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CODE 1.2.10**SURVEY AND CHARACTERIZATION OF CORBELLED DOME
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e-mail: fernandocerqueirabarros.arq@gmail.com, web: <http://www.fa.up.pt>**KEYWORDS:** Corbelled dome; vernacular heritage; granite stone; laser scanning.**ABSTRACT**

The act of overlaying stones to build masonry structures is one of mankind's most intuitive and resourceful achievements. Masonry buildings can be found all over the world, built with a wide diversity of materials and serving for all kind of purposes.

In rural northwestern Portugal, in a granitic highland landscape of scarce resources, for centuries, local farmers used masonry in order to make the territory suitable for farming. In their effort to increase production and, by doing so, to improve their living conditions, a specific mountain agro-pastoral system was developed. Supported by communitarian labour, this system was based on terrace farming and temporary mountain plateau settlements, called *brandas*, composed of granite corbelled dome buildings. In spite of its perfect adaptation to the harsh local conditions, this heritage's morphological and typological diversity and constructive inventiveness is endangered due to decades of rural exodus and, thus requiring urgent study and protection.

The research project aims to study this heritage from morphological, typological and constructive points of view, with the objective of proposing guidelines towards its preservation. To achieve the established goals, a four stage based methodology was established.

Literature review and fieldwork surveys were performed in the first stage, in order to identify possible case studies. On the second stage, an exhaustive geometrical survey and a case study analysis were undertaken and complemented with the local granite's physical and mechanical characterization. The third stage aims to do an overall structural safety evaluation of the corbelled domes, based on numerical analysis. In the final stage, consolidation and preservation guidelines to safeguard this architectural heritage will be proposed. This paper presents the results of the first stage, along with a glimpse of the second stage.

1. INTRODUCTION

Corbelled domes buildings in Portugal represent one of the most intriguing and exquisite forms of vernacular heritage existing in the rural landscape. Among the rural heritage identified during the mid-

20th century Portuguese rural population surveys [1]–[3], several different typologies of corbelled dome buildings were identified around the country. Of unknown origin and still in use at the time, this heritage has now lost its place on daily use due to rural exodus and the abandonment of traditional farming and pastoral livestock production [4], [5]. In order to assess what remains of this abandoned heritage and complete the existent knowledge with scientific data and accurate building features analysis, a research campaign was set in motion. A transboundary research team (Portuguese/Spanish) was assembled and the corbelled dome high mountain heritage of the Gerês/Xures Transboundary Biosphere Reserve (Portugal/Spain) was selected as the first study case [6].

2. CORBELLED DOME HERITAGE’S BASIC PRINCIPLES AND CONTEXT

Corbelled domes can be described as structures built by overlapping layers of masonry (stone or adobe), jutting toward the centre, built in horizontal rings or in a spiral movement until meeting at the top [1], [7], see Figure 1. Considered of less relevance by the scientific community, the structural behaviour of corbelled domes is still less studied than other vernacular structural systems. According to the existent scientific literature, the corbelled structural behaviour is based on the balance achieved by the combination of the vertical transfer of forces to the base of the dome, and on the horizontal actions resulting from masonry units’ interlocking and friction [9].



Figure 1: Examples of the study area’s corbelled domes. Examples from *branda* of Gêmea Group B’s buildings.

Corbelled domes, arches and vaults’ constructive knowledge is spread all around the world, either in vernacular or in monumental buildings, from dwellings to infrastructures and palaces. Its origin is still uncertain, being the megalithic times and the Mesopotamian civilizations (around 6000 years) pointed out by several authors as its most probable origin [1], [8]. Very common around the Mediterranean, as shown in Figure 2, this building technique is also referred to as intermediate solution between the pillar and lintel and the arch and dome systems [9], and it may preceded these technologies in many cultures.

