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Techniques and characteristics of traditional earthen masonry walls. The case of Spain

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Abstract

This article presents a detailed study of the traditional construction with earthen masonry walls based on 553 case studies throughout Spain. In order to facilitate their identification and interpretation, the variants in this study have been assorted into constructive groups with similar characteristics. In the discussion chapter, a quantitative analysis of the results is provided, highlighting the most common variant. Conclusions reflect on how the combination of opportunity and adaptation to the context - characteristics essential to vernacular constructions - shed light on a wide range of alternative techniques in this architecture. This article further expands on the existing information on earthen masonry, essential to proposing studies and projects aiming to protect, retrofit and consolidate this type of architecture in Spain and other countries.

Keywords: Traditional architecture, earthen architecture, earthen masonry, adobe, sod, marl

1. Introduction

Earth is a construction material known practically since the origins of Architecture and is especially prevalent in Spain, given the variety of buildings which use it (Mileto et al. 2017a). These buildings can be made using a wide range of techniques that have commonly been classified in three major groups: earthen monolithic walls, earthen masonry walls and earth as a mixed structure (Houben and Guillaud 1984; Stulz et al. 1997). The first of these groups is composed by techniques resulting in massive, unitary elements that have a reduced amount of joints. Earthen monolithic walls include techniques like rammed earth, poured earth, cob and dug out architecture. Earthen masonry techniques are based on the employment of different kinds of earthen blocks (such as adobes, sods, clods and turfs) for the construction of bonded walls. Finally, earth as a mixed structure comprises both the use of soil as a coating (earthen pavements, roofs and renderings) and its employment to infill or daub mixed walls, namely half-timber and wattle-and-daub constructions.

Currently the earliest accounts on the use of earth in masonry walls are found on adobe constructions in the banks of the Tigris and Euphrates rivers and date from 9000-8000 BC (De Hoz et al. 2003). From this point on, construction using earth blocks expanded or spontaneously appeared in different parts of the world. To this day it is one of the most widely used constructive systems worldwide.

Earthen masonry walls are based on the use of small blocks of variable proportion and composition which are combined to create different types of bonds. Their mass is generally composed of earth with some sort of shrinkage limiter: plant (fibres), animal (hair, bristles) or mineral (aggregate, lime, gypsum, etc.). The preparation of earth in small units allows better control of the drying process, making it easier to establish the quality of the material as well as how it is handled during the construction process (Fernandes and Tavares 2016; Guillaud 2008). Once these blocks have been prepared for use they can be employed in the construction of different structural elements including outer walls, partition walls, vaults, domes and arches.

The erection of any earthen building must begin with the construction of foundations to guarantee the correct load transmission to the soil while protecting the walls from damp. Stone or ceramic brick plinths are often placed above these foundations to separate the springing of earthen walls from the soil on the ground in order to definitively prevent walls from being affected by rising damp (De Hoz et al. 2003).

In the building process, the masonry units can be placed forming different bonds. The choice of a specific bond depends on the features desired and wall thickness needed. As in the mixture used to make the adobes, the mortar used to bond these walls is usually earth, although it sometimes includes other materials such as lime, gypsum, vegetable fibres, sand or gravel, which improve its properties or reduces its drying shrinkage (Fernades and Tavares 2016). Mortar is observed on all the joints of the bonding, both head and bed joints, or only in bed joints in which case the head joints appear dry or open, depending on the original intended use of the building and the quality of the fabric.

The mixes of clay and fibres used to manufacture mortar are also used regularly to render walls. This coating, that in Spain receives different names such as *tarrajeo*, *embarrado* or *trullado*, protects the fabrics from weathering and conceals the possible irregularities in the wall. Depending on the materials available in the region, the importance and use of the building and the purchasing power of the owners, these renderings can either be omitted or reinforced with tougher materials including gypsum or lime mortar, or coated with tiles, slate, shingles or wooden boards.

These variants in the different forms of building with earth can also be combined with other structural elements in different materials to make up a variety of mixed walls. For this reason, studies aimed at the analysis and classification of technical variants are essential to understanding these walling systems. However, there is an inherent sense of opportunity to these humble solutions which are always adapted to the available materials and open up new paths, branching out in present and future taxonomic tasks (Vegas and Mileto 2014).

2. State of the art

The interest in earthen architecture which appeared in Europe following the 1970s energy crisis has grown progressively (Guillaud 2012). This concern has been boosted by the desire to develop a more sustainable architecture compatible with the planet and its limited resources, and by the existence of a wealth of historical-architectural earthen heritage, which must be cared for, as well as by the need for inexpensive alternatives which are safe for at least a quarter of the world population who, according to the Lyon Declaration, live in earthen buildings (Joffroy, Guillaud and Sadozaï 2006). Aiming to respond to these concerns, in this decade the first international conferences on earthen architecture were organised. Among them, the *International Conferences on the Conservation of Mud-brick Monuments* must be outstood as the grounds of the present *Terra. World Congresses on Earthen Architecture,* which are considered the most important conferences in the field.

This international context prompted the appearance in the 1980s in Spain of interest in earthen monumental heritage, built mainly in rammed earth, which continued to grow over the decades that followed (including: Martín, Corral and Garabito 1980; Roldán 1983; Alonso and Cid 1994). These early works have progressively evolved into in-depth studies and overviews of the topic (Vegas and Mileto 2014; García-Soriano 2015). However, it was over a decade before a true interest in the study of earthen vernacular architecture appeared. As a result, after the publication of the last treatises previous to the final establishment of metal and cement in construction (among others: Marcos 1879; Ger 1898; Barré 1899) it was not until the 1990s that a new concern for the recovery of these techniques appeared.

This newfound awareness was prompted by the work of numerous experts who carried out studies on existing constructive techniques (Fernández Palicio 2015; Font Arellano 2012), architectural typologies (García Grinda 2005; Paredes and García 2006) and intervention experiences (Canivell and Graciani 2015). However, these studies are usually focused on individual buildings or particular towns and regions and do not provide with a joint vision of Spanish traditional architecture. The first initiatives to tackle with the formation of a panorama of this patrimonial ensemble were prompted by extensive research within Europe (Guillaud 2008; Correia, Dipasquale and Mecca 2011) or the Mediterranean context (Braizinha 1993; Achenza, Correia and Guillaud 2009). However, these initial efforts took the form of collections of short texts and were unsuccessful on offering a comprehensive representation of the field (Font Arellano et al. 2011). This made it necessary to develop homogeneous global research on this heritage and to provide a complete global vision of this patrimonial ensemble within Spain. The initial approaches to this research, that aims to cope with this need, were well received in different technical forums (Mileto et al. 2017a and 2017b). This article examines the main results obtained during research on traditional earthen architecture in Spain.

3. Objectives

Knowledge is an essential requirement for preservation. Only what is named can be referred to and, therefore, recognised and valuated. Consequently, the main goal of the present article is to identify and to understand constructive techniques and variations in Spanish earthen masonry walls. This knowledge and recognition will definitely contribute to valuate this architecture and favour its future preservation.

As a starting point, this article aims to offer a global panorama of earth masonry techniques used in the Spanish traditional architecture. To achieve this goal, it comprises the constructive characterisation of a broad sample including study cases spread all over the country. Expanding on this general objective, a series of specific goals can be drafted:

- **Identify the main walling techniques using earth masonry in Spanish vernacular architecture**, describing their most important features and studying their constructive process.
- **Recognize the different variations of these techniques**, detailing their singularities and defining characteristics.
- **Structure the registered techniques and variations in a comprehensive classification system,** that eases their understanding and assists in the constructive analysis of new study cases.
- **Reflect on the characteristics of Spanish earth masonry**, aiming to contribute to a better understanding of this architecture, to enhance its perception as a valuable patrimonial ensemble that must be preserved and to provide with a basis of knowledge that fosters the development of compatible interventions.

4. Methodology

The methodology used for the work presented in this article was based on the analysis of case studies extracted from an extensive database of traditional earthen architecture in Spain. For the formation of the database, 1,696 earthen constructions in 394 municipalities of 43 Spanish provinces were documented (Fig. 1a). These examples include cases illustrating the different earth-building techniques, namely rammed earth, earth masonry, earth-filled half-timber and wattle-and-daub walls. The research presented in this article covered the cases built using earthen masonry walls and involved the analysis of 553 constructions in 184 municipalities from 25 provinces (Fig. 1b).

The resulting sample was analysed following a series of qualitative and quantitative procedures. Qualitative approach included the in-site assessment of the buildings, the detailed analysis of their constructive system and the geographic mapping of the cases, while quantitative methods involved the statistical study of the presence of the different variations. This methodology aimed to identify the different earth masonry techniques that have been used in Spanish vernacular architecture and to define their main features, their location and their frequency.

