ABE IEE ADVANCES IN BUILDING EDUCATION INNOVACIÓN EDUCATIVA EN EDIFICACIÓN

Definition of the characteristic masonry house for seismic vulnerability assessment in the Historic Centre of Cuenca, Ecuador

Definición de la vivienda característica de mampostería para evaluación de vulnerabilidad sísmica en el Centro Histórico de Cuenca, Ecuador

David Cajamarca-Zuniga **[1-2*]*, Carlos Julio Calle*** **[2-a]*, Dorian Marín*** **[2-b]*, Michael Morocho*** **[2-c]**

[1] *Institute of Industrial and Civil Engineering, National Research Moscow State University of Civil Engineering, Russia*
[2] *Carrera de Ingeniería Civil, Universidad Católica de Cuenca, Ecuador*
[*] *cajamarca.zuniga@gmail.com, Moscow, 129337, Russia, +792663234403*
[a] *cjcallec@ucacue.edu.ec* , [b] *marin.dorian.95@hotmail.com* , [c] *ymmorochog27@est.ucacue.edu.ec*

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HIGHLIGHTS

- Seismic vulnerability analysis considers the characteristics of a building to quantify damage.
- The characteristic dwelling is a two-storey masonry house with 2 transverse spans.
- The first-order area of the Historic Centre of Cuenca includes 2885 dwellings.

TITULARES

- El análisis de vulnerabilidad sísmica considera las características de una edificación para cuantificar el daño.
- La vivienda característica es una casa de dos plantas con 2 vanos transversales.
- El área de primer orden del Centro Histórico de Cuenca incluye 2885 viviendas.

ABSTRACT

The historic centre of the city of Cuenca is a UNESCO World Heritage Site and is located in a zone of high seismic hazard. For these reasons, the Urban Development Plan of Cuenca sets out the need to implement measures for the conservation of buildings. The analysis of the seismic vulnerability of buildings makes it possible to develop effective strategies for the prevention and mitigation of damage and reduction of losses due to earthquakes. Since seismic vulnerability analysis considers the characteristics of a building to quantify damage, it is necessary to determine a model that appropriately reflects the structure of the building under study. The aim of this work is to define a characteristic brick masonry house in the Historic Centre of Cuenca (HCC) and to generalise its architectural features, geometry, structural system and materials. The results of the analysis of field data collected in the HCC comprising 2885 dwellings are presented. Each dwelling was characterised by 5 geometrical and 3 structural parameters. Statistical frequency diagrams were elaborated to define the most representative variable for each parameter. By spatial superimposition in the ArcMap program, the characteristic dwelling was defined as a two-storey masonry house with two transverse and three longitudinal spans and a cantilever on the front façade. The structural system consists of 17 cm thick brick walls, confined by reinforced concrete columns and beams, timber floor structures and a gable roof with ceramic tiles.

Keywords: *Assessment; Brick; Earthquake; UNESCO; Cultural Heritage; Masonry structures.*

RESUMEN

El Centro Histórico de la ciudad de Cuenca es catalogado por la UNESCO como Patrimonio de la Humanidad y se encuentra ubicado en una zona de alto peligro sísmico, por estas razones el Plan de Desarrollo Urbano de Cuenca plantea la necesidad de implementar medidas de conservación de las edificaciones. El análisis de la vulnerabilidad sísmica de las edificaciones permite desarrollar estrategias efectivas para la previsión y mitigación de daños y reducción de las pérdidas debidas a los sismos. Dado que el análisis de la vulnerabilidad sísmica considera las características de una edificación para cuantificar el daño, es necesario determinar un modelo que refleje de manera apropiada la estructura en estudio. El objetivo de este trabajo es definir una vivienda característica de mampostería de ladrillo en el Centro Histórico de Cuenca (CHC) y generalizar sus características arquitectónicas, geometría, sistema estructural y materiales. Se presentan los resultados del análisis de información de campo recolectada en el CHC que incluye 2885 viviendas. Cada vivienda fue caracterizada mediante 5 parámetros geométricos y 3 estructurales. Se elaboraron diagramas de frecuencia estadística para definir la variable más representativa de cada parámetro. Mediante superposición espacial en el programa ArcMap se definió que la vivienda característica es una casa de mampostería de dos plantas, dos vanos transversales, tres longitudinales y un voladizo en la fachada frontal. El sistema estructural comprende paredes de ladrillo de 17 cm de espesor, confinadas por columnas y vigas de hormigón armado, entrepisos de madera y techo a dos aguas con tejas cerámicas.

Palabras clave: *Evaluación; Ladrillo; Terremoto; UNESCO; Patrimonio Cultural; Estructuras de mampostería.*

1. INTRODUCTION

The seismic vulnerability of a building is a value that defines and quantifies the type of structural damage, failure mode, and resilience of a structure under probable earthquake conditions at a given site. The aim of seismic vulnerability analysis is to assess the impact of earthquakes on structures and to develop effective risk management and mitigation strategies to prevent damage and minimise losses from earthquakes [1]. Seismic vulnerability assesses and quantifies the structural damage of a building due to the characteristics of the structure itself. The seismic vulnerability of a structure can be assessed using empirical, semi-empirical or analytical methods. The analytical method for determining the seismic vulnerability of a building is based on a structural three-dimensional non-linear dynamic analysis of its numerical model [2, 3]. Consequently, in order to perform a proper seismic vulnerability analysis, it is important to have a numerical model that represents the actual structure under study as accurately as possible. For this purpose, it is necessary to define the materials, geometry, architecture and structural system of the building.

