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A parameterization of brick-reinforced rammed earth in Valencian Region (Spain)

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ABSTRACT: The study conducted on buildings with strong presence of brick-reinforced rammed earth walls, within the province of Valencia and its surroundings, has permitted the discovery of some details of this constructive technique and has thrown light on their reason for being implemented. Due to this, it has been considered relevant to establish a comparative table of the distinct constructive combinations. The study of the variants of the techniques, in-situ surveys, the bibliography and existent documental sources have helped to reach a first approach regarding the constructive variants found containing the three basic elements constituting the constructive brick-reinforced rammed earth wall essence: nucleus, bricks and lime crust. This first hypothesis of a chrono-typological sequence of the technique, which had previously only been considered unchanged with time, facilitates the understanding of its origin, development and decline; therefore confirming a logical technology which matured along the centuries, adapting itself to specific architectural typologies.

1 INTRODUCTION

Many authors have addressed the subject of the brick-reinforced rammed earth, and rammed earth in a broader sense. However none of the papers nor the articles to date have discussed the variants of rammed earth walls with bricks in detail, nor the varying nature of its constructive characteristics over the centuries. Here lies the novelty of this research.

Starting with a review of existing literature on the subject, we look at notable examples of this construction technique within the Region of Valencia, especially those concentrated in the province of Valencia, Spain (Table 1). Fifty-one buildings of differing types and ages were catalogued for this study. Thanks to this work of comparison, we have been able to put forward an initial theory regarding a possible chrono-typological pattern to this ancient constructive technique.

2 RAMMED EARTH WALLS WITH BRICKS

2.1 *Background and origin*

This technique is one of the most common variants of wall found in the East of the Iberian Peninsula.

The final appearance of a wall made using this technique is clearly identifiable: at first glance one notices a regular rhythm of bricks which appear to arranged in the background compared to the smooth “plastered” facade, as the bricks are slightly recessed inside the wall (Fig.1).

The direct origin of the technique is uncertain, with it being the result of several factors and numerous technological developments linked to the supply of raw materials and varying constructive demands. In reality, the implementation process of the walls is very similar to that of the lime-crusted rammed earth wall. After the completion of a foundation and subsequent base, usually with a stone or brick masonry base of 50–60 cm in height, the formworks are put in place. Until this point, the construction process is similar to that used in other types of rammed earth wall. In the next phase, a layer of lime mortar is poured together next to the forms, followed by a layer of earth (to the same level as the mortar). Finally a brick is laid on top of the layer of mortar and earth against the formwork. After the placement of the second stratum begins (Fig.2). Thus, the brick is embedded inside the wall, except from one side which is placed against the formwork. In addition, the shocks produced during the ramming process of the different layers results in the bricks moving slightly from the surface of the formwork into the depth of the wall, in such a way that some of the lime mortar partially covers the head of the brick (Cristini, 2012).

Table 1. Locations presented in the study, divided by province (authors).

Province	Location
Valencia	Valencia capital Xirivella Alaquás Xativa El Puig Albalat dels Sorells Benifaraig Alfara del Patriarca Picanya Luchente
Castellón	Castellón Borriana La Villavella Mascarell Vila Real Partida de Fadrell Alquería del Niño Perdido
Alicante	Elche Cocentaina

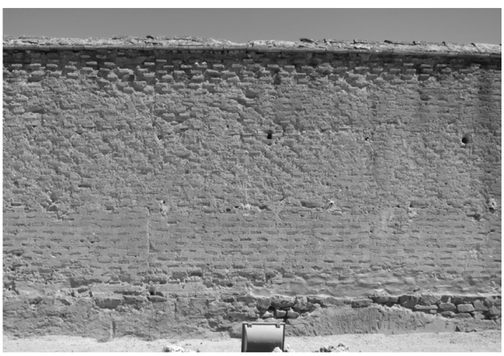

Figure 1. Brick-reinforced rammed earth wall; fencing wall of la Cartuja del Puig, Valencia (authors).

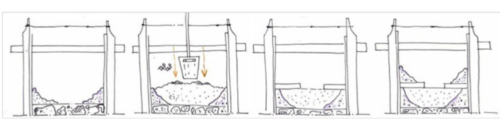

Figure 2. Resume of construction process: rammed earth wall with bricks (authors).