The constructive description of case studies was undertaken through a taxonomic analysis based on a series of successive classifications. This method made it possible to examine different aspects of the technique separately, and to quickly provide a complete description of each example based on the combination of the different sections. During this stage, each of the constructions studied was classified according to different factors (Fig. 2):

- *Type of block*: describes the features of the units used for the fabric. Throughout the sample, the use of adobe, sod and marl blocks has been registered.
- *Type of bond*: specifies the way in which the mudbricks are laid. Stretcher, header, rowlock and shiner bonds have been examined, as well as different combinations among them (Fig. 2a).
- *Type of layering mortar*: simple earth mortar, with clay as a sole physical binder, or mortars with chemical binders such as lime, gypsum, etc. or combined variants, etc.
- *Presence of insertions in the fabric or the joints*: reflecting the insertion into the fabric of courses with varying proportions of other materials (ceramic bricks, stone…) and the creation of corners replacing adobe with ceramic bricks while respecting the bond, or the insertion of shards, flat stones, iron horseshoes or reeds in the joints in order to improve mechanical behaviour, resistance to erosion and durability.
- *Presence of external structural elements combined with the fabric*: records the existence of buttresses, sleepers, wall plates and wooden frames resulting in mixed structures (Fig. 2b).
- *Wall coatings*: records the presence of any sort of elements to protect the fabric, usually clay and straw, lime mortar, gypsum renderings or a combination of them (Fig. 2c).

The information relating to the techniques resulting from the classification of cases was recorded using a specific datasheet. Study methods systematised with the use of datasheets are tools which facilitate the constructive analysis of the cases, aiding the data collection process and facilitating building comparison and the extraction of conclusions. The datasheets used in this study, created with *Filemaker* software, follow this structure (Fig. 3):

a. **General description of the technique:** descriptive *title* of the technique recorded, *code* following the pre-established nomenclature, affiliation of the technique to a *constructive group* and *description table* summarizing its characteristics.

b. **General data of the technique:** *number of cases identified, principal typology, type of main use, location* of cases found, and a *main case* representative of the technique described.

c. **Constructive and structural characterisation of the technique:** *Type of block, structural elements external to the fabric, type bond* and *presence of coatings and insertions*.

d. **Observations.**

e. **Other cases,** complementing the main case mentioned above with up to four examples.

The classification system used allows the rapid restructuring of information to organise examples into different groups. Thanks to this, results are obtained for partial classifications depending on the aspect considered. Qualitative and quantitative results are obtained applying this method to a large sample, identifying many variants and ascertaining how far these are representative within Spanish traditional architecture using earthen masonry.

The results of the study have been assorted into groups of techniques following similar constructive logics. The different techniques identified within each group are distinguished as common variants or isolated variations, based on whether they are commonly found in the sample or appear anecdotally. It is considered that for a variation to be considered a common variant it must represent at least 5.00% of the cases recorded in a group.

In statistical terms the examples studied were considered a sample with infinite population n=553. Assuming a level of trust of 95% (α = 5%) for results and a maximum estimation of the variability of responses in the population (p = q = 05), the sample error considered in the study is 4.2% according to the following expression:

$$e = \sqrt{\frac{z^2 \cdot p \cdot q}{N}}$$

where e is the sample error value, z a constant of 1.96 for the level of trust established, $p{\cdot}q$ determines the variability of the sample and N its size.

Other uses of earthen masonry that have been registered during the field work process, namely adobe domes and auxiliary elements, have been also described in order to provide with a broader view of the richness of this architecture.

5. Results

5.1. Types of units used in Spanish earthen masonry

The units used in earthen masonry walls are varied and can be produced following different manufacturing processes. Based on the characteristics of these elements these techniques have been classified into **constructions with modelled earthen blocks**, such as adobe or clay lumps and **constructions with cut earthen blocks**, such as sod and marl.

The many variants of adobe walls have been used in 93.9% of the case studies and can be found throughout most of the territory. However, they are particularly common in the inner provinces of the north half of the Iberian Peninsula (Fig. 1b). The presence of marl and sod is more anecdotal, accounting for 4.3% and 1.3% of the sample and has only been registered in the regions of Valle del Tera in Zamora, and La Limia in Ourense. Nevertheless, examples in Valle de Bernesga in León and Laguna de Nava in Palencia are also cited in specific publications (MECD 2017).

5.1.1. Modelled earthen blocks

Adobe units are the most common earthen masonry blocks and by far the most frequently included in specialised publications. These parallelepiped elements are obtained by moulding and drying a clay paste in the open air and used in several types of fabric (Fig. 4a). There are substantial variations in size. In the cases analysed (García-Soriano et al. 2018) the average size of block is approximately 36 x 18 x 9 cm, although large variations as 40 x 40 x 7 cm (Valencia) or 24 x 11 x 8.5 cm (Piqueras del Castillo, Cuenca) have been recorded. In the region studied, these adobes are often made up of a mix of earth, water and straw. However, it is not unusual to find them stabilised with lime or gravel or to find mudbricks made solely of earth when soil characteristics allow (MECD 2017).

In different parts of the world masonry buildings can be found with blocks of a composition similar to adobe but modelled by hand without using specific moulds (Houben and Guillaud 1984). These units are known in Spain as *glebas,* clay lumps, (MECD 2017) to be freshly piled without mortar (Fig. 4b) or manual adobes, which are air-dried, to be bonded with mortar (Fig. 4c). As moulds are not used, manual adobe allows for a greater variety in size than moulded adobe (Ruiz Checa and Cristini 2012). However, at present, both clay lumps and manual adobe are scarce and only found in constructions conserved on archaeological sites (Chirinos and Zarate 2016; Mileto and Vegas 2018). No examples of manual adobes nor clay lumps were found in the studied sample.

5.1.2. Cut earth blocks

Although much less frequent than adobe, sod and marl are probably two of the earliest constructive materials employed by humans (Lewis 2016). Both techniques are based on the extraction of earthen blocks straight from the ground to be directly used in the building.

Marl (Fig. 5a) are prism-shaped earthen blocks cut from a compact soil free of plant substratum to ensure that they maintain their cohesion even after extraction (MECD 2017). As these blocks tend to be roughly the same size as those of adobe, they can easily be confused, especially when eroded. However, given that moulds are not used the marl in an individual building tends to display greater variations in size, making it easier to identify. As some of the studied examples have shown, the edges and heads of the marls occasionally show traces of the stratification of the soil or marks produced during the cutting and extraction process.

Sods (Fig. 5b) are cut directly from pastures and owe their consistency to the matted roots of the grass which grows in them (MECD 2017). The best soil for the production of sod comes from pastures of grass with thick roots, which keep the soil beneath them from falling apart even after drying. The grass is normally scythed to the ground before the blocks are cut and allowed to dry partially. Once the sods have been prepared to be used, they are placed with the plant layer facing downwards and the roots facing upwards to prevent grass from growing (Lewis 2016).

In most cases, sod walls spring from a stone plinth and are used as a non-loadbearing enclosure in buildings whose structure is made of another material (Fernández Palicio 2014). In the past these were also used as structural elements for simple buildings or for the erection of dikes, embankments and defensive walls (MECD 2017). However, at present vestiges of these uses are almost only found in archaeological remains.

Such units can also be used as finishing elements for roofs and enclosures. In these cases, commonly found until recently and known as *tapines* in the Cantabrian Coast, tend to be finer and conserve the layer of grass on top in order to encourage its growth (MECD 2017).

5.2. Construction techniques in earthen masonry in Spain

The classification method applied allowed the identification of 27 common constructive solutions using walls with earth blocks and up to 13 less frequent alternatives (Table 1). For ease of identification these 40 variants have been assorted into the 8 groups presented in this chapter. This section also includes subchapters regarding the use of adobes for the construction of vaults (5.2.6.), their utilisation to fill in, complement and homogenise buildings raised using other materials (5.2.7) and a collection of the most common coatings used in their protection (5.2.10.).

5.2.1. Simple adobe fabrics

The defining feature of technical variants included in this group is the use of the same homogeneous material (earth mixed with animal, plant or mineral by-products) to produce both adobe and layering mortar. The material most frequently used in the construction of the case studies is simply earth, often mixed with straw or gravel, trusting completely in the binding properties of clay. However, it is also common to find fabrics using mixes of earth and lime, or earth and gypsum, to produce both the adobes and the mortar used to lay and render them. In these cases, the physical binding role of the clay is complemented with a chemical binder.

The most common variant is that of **adobe fabrics in header bond** (Fig. 6a). These result in one brick thick walls, able to withstand considerable mechanical loads, particularly if these affect the wall homogeneously. The successive courses are staggered to prevent the continuity of head joints. Given this difference, the jambs and corners can only coincide with the modulation of the adobes in alternate courses. In order to avoid using adobe blocks cut longitudinally in half, at these points the unit to be split and the following one are usually replaced with adobe rotated 90 degrees and cut transversally three quarters of the way along.