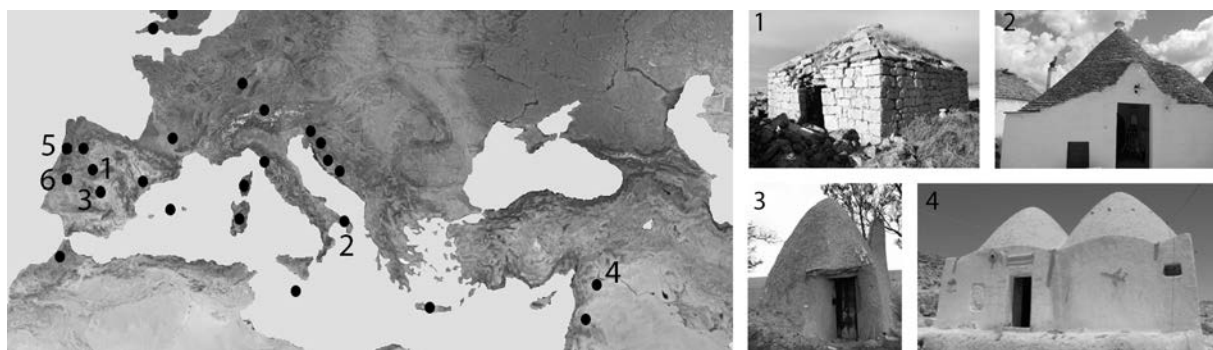


Figure 2: Corbelled dome heritage around the Mediterranean, (after Jovanec [10]). Examples of corbelled dome buildings around the mediterranean: (1) and (3) *chozos de viñas*, Spain [11]; (2) *trullo*, Italy [12]; (4) *earth dome dwellings*, Syria [7]; (5) CB - *abrigos* or *cortelhos* and (6) CA - *safurdas* or *forños*, Portugal [2].

In scientific literature, two main groups of corbelled dome buildings can be identified [7], [10]. The first and smaller group is composed of corbelled dome buildings with mound, like the Mycenaean (Greece, 14th century B.C.) or Populonia *tholoi* (Italy, 7th century B.C.), related with ceremonial and funerary functions. The second and larger group is composed of corbelled dome buildings without mound. In this group one can find the majority of the existent vernacular corbelled dome heritage, including the ones analysed in this paper. Attending to this group's diversity of buildings, one can assume them to be the outcome of a combination of factors such as between farming needs, climate adaptation and available local materials [7]. In the Portuguese context, very few examples of the first group exist. According to the previously referred studies, farming and transhumance support buildings, isolated or in groups of buildings, are the most representative typologies in comparison with other specific types of buildings like mills or ovens. Permanent dwellings were not identified in these studies. Attending to corbelled domes' building features, Oliveira [2] organized morphologically the observed buildings in two groups. As shown in Figure 3, the first group is composed of buildings in which the corbelled dome's intrados is part of the wall (CA), either starting from the ground (CA1) or from the wall's section (CA2). In the second group, domes start from the top of the walls (CB). While group CA buildings were observed across the majority of the Portuguese territory, group CB buildings were a local response to the context of the transboundary highland region of the Gerês/Xures region.

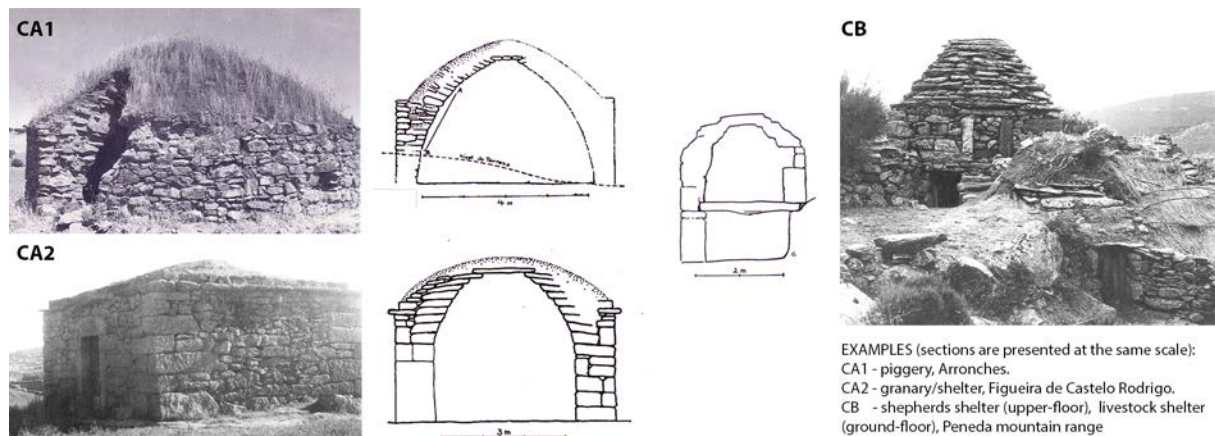


Figure 3: Portuguese corbelled domes' buildings morphological groups as presented by Oliveira [2].