2.2 *Technical details*

A wall made using brick-reinforced rammed earth technique is a double wall: one part stronger and visible, and one interior and weak. What we have is an earth core with a crust composed of bricks and rows of lime mortar (Fig.3).

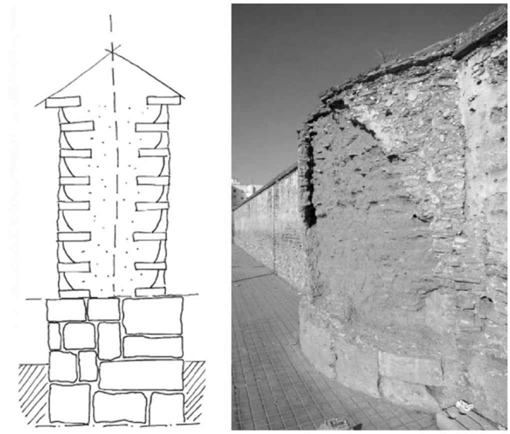

Figure 3. Detail of the fencing of San Miguel de los Reyes, Valencia (authors).

Furthermore, in many cases you can see different types of bricks in the wall itself, of differing colors and dimensions. We must take into account that in the case of many buildings the ceramic components came from other collapsed constructions. The final appearance of many of the facades, if we focus solely on the ceramic elements, is heterogeneous in terms of shapes, colors and textures.

The presence of aluminum silicate, found both in the earth and in the ceramic bricks, gives the structure strength and stability. In fact, this bringing together of earth and bricks is not incidental, but in fact follows a precise spatial arrangement, which gives the structure particular mechanical and physical properties. The presence of the bricks, with their rough and porous properties, prevents horizontal slippage between the layers of earth. In the case of a monolithic earthen wall, the risk of slippage of one layer to that below, caused by a horizontal force such as an earthquake, is much greater than when bricks are inserted. The bricks also act as connectors between the lime crust and the interior earthen filling, and between the layers of rammed earth itself (Cristini, Ruiz Checa, 2009).

3 ANALYSIS AND CASE STUDIES

3.1 *Historical and geographical setting*

The brick-reinforced rammed earth constructive system went through its period of maximum development and employment between the mid-fourteenth century and the second half of the seventeenth century. Indeed, the analyzed case studies are primarily from this historical setting. By the 18th and 19th centuries, the technique was being modified progressively, being replaced by brick or pillars structures. Gradually, the presence of the technique in urban areas is reduced, until its progressive decline and subsequent fall in the eighteenth century.

3.2 *The election of case studies*

The discriminating factors considered for the selection of the case studies were essentially threefold (Fig.4):

1. Reference to documented historical data from literature. A detailed study of existing sources and notable examples of this technique in the Region of Valencia was made.
2. A significant presence of visible rammed earth walls. The selection of buildings where an interesting sample of wall is visible meant that the surface of the rammed earth set to be studied ought to be at a minimum height of 50 cm and with a minimum visible area of elevation of 1 square meter.
3. Dating, trying to identify examples from different origins, covering the indicated chronological range.

After establishing these initial criteria it was necessary to create a template of study: an effective tool to catalogue and subsequently study the selected cases, each of which was distributed according to a specific sequence of items:

- Century of construction
- Previous interventions
- Width of the wall
- Vertical and horizontal distance between the bricks
- Size, colour of the bricks and bonding used
- The composition of the crust and the type of binder used for the crust
- The relationship between the surface area of the bricks and the crust
- Presence of lime plaster in the finishing
- Pathologies present.

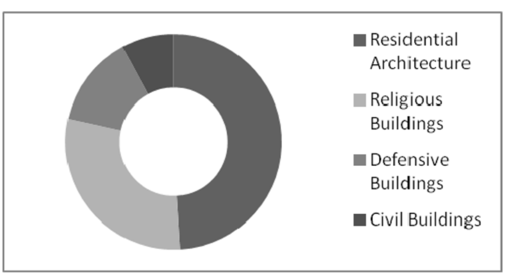

Figure 4. Type of construction (authors).