In multi-storey buildings this type of bond is often found on ground floors, combined with **adobe fabrics with stretcher bond** (Fig 6b) on the upper levels. The resulting constructions have thick resistant walls on the first level which suffers highest structural stress, and half brick thick sections on the upper floors, which provide lighter enclosures while requiring less space and material. As in the case of adobe fabrics with stretcher bond, it is possible to find single- or two-storey buildings rendered completed with stretcher bond. This is however more common in mixed walls where adobes share structural responsibility with other constructive elements.

It has been found a rare variant which uses units of the same size both in their stretchers and headers to make **square adobe fabrics**. This system makes it possible to build walls with one brick thickness and with half the number of joints with header bonds and is considered more stable in the event of an earthquake than those which use common adobe (MVCS 2017). However, the heaviness of these units, approximately 40x40x7 cm makes them difficult to handle and has limited its diffusion.

The use of **adobe fabrics with shiner bond** (Fig. 6c) results in very thin 7 - 15 cm walls. The loadbearing capacity of the walls executed in this bond is limited and only a couple of cases have been identified of its use in single fabrics with a structural role. In these cases, walls are usually constructed using mudbricks stabilised in mixes with high proportions of lime or even cement. In contrast, high thermal inertia of the soil has enabled the use of walls with shiner bond for façade non-bearing, even in residential buildings.

Adobe fabrics in stretcher and header bond (Fig. 6d) are the most common variant in simple fabrics, after walls with header bond. This typology covers several types of bond which combine adobes placed with the edge and head showing. These variants improve the bond of one brick thick walls compared to adobe fabrics with header bond and allow one-and-a-half brick thick walls capable of withstanding large loads to be built. **Adobe fabrics in rowlock** (Fig. 6e) or others with more complex bonds such as **stretcher, header and rowlock** (Fig. 6f) have been rarely found but which contribute to the great richness of adobe as a constructive system.

5.2.2. Adobe fabrics with chemical binder layering mortar

This group includes different variants of adobe fabric where layering mortars are stabilised with chemical binder to increase resistance to erosion and in turn the durability of walls. The most common variant is made up of **adobe with lime or gypsum layering mortar** (Fig. 7a). The stabilisation of earthen mortar with a chemical binding material improves joint weathertightness, as well as resistance, cohesion and durability of the construction by halting potential erosion due to water runoff or rising damp. In areas with a strong tradition of gypsum or lime production such as the south of Aragón it is common to stabilize earth with chemical binders to produce both layering mortars and adobes themselves. These cases, that are included in the ensemble described in *5.2.1*, result in homogeneous walls with high mechanical resistance and resistance to damp.

5.2.3. Adobe fabrics with insertions in joints

The fabrics included within this group include elements inserted in joints to limit erosion, improve the adherence of the rendering or increase the monolithic nature of the walls. A common variant among this sort of bond are **adobe fabrics with ceramic fragments inserted in joints** (Fig. 7b) which tend to be pieces of ceramic bricks, floor, wall or roof tiles, probably from reused or defective units. Two subvariants were identified for this type: inserting fragments in the joints between the adobes along their entire perimeter or placing them vertically only on the head joints of the fabric. In some areas where slate rock is found or traditionally used for construction it is possible to find **adobe fabrics with flat stones inserted in joints** (Fig. 7c). The function of these elements is similar to the role of the tile fragments described earlier and they have only been found in the head joints of the fabrics.

Filling in the deteriorated parts of the wall with ceramic materials and small stone pebbles is traditionally used in building maintenance. At first sight these interventions might be confused with insertions in the joints or bonds of earthen masonry constructions. However, these are repairs carried out later to repair and strengthen the fabric, and not to be confused with technique variants.

Some walls incorporate other elements whose only aim is to improve the union between the bond and the coating. This is the case of the **adobe fabrics with iron horseshoe fragments inserted in the joints** (Fig. 7d), a rare variant documented in the province of Burgos. However, when these buildings are no longer maintained correctly, and the rendering becomes detached, the iron is left exposed and begins to rust, potentially becoming a source of degradation for the fabric they are supposed to protect.

The joints of the adobe fabrics can also be reinforced to provide walls with some resistance to tension and bending or simply to increase the connection in critical areas. One example of these variants are **adobe fabrics with wooden boards at the corners** (Fig. 7e). The aim of these elements is to improve the connection between perpendicular walls such as façades and main walls by placing alternating courses of embedded boards at regular intervals in the two converging walls. Some individual accounts of the use of these elements have been identified in the province of Zamora. However, this solution cannot be considered a one-off as references can be found to the use of wooden boards to connect rammed earth walls in other regions of Spain (Vegas and Mileto 2014). Finally, it is worth highlighting the **adobe fabrics with reed joints** (Fig. 7f) (Correia, Dipasquale, and Mecca 2011; Pérez 2018), an infrequent variant found in the province of Valencia and using cane bundles embedded in joints in order to improve the connection between perpendicular sections.

5.2.4. Adobe fabrics with insertions in corners

This type is rare and covers buildings where adobe on the corners is replaced by elements in other materials such as ceramic bricks, respecting the bond of the fabric. The aim of these insertions is to increase the resistance of the construction to erosion, damp and mechanical impact in the most exposed areas. Therefore, in these cases it is also common to use ceramic brick for door and window jambs

The examples identified during this study show insertions with ceramic elements, making up what could be termed **adobe fabrics with ceramic brick corners** (Fig. 8). Some variations can be found among these examples. Sometimes all the original earth blocks of a corner are replaced to form continuous ceramic brick corners. However, it is also possible to find buildings where these units have been replaced in alternating courses, leaving corners where earthen and ceramic bricks are combined. Although continuous corners affect the entire height of the corner, they are placed solely to increase durability of constructions and cannot be considered mixed walls, unlike stone or ceramic brick buttresses.

5.2.5. Adobe fabrics in mixed walls

These walls are built combining a wall section bonded in adobe with elements executed with other materials that help to increase the resistance of the wall. In most cases, these variants include vertical supports on the corners or along the walls. These buttresses or uprights support the timber wall-plates and sleepers of floors and roofs, partially unloading on the earthen walls. The most common variants are the **adobe fabrics with ceramic brick buttresses** (Fig. 9a) and **adobe fabrics with stone buttresses** (Fig. 9b).

However, depending on the materials available in each area other solutions have been documented. For example, **adobe fabrics with gypsum and rubble coffered buttresses** (Fig. 9c), found mostly in the provinces of Teruel, Zaragoza and Guadalajara, or **adobe fabrics with timber uprights** (Fig. 9d). The constructions in this last typology have been considered to be similar to large-panel half-timber walls by some authors (De Hoz et al. 2003). However, these walls are the result of combining a wall in adobe with a timber frame and unlike half-timber they do not constitute a single building technique.

The addition of one or several ceramic brick courses in adobe walls at regular intervals is also a common resource. However, adobe buildings using brick courses also tend to include vertical elements and it is infrequent to find the former on their own. In these cases, the ceramic bricks are usually placed every few courses of adobe, often becoming **fabrics alternating earthen and ceramic brick courses** (Fig. 9e), rather than sections of adobe with ceramic brick courses in the strict sense. Sometimes, flat stones placed in horizontal joints between adobes reach a remarkable size and can no longer be considered mere insertions in the wall, but **fabrics alternating adobe and flat stone** (Fig. 9f).

The use of ceramic brick courses combined with buttresses is much more common. In general, in these cases the ceramic brick courses are placed further apart, often coinciding with the upper and lower limits of openings. Ceramic buttresses are normally used in these constructions, resulting in **adobe fabrics with ceramic brick courses and buttresses** (Fig. 10a). However, cases of **adobe fabrics with stone buttresses and ceramic brick courses** and **adobe fabrics with stone buttresses and courses** (Fig. 10b) have also been identified.

Adding wooden sleepers and wall plates to adobe walls is particularly useful in load distribution. Unlike buttresses and uprights, these elements do not absorb the stresses that constructions need to transmit. In spite of this, they are efficient in the distribution of excessively concentrated loads and help the adobe section work homogeneously, hindering the appearance of fissures. **Adobe constructions with wooden wall plates** (Fig. 10c) are frequent solutions, often combined with buttresses. In these cases, in addition to distributing the loads along the fabric, the wall plates increase transmission to the buttresses, fostering their efficiency. Depending on the materials used, the most common variants are **adobe constructions with wooden frame** (Fig. 10d) and **adobe constructions with wooden wall plates and stone buttresses** (Fig. 10e)**.** However, other less common solutions sometimes found are **adobe constructions with wooden wall plates and ceramic brick buttresses** and **adobe constructions with wooden wall plates and gypsum and rubble coffered buttresses**.

In traditional earthen buildings it is possible to find other wooden elements embedded in the walls as in the case of ties absorbing horizontal thrust in some sloping roofs, which must not be confused with wall plates. These elements are placed to control load transmission to the walls but remain independent from them and do not aim to alter their mechanical behaviour.

