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A HISTORICAL SPANISH TRADITIONAL MASONRY TECHNIQUE: SOME FEATURES ABOUT *TAPIA VALENCIANA* AS A REINFORCED RAMMED EARTH WALL

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REINFORCED RAMMED EARTH WALLS IN SPAIN

The diffusion of rammed earth techniques in Spain can be explained in term of the low cost of the construction process and to the use of local, abundant raw materials with good mechanical performance. For these reasons *tapia*, as a rammed earth wall is called in Spain, is visible in all types of architecture, whether humble, religious or defensive buildings. Plinius documents the presence of some earth fortifications along the Iberian Peninsula, probably the traces of a Punic conquest.

The legacy of the Roman Empire spreads in Spain the use of *opus caementitium*, like a filling of *opus lateralicium* or cyclopean walls. But this is just a short parenthesis because a variety of earth construction's techniques take roots in the peninsula, coming from the North African Muslim Empire, at the beginning of 8th century.
After the Christian conquest (*Reconquista*), *tapia* walls are still part of the traditional constructive culture, whether in peasants' shelters or in farms or stores. This development grows until the 20th century, when concrete or brick masonries replace this traditional rammed earth technique.

The clearest and simplest definition of *tapia* is: "*Tapia* is a rammed earth wall made with a *tapial*, as is called the quarter-deck" (ALGORRI-GARCIA AND VASQUEZ ESPÍ). These words can suggest some more features about the technique, for example: the use of cheap materials, the easy transfer and recovery of the quarter-deck, the quick operations for the assembling of the wooden structure, the stability during the flowing and tamping of the rammed earth… and so on.
The widespread and simplest type of *tapia* is made with a mixture of earth and water, rammed in the quarter-deck, with corners reinforced by bricks or stone masonries. But from this basic recipe, it is possible to develop some more reinforced solutions, with the addition of stones, straw, reeds, timber or bricks and lime.

Like other techniques based on rammed earth, *tapia* walls show a special resistance against the weather's attacks, as can be seen in well-preserved ancient Andalusian masonries traces all along the Iberian Peninsula.

The earth filling inside the quarter-deck is made by layers, rammed with special mace-like tools called *pisones.*
The maces show a great diversity, both in measure and type; anyway, the basic ones consist of a heavy stone or metallic element, with a special conic section and a handle, useful for the vertical ramming and tamping of the earth layers. If the earth wall is well rammed, it will be preserved through the ages.
The layers consist of ten or twenty cm of earth, treated with a cyclic pouring of water and with a bed or earth that prevents the "stuck" between the mace and the surface. Some authors identify the dull sound of the ramming process *–tap-tap–* as the onomatopoeic source of *tapia.* We can also see how, in the outskirts of Valencia, a special yellowish earth is traditionally called *tap* (made with a special mince of clay travertine). The layers of *tap* identify the passage between the fertile strata of the soil and the deeper limestone layers. Thus, for all these features, *tap* can be used in the *tapia* wall like a great raw material.
The rhythm of the ramming process is quite fast and the experienced workers are able to raise high walls just in one day of work. Some historic documents witness to the speed with which Muslim workers, during the siege of Christian conquerors, constructed the city-walls of *Granada* and *Baza* in one single night.