Thus, every building has a set of data, which can be used in order to compare the fifty-one examples of walls with rammed earth and bricks. By studying and analyzing the selected case studies it soon became clear how some features vary with some regularity and progression, suggesting the existence of macro-families which bring together the constructive characteristics of the different rammed earth walls with bricks analyzed. Using this type of analysis, along with the information seen from the results tables and the comparison of some important buildings, we were able to extrapolate four macro-groups of brick-reinforced rammed earth in Valencia region:

- *Type I*
- *Type II*
- *Type III*
- *Type IV*

This subdivision does not purport to denote marked divisions between one or another variant of type. Rather, it acts more as a guide that can help in the reading and analyzing of some examples of buildings constructed using this technique.

4 THE TYPOLOGIES

According to this basic classification, and following a chronological, technical and constructive logic, four main constructive variations related to certain technological changes could be observed.

The research aims to identify the origin of the technique in the 14th century, beginning with the lime-crusted rammed earth wall and its demise, possibly during the 18th century coinciding with the progressive use of many more bricks in construction. We have wanted to highlight that these typologies are not completely detached from one another; but that each has evolved from the previous variation.

4.1 *Type I*

Chronologically, type I is the first of the identified groups: the analyzed buildings were constructed within a time period that is believed to span the 13th and the 14th centuries. In all the cases studied, this variant of brick-reinforced rammed earth wall is found in defensive buildings (defensive walls or towers).

Coherent with their function, the width of the walls is notable: from 120 cm up to 240 cm. The core of the wall is earthen and, due to its great width, the presence of additional fragments of bricks or stones can be observed. These elements help compacting the interior of the wall, and mean that the main thickness of the wall is not only made of rammed earth. By observing sections of these examples we can see how the lime crust reaches a thickness of between 30 and 35 cm, always with the aim of providing protection. A lime crust of this thickness behaves almost like an additional body to the main rammed earth wall. In the majority of these first examples, the bricks are stretcher laid. In other words, the ceramic components do not join the earthen core with the lime crust. Thus, what you get is the protection of the earthen core from various elements, whether that is from the lime crust or the bricks. The bricks are not arranged in a regular manner, and differing horizontal and vertical distances can be seen between the bricks. This type of arrangement is characterized by rows of bricks which are almost continuous, each very close to the other. On the other hand, the vertical separation between the bricks is vast, reaching up to 25 cm (Martella, 2014) (Fig.5).

4.2 *Type II*

The buildings with variants within this group date roughly from the 14th to the 16th century. The construction technique, unlike that of the previous variant, reveals a broader purpose for the construction, such as religious buildings or examples of residential architecture.

For this reason, according to the building typology, the wall thickness is significantly reduced. The walls in question are between 40 and 60 cm wide. In proportion with the total width of the wall, the thickness of the lime crust also decreases, although it remains relatively substantial (5 to 10 cm thick). As the thickness of the lime reduces, the presence of aggregates in the layer of lime increases. Gravel and pebble of a sufficiently large grain (1–2 cm) are the aggregates of choice. The decision to add these items to the lime mixture is probably due to the improved adhesion with the final lime finish (lime plaster) which they provide. The arrangement of the bricks also changes, moving on from stretcher laid seen in the previous variant, to header arrangement. Without doubt, this arrangement of bricks, along with the narrower width of the lime crust, gives the structure greater stability and strength: the two bodies of the wall are connected in a way that can be likened to a zipper, each part collaborating with the other. The layout of the ceramic components is more homogeneous than in the first group analyzed: in many cases the horizontal and vertical distances between the components comes to the same, ranging from 6 to 15 cm. By decreasing the distance between the laid bricks, compared to the first variant analyzed, the amount of ceramic elements used for the building of the wall increases proportionally, and the amount of externally visible lime decreases (fig.6) (Martella, 2014).

