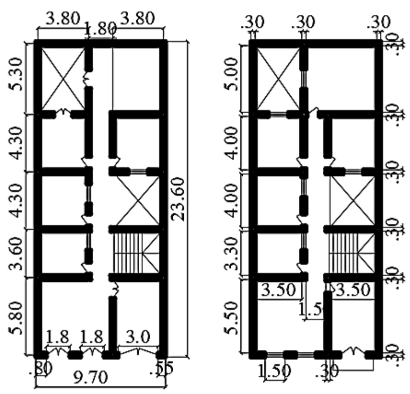
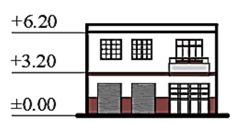
Description	Floors	Facades
Small-Area (40 m2 to 120 m2) First floor area= 120 m2 Front to back ratio = 0.50 Front façade: two vertical alignments with door-window type openings. Ground floor use: commercial and residential. First floor: housing.	 Ground floor First floor	 Front facade
Area-Average (120 m2 to 200 m2) First floor area = 175 m2 Front-to-back ratio = 0.48 Front façade: four vertical alignments with door-window type openings. Ground floor use: commercial and residential. First floor: housing.	 Ground floor First floor	 Front facade
Area-Large (200 m2 to 300 m2) First floor area = 230 m2 Front-to-back ratio = 0.41 Narrow front. Front façade: three vertical alignments with door-window type openings. Ground floor use: commercial and residential. First floor: housing.	 Ground floor First floor	 Front facade

Figure 6. Typical BM-buildings in the Historic Center of Cuenca [13].

4. The Analysis

The capacities of a building in the non-linear range can be studied by means of its capacity curve. This representation correlates the displacement of the upper level of the building against its base shear, product of the action of lateral forces increasing. In many cases, the use of nonlinear static pushover analysis has been preferred over other methods because of its relative ease of application [21]. The pushover analysis ends when a target displacement or failure condition is reached.

4.1. Mechanical characterization of walls and floor system

Currently, the seismic vulnerability project: Seismic damage scenarios of the built heritage of the Historic Center of Cuenca, which is being developed by the RSA, shows results regarding the mechanical characterization of the masonry used in the construction of walls of the URM-buildings of HCC. The values shown in figure 7(c) correspond to values proposed in the aforementioned project and have been used in the present study.

Floor systems have an important role in the transmission of seismic actions to the different elements of a structure. Rigid diaphragms transfer the lateral load to the walls of the structure in proportion to their stiffness, on the other hand, flexible floor diaphragms cause the walls to act independently depending on their degree of flexibility [25]. The floors and roofs used in the HCC buildings in the late 19th century and during the 20th century were built with wood as the main material [26]. One-way wood floor systems, such as those in HCC, constitute flexible floor systems. The flexible diaphragm model used in this work consists of the macroelement outlined in the figure 4. According to [27,28], the value of shear stiffness (G) for timber floors in HCC varies between 5 and 20 MPa. In this study, a value of G equal to 10 MPa has been established, corresponding to the average of limit values.

4.2. Considerations about study parameters

Due to the existence of different types of brick units at the time, a variation in wall thickness ranging from 15cm to 30cm can be found [13] to brick-URM in HCC. The brick wall thickness (t) is an important parameter in the analysis of the structural capacity of brick-URM buildings, the shear and bending resistance of columns and beams is closely related to cross section of walls, therefore, to verify the influence of this parameter three values of wall thickness were established: 15, 20 and 30 cm.

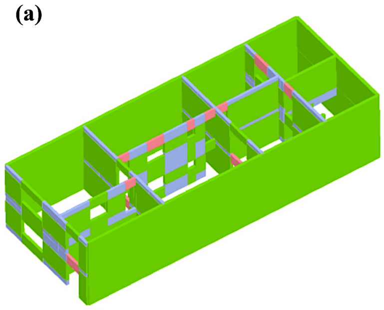
In addition to wall thickness, the compressive strength (f'm) of the masonry has a significant contribution to the lateral force capacity of brick-URM buildings. This parameter is directly related to the mechanical characteristics of components constituting masonry (brick units, mortar joint). There are several empirical expressions ([29–31]) that allow defining f'm as a function of the properties of brick units and mortar joint. The f'm values used in the development of this research have been obtained employing formulations and following bibliographic research on the characterization of masonry developed in the city of Cuenca ([32–37]). An average value of f'm equal to 3.00 MPa was established. To determine how much the variability of f'm affects the structural capacity of the brick-URM buildings, three values for f'm were specified: 1.50, 3.00, and 6.00 MPa.