TAPIA IN VALENCIA'S SURROUNDING

There is a great variety of *tapia* walls in the region of Valencia, and this is visible both in constructive element solutions and in structural strengthening.
Monolithic *tapia* walls have a completely rammed earth wall structure. there are some variations, due to the percentage of earth employed or to the treatment of the joints between one layer and the other.
Ordinary *tapia* walls have a core structure with a blend of earth without additions; in this process, earth is scarcely ventilated or wet, because the preparation of raw materials is quite simple.
Improved *tapia* walls have an enriched earth blend, with some additions, like gravel or selected pebbles to improve the ramming process. Frequently workers put lime in the earth mixture (or in the inner faces of quarter-deck) to improve the consistence and the durability of finished walls.
Lined *tapia* walls are traditional rammed earth walls, but they present an external protection made with a coating of lime mortar.
Lime and earth *tapia* walls show a succession of lime and earth layers, which is visible in the cross section of the wall. With this "trick" the adhesion is improved and, at the same time, the finishing treatment is smoother and more homogeneous than in traditional *tapia* walls.
***Tapia valenciana* walls** have an improved structure due to the presence of bricks, slapped in the wet earth mixture between one layer and the next, as we have realized in an in scale 1:100 model (see fig.1). The final aspect of these walls is a bit odd and irregular. They look like imperfect brick masonry with oversize joints and with a smooth finishing coating around the bricks.
Reinforced *tapia* walls are structures with some reinforces, like layers of bricks, stones or lime. Apart from the type of the materials employed, the purpose of all these solutions is to strengthen the wall.

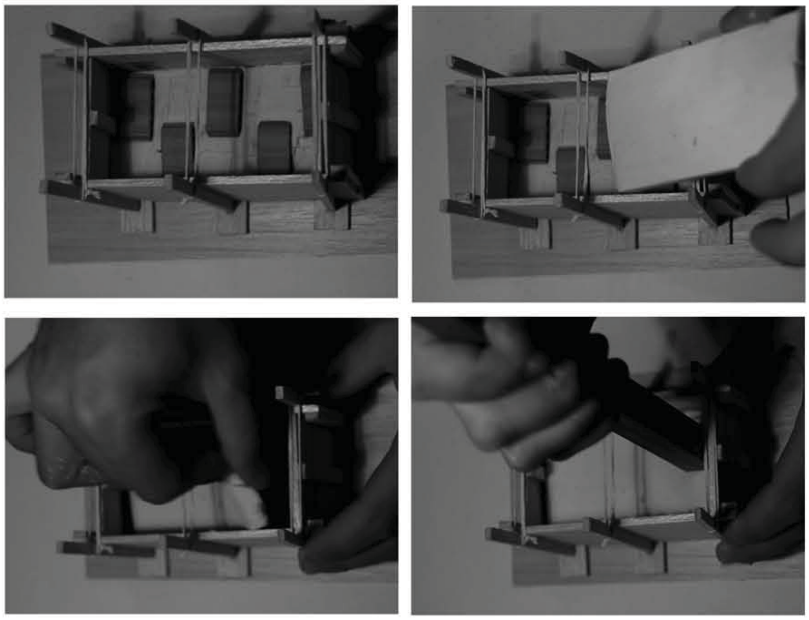

Figure 1: model development, where is visible the process of placing bricks in the quarter-deck (Cristini – Ruiz Checa)

FEATURES OF REINFORCED BRICKS *TAPIA* WALLS

Both the history and diffusion of the *tapia valenciana* walls have been met throughout the centuries by neglect and incomprehension. From the point of view of the history of construction, these walls have not been appreciated and valued as they probably should have. In general, we have not found the same level of knowledge and appreciation of this construction technique as we can discover about stones or brick masonries.
As we said before, the origin of the *tapia* technique can be found both in late and Muslim traditions; it is really an ancient well-developed technique, but it has been always related to scarcity of economic and technical resources in construction.
As AMADEO SERRA DESFILS said, monolithic *tapia* walls, employed in local architecture, is probably the forerunner of *tapia valenciana* walls. But in general it's quite difficult to find a clear evolution between a type of wall and the other, due to the continuous and local experimentations of raw materials and mixture.

FRAY LORENZO DE SAN NICOLAS writes in 1663 that "*tapia valenciana* walls are made with earth, half bricks and lime, making beds progressively, obtaining incredible performing walls…" and this reference is actually one of the clearest about this construction technique.
Certainly, this definition asserts that the walls are incredibly strong, and the basic 'recipe' for their construction includes the alternation of different lime and brick strata.

MANUEL GALARZA TORTAJADA adds "…although the first documents about monumental *tapia* walls date back to the 16th century, in the 15th century we can already find *tapia valenciana* walls in some vernacular constructions, and some traces of these walls are still visible nowadays."