4.3 *Type III*

This solution is typical in household buildings; and outside of urban areas it is especially common in many farmhouses. The approximate dating of the buildings included in this group varies from the 16th century to the 17th century. The width of the wall decreases gradually depending on the type of building, ranging from 55 to 35 cm thick. Buildings such as farmhouses or private homes do not in fact need walls of great thicknesses. Buildings of this kind are made with raw materials found in the local area and at the least possible expense. Other characteristic features of these walls can also be read from an economical perspective and in terms of the speed of construction of the walls: the lime crust has been reduced notably, reaching

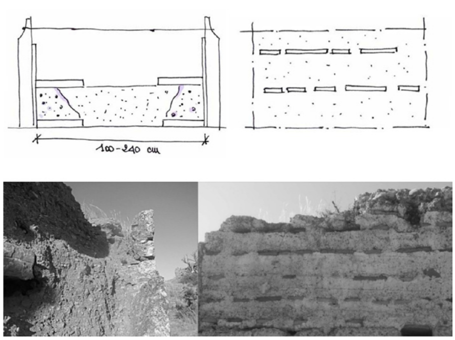

Figure 5. Details of Type 1-wall. Section and elevation of Nules Castle, Castellón (authors).

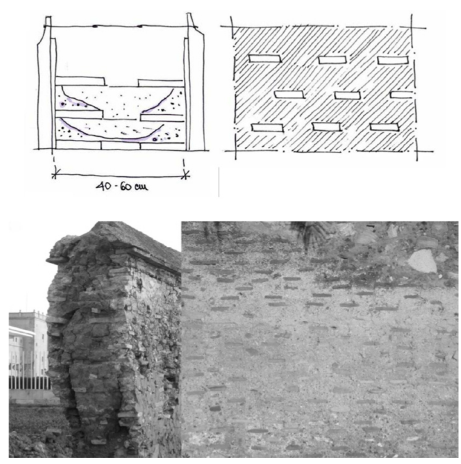

Figure 6. Details of Type 2-wall. Section of the fencing of San Miguel de los Reyes; Elevation Mascarell citywall, Valencia (authors).

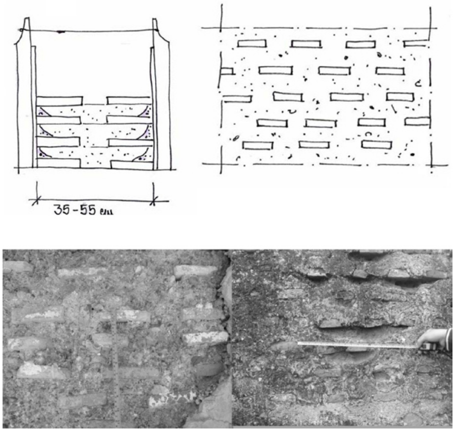

Figure 7. Details of Type III-wall. Detail of the elevation of Convent of San Diego, Alfara Patriarca, Valencia; detail of the elevation of the fencing, Carabona Tower, Burriana (authors).

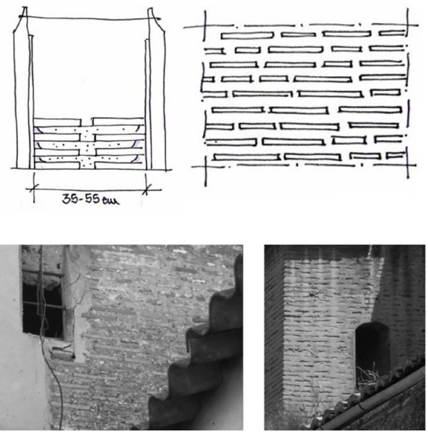

Figure 8. Details of Type IV-wall. Elevation of the Farmhouse of Falco, Godella; Elevation of Saint Ursula Church, Valencia (authors).

widths of just 2 cm, and aggregates of a large size are always included. The reduced width of the wall and the presence of bricks header arranged means that the structure is more resistant and stronger than the other variants. The bricks strengthen the earthen core, fulfilling a role that goes beyond the protection of the core of the wall. This type of solution, with all its features, already begins to resemble brickwork. When we analyze the elevations we see that these walls are characterized by the regular arrangement of bricks. The distance between them, whether that be horizontal or vertical, decreases even further compared to the previous solutions, from 10 to 4 cm. When observing these examples pathologies such as the partial erosion of the lime crust, due to its reduced thickness, can be seen (Fig.7) (Martella, 2014).