Finally, among the mixed walls it is worth noting **constructions with adobe and ceramic brick bonded leaves** (Fig. 10f). These constructions are very rare but of great interest. They combine an exterior ceramic brick leaf, increasing the resistance of the wall to the elements and providing an exterior finish to an interior leaf of adobe which increases the resistance of the section while reducing the overall cost of the construction. Both leaves can be placed in stretcher and header bond to connect them on the inner faces. Another variant of this technique is **adobe construction between ceramic brick leaves**, consisting in adobe leaves confined between ceramic brick walls.

5.2.6. Adobe vaults and domes

Vaults and domes are constructive systems which can bridge spans by using elements working under compression. Although these structures are usually associated with stone and ceramic masonry architecture, they can also be built using other materials such as adobe, lime concrete or coffered rubble with lime mortar.

Adobe vaults have been systematically used in Spanish traditional architecture to build kilns and are closely linked to certain constructive typologies such as the peasants' shacks and agricultural sheds in different areas, including Castilla y León and La Rioja (Abril and Lasheras 2015; Vegas et al. 2010).

The techniques usually employed in the construction of these elements are the systems of kiln vaults and corbelled vaults (Fig. 11). The **kiln vaults** are built by successively creating different rings which slope progressively to the centre of the building until the element is closed (De Hoz et al. 2003). In this system the superimposed adobe rings work under compression and are stabilised thanks to the natural tendency of all the masonry units to slide inwards. While building the vaults, before closing the rings, the adobes remain in place thanks to the good adherence properties of the clay mortar used to bond them. In contrast, the **corbelled vaults** are based on successive courses of adobe placed horizontally and progressively projecting over the adobes placed underneath to close the space, also with no need for centring. These can cause problems with stability in the upper part of the dome, where the spherical geometry requires an increasingly larger overhang. For this reason, corbel vaults tend to form pointed sections which also help to facilitate the runoff of water and increase the durability of earthen finishes (Abril and Lasheras 2016).

5.2.7. Adobes to fill in, complement and homogenise

Apart from building complete elements such as walls, vaults and domes, adobe has been widely used in Spanish traditional architecture as an auxiliary material in the construction of buildings in combination with other techniques. Thanks to the small size of the units, adobe constructions can be adapted with ease to irregular or non-orthogonal geometries and have frequently been used for intermediate courses in **walls** in rammed earth or other materials, providing them with a flat crowning to support a roof or as springing for the next level. For this reason, adobe is also commonly used to **create slopes** in the gables of rammed earth walls, being difficult to adapt this technique to triangular shapes, or to fill in gables in gable roofs with wooden ties embedded in the wall. **Filling in the panels in half-timber** is one of the most common uses of adobe.

This study has also identified its use as a complement in different varieties of earthen construction (Del Río and Jové 2015), such as **poured earth walls with adobe buttresses**, **rammed earth walls with adobe courses and buttresses** (Fig. 12a), or adobe-faced **rammed earth walls**. Other variants such as **rammed earth walls with intermediate adobe courses** were not recorded in the analysis of the cases studied, although they are featured in the literature consulted (Vegas and Mileto 2014). Finally, the frequent use of adobe constructions to cover **openings** during the alterations of many traditional buildings through their long useful life should also be noted.

5.2.8. Sod constructions

The use of sod for the construction of loadbearing structures has been mentioned by some authors based on oral accounts (Fernández Palicio 2014) or historical photographs (Lewis 2016). The sample studied included **sod constructions with header bond** in fencing elements with no roof and, more frequently, header bonds or header and stretcher bond to build non-loadbearing enclosures in buildings on structures with other materials, mostly stone and wood. Sod constructions documented are usually laid without layering mortar and are uncoated.

The most common variants of mixed walls are **sod constructions with wooden uprights** and **sod constructions with stone buttresses** (Fig. 12b). Sometimes, the size and elaborate stonework on the ashlar used for the construction of the buttresses and the plinth contrast with the simplicity of the earth blocks of the enclosure of the buildings. Other common uses include a stretcher, header and herringbone bonds to **fill in roof gables** or **openings**.

5.2.9. Marl constructions

Due to their size and characteristics, marls are used in a similar manner to adobes and detailed observation of the construction is often needed to distinguish them. The use of these earthen blocks as loadbearing elements has been recorded in auxiliary constructions and fences and one- and two-storey residential buildings.

Marl constructions are usually set and sometimes rendered in earth mortars. The use of joints set or rendered with chemical binders is not recorded among the case studies in this research. The execution of simple **marl fabrics with header bond** and **marl fabrics with header and stretcher bond** have been recorded. Marls in stretcher bond or rowlock, stretcher and header bond have only been documented in buildings with independent bearing elements.

In most cases mixed marl constructions include vertical elements supporting the perimeter joints of floors and roofs, liberating earthen walls of part of their load. The most common variants are the **marl fabrics with wooden uprights** (Fig. 12c) and the **marl fabrics with stone buttresses**. No evidence has been found of their use combined with ceramic elements. On other occasions, these walls include sleepers or wooden wall plates which distribute the concentrated loads introduced by elements such as roof beams along the wall. As these are sometimes separate or combined with structural elements, different constructive variants can be found, including **marl fabrics with wooden wall plates**, **marl fabrics with wooden frames** and **marl fabrics with stone buttresses and wooden wall plates**.

Finally, it is also worth highlighting the frequent use of marl to **fill in gables and openings** or to complement other constructive earthen techniques such as marl-faced **rammed earth with marl courses** or marl-faced **poured earth wall** (Fig. 12d).

5.2.10. Wall coatings

Coating is a layer of any material used to cover the surface of an element to increase its durability and provide it with a finish. Walls bonded with earth blocks have traditionally been treated on the surface in order to protect them from wind and rain erosion and to improve their image. The most common finish in earthen constructions is clay and fibre rendering (Fig. 13a). This type of rendering uses a mix with a composition similar to that of adobe but with smaller fibres, such as animal hair or chopped straw. When possible, these clay renderings were **limewashed** to fix the particles and make the construction hygienic, while providing an aesthetic finish. On other occasions, the rendering directly uses chemical binding materials such as **gypsum** or **lime mortar** (Fig. 13b).

A rare finish that is worthy of mention is the vertical thatching of walls (Fig. 13c). These finishes cover vertical walls with fibres, placing superimposed courses of sheaves of straw. These plant bundles protect the mudbricks from the elements, collecting rainwater and directing it outwards as a steep roof would.

6. Discussion

Earthen masonry is a group of techniques that covers a wide range of solutions, such as *simple adobe masonry* (adobe masonry in header bond, adobe masonry with stretcher bond, adobe masonry with shiner bond, etc.), *adobe masonry with insertions in joints* (adobe masonry with ceramic pieces inserted in joints, adobe masonry with reed joints, etc.*), adobe masonry with insertions in corners* (adobe masonry with brick corners), *mixed adobe masonry* (adobe masonry with brick buttresses, adobe masonry with timber uprights, etc.), *sod masonry* and *marl masonry*.

According to the results of the research, the type of blocks predominantly used in earthen constructions is adobe. These were used in the construction of 93.9% of the case studies. Constructions with marl account for 4.7% of the sample studied, while those executed with sod account for 1.4%. However, all the cases recorded for construction with sod and marl are found concentrated in three locations chosen expressly in the data collection campaigns in view of information on these techniques. Therefore, it can be assumed that in terms of percentages the survival of these solutions in Spanish traditional architecture is testimonial rather than reflected in the data.

When examining adobe and its execution in detail it is interesting to note how 63.1% of cases studied -over half- are made of simple constructions composed purely of earth. These data are undoubtedly a clear indicator of adobe's ability to withstand the usual mechanical and functional demands of vernacular constructions. Moreover, a considerable number of constructions included external bearing elements or had been bonded using stabilised layering mortars, occurring in 36.9% and 11.7% of cases studied of adobe, respectively. Adobe fabrics with insertions in joints or corners are scarcer, only accounting for 2.9% and 0.8% of the adobe masonry constructions

The most common bonding system is header bond, used in 47.1% of cases. Stretcher bond and stretcher and header bond are also used in 19.4% and 32.2% of cases respectively. The simple adobe constructions with header bond, which combine the most frequent structural design and bonding, are the predominant variety and cover 34.8% of the sample.

7. Conclusions

Although based on the same constructive logic, this study has revealed the incredible wealth and variety of traditional architecture in earthen masonry. Despite specifically applied to Spain the methodology followed for this research can offer a valuable example for the study of other contexts where masonry techniques using earth blocks are found. Equally, the wealth of solutions identified can open up further lines of study for other researchers and settings. The materials available in the immediate surroundings of these buildings, the experience accumulated over generations and the inherent sense of opportunity of these constructive systems have provided multiple solutions which adapt optimally to the specific characteristics of every region. This creates a comfortable architecture with low environmental, economic and landscape impact from which valuable lessons can be learned towards the development of a more sustainable contemporary architecture.