As their name indicates, *tapia valenciana* walls have always been included into the "big family" of reinforced rammed earth techniques. These structures show not only good cohesion between the materials, in order to guarantee their strength, durability and performance against accidental subsidings or dynamic actions; they also show an improved final and permanent coating, which allows preservation without a periodical maintenance, while at the same time providing a stable and decorative finish exterior surface.

According to FRAY LORENZO DE SAN NICOLAS's definition of rational constructive process, we can describe this technique as a wise mixture of different materials, like bricks and earth, fitted in a regular sequence of layers and combined by *tapial*, a recycled quarter-deck.
The main difference between traditional *tapia* wall and the *tapia valenciana* wall lies in the use of bricks, in the beds of rammed earth, slapped in the wet earth mixture between each layer and the next. Between each brick and the next, there is an empty space, which is as big as the head of one brick (see fig.2). As we said before, the final aspect of these walls is a bit curious. They look like imperfect brick masonries with oversize joints and with a smooth finishing coating around the bricks. The coating's relief is like a "crust" of lime mortar, similar to the finishing of "lime and earth" *tapia* walls.

After the foundation, *tapia valenciana* wall needs a well-done base, made with either bricks or worked stones: The base can be useful for the assembly of the quarter-deck, the making of perpendicular and the lining up of the walls.

Beginning from the base the worker starts the sequence of the strata:
- Distribution of the first "lime and earth layer"
- Placing the bricks, with the head towards the quarter-deck (the space between the bricks is as big as their heads)
- Placing the bricks in the half thickness of the stratum
- Shed of the second "earth and lime layer" (same thickness as in the first stratum)

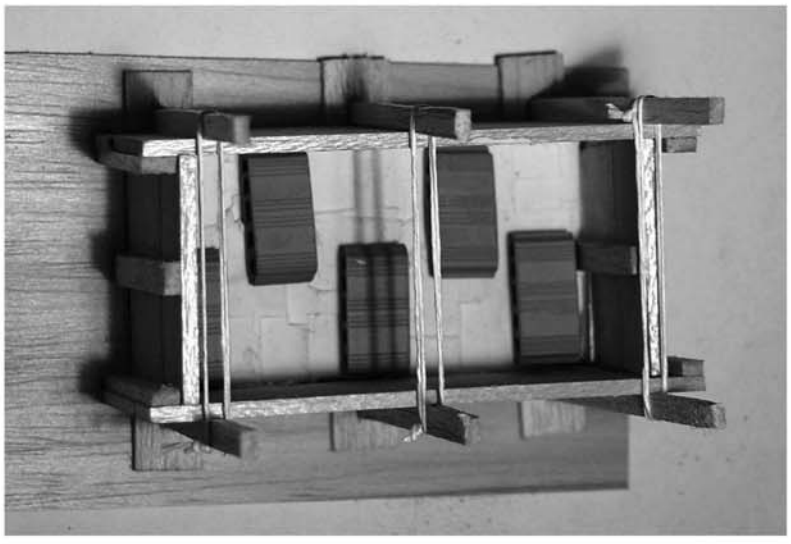

Figure 2: detail of the model of the quarter deck (Cristini - Ruiz Checa)

Later the worker begins the ramming process, moving the mace from the center of the quarter-deck towards the edges, favoring the flow of the earth and lime mortar, wrapping up the fitted bricks. Some authors say that the impact of the mace can displace the bricks from their position, whereas this study considers these minimal movements irrelevant. Due to this flow, the oversize joints give relief to the wall, while the bricks are sunken in. Sometimes the inner faces of the quarter-decks are treated with lime mortar; above all in the side boards (spreading 2 cm of lime mortar), the strata can improve the joints between the modules, during the same construction process, as we have seen in the in - scale model (see fig.3).