Regarding the lateral displacement capacity of columns and beams, it was considered relevant to take into account the multi-linear models proposed in [16], to represent the force-displacement curves of springs used in the equivalent portal frame configuration. To establish the F-D curves of elements subjected to shear and bending, maximum drift values equal to 0.4 and 0.6, respectively, were used. The proposed multi-linear models are capable of describing the response of URM members (columns and lintel beams) up to very severe levels of damage [38]. They would give result, therefore, in pushover curves on which they could more reliably establish the correlation between damage and performance levels.

4.3. Validation of the proposed model

The purpose of this task was, as an additional validation of the proposed model (section 2), to compare the results obtained by analyzing the Medium-Area model, with a wall thickness equal to 20 cm, using the Tremuri and Ruaumoko programs. The results can be seen in figure 7d, it can be verified that the capacity curves show a good correlation using the two programs.

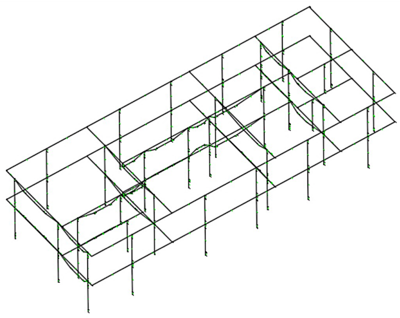
(a)



(c)

Brick masonry		
Young modulus (E)	[MPa]	1680
Shear modulus (G)	[MPa]	500
Compressive strength (f_u)	[MPa]	2.8
Shear strength (f_{vk0})	[MPa]	0.6
Specific weight	[kN/m^3]	14
Brick units		
Tensile strength (f_{bt})	[MPa]	1.8
Mortar joints		
Cohesion (c)	[MPa]	0.2
Friction coefficient (μ)	-	0.7

(b)



(d)

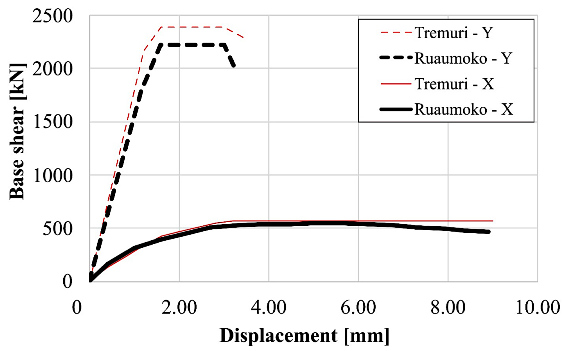


Figure 7. Results comparison: a) Tremuri model; b) Ruaumoko model; c) Mechanical properties of masonry; d) Pushover curves.

4.4. Pushover parametric analysis

To demonstrate the effect of the variability of t and f'm, on the seismic performance of typical brick-URM buildings of HCC, the evaluation of 27 structural models that correspond to the variation, as a function of the plan area of the prototype buildings, of t and f'm was developed (Figure 9). Each model was subjected to a lateral load pattern, proportional to the first vibration mode of the structure, to obtain the corresponding capacity curve.

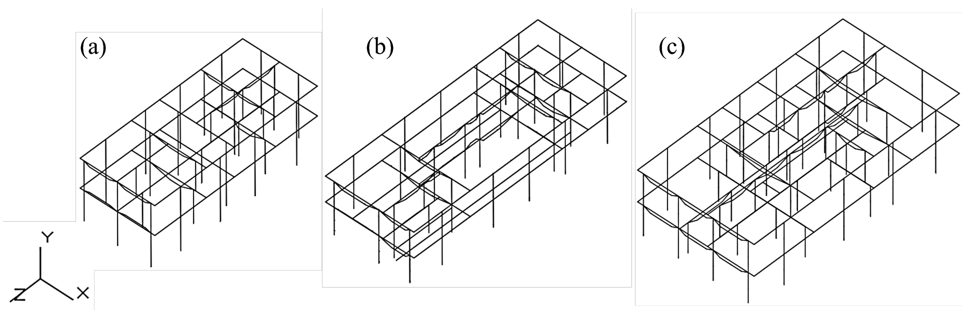


Figure 8. BM-buildings base models implemented in Ruaumoko-3D: a) Small-Area, b) Medium-Area and c) Large-Area.