Lastly, the development of studies like this and the progressive understanding of this architecture are essential to the diffusion of its perception as valuable global heritage which should be conserved. These works also provide valuable information for the development of interventions compatible with the nature of these buildings. Detailed knowledge of the materials and techniques of traditional construction encourage the valorisation processes, transcending local limits and contributing to the dissemination of heritage culture. This knowledge is fundamental for the recognition and understanding of earthen masonry constructions and will definitely contribute to their preservation.

Note

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Captions

Figure 1. Location of the case studies: a) Full database; b) Earthen masonry constructions (Authors).

Figure 2. Different features of the cases considered in the constructive characterisation: a) Type of block and bond; b) External structural elements; c) Wall coating (SOStierra).

Figure 3. Datasheet used to record the results of the constructive characterisation (Authors).

Figure 4. Modelled earthen blocks: a) Adobes; b) Clay lumps; c) Air-dried manual adobes (Authors).

Figure 5. Cut earthen blocks: a) Marl; b) Sod (Authors).

Figure 6. Simple adobe fabrics (Drawings: SOStierra. Photos: Authors and L. Villacampa).

Figure 7. Adobe fabrics with chemical binder layering mortar or insertions in joints (Drawings: SOStierra. Photos: Authors and M. Diodato).

Figure 8. Adobe fabrics with insertions in corners (Drawings: SOStierra. Photos: Inventario de Arquitectura Vernácula de Extremadura and E. Sevillano).

Figure 9. Adobe fabrics in mixed walls (Drawings: SOStierra. Photos: Authors, M. Diodato, L. Villacampa and B. Arnáiz).

Figure 10. Adobe fabrics in mixed walls (Drawings: SOStierra. Photos: Authors, E. Sevillano, B. Arnáiz and J. Agudo).

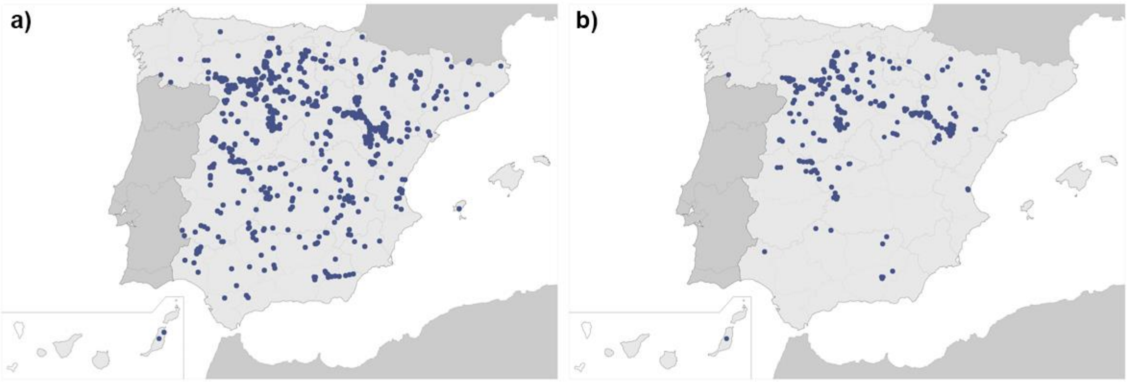
Figure 11. Adobe vaults: Corbelled shed in Urueña, Valladolid, and kiln in Molezuelas de la Carballeda, Zamora (Authors).

Figure 12. Other traditional walling techniques using earthen masonry (Drawings: SOStierra. Photos: Authors and E. Sevillano).

Figure 13. Traditional wall coatings (Drawings: SOStierra. Photos: Authors).

Table 1. Statistical presence of each constructive variant within its group and the complete sample.

Figures



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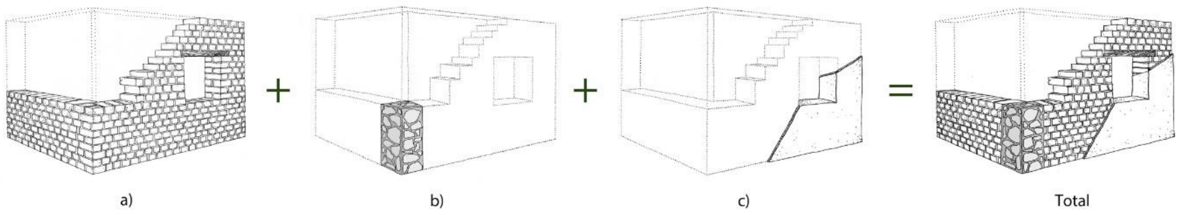

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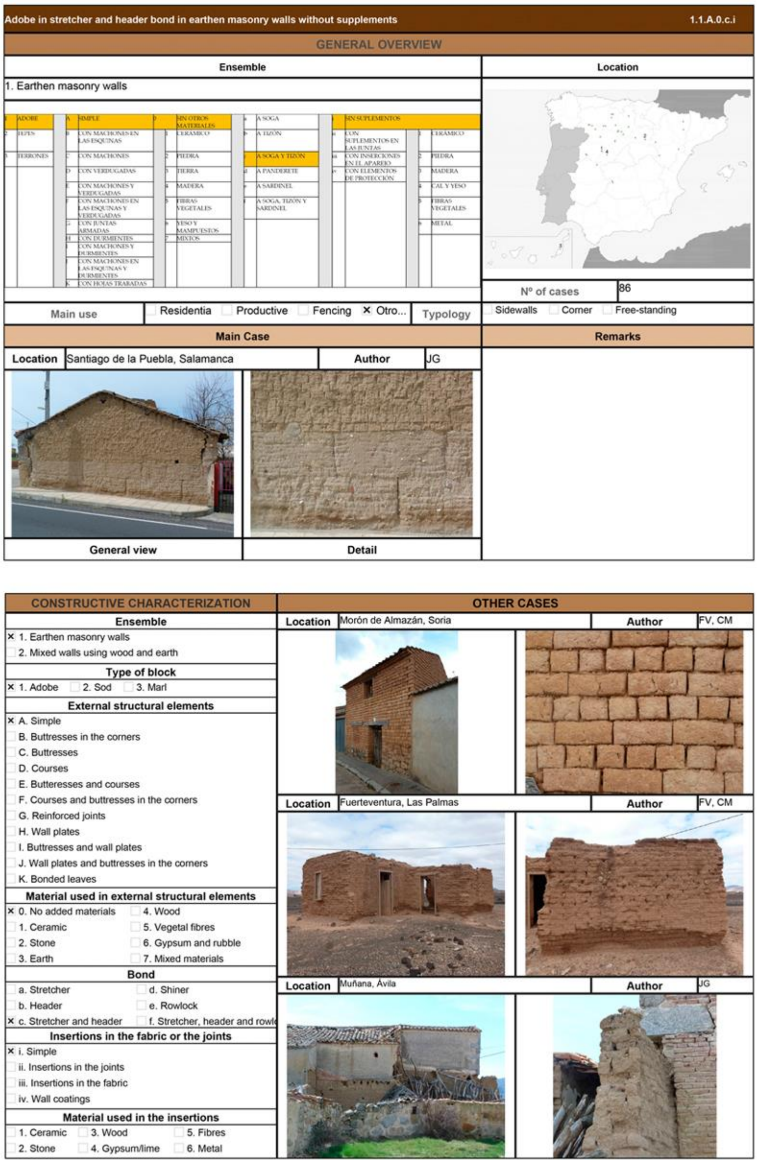

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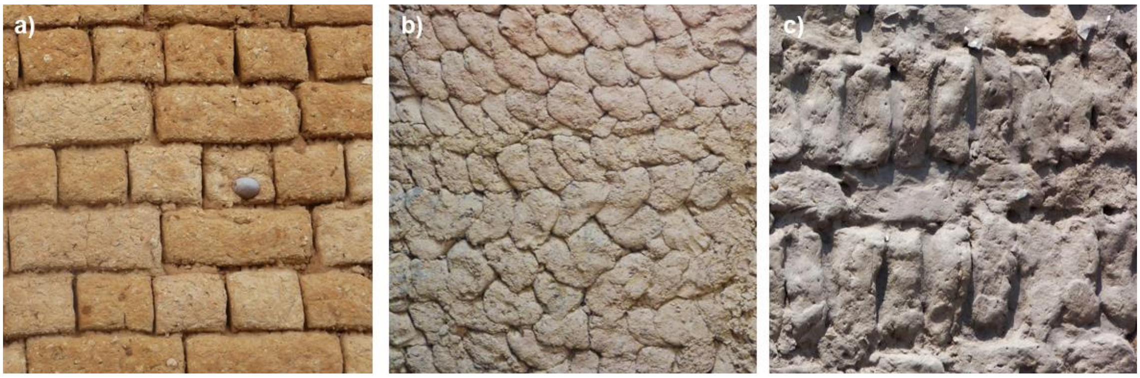

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Figure 5. Cut earthen blocks: a) Marl; b) Sod (Authors).