3. FIELDWORK SURVEY

The studied corbelled dome heritage was an outcome of a specific agro-pastoral system, based on shared work and scarce resources management. Becoming a way of life, this system was developed over centuries and adapted to the harsh highland region. The origin of this specific context adapted response is uncertain. It derived from the lowland region's way of life, based on individual family work and property, into a system of shared work and management of basic farming infrastructure. Due to commonly shared effort, vertical transhumance became possible. Livestock was moved up to the mountain plateaus during the warm season, freeing near village terrace pastures for grain production, and would be moved back down after the harvest, already in the beginning of the cold season. Local populations occupied the territory resorting to: (i) villages formed by small concentrated settlements, called *lugares*, dispersed around the mountain and placed near very narrow valleys or fertile land pockets; (ii) owning each one large areas of terraces for farming; and (iii) networks of temporary mountain plateaus' settlements called *brandas*. While in nearby Amarela and Gerês mountain ranges existent *brandas* were used mainly for livestock production in pastoral system (livestock *brandas*), see Figure 4a, in the Peneda mountain range, it became possible to farm in some mountain plateaus, using the existent *brandas* simultaneously for livestock and farming (mixed *brandas*), see Figure 4b. By combining both functions, corbelled dome buildings were adapted for a more prolonged stay in the mountain. To do so, buildings formed individual groups, simplified or more complex, with external enclosed areas, gaining farms, networks of paths and irrigation infrastructures. Gable roof buildings were added later, with the same function as the two-storey buildings. A morphological and typological synthesis of the survey area's corbelled buildings is presented in Figure 5.

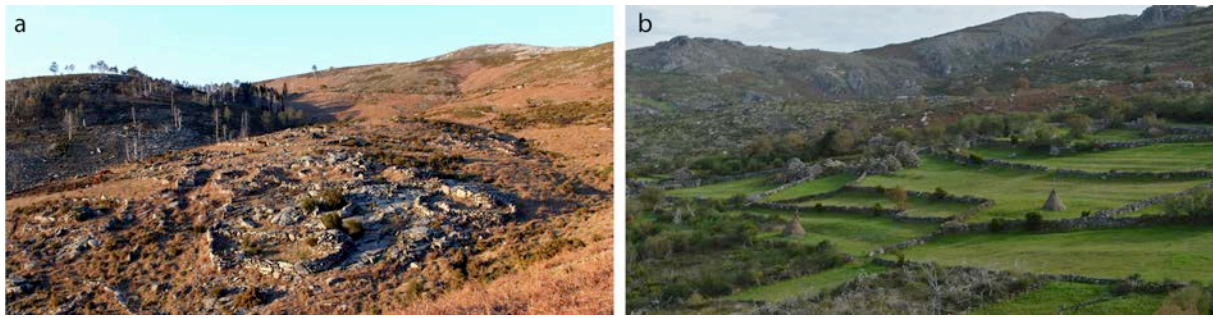


Figure 4: Examples of: a - livestock *branda* (*branda* of Burzavô, Cabana Maior); b - mixed *branda* (*branda* of Gêmea, Sistelo).