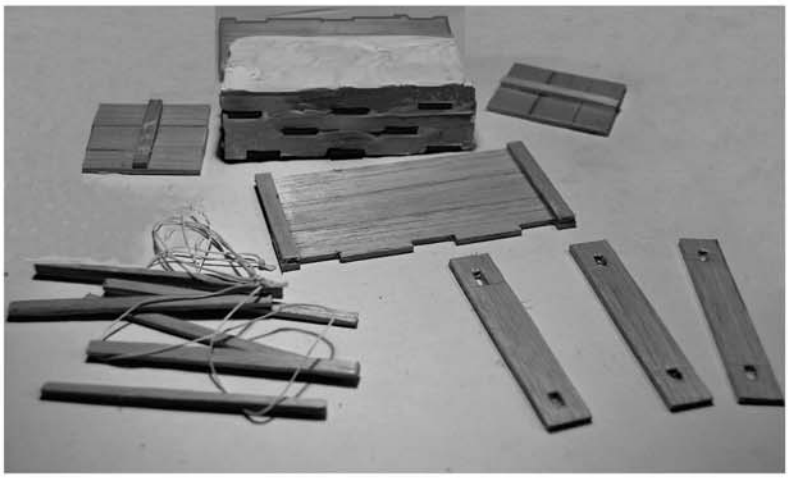

Figure 3: model with the components of the quarter-deck of a *tapia valenciana* wall (Cristini - Ruiz Checa)

PROPERTIES OF BRICKS IN *TAPIA* WALLS

Both bricks and *tapia* walls have a common raw material, clay (aluminium silicate). But generally all the materials used in the *tapia* process, like mortars or plasters, are really fundamental for the durability and stability of the wall's integrity.

We can underline the main types of performance of bricks in *tapia* walls, such as:
Bricks layers in rammed earth wall. In this case bricks are arranged between the modules, so as to improve the response against the soil's dampness, through a process based on the relation between differential porosity/granulation of earth and clay. This technique is typically used in the inner regions of Spain, like *Castilla y León,* in which we can see local architecture with brick layers between the *tapia* modules or in the base of the walls. One or two brick layers guarantee the impermeability of the wall and a homogeneous load transmission.

Bricks buttresses in rammed earth wall. In this case *tapia* walls have buttresses, in the corners, made with bricks. This solution can reinforce the walls and it can improve the joints between the modules of rammed earth. These walls, visible in the inner regions of Spain, leave the loading capability to the buttresses instead of rammed earth modules. T*apia* walls in this case are used just like a partition between toothing-brick corners.

Bricks in *tapia valenciana* walls. This is the most complete and most functional brick reinforcement. This technique uses bricks not just in some separate layers or only in the base. The complete structure uniformly includes bricks in all earth modules (see fig.4).

Figure 4: Correct or wrong placing of the bricks in the quarter-deck (Cristini-Ruiz Checa)

PROPERTIES OF BRICKS IN *TAPIA VALENCIANA* WALLS

What is the function of bricks here? What is exactly the role of bricks in *tapia valenciana* walls? We analyze below different functions and reasons of this use, from the point of view of improved mechanical and structural performance:

Increase in wall's capability against friction stress

After considering Spanish new legislation on concrete structure (EHE-art.47), we can analyze friction stress in concrete joints as:

$$\tau_{r,d} \leq \tau_{r,u}$$

$\tau_{r,d}$ calculated Friction Stress

$\tau_{r,u}$ breakdown Friction Stress (limit of Friction Stress)

Considering that breakdown Fricion Stress $\tau_{r,u}$ has the value of, equation 1:

$$\tau_{r,u}=b(1.30 - 0.30\ (f_{ck/25})f_{c,d} > 0.70\ bf_{ctd} \qquad (1)$$

where b can be:

0.80 for wrinkled composed surfaces with connections' elements

0.40 for wrinkled surfaces

0.20 for low wrinkled not composed surfaces

And where f can be:

f_{ck} weakest concrete joints' compressive strength
f_{ctd} weakest calculated concrete traction's strength

The procedure has a penalty due to the presence of dynamic actions that influence 50% of the $\tau_{r,u}$ value; similarly, the hanging loadings ignore the concrete cohesion tribute.
Anyway, if we extrapolate friction stress from concrete examples to rammed earth case studies, we can consider the same factors, like adherence or joints connections between the layers.
We can assume **b** index is between 0.40 and 0.20 in traditional rammed earth walls, where earth layers have low wrinkled surface; In spite of the case of *tapia valenciana* walls. In these structures we can consider **b** index ≅0.80, because the presence of bricks, slapped in rammed earth wall, increase the value of the wrinkled composed surface.
The bricks have the fundamental role of connections, like elements that absorb the friction stress.