A general characteristic of buildings in historic centres is that they were designed and constructed before the introduction of seismic design codes, so they are primarily designed to resist the action of gravity loads. In seismically active regions, structures are subjected to significant lateral seismic loads that completely alter the work of the load-bearing elements [4]. Seismic actions induce a biaxial stress state in masonry that affects both the local and overall stability of the structure. The damage evolution under this stress state depends on the physico-mechanical properties of the masonry materials and the contact interaction between them.[5–9].

J. Ayora [10] conducted one of the first studies on seismic vulnerability of Cuenca. The study considered seismic scenarios that accounted for factors such as site geology, soil type, seismic activity, and instrumentation. The aim was to produce a seismic vulnerability map of the site. This study presents a seismic vulnerability map of the studied dwellings. It concludes that most of the damage occurs in two-storey buildings. However, it does not carry out structural modelling. J. Jiménez [11] conducted a study on seismic vulnerability based on the cadastral database of the city of Cuenca. This work models masonry buildings with reinforced concrete confining frames and estimates total damage and vulnerability indices of structures. However, this work did not take into account the characteristics of the materials and the specific structural typology in the study area. Based on the nonlinear static pushover method applied to a numerical model, A. Ortega [12] carried out a seismic vulnerability study of 3 randomly selected masonry houses located in the peripheral zone of the city of Cuenca. R. Quezada [13] describes 6 types of masonry houses that are structurally representative of residential buildings in the Historic Centre of Cuenca (CCH). He presents the corresponding geometric and architectural dimensions, but did not perform a numerical simulation to determine the stress-strain state under seismic actions.

The analysis of the development of housing construction characteristics in Cuenca reveals that one of the initial building methods employed was dry-stone masonry or masonry with natural stones and mud mortar joints. This was followed by the traditional “*bahareque*” construction method, consisting of wooden frames and reeds (*Phragmites australis*) bound together with '*cabuya*' (*agave fibre*) and filled with fibre reinforced mud with the use of vegetable fibres [14].

Fig. 1: *Regional traditional "bahareque" construction technique.*

In Ecuador, the production of ceramic bricks dates back to 1565 [15], however, their massive use was developed during the 19th and 20th centuries when bricks began to be used massively to construct hotels, churches, public and financial buildings [16]. In the first half of the 20th century, low-rise houses were built while conserving the colonial architecture. The used construction system was a combination of bahareque and adobe masonry with a thickness that varied from 50 to 120 cm. The floor and roof systems were constructed using wooden beams directly supported by the walls [17]. In the 1960s, near the city of Cuenca, the "Guapán" cement plant was installed, and wooden columns began to be replaced by reinforced concrete ones; the walls were made of brick masonry and the floors structures of wood [18]. At this time, horizontal reinforced concrete beams began to be used, reducing the height of the storeys to measures ranging from 3 to 4 meters. A particular feature of this period was the increase in the use of bricks as a building material. The thicknesses of the bricks ranged from 20 to 30 cm [17]. In the 1970s, ceramic brickwork began to replace adobe brickwork on a large scale. The typical structural system consisted of a reinforced concrete frame with masonry infill to form a confined masonry system. In the 1980s, the use of reinforced concrete lightweight slabs began, replacing wooden floor structures.

At present, the historic centre of Cuenca is a UNESCO World Heritage Site and the "Urban development plan of Cuenca (2009)" foresees the need to implement specific provisions for the conservation of the buildings and structures of the historic centre of the city. This paper presents the results of a field study for the definition of the characteristic brick house in the historic centre of Cuenca. The defined house with its geometry, materials and structural and non-structural elements will be the basis for the numerical model and further vulnerability study.

2. METHODS

In order to identify the characteristic masonry house for the further study of seismic vulnerability in the Historic Centre of Cuenca (HCC), a database of dwellings in the HCC was generated. Each dwelling within the study area was characterised by 8 parameters: plan geometry, elevation, number of spans, roof type, facade configuration, structural system and wall material. Statistical frequency plots were generated to identify the most common variable within each identified parameter.

ArcMap software was used to apply the proposed approach, as it has powerful data management tools and allows the spatial representation of houses with each parameter [19–21]. A database was created based on the information collected from the field survey and related to the attribute table provided by the programme for each georeferenced polygon representing each dwelling. With the prepared spatial information, a characteristic dwelling was identified by superimposing polygons containing the most repetitive variables, i.e., those variables that statistically represent a group of dwellings. Once the group of houses had been identified, a second stage of fieldwork was carried out, consisting of a detailed survey of the geometric and mechanical characteristics of their structural and non-structural elements. With the detailed characteristics of the group of dwellings, a statistically representative house was chosen, which allows us to generalise both the architectural configuration in plan and elevation, as well as the materials. Finally, this information was used to create a model of a typical masonry house in the historic centre of Cuenca for the subsequent seismic vulnerability study. The seismic vulnerability assessment is not part of the scope of this work.