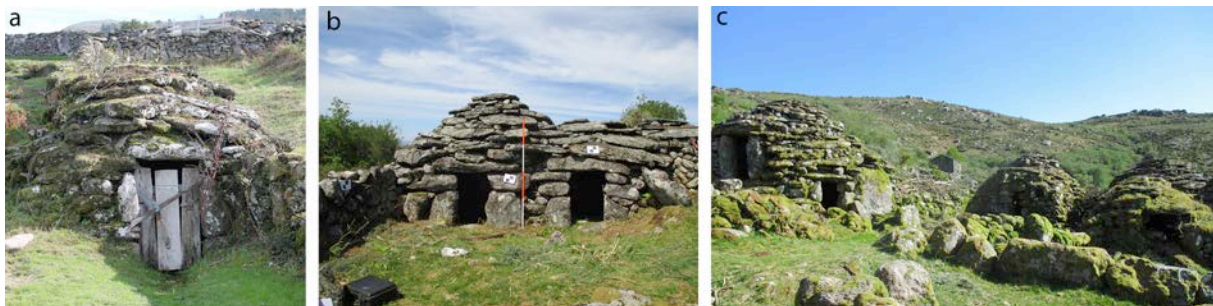
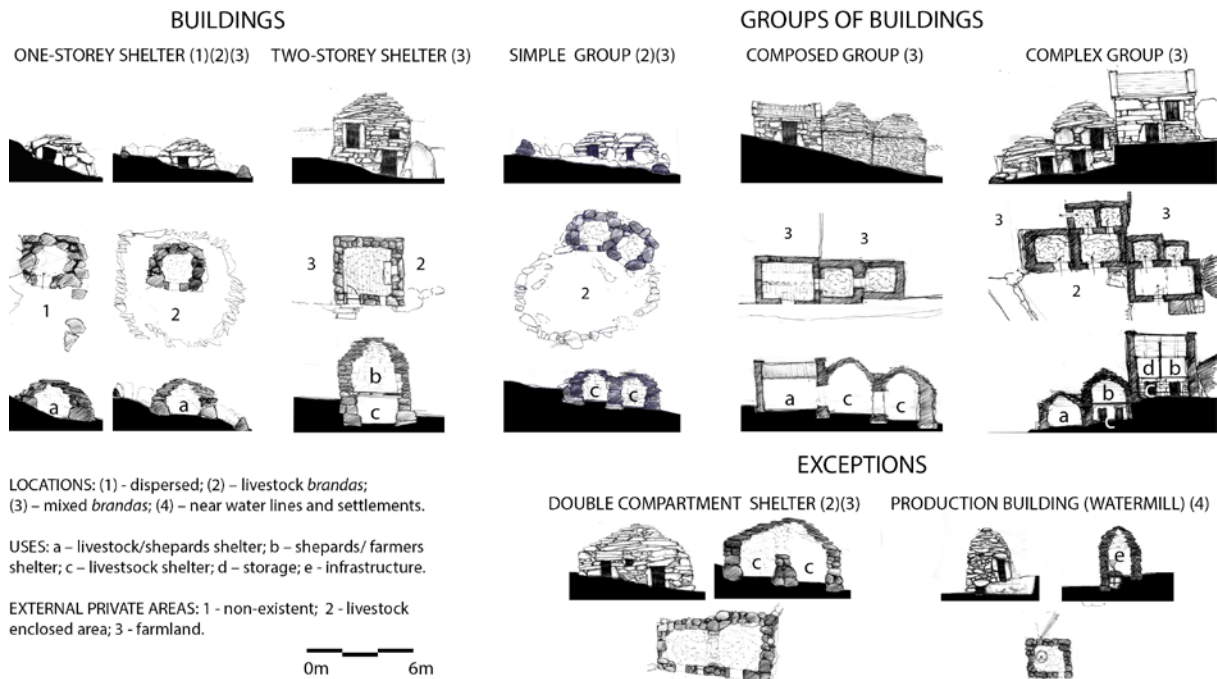


Figure 5: *Brandas* of Alhal and Gêmea corbelled dome buildings' morphological and typological schemes. Images of different examples of buildings and groups of buildings: a - one-storey isolated shelter in *branda* of Alhal; b - simple group in *branda* of Gêmea; c - two composed groups in *branda* of Gêmea.

3.1 On-site survey

The survey discussed here was performed in two groups of corbelled dome buildings (Group A – 41°58'26.6" N 8°19'29.3" W, and Group B – 41°58'19.5" N 8°19'30.2" W) of the *branda* of Gêmea (1010 m above sea level), that along with the *branda* do Alhal (740 m above sea level), belong to the *lugar* de Padrão (495 m above sea level), of the village of Sistelo (300 m above sea level), in Arcos de Valdevez Municipality. Both *brandas* are examples of mixed *brandas*, and are located in the Peneda mountain range. Groups A and B, see Figure 6, are examples of complex groups.



Figure 6: Views (V) from Group A (V1;V3;V4;V5) and Group B (V2;V6;V7;V8) buildings. Each one is composed of: one two-storey shelter; eight one-storey shelters; one gable roof building.

In order to get a detailed and accurate documentation of the buildings, laser scanning technology was selected for the digital recording. Laser scanning is a remote, non-destructive technology that is able to automatically record millions of 3D coordinates of an object's surface [13].

Depending on the equipment, the accuracy of the measurements can reach up to a few millimetres. Due to the limited access to the corbelled dome buildings, only static scanners were used. The scanner used in the survey works was the Faro Focus 3D, which measures distances using the principle of phase shift at a wavelength of 905 nm. This device measures distances in a range of 0.60–120 m with a point measurement rate of 976,000 points per second. It has an accuracy of 0.015° in normal lighting and reflectivity conditions.

The field of view extends 300° vertically and 360° horizontally with a 0.009° of angular resolution and the returning intensity is recorded in 11-bit format. Additionally, this laser scanner includes a double compensator in the horizontal and vertical axes. The field works consisted on the recording of 3D images of the constructions from both their exterior and indoor faces. In order to align all the point clouds in a common coordinate system, artificial targets were required. In order to ease the registration process, the scanner was levelled during the recording of all the point clouds.

