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Drâa valley earthen architecture: construction techniques, pathology and intervention criteria

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Abstract
The Drâa valley is located in the south east of Morocco, near the Sahara desert, and houses one of the greatest earthen architecture heritage in the World. The present work shows the results of an investigation carried out on the earthen constructions in the Drâa valley, with the aim to know and to document the local building culture and the traditional construction techniques. The built heritage of the Drâa valley is worthy of study because it represents an excellent example of how local population was able to meet, in an excellent and sustainable way, the environmental challenges, starting from the environment and climatic features and from the availability of the construction materials. Unfortunately, the change of life style and the "race to progress" is producing a gradual loss of the traditional constructive culture and the related technical know-how, developed over the centuries. Such difficult situation is confirmed also by the lack of master masons and new skilled workers, jointly to the massive diffusion of the concrete construction. Consequently, many of the earthen building of the Drâa valley have been abandoned or lack the necessary maintenance. The present work tries also to investigate the main recurrent pathologies of traditional buildings and settlements in order to suggest some intervention guidelines (and related safeguarding criteria) for the conservation, preservation and enhancement of this rich heritage.

Keywords: Drâa valley, rammed earth, earthen bricks, earthen building techniques, earthen building pathologies

1. Introduction
1.1 The Drâa valley
The Drâa valley is located in the south east of Morocco, near the Sahara desert, and consist in the central part of the homonymous river; the Drâa river, in fact, born in the Saharan side of the High Atlas Mountains, creates a wide valley which cut the Anti Atlas chain, then, turning south west, follows the same chain along the Sahara Desert finally reaching the Atlantic Ocean. Actually the river has a very scarce water flow and water reaches the Ocean once every 30 years.
The Drâa valley consists of a six oasis system and it is characterized by a date-palms forest. The date palm is a base of the pre-desert oasis ecosystem because it creates shade and humidity and permits the cultivations of fruit trees and vegetables under it.
The pre-desert climate is hostile, warm and dry, with very marked temperature changes, both daily and seasonally (Baglioni, 2009; Baglioni et al., 2012).
Due to the richness of the palms forest, inserted in a very arid and rocky landscape, this area was chosen, already in antiquity, for human settlements and supported ancient agricultural communities (Fig. 1).

1.2 The building heritage of the Drâa valley
The Drâa valley houses one of the greatest earthen architectural heritage of the World; it consists in over 300 *ksur*, Berber villages entirely built with the raw earth techniques (VV. AA. [a], 2005). These rural and fortified villages are characteristic of the Drâa and Dadès valleys and they date from the XVth century, period when the sedentary Berber population needed to protect the villages with high walls and defensive towers, due to the continuous attacks of the nomadic Berber tribes. From the IX to XVth century the Drâa valley was also one of the most important caravan routes between Europe and Timbuktu city, in Mali (Fig. 2).

Figure 1: View of the Drâa valley.

Figure 2: View of Tissergatt Ksar

The *ksur* (singular *ksar*) shows a very dense urban fabric, with houses (*dâr*) built upon each other, in order to reduce the surfaces exposed to the warmth; in addition, often the first floor is built as a bridge on the road, thus creating, below, a fresh and dark tunnels grid, that protect from heat and sand storms. It is interesting to see how this type of aggregation simulate the underground architectures, enjoying the advantage of thermal insulation and, at the same time, solving the big problem of ventilation (Bourgeois, 1988).
In addition to *ksur*, the valley is populated also by *kasbah*, big fortified houses belonging to Berber families that protected the villages and surrounding territories, or, later, belonging to the representatives of Pasha Glaoui, who exercised administrative control until the Morocco independence.

2. The housing typology of the Drâa valley

2.1 The patio house

The typical housing type in the Drâa valley is the patio house, that is constant and recognisable both in the *Kasbah* and in the *dâr* (houses into the *ksur* villages). This type, with its specific and different models, is spread not only throughout Morocco, but throughout the Arab World and the Mediterranean; the different size and shape of the patio are determined partly by the local building techniques and the climate, and partly by the local traditional culture. Finally the “patio” is a typical space of the Arab-Muslim housing and it is identified with the centre of the home and the heart of the family life.