2.1 Determination of the study area and the characteristic dwelling

The Historic Centre of Cuenca (HCC) has about 10000 properties and is subdivided into the following areas: the first-order area, the respect area, the special area, and the archaeological area. According to [22], 60% of a total of 2885 houses evaluated within the HCC present seismic vulnerabilities, mainly because the building materials used do not have adequate inelastic behaviour [23].

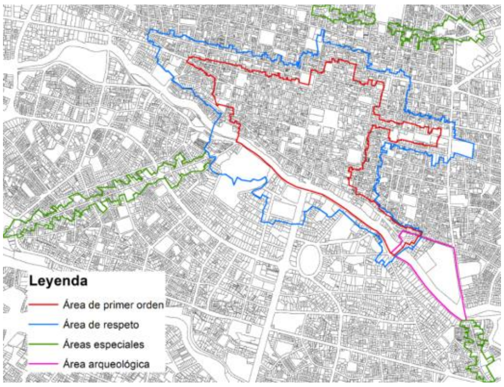

Fig. 2: *Subdivision of the Historic Centre of Cuenca (HCC). Source:* [24].

The first-order area (Figure 2, red inner boundaries) is the area of study of this work. In order to spatially managing the information and identifying the areas of interest that correspond to this study, polygons were created in ArcMap software to represent the properties of the first-order area of HCC (Figure 3), to which attributes were assigned based on the field collected information.

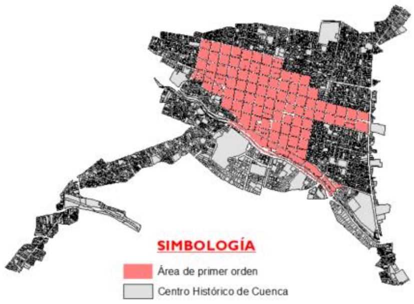

Fig. 3: *First order area properties in the HCC.*

Within the first order area of the HCC, we have identified a zone of 1110 dwellings where the majority of houses have structural systems composed of ceramic brick masonry, which is the subject of this study (Figure 4). In this zone 856 houses have brick masonry, which represents 77% of the sample size. This study area embodies 39% of the first-order area of the HCC and represents a statistical sample for the identification of the characteristic housing for further studies.

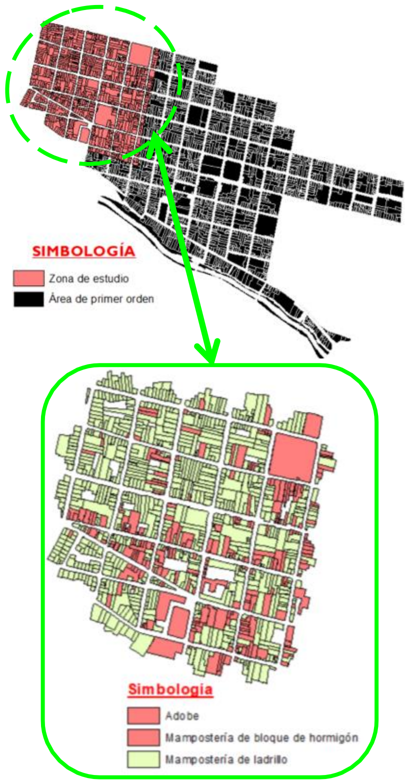

Fig. 4: *Clay brick masonry dwellings in yellow colour. Adobe or concrete block masonries in red colour.*

2.2 Parameters for the characterisation of the typical dwelling unit at the HCC

A representative sample size is determined in order to achieve high reliability of the results within the study area. From a total of 1110 houses, 287 houses are statistically required to idealise a generalised HCC model. The geometry and structural configuration parameters considered are shown in Table 1.

***Table 1**: Parameters for the database conformation.*

Statistical population, (number of houses)	1110
Minimum statistical sample size, (houses)	287
Parameters	
Geometry	Plan configuration
	Facade configuration
	Number of storeys
	Number of transversal spans
	Roof configuration
Structural configuration	Structural system
	Material of structural elements
	Wall material

Each parameter presented in Table 1 was examined individually to determine a variable that is representative within that parameter. For this purpose, georeferenced maps were produced. These maps were generated by creating polygons in ArcMap representing each house in the study area with its respective characteristics.

3 RESULTS AND DISCUSSION

Plan configuration: This parameter was chosen because one of the most serious problems that can occur in a structure due to seismic actions is torsion in plan, since the uniformly distributed lateral force is not supported by a uniformly distributed lateral resistance in the structure, which can generate a torsional failure mode related to structural irregularity in plan.

As shown in Figure 5, houses with rectangular floor plan configuration (525) are the most representative for this parameter, followed by asymmetrical (301) and in smaller proportion and which do not represent the sample are buildings with "L" shaped floor plans (197) and square floor plans (88).