This operation also guarantees that the final point cloud is levelled. During the scanning, the angular resolution of the scanner was set to 6 mm at 10 m for the indoor scans, and 3 mm at 10 m for the exterior point clouds.

Due to the complex geometry of the constructions, a large number of scanner positions were required to complete the exterior and indoor scanning of all constructions.

For Group A, a total number of 29 scanner positions were required, and a total number of 26 scanner positions were required for Group B. The time required for the scanning of each group of corbelled dome constructions did not exceed four hours. Figure 7 shows an aerial view from Group A and Group B of the two groups of constructions surveyed.

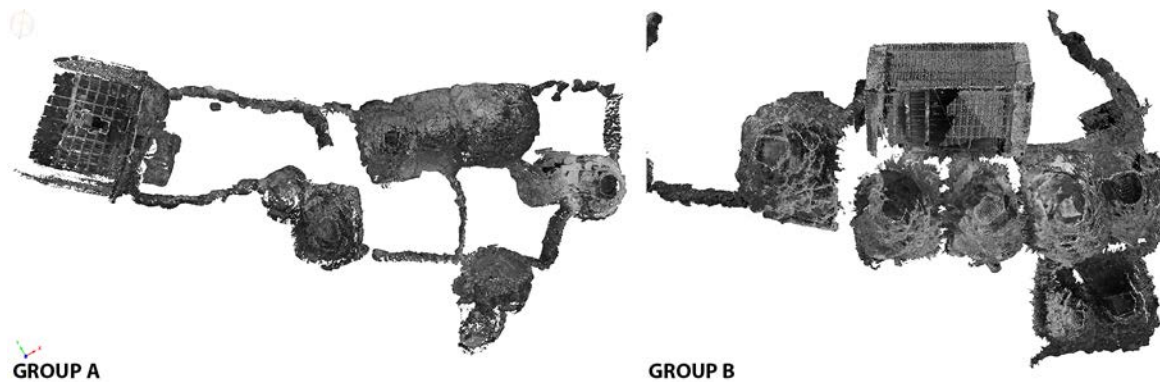


Figure 7: Laser scanner generated aerial views of Group A and B constructions.

As might be expected, those scanning works produced a huge amount of points that had to be post-processed in order to optimize the point cloud and remove redundant data. This was necessary to ease the handling of the point clouds and to perform the documentation in an efficient manner. The first task consisted of performing the alignment of different scanner positions using the coordinates of the artificial targets measured in the field. Next, noisy points of non-desired objects such as vegetation were removed from the point cloud. The following step consisted of the segmentation of the point cloud in three main features: (1) ground points (that are lately used to define the Digital Terrain Model (DTM)), (2) buildings and (3) enclosing walls. In order to optimize the density of the point clouds and to remove redundant points, a spatial filtering was applied using octree structures. The parameter for this filter was the size of the minimum cube in the octree structure, which was set as 1 cm for the buildings and enclosing walls, and 25 cm for the ground (that define the DTM). Figure 8 shows a perspective view of Group A and half a building of Group B (B7), where details of the indoor and exterior faces of the dome can be perceived.

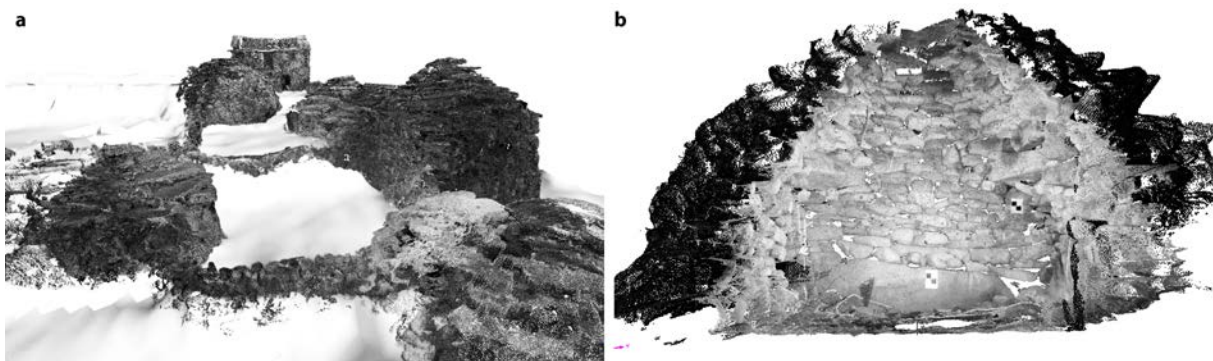


Figure 8: Examples of laser scanner generated images: a - perspective view of Group A; b - B7 cross-section

Once the point cloud of each individual building was segmented, cross-sections of three orthogonal reference planes were extracted in order to perform the building's dimensional analysis, see Figure 9.