The pushover analysis of the numerical models was performed in the X direction (figure 8), this direction corresponds to the orientation of walls that show lower lateral load capacity compared to walls oriented in the Z direction. Figures 10, 11 and 12 present the pushover curves in the considered direction for the small, medium and large area models respectively.

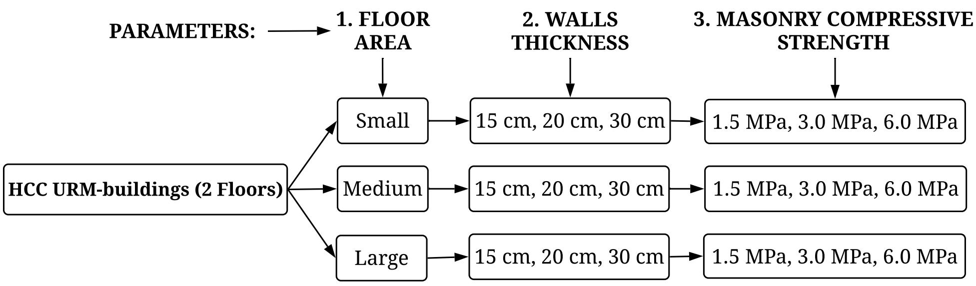


Figure 9. Proposed scheme for parametric analysis of BM-buildings

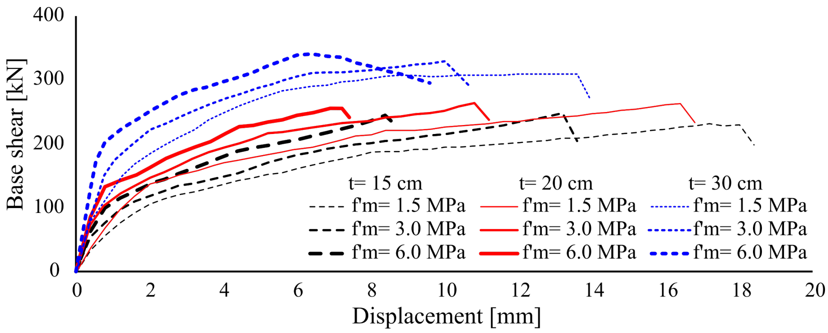


Figure 10. Pushover curves: Small-Area.

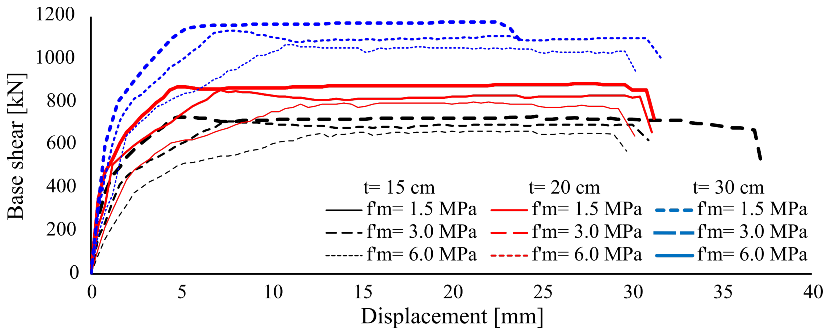


Figure 11. Pushover curves: Medium-Area.