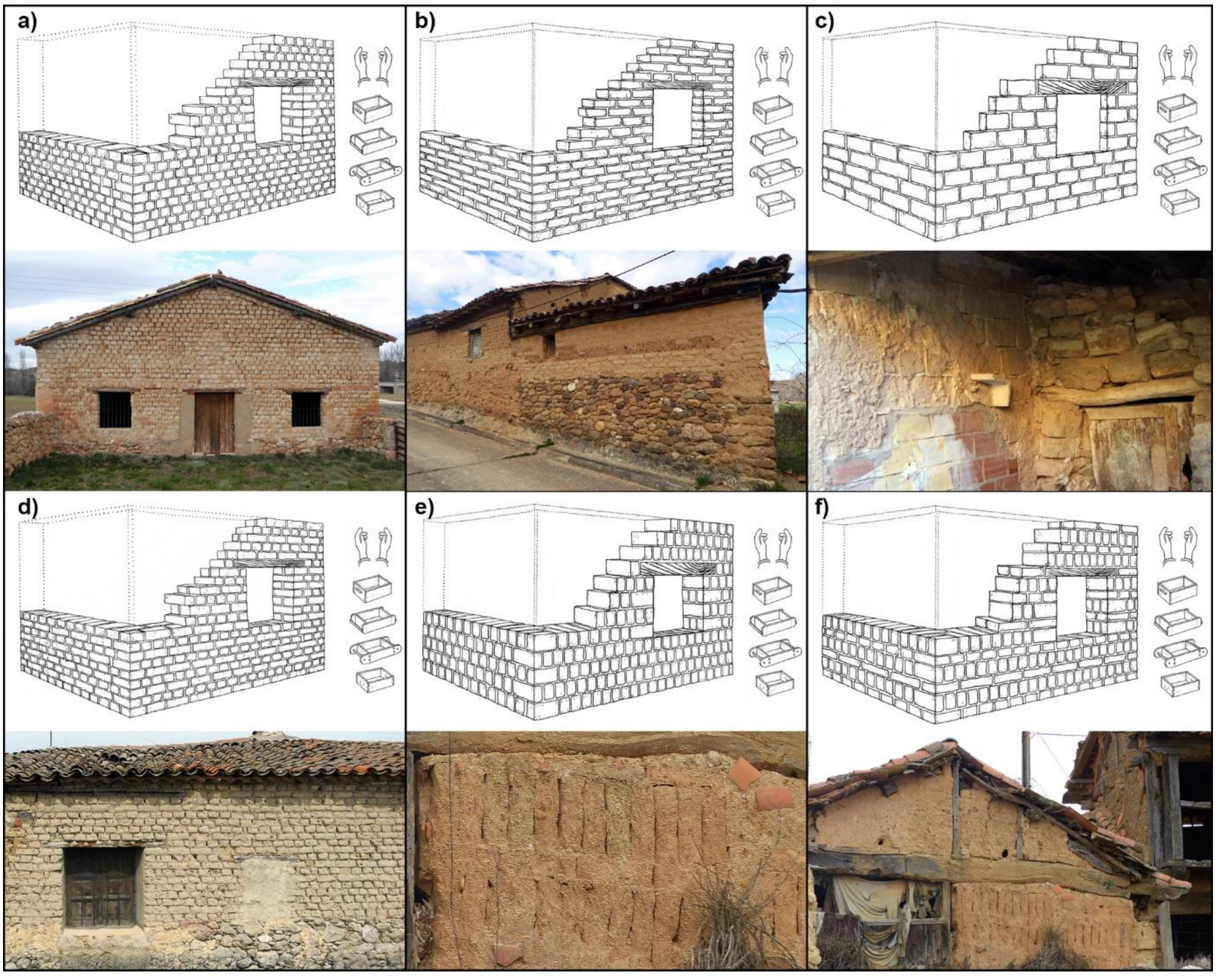


Figure 6. Simple adobe fabrics (Drawings: SOStierra. Photos: Authors and L. Villacampa).

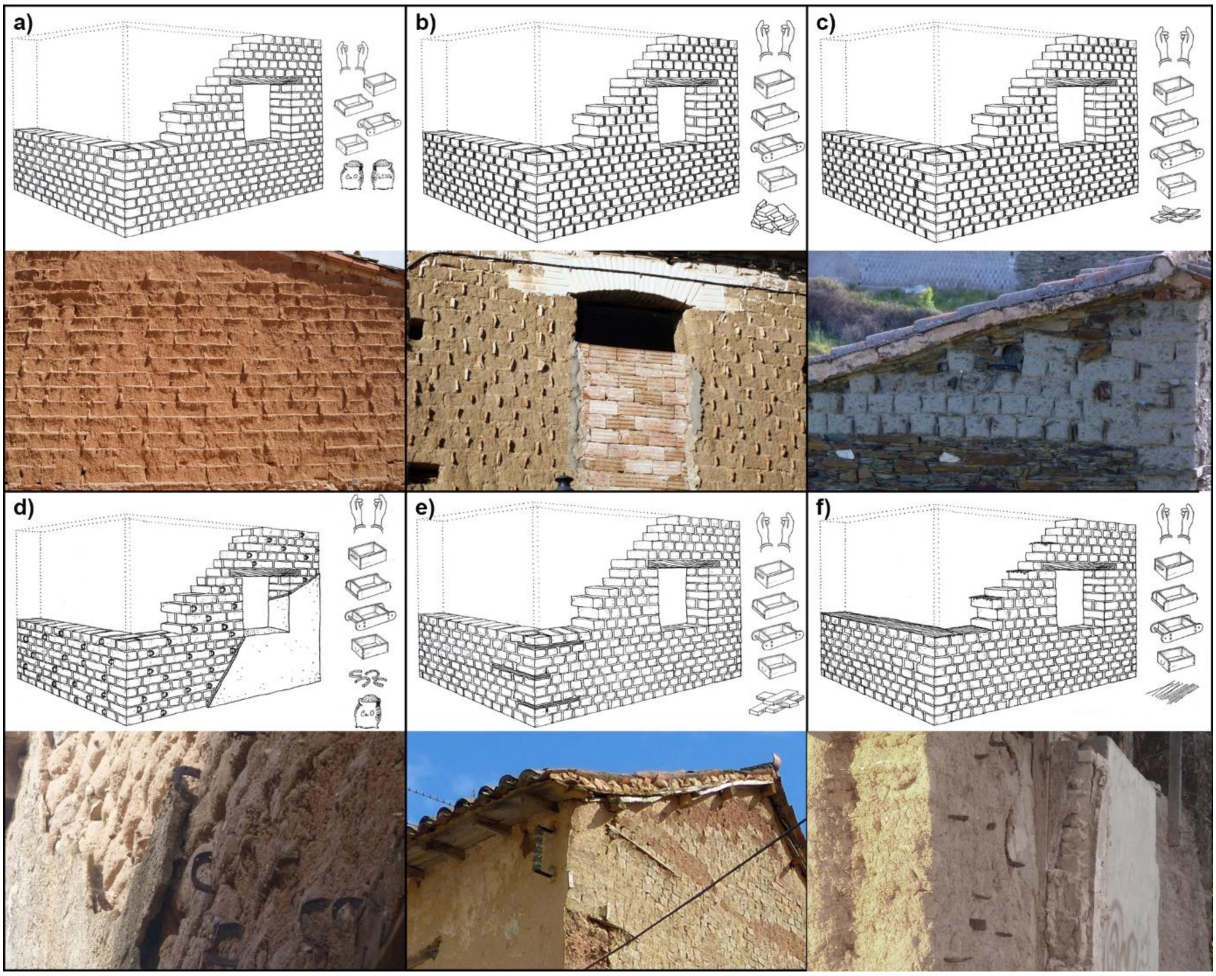


Figure 7. Adobe fabrics with chemical binder layering mortar or insertions in joints (Drawings: SOStierra. Photos: Authors and M. Diodato).