In the Drâa valley buildings, the patio is defined by a perimeter gallery present at each floor, which creates a transit area between the central vacuum (patio) and the private rooms. The patio plays a very important role in the building because it ensures illumination and ventilation, and its importance is also expressed by the presence of very rich architectural details and decorations (Baglioni, 2009) (Fig. 3).

Figure 3: Examples of patios into the houses

In the Drâa valley, characterized by a pre-desert climate, the use of patio houses and a compact urban aggregation, represents an effective response to hard weather conditions, due to the reduction of the external surfaces and to the function of the patio as a source of light and ventilation. The patio limits the direct insulation of ground floor and guaranties the indirect lighting of all the facing rooms; it also, like a chimney, pulls up the warm air, contributing to the rooms cooling and creating a pleasant ventilation. (Baglioni et Mecca, 2010).

2.2 The dâr

The *dâr* is the common house and is generally built on three floors. The ground floor rooms are normally used as stables, agricultural equipment and non-perishable domestic reserves, with the exceptions of the central patio who can be used as a summer living room (only when is covered on the top, and so being fresh because it isn't invested by direct radiation). The first floor, called *assfalou*, is a more private habitat and it is forbidden to the strangers; it is a sphere reserved for women that consists of the kitchen, the bedrooms and the storeroom for food reserves. The second floor is accessible and enjoyed by the guests and has direct access from the stairs, without necessity of crossing the *assfalou*. This plan has a covered part, where there is a living room called *mesria*, and a big terrace that is used to sleep on summer nights and to perform other household activities (Fig. 4).

The house is almost completely introverted, only rare windows can be found on the external walls, but never on the ground floor, in order to ensure privacy and confidentiality. The windows are quite small and shielded from wood or metal gratings, called *musharabia*, able to filter the strong outdoor light and to limit the interior visibility (but however, ensuring a cross-ventilation). Also the terrace is always surrounded by high walls to maintain privacy from neighbours. The house looks modest, but hospitable and adapt to the need of a peasant society, once nomad. For these reasons, the spaces have not a great specialisation, the same room being used as living room, dining room or bedroom, depending on needs and circumstances. So the people practise the daily or seasonal nomadism into the house, which consists in living, according to the different periods of the day (or of the year), in different rooms of the house, to enjoy the best possible comfort conditions (Bounar and Chalid., 2004; Baglioni and Mecca, 2010).

2.3 The Kasbah

The *Kasbah* are big fortified houses. In the simplest case, the *kasbah* maintains the quadrangular type plan with the central patio, but, unlike the common house (*dâr*), is larger, both in plan and in high (it can reach 6 floors), and presents towers in the corners. It belongs to large families, powerful and wealthy and often is more articulate and occupies large areas by combining several central patio buildings. The *kasbah* is thus divided into different areas, private or publicly, available for the various members of the family, servants or guests, and with distinct uses (VV. AA.[(b], 2005; Baglioni and Mecca, 2010) (Fig. 5).

Figure 4: The upper floor of the *dâr* in Tissergat ksar.

Figure 5: A Kasbah in Tissergat ksar

3. The buiding culture of the Drâa valley

In the traditional building techniques of Drâa valley, the major role is played by the earth material, used in many different situations (and ways), which proves to be the most suitable material for an effective response to warm and dry climate of the place.

3.1 The building yard (Baglioni, 2009; Baglioni and Mecca, 2010)

The raw earth buildings site are traditional and managed by small artisan "company" consisting of a master chief, called *maâlem*, and a variable number of workers (no more than a few units). The working tools are related to the type of site; they are traditional and made by craftsmen.