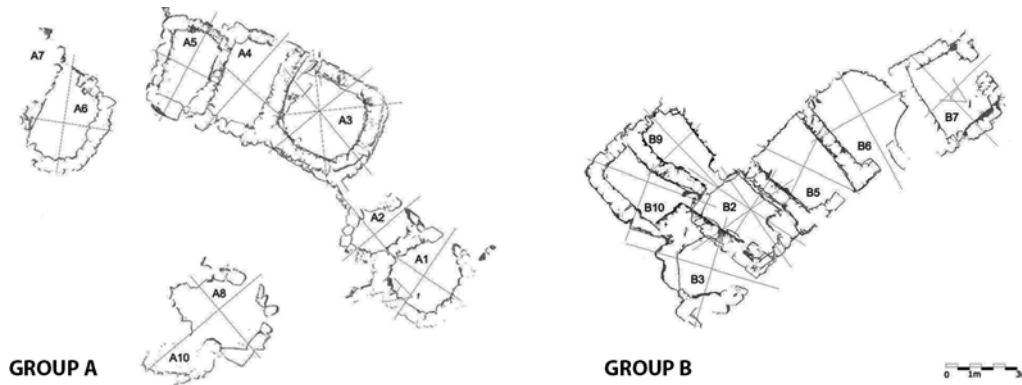


Figure 9: Laser scanner generated horizontal sections showing vertical cross-section reference plans.

4. Analysis and discussion of results

Based on the data gathered by the laser scanner survey, the data analysis was organized in groups of building's features, measured directly on the 3D point cloud models, as presented in Figure 10.

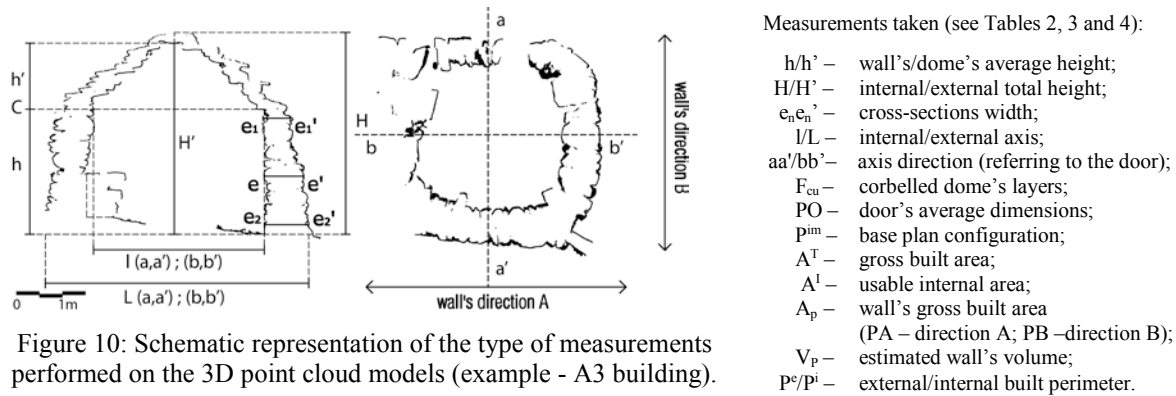


Figure 10: Schematic representation of the type of measurements performed on the 3D point cloud models (example - A3 building).

4.1 Morphological and typological analysis

In order to perform a morphological and typological analysis, the gathered information was analysed according to two main groups of features, as shown in Table 1. The information analysis was divided in a vertical section analysis (Features 1) and on a horizontal section analysis (Features 2). Different architectonic and constructive features were compared according to the ratios showed in Table 2.

Table 1 – Analysed Features.