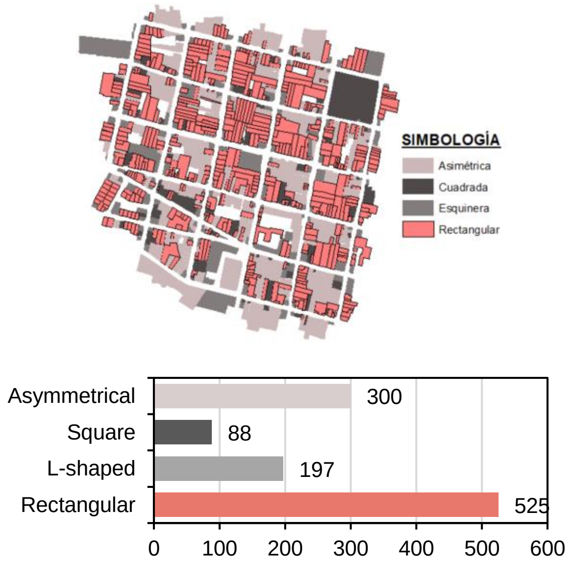

***Fig. 5:** Number of houses by plan configuration.*

Facade configuration: The development of masonry façades is also due to the evolution of the building structures themselves. The spans of the frame structures have been increasing and losing stiffness, which translates into a greater deformability of the structures in the horizontal direction, which directly affects the behaviour of the brick façades under the action of lateral loads. Most facades in the study area contain openings for windows and doors (560). This is important to note since façade walls with openings are more susceptible to stresses and the formation of diagonal cracks due to the loss of stiffness in the horizontal direction. In smaller proportion and not representing the statistical sample are the concrete (209) and adobe (119) wall facades.

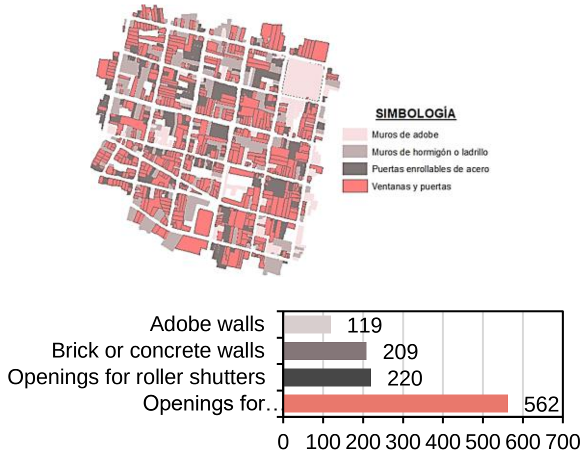

***Fig. 6:** Number of houses by façade configuration.*

Number of storeys: In order to determine the natural vibration period of the structures, it is important to know their height; therefore, the number of storeys of the building is an important parameter to consider. The dwellings in the statistical sample have 2 and 3 floors (467 and 322 respectively). The dwellings with 1, 3, 4, 5 and 6 storeys are smaller in proportion to the required sample and represent 287 buildings and will not be taken into account for the determination of the characteristic dwelling.

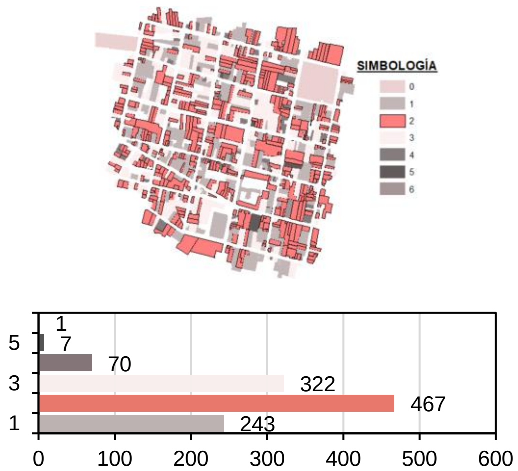

***Fig. 7:** Number of houses by number of storeys.*

Number of transversal spans: The number of spans in houses with frame structural systems is important since it increases or reduces the stiffness of the structural system in the studied direction. The houses with one and two transversal spans are within the required sample size (291 and 545, respectively). 220 dwellings have three transversal spans and were not considered part of the sample. Dwellings with four, five, six, seven, eight, nine, and ten spans involve 39, 6, 1, 4, 1, 2, and 1 house, respectively.