The masonries techniques used are based on the rammed earth, called *alleuh*, and the earthen brick, called *toub*, used separately in different parts of the building

3.2 Rammed earth building technique (Baglioni, 2009; Baglioni, Mecca et al. 2010)

The rammed earth technique allows to realise very thick (40-100cm) continuous bearing walls. This construction system, performed by shifting a single formwork, from block to block, involves the adoption of a constant thickness of the wall along all perimeter, and generally also on the whole height; a possible variation of the wall’s thickness may occur in the change of storey. For a 3-storey building, as the *dâr*, 40-50 cm of thickness masonry is enough, while for highest buildings, as the *kasbah*, more relevant thicknesses are needed, until about 60-100cm. The height of the floors is variable, from 2.5 to 5m, but is always proportional to the height of an entire number of rammed earth blocks (Fig. 6). As for masonry buildings, a particular attention should be paid in the connections in order to ensure mutual collaboration among the blocks, among walls, or among walls and partitions. Analysing the actual situation it is evident that the connection (toothing/overlapping) in the corner and among walls and partitions is not always successfully; thereby this determines a non-cooperation and non-joining among the walls that tend to separate and act as single walled sheet. In the Drâa valley, the rammed earth masonry is principally used for the walls of the lower floors, and for the partition and identification walls of the land ownership. All the buildings are generally built on a stone base of various height. The rammed earth, for its mode of implementation, exhibits some discontinuity points, consisting in the holes left by the inferior transverses of the formwork, once unthread. The holes and the joints between the rammed earth blocks are weak point in the masonry and favourite channels for the water infiltration; for this reason, the cracks in the walls are mainly located close to them.


Figure 6: Rammed earth masonries of a Kasbah in Tamnougault (left).
Figure 7: Earthen brick masonries in the patio in Amzrou (right).

3.2 Earthen brick building technique (Baglioni, 2009; Baglioni, Mecca et al. 2010)

The earthen brick (adobe) masonry is generally used for the perimeter walls of the upper floors, that are subject to minor weight, and in presence of finishes and decoration.

In some cases, where pressing the earth inside a formwork may be difficult or even impossible, portions made by earthen bricks into the rammed earth masonry can be found. The earthen brick is then used to complete the masonry above the wooden lintels, or to support them, or between floor beams, becoming here a string-course into the rammed earth masonry.

Whole monumental openings in prestigious buildings (*kasbah*) or in the fortified walls of the villages, are built on earthen bricks, so that arches and decorations can be easily realized using special dispositions in the earthen masonry (Fig. 8 et 9).

Earthen bricks play their major role in the patios, reaching the maximum of their bearing and decorative capacity: in the patio, pillars and walls are entirely made of earthen bricks (Fig. 7).

Even the partitions, not load-bearing inside the houses, or the perimeter walls of the skylights along the tunnel lanes, are made of earthen bricks.

The earthen bricks are produced in different sizes but they are craft products, therefore their size varies from site to site and from village to village. Typically the walls have thicknesses of about 40, 50 or 60cm and can shrink at the upper floors; the masonry is based on a disposition of 2, 3 or 4 edges, depending on the size of the earthen brick but very variable. The mortar consists of a mixture of earth and water, in which straw is rarely added. In an earthen brick masonry, the mortar is laid in horizontal joints between the courses, but rarely in vertical ones; the joints are 2 - 4 cm thick.

A lacking order in the earthen bricks disposition and the presence of mortar only in the horizontal joints does not ensure proper cooperation among the elements with the consequence of lack of linkage and low resistance of the earthen brick masonry. However, where a load-bearing capacity is required, usually on the lower floors or patios, the earthen bricks disposition is clearly more regular and well-executed.


Figures 8 et 9: Examples of a decoration made with earthen brick masonries in Tamgrout and Tissergat ksur.

3.3 The horizontal structures (Baglioni, 2009; Baglioni, Mecca et al. 2010)

The date palm wood, as the only available wooden material, is used to realize doors and windows lintels, and horizontal structures of the floors. Its mechanical performances are low, because its trunk consists of bundles of parallel fibres that, subjected to loads, do not ensure effective mutual cooperation and suffer intense inflections. This structural problem is restrained maintaining the beams extension relatively small, generally from 2 to 2.5m (up to 4 m); this size becomes a real “module” for any building’s construction.