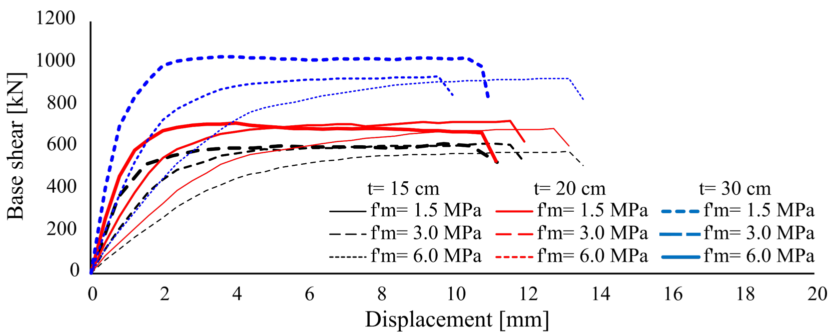


Figure 12. Pushover curves: Large-Area.

5. Results and discussions

A detailed numericals models were prepared in accordance with the experimental setup, using a macro-modelling technique for the masonry wall. The models were calibrated and validated in accordance to the available experimental results. The influence of the parameters wall thickness and compressive strength of masonry on the lateral capacity of typical HCC buildings are summarized in table 1.

Table 1. Maximum base shear values and variation percentage respect thickness (t).

t [cm]	f'm [MPa]	Max. Base shear Small-Area [kN]	Max. Base shear Medium-Area [kN]	Variation %	Max. Base shear Large-Area [kN]	Variation %
15.0	1.5	231.5	666.2*	-	578.2	-
20.0	1.5	263.6	798.4	19.85	666.9	15.35
30.0	1.5	322.2	1066.9	60.15	912.1	57.76
15.0	3.0	248.8	711.6*	-	618.2	-
20.0	3.0	264.4	854.6	20.09	694.5	12.35
30.0	3.0	358.9	1133.8	59.32	915.6	48.11
15.0	6.0	243.9	734.3*	-	618.5	-
20.0	6.0	275.1	887.9	20.93	710.6	14.89
30.0	6.0	370.9	1172.1	59.64	1007.5	62.90

* Reference values

Table 2. Maximum base shear values and variation percentage respect compressive strength (f'm).

f'm [MPa]	t [cm]	Max. Base shear Small-Area [kN]	Max. Base shear Medium-Area [kN]	Variation %	Max. Base shear Large-Area [kN]	Variation %
1.5*	15.0	231.5	666.2	-	578.2	-
3.0	15.0	248.8	711.6	6.82	618.2	6.92
6.0	15.0	243.9	734.3	10.21	618.5	6.96
1.5*	20.0	263.6	798.4	-	666.9	-
3.0	20.0	264.4	854.6	7.03	694.5	4.14
6.0	20.0	275.1	887.9	11.20	710.6	6.54
1.5*	30.0	322.2	1066.9	-	912.1	-
3.0	30.0	358.9	1133.8	6.27	915.6	0.38
6.0	30.0	370.9	1172.1	9.86	1007.5	10.45

* Reference values

Taking as reference the maximum base shear with f'm= 1.5MPa, obtained for t= 15cm and comparing it with the results for t= 20cm and t= 30cm, we can evidence an increase in the maximum base shear of 19.85% and 60.15% when t varies from 15cm to 20cm and from 15cm to 30cm respectively. Similar behavior occurs for f'm= 3.0Mpa and f'm= 6.0MPa (table 1). In contrast, variations of f'm (1.5MPa to 3.0MPa and 1.50MPa to 6.0MPa) for t= 15cm, produce increases in the maximum shear strength in percentages equal to 6.92% and 6.96% respectively. The same occurs for values of t= 20cm and t= 30cm (table 2).

6. Conclusions

The input parameters for generating models of BM-buildings have been determined from experimental test and guidelines available in the literature. Three typical buildings representative of the HCC have been modeled and parametrically analyzed. The outputs are pushover curves showing the base shear capacity of 27 models. After reviewing the results, we can establish that the most influential parameter on the base shear capacity of HCC buildings is the wall thickness. Additionally, it was found that the Medium Area model presents the best seismic behaviour. Analyzing the pushover curves of Medium-Area model, we verified the highest values of base shear and displacement for variations in wall thickness - masonry compression strength. This tendency would imply that the architectural distribution of walls and floors defined for the Medium-Area model is better and both the base shear and the ductility of the buildings are not a function of floor area. Future work will analyze this aspect in more details, and it is proposed to define the influence of wall density on the seismic capacity of the UM-buildings.

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