We have to consider that the right position of bricks has a fundamental role in the final wall performance. The presence of brick connections can aid the structure also in case of seismic action (the Valencia region, according to NCSE Spanish Seismic Code, has seismic basic acceleration aca_b=0.06g) or in case of local subsiding (the Valencia region has a slime and mud soil with low admissible tension). In accordance with some *tapia valenciana* documented walls $ -like *Almudin* (Valencia's granary-1417), *Trinidad* Monastery (1445), *Patriarca* Seminary (16th century)- we can verify the chronology of earthquakes in the city. In 1395 an important seismic action took place in Valencia, and the development of this technique, suitable for seismic areas, can be influenced by this tragic event.

We have to consider that *tapia valenciana* walls are made with a plastic mixture of earth and lime; so the constructive process becomes crucial.
The more the ramming process increases, the more the deformations due to horizontal pressures grow. The earth, thanks to the presence of ceramic connections, is confined between the bricks (always disposed with the heads towards the quarter-deck – see fig.5) and so the horizontal deformation is reduced. If the pressure of the mace increases, we can see how the compactness of the wall increases too; also the adherence between the lower layer and the upper one is improved.
In the case of reinforced concrete walls, there are metallic vertical elements which support the friction stress; this can be compensated, in *tapia valenciana* walls, with the use of ceramic connections.
All these factors turn this rammed earth construction technique into a unique solution -from the point of view of mechanics, outer finishing and construction process.

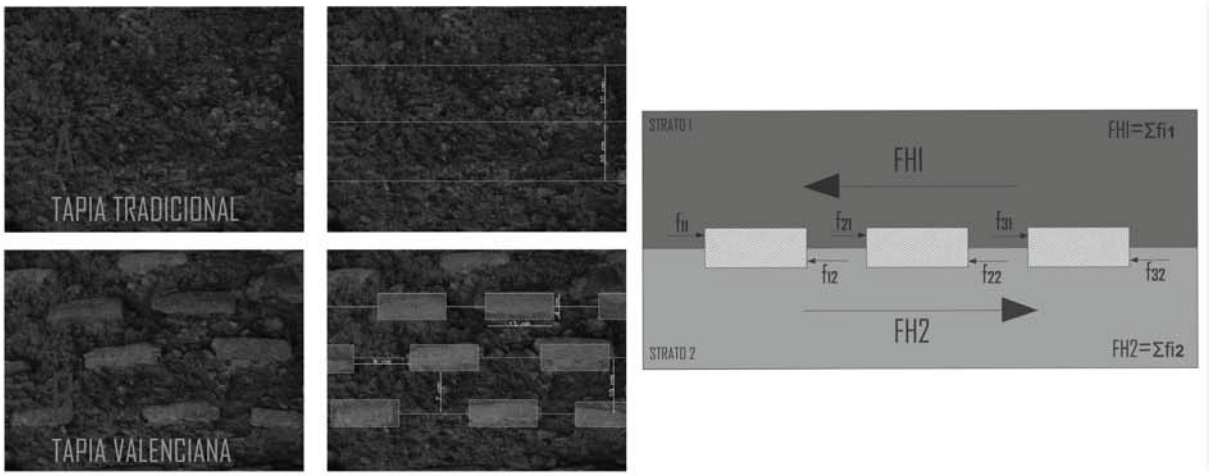

Figure 5: the role of ceramic connections in *tapia valenciana* wall, reinforced respect a traditional *tapia* wall (Cristini-Ruiz Checa)

CONCLUSION

The combined presence of earth and bricks in the quarter-deck guarantees improved results performance against friction stress (for seismic actions or for subsiding); also the mixture of properties of earth and baked clay improves the walls' performance.