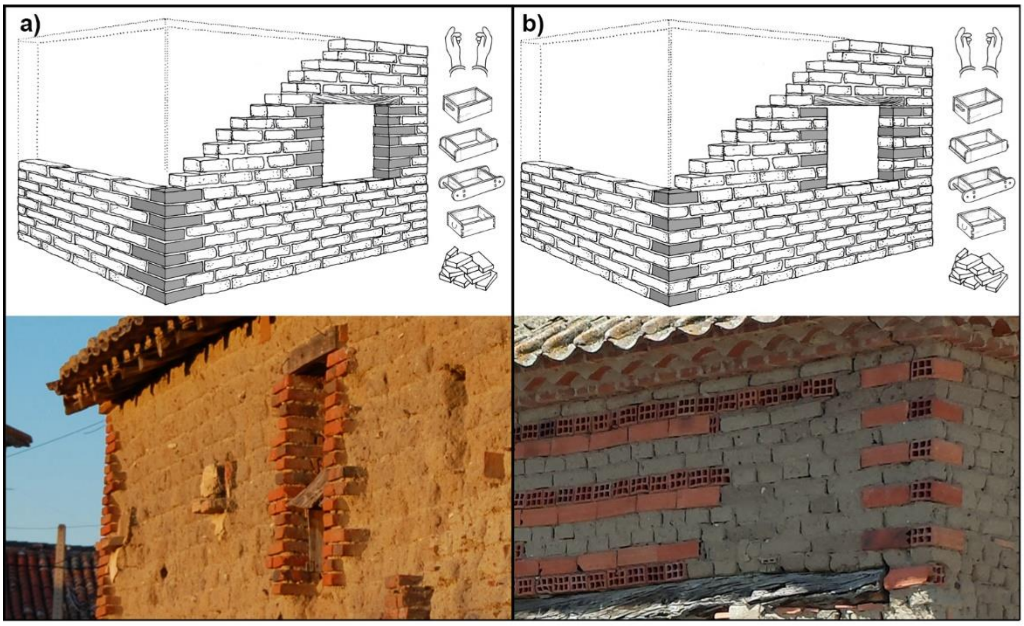


Figure 8. Adobe fabrics with insertions in corners (Drawings: SOStierra. Photos: Inventario de Arquitectura Vernácula de Extremadura and E. Sevillano).

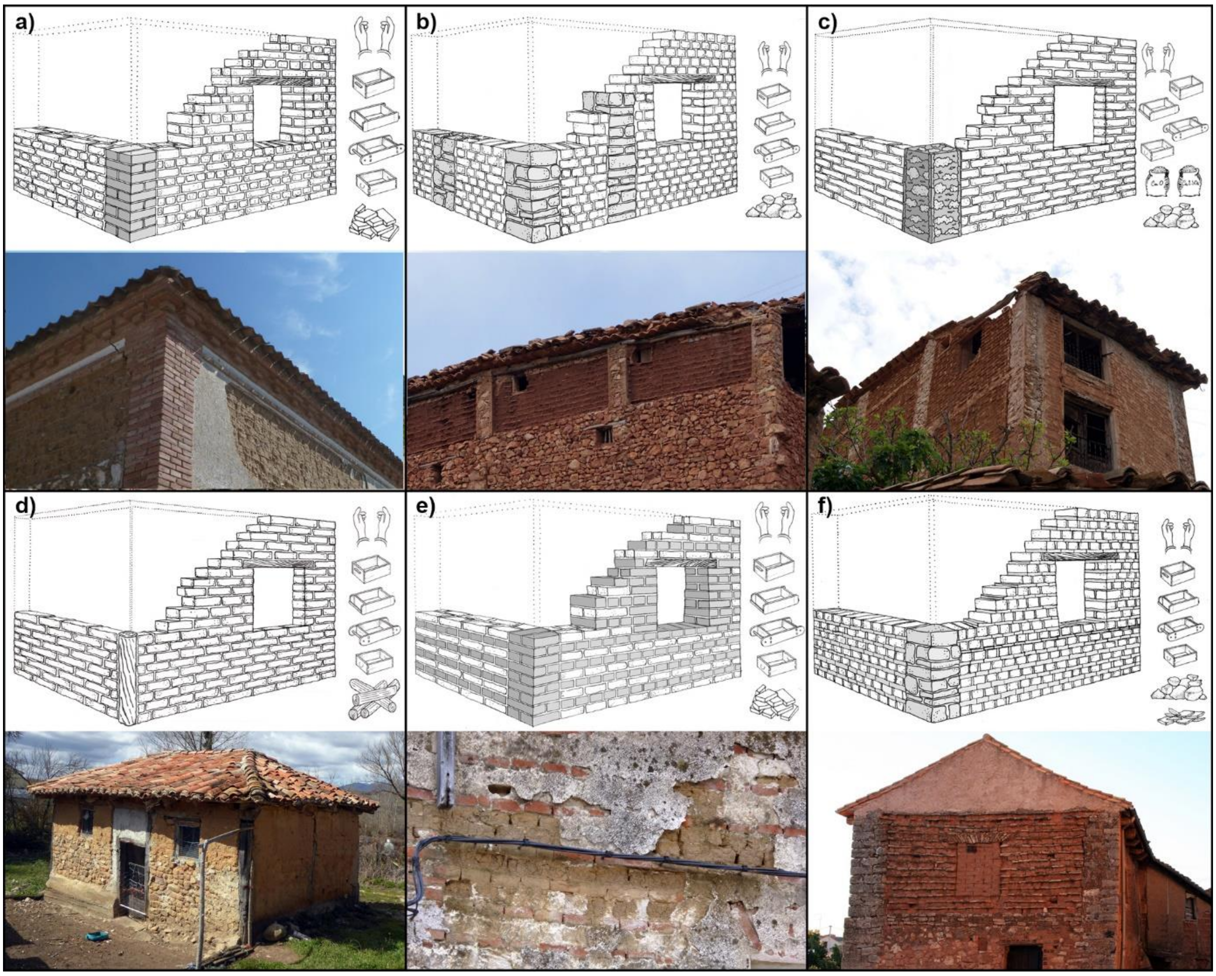
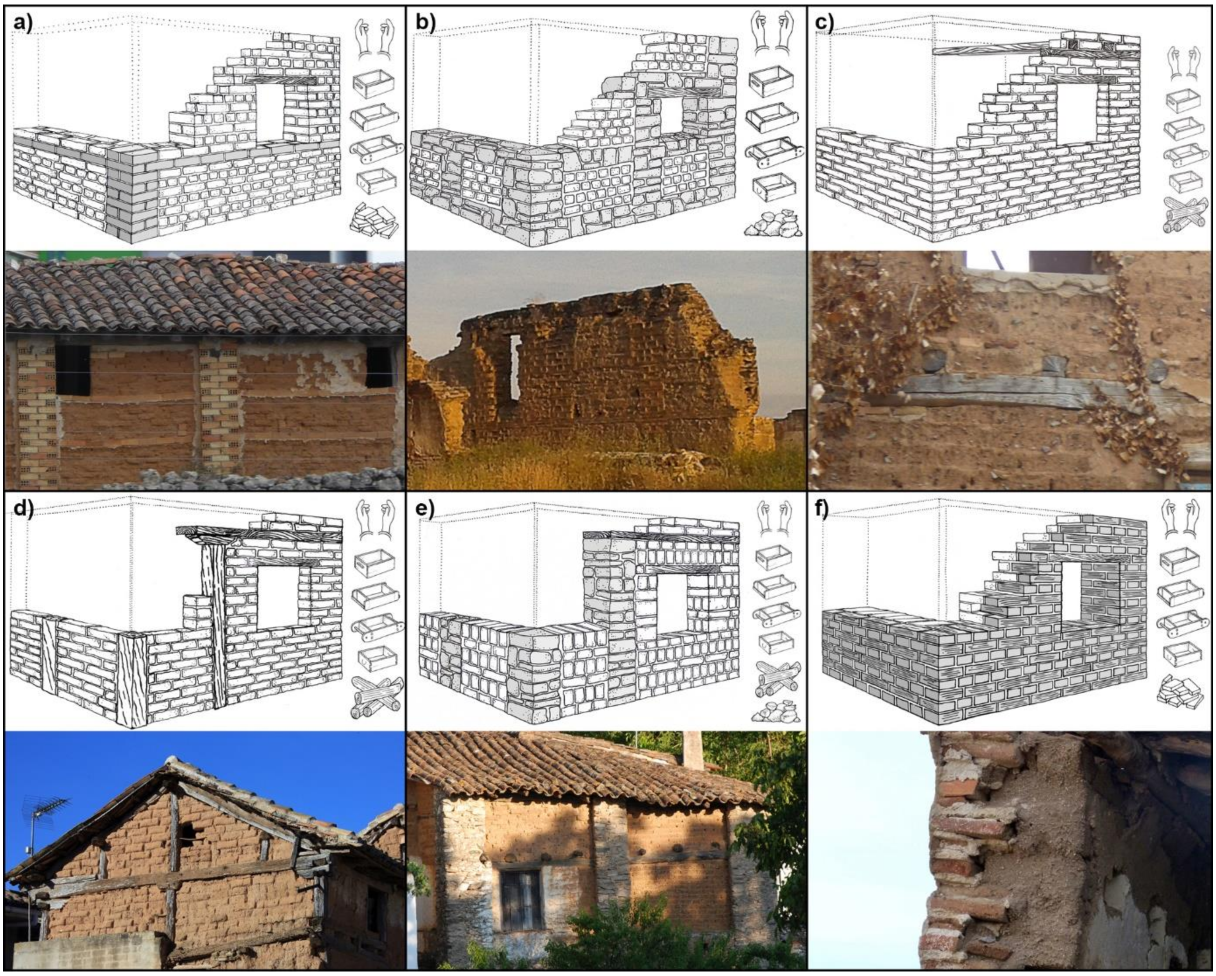


Figure 9. Adobe fabrics in mixed walls (Drawings: SOStierra. Photos: Authors, M. Diodato, L. Villacampa and B. Arnáiz).