FEATURES 1	H (m)	H' (m)	h (m)	h' (m)	F_{cu} (un)	$L_{aa'}$ (m)	$L_{bb'}$ (m)	$l_{aa'}$ (m)	$l_{bb'}$ (m)	$e_1 e_1'$ (m)	$e_2 e_2'$ (m)	PO (mxm) x (un)
Group A	2.78	2.63	1.64	0.99	7	3.36	2.96	2.76	2.36	0.52	0.67	1.00x0.60
Group B	3.19	3.04	1.68	1.36	9.13	2.93	3.66	2.28	3.01	0.56	0.61	1.20x0.70
FEATURES 2	p^{im}		A^T (m ²)	A^I (m ²)	A_p (m ²)	V_p (m ³)	A_{PA} (m)	A_{PB} (m)	P^e (m)	P^i (m)		
Group A	□		13.21	5.86	6.72	11.69	4.41	4.63	13.42	9.49		
Group B	□		14.82	7.03	7.24	11.99	4.01	5.75	14.78	10.02		

Table 2 - Features 1 and 2 comparison ratios.

	wall's slenderness		axis/ wall's height		axis/ total height		corb. dome's span/ int. height		wall's area/ gross built area		
	h/e	H/e	$L_{aa'}/h$	$L_{bb'}/h$	$L_{aa'}/H$	$L_{bb'}/H$	$l_{aa'}/h'$	$l_{bb'}/h'$	A_p/A^T	A_{PA}/A^T	A_{PB}/A^T
Group A	1.53	4.36	2.07	1.83	1.21	1.06	2.95	2.47	0.52	0.33	0.37
Group B	2.20	5.18	1.83	2.27	0.95	1.18	1.82	2.47	0.49	0.27	0.40

By analysing the ratios computed, the following conclusions can be extracted:

- i. Group B has larger buildings than Group A, and each individual building is organized according to a predominant internal axis (l_{aa} or l_{bb});
- ii. Shepherds/farmers shelters are the highest buildings (H) and the only ones with two storeys, but are not the buildings showing the larger gross built area (A^T);
- iii. Concerning the base plan's shapes (P^{im}), these are rectangular shaped buildings, with rounded corners. Only smaller buildings show circular shaped base plans ($A^T < 15 \text{ m}^2$);
- iv. By comparing rectangular and circular shaped buildings showing the same range of horizontal axis, due to their base shape, rectangular buildings show higher gross built area;
- v. Group B wall's ($L_{aa}/h=1:2$) are slenderer than Group A walls ($L_{aa}/h=1:1.5$), and both are considerably less slender walls than the existent gable roof buildings ($L_{aa}/h=1:10$);
- vi. In spite of the apparent vertical proportion imposed by the corbelled domes' conic shape, a closer look at the ratio between buildings' axis (L) and total height (H), shows an average ratio (LH) of 1:1. Applying the same criterion to the wall's height (h), we obtain an average ratio (L/h) of 1:2. The ratio between the corbelled domes span (l_n) and height (h') results in average ratios (l/h') that vary from 1:2 to 1:3. One can conclude that these are horizontal proportion buildings;
- vii. Dividing the wall's gross built area (A_p) with the building's gross built area (A^T), an average ratio (A_p/A^T) of 1:1/2 was obtained, showing that 50% of the studied buildings' gross built area corresponds to masonry walls (mass and voids);
- viii. These results shows that *brandas* corbelled dome buildings are heavy mass buildings;
- ix. Simultaneously, applying the same criterion to the different directions of individual buildings' walls, (A_{PA} and A_{PB}), it can be concluded that walls in transversal direction to the entrance (A_{PB}) have more area than parallel ones ($A_{PB}/A^T > A_{PA}/A^T$). If the group configuration is taken in to account, attending to the fact that several transversal walls are shared by two adjacent buildings, one has in Group A $A_{PA}(28,30\% \text{ of } A^T) < A_{PB}(30,38\% \text{ of } A^T)$ but in group B, with more shared walls, $A_{PA}(23\% \text{ of } A^T) > A_{PB}(15\% \text{ of } A^T)$. This result shows that group solutions represented a considerable gain in building resources management, in comparison with individual buildings with the same base plan configuration.

4.2 Building technique analysis

A building technique analysis was performed based on the on-site observations using conventional geometrical surveys and the laser scanner data. The first observations revealed that local masonry was built resorting to local available granite stones, either gathered in the process of preparing the land for farming or pasture, or by extracting them from nearby large rock outcrops. Plate shaped granite masonry units were gathered in outcrops and the shape resulted from natural fractures on the bedrock, caused by water penetration (erosion). The main features of walls and domes' masonry units are presented in Table 3.