Thanks to the presence of bricks, the process also increases the efficency of execution. Bricks improve the distribution of loadings between the layers, provide the sharing of the stresses, and regulate the strata. There is no doubt that it's a cheap and easy reinforcement technique, due to the availability and price of bricks (cheaper and easier to prepare and use as compared to lime mortar).

We can use fewer bricks than a traditional masonry, just using some elements in a "zipper" sequence, for joining and connecting the rammed earth wall. (In some examples, like *Alacuas* Castle, or *Alqueria de Chirivella* farm, close to Valencia, we can see walls and towers, almost 15 m high – see Fig.6).

While the workers are building the wall, at the same time they are preparing the finish coating, in an "all in one" construction process that doesn't need a finish treatment after the main procedure. The same finishing layer, a crust, provides both bricks and earth mixture with double protection against rain and mechanical degradation.

The combined use of earth and bricks synthesizes Vitruvius's categories of *utilitas, firmitas and vetustas,* as these clear, simple but functional reinforced walls show.

We can appreciate an increase of mechanical-structural properties, an improvement of economic and construction resources, and a contemporary aesthetic finishing solution to the walls. The final surface presents a special, well-done stratum, due to the modular rhythm, to the regular setting of the bricks, and to the alternation of light and shadow in specific sunken bricks.

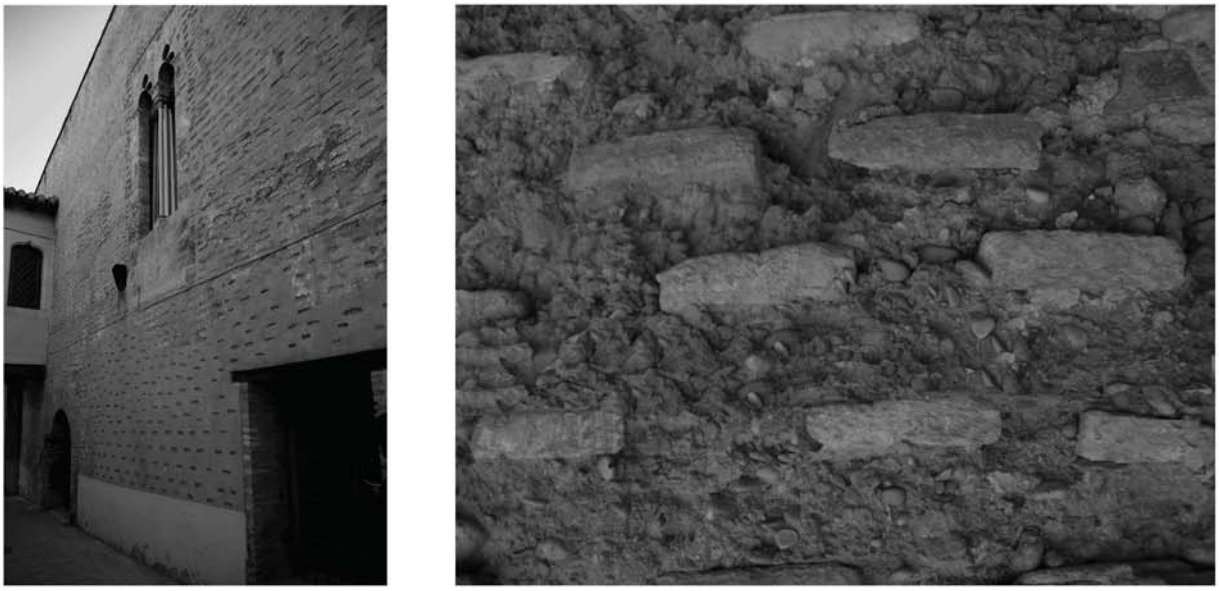

Figure 6: details of *Alqueria de Chirivella* farm, close to Valencia (Cristini-Ruiz Checa)

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