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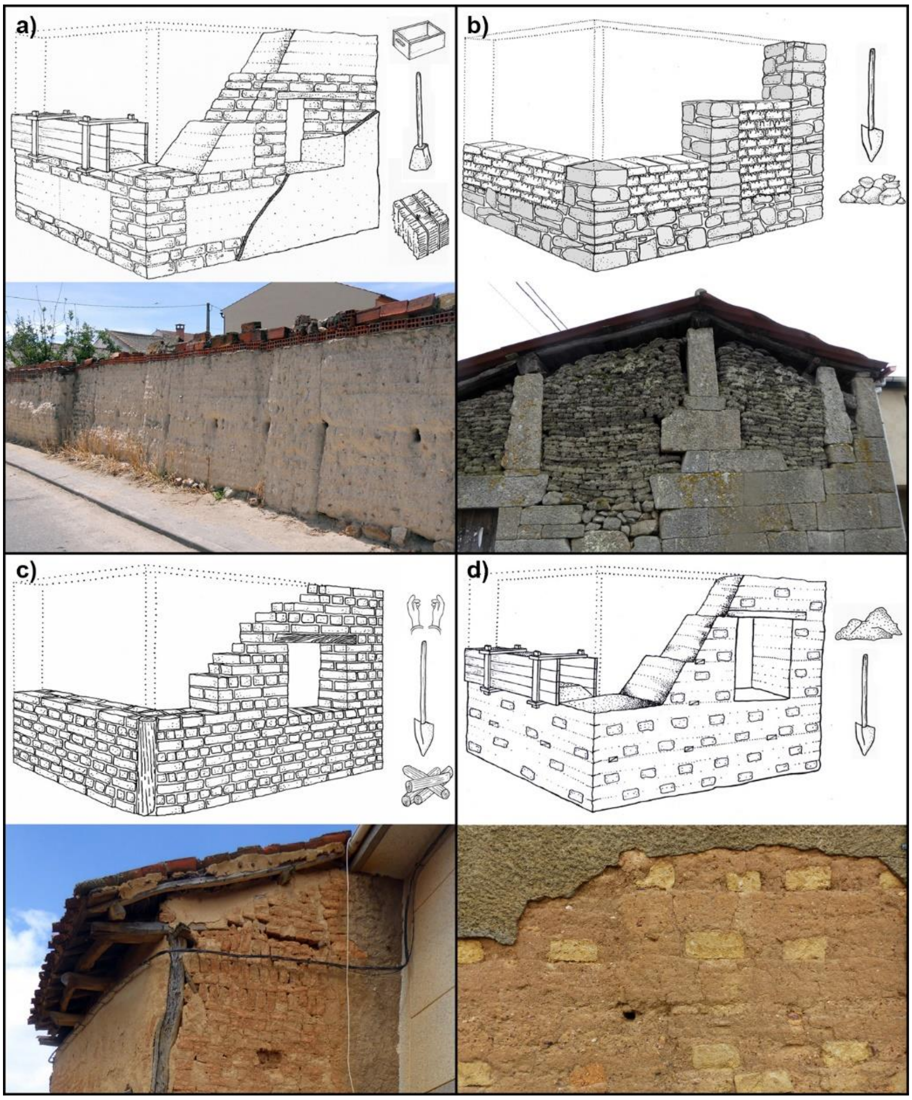

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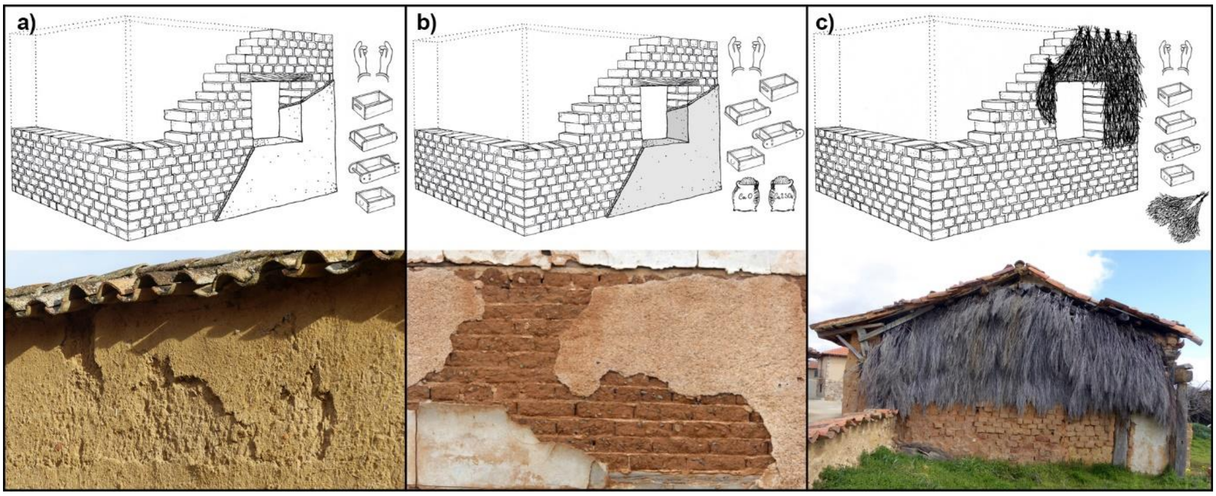

Figure 13. Traditional wall coatings (Drawings: SOStierra. Photos: Authors).

Table 1. Statistical presence of each constructive variant within its group and the complete sample.

	Presence within the group	Presence within the complete sample
Simple adobe fabrics	**100.0%**	**63.1%**
Simple adobe fabrics in header bond	55.2%	34.8%
Simple adobe fabrics with stretcher bond	11.8%	7.4%
Simple square adobe fabrics	0.3%	0.2%
Simple adobe fabrics with shiner bond	0.3%	0.2%
Simple adobe fabrics in stretcher and header bond	31.8%	20.1%
Simple adobe fabrics in rowlock bond	0.3%	0.2%
Simple adobe fabrics in stretcher header and rowlock bond	0.3%	0.2%
Adobe fabrics with chemical binder layering mortar	**100.0%**	**11.7%**
Adobe fabrics with lime or gypsum layering mortar	100.0%	11.7%
Adobe fabrics with insertions in joints	**100.0%**	**2.9%**
Adobe fabrics with ceramic fragments inserted in joints	60.0%	1.7%
Adobe fabrics with flat stones inserted in joints	20.0%	0.6%
Adobe fabrics with iron horseshoes inserted in joints	6.7%	0.2%
Adobe fabrics with wooden boards at the corners	6.7%	0.2%
Adobe fabrics with reed joints	6.6%	0.2%
Adobe fabrics with insertions in corners	**100.0%**	**0.8%**
Adobe fabrics with ceramic brick corners	100.0%	0.8%
Adobe fabrics in mixed walls	**100.0%**	**36.9%**
Adobe fabrics with ceramic brick buttresses	14.0%	5.2%
Adobe fabrics with stone buttresses	21.8%	8.0%
Adobe fabrics with gypsum and rubble coffered buttresses	7.7%	2.8%
Adobe fabrics with timber uprights	7.3%	2.7%
Fabrics alternating earthen and ceramic brick courses	2.1%	0.8%
Fabrics alternating adobe and flat stone	0.5%	0.2%
Adobe fabrics with ceramic brick buttresses and courses	7.8%	2.9%
Adobe fabrics with stone buttresses and ceramic brick courses	1.0%	0.4%
Adobe fabrics with stone buttresses and courses	0.5%	0.2%
Adobe fabrics with wooden wall plates	9.3%	7.1%
Adobe fabrics with wooden frame	16.1%	5.9%
Adobe fabrics with wooden wall plates and stone buttresses	5.7%	2.1%
Adobe fabrics with wooden wall plates and ceramic brick buttresses	2.1%	0.8%
Adobe fabrics with wooden wall plates and gypsum and rubble coffered buttresses	3.1%	1.1%
Fabrics with adobe and ceramic brick bond leaves	0.5%	0.2%
Adobe fabrics between ceramic brick leaves	0.5%	0.2%
Sod constructions	**100.0%**	**1.4%**
Simple sod fabrics with header bond	12.5%	0.2%
Sod fabrics with wooden uprights	50.0%	0.7%
Sod fabrics with stone buttresses	37.5%	0.5%
Marl constructions	**100.0%**	**4.7%**
Simple marl fabrics with header bond	29.2%	1.3%
Simple marl fabrics with header and stretcher bond	16.7%	0.8%
Marl fabrics with wooden uprights	12.5%	0.6%
Marl fabrics with stone buttresses	16.7%	0.8%
Marl fabrics with wooden wall plates	12.5%	0.6%
Marl fabrics with wooden frames	8.3%	0.4%
Marl fabrics with stone buttresses and wooden wall plates	4.3%	0.2%