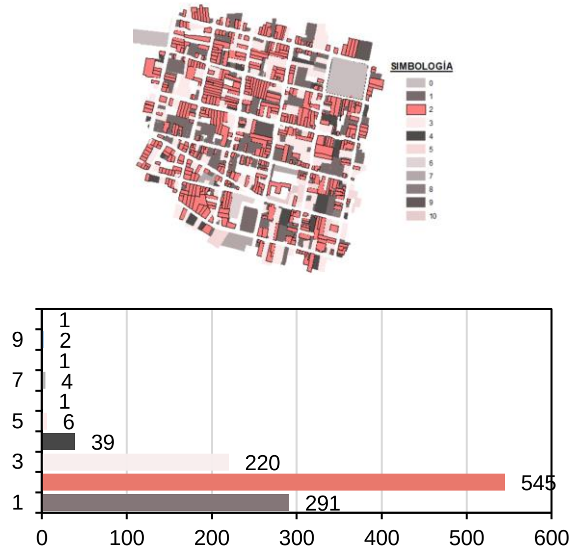

***Fig. 8:** Number of houses by number of transversal spans.*

Roof configuration: This is a critical parameter for seismic-resistant studies because it affects the distribution of masses in height. Depending on the type of roof and occupancy, the structure will behave differently. The types of roofs studied include gable roofs (614) and flat roofs (307), which are within the statistical sample. Additionally, 189 houses have shed roofs, but they are not included in the statistical sample.

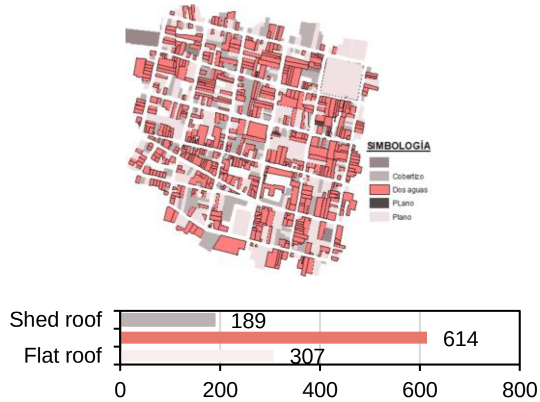

***Fig. 9:** Number of houses by roof configuration.*

Structural system: This is a key parameter for modelling as it depends on the building's structural configuration. This parameter considers the materials that constitute the load-bearing structural elements. The structural system with reinforced concrete portal frames and masonry walls (856) represents the statistical population as it greatly exceeds the minimum sample size (287). The other structural systems will not be studied.

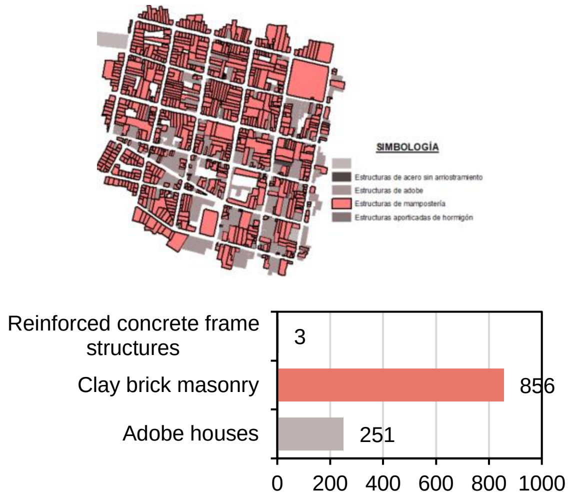

__Fig. 10:__ Number of houses by type of structural system.

Wall material: As described in the previous parameter, the most commonly used structural system is the concrete portal frame with masonry walls. However, the walls used to confine the portal frame system are sometimes not rigid enough to withstand the stresses to which they are subjected. Therefore, understanding the type of material and its mechanical properties is essential for the development of this research. The variable to be studied within this parameter consists of dwellings with ceramic brick masonry walls, which make up 841 units. The presence of houses with adobe walls (243) is of lesser consideration and should be the subject of another study, given their physical-mechanical properties make them highly vulnerable to seismic actions.

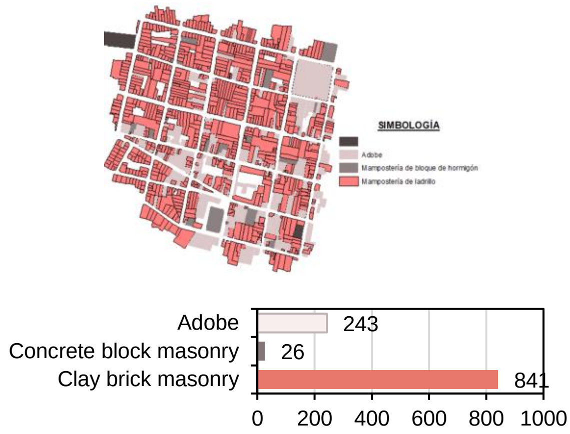

__Fig. 11:__ Number of dwellings by type of wall material.

To determine the type of dwelling for the subsequent mathematical model and corresponding seismic vulnerability study, we consider the variables that are statistically representative of the sample universe. On the basis of the minimum statistical sample size, if 287 houses have the same similarity, the variable is considered to be statistically representative. Once the variables have been defined, we identify a group of houses that meet the minimum defined variables. This process was carried out using ArcMap software through a process of overlapping layers. The programme identifies a group of houses that meet the minimum set of parameters and selects only those polygons that meet the minimum criteria (Figure 12).

__Fig. 12:__ Group of characteristic dwellings selected based on the most representative variables.

The result shows that 164 dwellings of the sample universe meet the minimum established parameters and have the most representative characteristics (Figure 13). From this group of dwellings, relevant configurations and properties are analysed to create a "characteristic masonry house" model. This model further will be the object to the numerical modelling.