The beams, both for floor and roof structure, are always disposed perpendicularly to the patio perimeter, with a varying inner axis depending on the presence or absence of further structural elements. When the joists are absent, the beams are very near, with an inner axis close to 30-50cm, otherwise the beams distance is about 2m, and the joists have an inner axis about 15-20cm.

A layer of canes, called *tataoui*, is put in place above the wood structure, with the functions of decoration, distribution of the loads on the wooden structure and limitation of the fall of dust (VV. AA. [b], 2005) (Fig. 10).

Above *tataoui* a layer of palm leaves, dried at the sun, was traditionally placed in order to further limit the fall of dust. Today, the palm leaves are replaced by a plastic sheet that can be easily found on the local market.

Figure 10: Example of horizontal structure made with palm wood and a layer of canes.

The floor is completed with two layers of pressed earth, rich in clay: the first layer is made with dry earth, the second, on the contrary, is made with a humid earthen mixture.
The roof is instead completed by three layers of pressed earth: the first layer is made of a humid mixture, prepared with a finer earth; the second has the function to absorb the possible water infiltrations therefore it's made of dry earth; the last one, in addition to be a finishing, is realized with a moist mixture of earth and lime or earth and straw in order to guarantee waterproofing. Lime is a natural stabiliser which makes the earth waterproof and, once dry, stronger.
The roof needs frequent maintenance because it is subject to degradation due to rain, wind and sandstorms. Maintenance is performed every 4 or 5 years, covering the existing with a new layer of earth and lime or earth and straw mixture, therefore the roof thickness increases gradually in the years.

3.4 The plaster (Baglioni, 2009).
Although often rammed earth and earthen bricks masonries are exposed (without plaster), the plaster in earthen buildings plays an important role, as the protection against wind, rain, humidity and temperature fluctuations.
The exterior plaster in the Drâa valley's architecture is made with a plastic mixture of clayey earth (from the palm forest), water and straw, to which animal dung and urine are often added. The straw is used as an additive for the plaster, in order to limit shrinkage and cracking. The animal dung, however, enhances the cohesion of the mixture and the waterproofing properties. The interior plaster is laid in two layers: the first layer, coarser, is made of a mixture of earth, water and straw; the second layer is made of a mixture of finer earth and water. To ensure its protective function, the exterior plaster needs a constant maintenance, which, in the Drâa valley is made every 4-5 years.

4. The building pathologies in the Drâa valley

The earthen construction pathologies in the Drâa valley are mainly related to three factors: the action of the atmospheric agents (water and wind), the deficiencies in building design, and the defects in the construction system; all are related to the lack or the inadequacy of maintenance (Baglioni, 2009; Baglioni et al., 2012) (Fig. 11).

4.1 Pathologies due to the atmospheric agents
Although we are in a pre-desert climate where rain is very scarce, the pathologies related to the water are very common, because the earthen buildings are particularly sensitive to water and humidity and then easily attacked.
All typologies of earthen masonries are very sensitive to moisture, as a matter of fact working as an hydrothermal regulator absorbing the air moisture and releasing it when the air is more dry. Nevertheless these absorption-desorption cycles generate the continuous onset of expansion and contraction in the material that, in the long run, may lead to a loss of cohesion.
The direct action of the rain on the wall's surfaces determines the progressive removal, for run-off, of the surface plaster particle, which, as time goes by, can expose them to the atmospheric agents.
The surface degradation phenomenon is accelerated by the continuous wind action, which, especially during the frequent sandstorms, exerts a real abrasive action.
If the surfaces are compromised, the water migrates and gradually infiltrates into the masonry. The infiltration may take place through capillarity, deeply entering into the masonry, or by gravity, percolating from top to bottom, inside the masonry; in both cases there is a progressive erosion of material, with the occurrence of cracks (Rovero and Tonietti, 2011).
Privileged channels of water infiltration are the internal joints into the wall, related to the construction technique. In the rammed earth masonries, even if the wall is built with continuity along the perimeter, taking for example two adjacent blocks, the next block is realized about half an hour after the other, therefore it exhibits a different shrinkage, which causes, during the drying phase, the separation of the vertical joints. The same problem happens among parts of the wall implemented at different times. In the rammed earth wall, other privileged channels for water infiltration are the holes left by the lower cross of the formwork. For the earthen brick masonries, the presence of mortar provides greater continuity in the masonry, but it is common practise, especially in the plugging masonry or in the terraces crowns, the use of the mortar only in the horizontal joints (Baglioni, 2009; Baglioni and Mecca, 2010; Baglioni et al. 2010).
Due to the previews considerations, it is evident that, in an earthen construction –and not only-, a fundamental role is played by the plaster, that protects the walls from the action of the atmospheric agents. A proper and frequent plaster's maintenance, while only limited to the deteriorated areas, therefore is essential as demonstrated