4.4 *Type IV*

What we have in this case is a variant which is linked to religious architecture (churches and monasteries) principally from the 17th century.

The width of the walls of these examples remains the same as that of the previous variant, with thicknesses of between 35 and 55 cm. When this technique is used in buttresses, the width increases so that transversal loads can be transferred to the ground. The arrangement of the bricks changes radically compared to the first buildings analyzed: in this case they cover the majority of the outer surface of the wall, in regular and continuous lines. The vertical distance between the bricks, which in previous cases reached up to 25 cm, has now been reduced to just 2 to 4 cm. The final appearance of these walls is similar to that of a brick wall structure, in this case, without the use of lime plaster.

In type IV-walls, the significantly smaller dimensions (compared to defensive walls) mean that the main responsibility for the structure of the building lies with the bricks. In this case the earthen core is almost secondary to the great abundance of ceramic components, which act together as a veritable autonomous structure.

The reduced distance between the bricks further emphasizes this new distribution of roles within the wall. In this case, due to the proximity of the ceramic elements, their function as protective elements intended to bind the wall, is secondary. One can no longer appreciate the "zip effect" which characterized the walls with moderate to thin layers of lime crust.

5 CONCLUSIONS

The study and analysis of all the examples is a task requiring considerable analysis and amalgamation of data, due to the complexity and variety of typologies found. The first investigatory phases were characterized by the search for and study of existing literature on the subject of rammed earth walls, and more specifically, of bricks reinforcement. This was followed by an *in situ* phase of documentation and data collection.

Through the comparison of the different cases it has been possible to establish parameters for this constructive technique, and subsequently the classification of four main macro-families, each of which brings together different yet specific constructive characteristics (Fig.9).

In all the cases, one can note how the brick, combined with lime crust, is the most important element. Its role has changed over the centuries. In the first defensive buildings analyzed, the sole purpose of the bricks, seen to be almost "drowning" in the lime, is the protection of the more vulnerable earthen core.

As the arrangement and bonding of the bricks in the façade changes, so does their function: from a "screen" to an element that provides greater strength to the wall as a whole. In fact, by decreasing the thickness of the lime crust (from 30 cm to 5 cm thick) the bricks connect directly to the earthen core, as such acting as a bond between the outer more resistant layer (the lime crust) and the innermost more fragile layer (the core).

The aim of the research centered on the analysis of a collection of elements which revealed the different uses of rammed earth walls with bricks within the Valencian Community. The aim was for the results to be sufficiently representative so as to permit the identification of the constructive logic, as well as to provide a literary viewpoint which could be used to understand many other cases not covered directly by this research.

In total, we have identified (Fig.10):

- 4 cases of Type I—wall
- 25 cases of Type II—wall
- 20 cases of Type III—wall
- 5 cases of Type IV—wall.

All the data collected and processed provides the following conclusion; how a constructive system shifts and adapts according to the specific requirements of each historical period. None of the essential elements disappears from the ensemble, rather their size and position within the wall

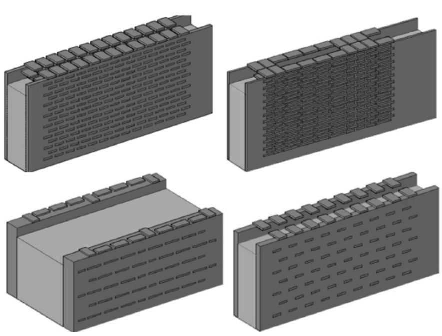

Figure 9. Graphical summary of the four types of walls and a proposal of the hypothesis of a chrono-typological evolution (authors).

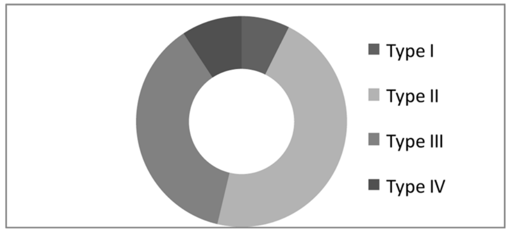

Figure 10. Percentage of different walls studied (authors).

is simply changed. The core, connectors and crust each go about playing a different yet decipherable role throughout the lifespan of the constructive technique.

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