Fig. 13: *Samples of houses representing the characteristic clay brick dwelling in the HCC.*

3.1 Characterisation of the Architecture and Materials of the characteristic house in the HCC

From the detailed study of the group of houses with the most representative characteristics, one house was selected. This house was built in the 1980s and consists of 2 storeys, 2 transversal spans, 3 longitudinal spans, a gable roof, concrete columns and beams, ceramic brick masonry walls, rectangular plan configuration, and a façade consisting mainly of openings for doors and windows.

Fig. 14: *Samples of houses representing the characteristic clay brick dwelling in the HCC.*

The characteristic house has a confined masonry structural system, wooden floor structures and a gable roof with clay tiles. The thickness of the confined brick masonry walls is 15-17 cm. The total height of the house is 7.95 m, the heights of the first and second storeys are 3.0 and 2.95 meters respectively. The house has two transversal spans of 3.25 m and 2.25 m and three longitudinal spans of 3.25 m, 3.00 m, 1.20 m, and 1 m of cantilever at the front.

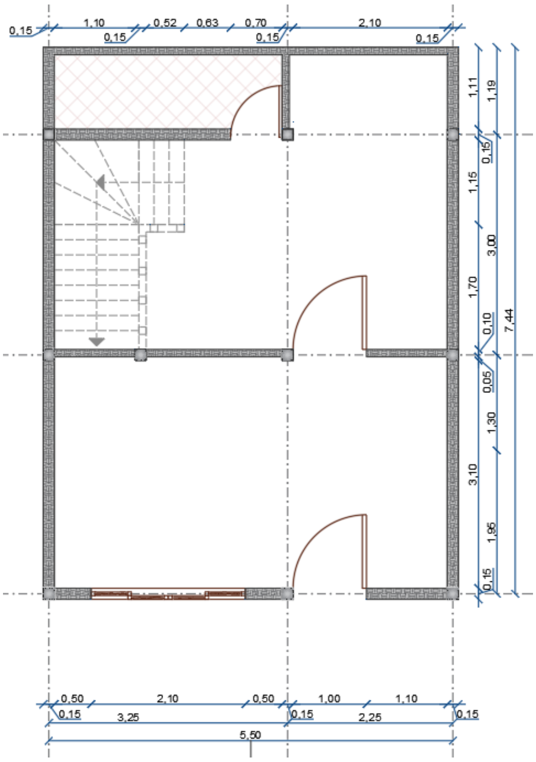

Fig. 15: *Architectural plan of the ground floor.*

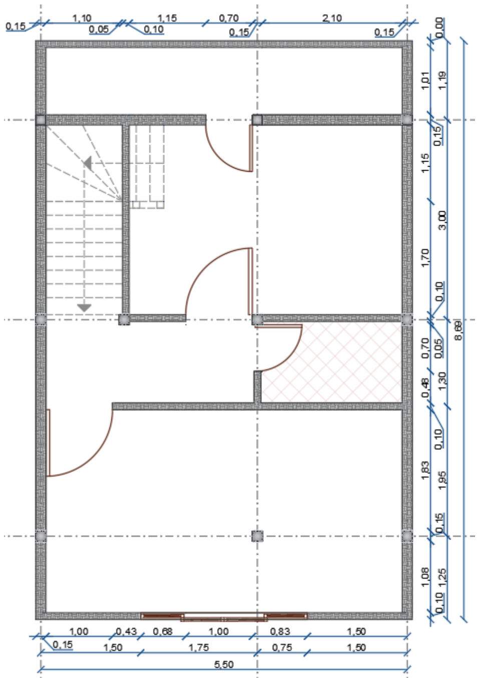

***Fig. 16:** Architectural plan of the first floor.*

The structural system of the characteristic house is composed of reinforced concrete confinement elements (columns and beams) that confine the unreinforced masonry walls, wood framing for the stairs, floor and roof structures, and a slab for the cantilever on the main façade.

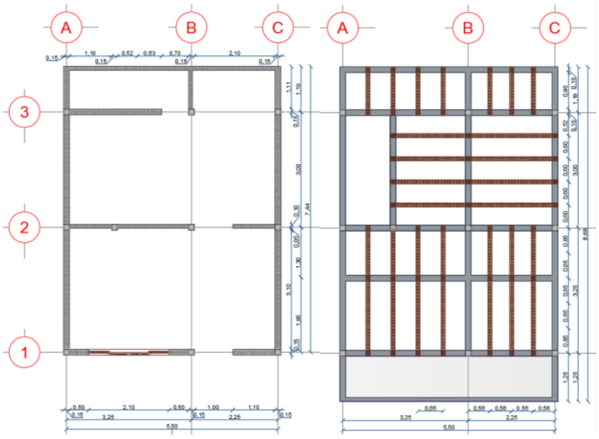

***Fig. 17:** Plan of bearing structural elements of the ground and first floors.*

The main façade and the architectural partitions consist of walls with window and door openings (Figure 18, Figure 19). This fact is of great importance to be characterized and must be considered in order to determine the structural behaviour of the whole structure.