Table 3 - Average dimension values of masonry units for main walls and corbelled domes.

	ee' (m)	walls (m)			corbelled domes (m)			F _{cu} (un)
		small	medium	large	small	medium	large	
Group A	0.65	20%	50%	30%	10%	40%	50%	8
		-	0.65x0.50x0.30	1.00x0.60x0.45	-	0.75x0.50x0.12	1.6x0.75x0.15	
Group B	0.60	20%	65%	15%	15%	35%	50%	9
		-	0.50x0.30x0.15	0.80x0.50x0.30	-	0.70x0.50x0.17	1.25x0.70x0.17	

Analysing sizes and distribution of the masonry units, one can conclude that:

- i. Medium size units prevail in masonry walls, and large size masonry units prevail in corbelled domes' masonry;

- ii. The shape and dispersion of the masonry units on masonry walls and corbelled domes were restricted by their function. Block shaped units prevail in the walls in order to sustain the dome's thrust and resist horizontal loads. Plate shaped units prevail in corbelled domes, to cover as much horizontal area with the minimal possible weight. Considering the masonry units' horizontal section, the walls' large size units are similar to the corbelled domes' medium size units. Considering the vertical section, the walls' masonry units present an average size 50% larger than that of the corbelled domes' units. The dispersion of the smaller size masonry units is on a slightly inferior average in the corbelled domes;
- iii. Attending to other observed corbelled dome buildings, the masonry unit's horizontal/vertical proportion influence on the dome's height and number of built layers (F_{cu});
- iv. As observed, due to the domes' cone geometry and the used building technique, larger units are concentrated in the lower half of the cone's structure, decreasing in size, due to the spiral diameter's decrease, until the capstone.

Attending to the information presented, the local heritage building technique can be defined as:

- i. Masonry walls building followed local dry stack tradition, built without or with a direct foundation, mainly with two-leaves cross-sections and very irregular stonework, with a high percentage of voids. Openings and corners were reinforced with larger masonry units. Masonry units presented very irregular geometries and were laid out in place and levelled resorting to shims. The resulting interface was very poor and the masonry units' interlocking was also very low. Structural stability was achieved by the walls low slenderness, heavy mass and the use of crosswise bounding stones. This combination of building features increased the walls' protection against deformations and out-of-plane loads. Smaller buildings, due to the average size of the used masonry units, were frequently built in single-leaf cross-sections;
- ii. The corbelled domes' conical shape was built on top of the structural box formed by the walls. The interface between the two sub-structures was performed resorting to the first course of the corbelled dome, which worked as masonry wall's structural bounding ring. Near the corners, the first layer was made of larger units simultaneously laid down in place over corners, solving in this way the geometrical problem of passing from the wall's rectangular shape box to the corbelled dome's conical shape;
- iii. The corbelled domes' masonry was built in crosswise masonry units, in an overlapping spiral movements around the central axis, starting from the top of the walls and ending at the dome's capstone. Larger masonry units were laid out jutting towards the centre, supported in an average of 2/3 of its horizontal section over at least two larger underneath masonry units, and leaving its central portion working as cantilever. Any resulting gaps were filled with smaller size units, and shims were used to improve the stability of larger plates. On the inside of the building, shims were placed over the edge of the supporting units, in order to give the above units a slope to wash out rain water and protect the interior. This process was repeated up until the capstone;
- iv. In the observed corbelled domes, forces flow through a large number of contact surfaces resulting from the very irregular units interface and large presence of small shims [14]. Simultaneously, through this particular building technique, dome's load is transfer to the walls not only by granite stones under compression, but also by its flexural behaviour.

5. CONCLUSIONS

As part of an ongoing research that aims to achieve a better understanding of vernacular heritage, the study here presented allowed observing closely a remote and relatively unknown type of building in Portugal. The great ecological, touristic and economical potential of these very small settlements became visible, in a time where rural landscape and its way of life regain importance. In comparison with other survey methods already tested, the potential of laser scanners as a survey method to perform accurate studies in such complex geometries, has proven as the most effective in this type of buildings' surveys. Some established ideas about this heritage were proven inaccurate. As such, being simple in its basic principles, the study shows the constructive complexity of corbelled dome

vernacular heritage, and simultaneously, the inventiveness of these remote populations in making the most of their resources. The rectangular shape instead of the circular shape, a huge resilience to time and climate almost without any kind of maintenance, the large dimension and very heavy mass of these structures, along with the morphological and typological complexity of some of the groups observed, are some of the outcomes of this study. The next steps in the development of an appropriated preservation and rehabilitation methodology to this very fragile and endanger heritage, are to extend this experience to the remaining territory, including structural assessments and damage surveys. Preservation guidelines associated with reuse strategies and a more adequate legal framework are the main challenges in assuring the survival of this particular heritage and its reintegration into the daily life of the local populations that built them in past generations.

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