by the cases of more advanced degradation, mainly related to the lack of maintenance or to the state abandon of the buildings.
A widespread phenomenon is the capillary rise, which affects both the base and corners walls: the water, through capillary action, going up the walls from the ground leads to various diseases, including swelling and detachment of parts of plaster and consequently of masonry layers.
In relation to the increase of rising moisture, the degradation can increase and also undermine the structure equilibrium: due to the dissolution of the underlying masonries layers, the above masonry tends to settle, causing cracks that promote infiltration and further degradation (Rovero et al. 2011).

Figure 11: Principal pathologies of the earthen buildings of the Drâa valley.

4.2 Pathologies related to design defects
The water-related diseases are often linked to construction "defects", as the inefficiency of the base and the weakness of some construction nodes, particularly with regard to the drip pipe.
The presence of a good stone basement limits the water capillary rise and protects the wall from water splashes and human actions (VV. AA. 2009); however, in the Drâa valley's architecture, the stone basements are not always present or sufficiently high (Baglioni, 2009; Baglioni and Mecca, 2010; Baglioni et al. 2010).
The connexion between the rainwater drip pipe and the wall represents a weak point in the building construction, because leakage or water seepage are often generated; such phenomena cause an heavy wall erosion where the water drains. Comparing the two drip pipe solutions used in the Drâa valley, one made with wood, or the most recent made with metal tube, the traditional wood solutions is certainly more compatible with the earth material (Baglioni, 2009). One of the more effective solution used, is the pluvial excavated in the wall and waterproofed with lime plaster, but it doesn't solve the problem of turning away the water from the base of the wall, which is therefore subject to the pathologies related to moisture rising. In any case, a good maintenance of the plaster can limit the damage.

4.3 Pathologies related to the limits of the construction techniques

A different class of diseases is linked to the "limitations" of the construction techniques, related to the specific location, to local cultures, and to local skills of workers. All these causes influence the construction process (VV. AA., 2009).

Analysing the built heritage, we note that the rammed earth masonries are often realised without vertical joints offsetting, and/or without connections in the corners or among the perimeter wall and the partitions - whether in rammed earth or earthen brick -. Both cases are related to economy factors which tends to minimise the use of rammed earth sub-module. From a structural point of view, the walls, in the absence of mutual toothing, work separately, being simply adjacent one to the other; also the absence of a ring beam at the storey level along the wall perimeter, doesn't help the achievement of the "wall box". Therefore, due to the natural separation of the joints and the weather action, the walls gradually tend to separate from each other; this phenomenon is testified by the presence of recognisable vertical cracks. These processes are accelerated by the land subsiding which often generate rotations of the walls – accompanied by overturning tendency - and the onset of "out of plumb". To limit such effects, in these cases, real stone buttresses against the walls are often employed (Baglioni, 2009; Rovero et al. 2012).

Weak elements of the Drâa valley buildings are also the horizontal structural elements (beams and lintels) made with palm wood, which, due of its fibrous nature, doesn't guarantee high structural performance. The fibres of the palm trunk, when are under load, tend to work separately producing a strong deflexion of the timber elements; such repeated action require an adjustment of the wall with the subsequent onset of cracking, mainly visible in the walls of earthen bricks.