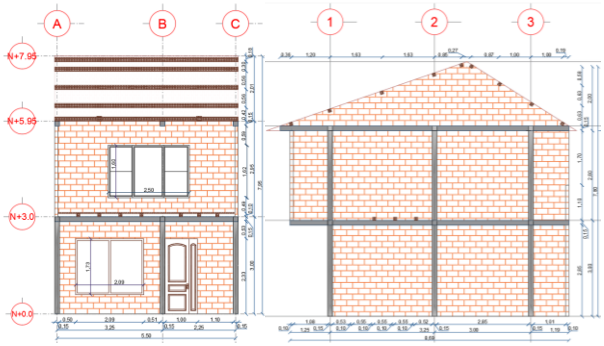

***Fig. 18:** Front and lateral facades.*

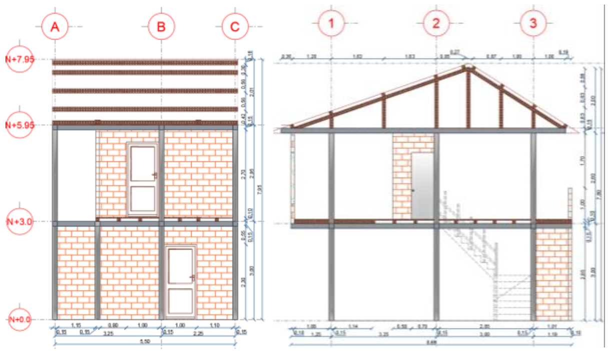

***Fig. 19:** Transversal and longitudinal sections.*

Most of the houses in the historic centre of Cuenca have timber floor structures, made up of 15×15 cm eucalyptus beams supported by concrete side-beams and embedded in the masonry. The roof structure is similar. In this case the bearing eucalyptus beams are supported by the side masonry walls (Figure 20).

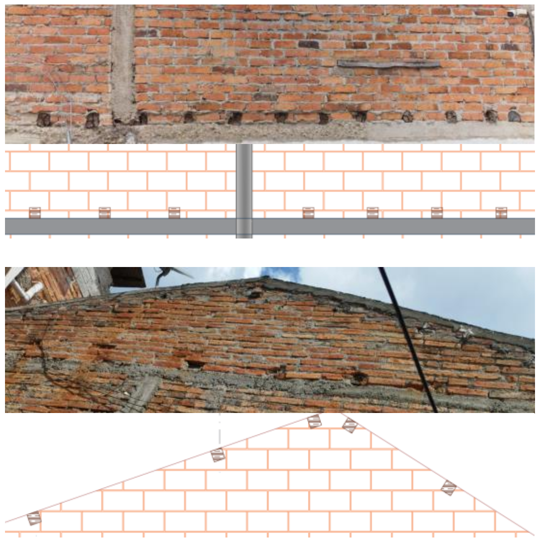

***Fig. 20:** Timber beams side-embedded in the masonry.*

Eucalyptus wood is one of the most widely used woods in the southern Andean region of Ecuador and in the city of Cuenca. The mechanical properties of eucalyptus wood for structural designing can be assumed according to [25] Table 2.

***Table 2**: Mechanical properties of eucalyptus.*

Static bending			
Modulus of elasticity	E	104 180.68	kgf/cm^2
Limit of proportionality	σ_{pl}	517.47	kgf/cm^2
Ultimate strength	σ_u	800.46	kgf/cm^2
Compression parallel to the fibre			
Modulus of elasticity	E	79 811.58	kgf/cm^2
Limit of proportionality	σ_{pl}	301.01	kgf/cm^2
Admissible stress	σ_{adm}	431.90	kgf/cm^2
Critical slenderness ratio	λ_{lim}	59	-

The mechanical properties of the fired clay bricks produced in the studied area have been experimentally determined by different authors. V. Arias and E. Durán [26] tested bricks produced in the regions of Sinincay, Racar and Caleras and determined a compressive strength of $f_{b,c}$ = 9.1 MPa and a bending strength of $f_{b,t}$ = 1.1 MPa for bricks from Sinincay; $f_{b,c}$ = 5.5 MPa and $f_{b,t}$ = 0.7 MPa for bricks from Racar; $f_{b,c}$ = 10.3 MPa and $f_{b,t}$= 1.1 MPa for bricks from Caleras. F. Neira and L. Ojeda [27] characterised the geometry and compressive strength of bricks from the regions of Mayancela and Tejar. They determined that the bricks produced in the same region of Mayancela have significantly different geometrical and mechanical characteristics. There are bricks with dimensions of 280x140x90 mm and a compressive strength of $f_{b,c}$ = 5.81 MPa, and bricks of 270x140x100 mm and a compressive strength of $f_{b,c}$ = 15.5 MPa. The bricks produced in Tejar are 280x140x100 mm with a compressive strength of $f_{b,c}$ = 8.12 MPa. E. Zalamea [28] tested bricks from the regions of Susudel, Oña and Sayausí and determined that the bricks produced in Susudel have a dimension of 265x125x78 mm and a compressive strength of $f_{b,c}$ = 10.6 MPa. The bricks produced in Oña are 257x119x75 mm and have a compressive strength of $f_{b,c}$ = 9.96 MPa. The bricks from Sayausí are 275x129x72 mm with a compressive strength of $f_{b,c}$ = 6.3 MPa. Recently, J. Molina, J. Rodas *et al*. [29] carried out a large experimental research and tested bricks from different regions of the Azuay province, and determined that the average dimension of bricks in this province is 257x128x72 mm, the compressive strength is $f_{b,c}$ = 10.2 MPa and tensile strength in bending is $f_{b,t}$ = 2.5 MPa. These results corroborate that the production of fired clay bricks in Ecuador do not meet any technical standard for geometrical and mechanical properties [15, 30].