The last problem, not in importance order, is connected to the implementation of arches, frequently used in the patios of the houses and in the entrance doors of the villages (Baglioni, 2009; Baglioni and Mecca, 2010; baglioni et al., 2010). The lack of a real key element, especially in lancet arches, combined with the use of joints of considerable thickness, which amplify the sagging, generates cracks, especially in correspondence of the central part of the ring, causing a gradual and "natural" separation into two semi-arches. This fact, when taking over a further breakdown of the springers, can lead to dangerous kinematism.

5. Intervention criteria

In a recovery project of an existing building, the diagnostic analysis is crucial to recognise the causes of the problems, and consequently to develop a targeted and specific intervention (Rovero et al, 2011). In addition, a restoration project may exhibit different "levels" of intervention, such as the reconstruction (partial or total), the structural strengthening, the introduction of new technological solutions.

A good building preservation relies, first of all, on a good and constant maintenance and on the recovery of the construction know-how (by which such buildings were generated). Unfortunately in the Drâa valley there are a progressive abandonment of the earthen houses, carried out in order to move to houses built with conventional materials; furthermore a loss of building knowledge, due to the scarce presence of the maâlem (master masons) and young apprentices is, daily, going on.

However, starting from the most common diseases, some general intervention criteria can be proposed, which are substantially based on the constructive "rule of art".

1) The first big problem is the water action. As regards the water infiltration by gravity, both for the rammed earth and earthen brick masonries, it is recommended to seal properly the natural joints separation, with a mortar of earth and lime; in fact the lime increases the cohesion and makes the earthen mix more resistant to water. It is also important to create a good sloping on the top of the wall to limit the runoff. For the rainwater canalisation the strengthening of the techniques already in place is suggested, as well a long drip pipe (rain gutters) and long down pipe – excavated in the wall and plastered with lime - able to "accompany" the water away from the base of the wall.

To limit the capillary rise phenomenon not only a high stone basement, of the same thickness of the wall, is necessary (not always present in the earthen Drâa valley's buildings), but also the creation of a perimeter drain off device (achieved by gravel insertion and an adequate slope of the ground, which could help to remove water from the base of the walls and avoid stagnation.

2) In order to protect the walls from the weather agents (rain, wind, sandstorms) a fundamental role is played by the plaster and the last layer of the covers, a "sacrifice layer" that must be frequently renewed and possibly stabilised with lime.

3) From a structural point of view, an important aspect is to ensure the walls continuity. First of all the vertical joints in the earthen brick masonry have to be filled with an earthen mortar (or even better earth and lime mortar);

then a correct connection (toothing/overlapping) among the wall elements, near the corners, has to be guaranteed. With this aim the "stitch-unstitch" technique, both for the rammed earth and earthen brick masonries, can be used if necessary.
It is also important to intervene on the cracks, according to the cases, through the insertion of horizontal timber elements, alternating on both sides of the wall; a different solution may consists on the use of the "stitch-unstitch" technique (using earthen brick even in the case of rammed earth masonry); finally a casting of earth and lime mortar (which increases the cohesion and the strength of the mortar) may be adopted.
A ring beam can be inserted, at the same level of the floors, in order to ensure the operation of the building as a box; for this purpose wooden chains connecting opposite walls may be useful too.
4) Finally, as regards the constructional defects of local techniques, it is suggested to avoid concentrated loads, which often occur in the beams supporting floors and roofs, by inserting the ring beams (curbs) or some devices able to distribute the loads. In the special case of the arches, a more accurate control of geometry and the introduction of an appropriate key element are necessary.
For all the described operations the use of materials as much as possible similar to the original ones is recommended (Boussalh, 2005; Zagrouj El Mamoune). In the Drâa valley they are mainly stone, earth, straw, and wood; introducing different materials (without prejudice to the localized use of more efficient wood beams in place of palm timber beams) has to be avoided since such solution was often an inadequate solution.

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