Other researchers carried out experimental studies on mortars. F. Neira and L. Ojeda [27] tested mortar specimens made in laboratory with a cement:sand ratio of 1:3. They defined that at the age of 28 days the specimens have a mean value of compressive strength $f_{b,c}$ = 10.2 MPa. P.A. Gomez [31] tested mortar specimens made in laboratory with a cement:sand ratio of 1:2, and defined that at the age of 28 days the specimens have a compressive strength $f_{b,c}$ = 16 MPa. However, S. González, J. Ludeña *et al.* [32] carried out an experimental research on mortar samples recollected directly from different construction objects. This work shows that the compressive strength of mortar varies from a construction site to other. There was determined values of compressive strength of $f_{b,c}$ = 11.6 MPa, $f_{b,c}$ = 8.7 MPa, $f_{b,c}$ = 12.9 MPa, and $f_{b,c}$ = 6.1 MPa.

In addition, it is important to note that the traditional thickness of the mortar joints for brick masonry buildings in the region is 15 mm.

The research results show that the confining reinforced concrete beams and columns have the same thickness as the masonry with. It is common to meet 15×15 cm sections and a reinforcement with 4Ø10 mm steel rebars and Ø10 mm stirrups with a separation of 15 cm (Figure 21).

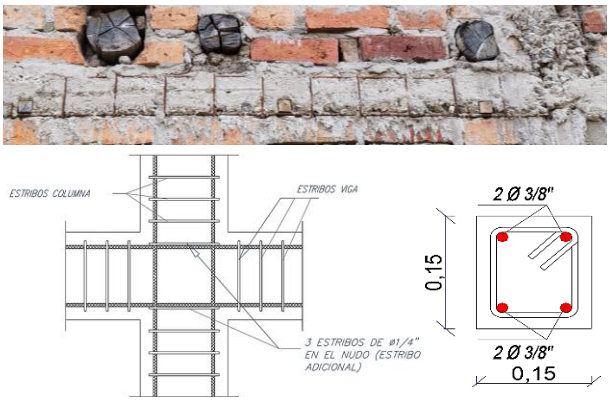

Fig. 21: *Reinforcement of confining elements.*

According to studies [3] and [33], the yield stress of steel reinforcing bars is $f_y = 420$ MPa, and the compressive strength of concrete is $f_c' = 32$ MPa.

The idealized computer model of the characteristic house of the HCC for further structural analysis and seismic vulnerability assessment is presented in the Figure 22.

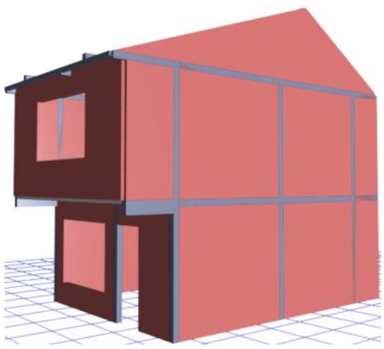

Fig. 22: *Idealised computer model of the characteristic masonry house in the HCC.*

4. CONCLUSIONS

For analytical seismic vulnerability assessment, it is necessary to have a numerical model that reflects the real structure under consideration as accurately as possible. In this work we have defined the characteristic house that statistically represents the brick masonry dwellings in the historic centre of Cuenca.

The architecture, geometry, material properties and structural typology of the characteristic house was defined. The characteristic house consists of confined brick masonry structural system, wooden floor structures and a gable roof with clay tiles. The thickness of the confined brick masonry walls is 15-17 cm. The total height of the house is 7.95 m, the heights of the first and second storeys are 3.0 and 2.95 meters respectively. The house has two transversal spans of 3.25 m and 2.25 m, and three longitudinal spans of 3.25 m, 3.00 m, 1.20 m, and 1 m of cantilever at the front. The properties of the constituent materials of the house (brick, mortar, wood, concrete and reinforcing steel) and the geometry of the load-bearing elements are presented. The model of the characteristic house presents a rectangular plan configuration and a façade. The defined typology represents a confined brick masonry house with symmetrical distribution in plan and elevation (floors with no significant discontinuities and / or misalignments in the axis of the walls) and openings in the facade and partition walls.

The presented model and information enable accurate structural analysis, resulting in a reliable assessment of seismic vulnerability of masonry houses in the historical centre of Cuenca..

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