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Studies for the restoration of the Islamic Bofilla Tower as an example of wood use in rammed earth structures

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ABSTRACT

This paper deals with the analysis of traces of wood technology in the Bofilla Tower, a medieval rammed earth Islamic watchtower close to Valencia. Although the principal material constituting the tower is earth, wood played a basic role in the construction and use. Indeed, wooden elements were used to execute the formwork, as reinforcement for the earthen structure and as structural material for the floors. At the time of restoration, the tower had completely lost its floors, ceilings and stairs, although traces of the original structure and small pieces of woodwork remained. Samples of various elements were extracted and anatomically examined in order to identify the timber. Only four types of timber were identified: olive, maritime pine, mulberry, and ash. Based on the few wooden remains found and the tests carried out, this paper analyses the use of different timbers found within the structure of the tower and tries to identify the provenance of the wood according to the organisation of the rural community living around the building. The paper concludes with a description of the restoration of the tower.

1. Foreword

Earthen architecture presents many structural and taxonomic studies, especially linked to the monumental character of traditional and historical artefacts (Graciani García and Tabales Rodríguez, 2008; Jaquin et al., 2008; Romero and López Osorio, 2012), and their sustainable and potential ecological value (Vázquez Espí, 2001; Carvalho and Lopes, 2012). There are numerous applications and hybrid versions of walls that rely on the combined use of earth and other components and supports, such as wood (Mileto et al., 2011a; Mileto et al., 2012). For instance the half-timber or wattle-and-daub techniques are two construction systems where timber frames or wooden trellises are associated with earth filling, the first for load-bearing structures and the second for non-structural walls. This is not the only historical and traditional application of this material to earthen walls. Less frequently, but just as effectively, timber has been used as a reinforcing element in rammed earth walls, as indicated in the presentation of this case study (an Islamic watchtower in the Province of Valencia, Spain).

At the time of study and restoration, the Bofilla Tower in Bétera (Valencia) had lost its wooden floors, ceilings and stairs, although imprints could still be observed in the rammed earth walls and in some of the beam ends. In addition, these walls still preserved thin putlogs from the formwork and remnants of sleepers and lintels. Therefore, the work aimed to study a miscellaneous repertoire of constructive footprints bound to wood technology and legible thanks to the plasticity of the clay used in the walls, in order to guarantee that the restoration and conservation project for the Bofilla Tower would preserve the original walls and all the wooden remains and the construction elements which were of great historical and cultural value. At the same time, the identification of these imprints in the walls (Warren, 1999; Mileto, 2010), together with the analysis of wooden fragments identified in situ, have helped to improve the knowledge of the construction of earthen structures and have ensured the reconstruction of the history of the building location (GPS: lat. 39.580124, long. −0.429165), inextricably linked to the life and history of the rural community that lived around the tower, through the materials found.

2. The tower

The Bofilla Tower in Bétera (Valencia) (Fig. 1), near the Spanish Mediterranean coast, is a defensive rammed earth structure erected in the Moorish era in the early 13th century (Bazzana and Guichard, 1978). Together with about forty similar structures, associated with farms, it is part of the protection and sighting system around the city of Valencia during the years of the Christian re-conquest (Rodriguez, 2008). Progressively abandoned in the 15th century, due to wars with the kingdom of Castile, famine and plague epidemics (López Elum,

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Fig. 1. Bofilla Tower before the conservation work (C. Mileto and F. Vegas).

Fig. 3. Putlogs of the formwork inside the walls of Bofilla Tower (C. Mileto and F. Vegas).

1994), the Bofilla Tower suffered about five hundred years of neglect and looting. At the time of study, the tower presented material degradation linked to environmental agents (microvegetation and dirt on the surface; erosion and loss of volume on the crowning; erosion due to increased capillary action on the base; washing-off, especially on the upper section of the south façade, etc.) as well as to human action (the removal of the voussoirs from the main door resulted in the major collapse of the north façade and the upper northwest corner) (Fig. 2). Degradation and pathologies, both human and natural, have not erased the information still found on the surface and in the walls which the 2009–2010 restoration project was able to bring to light (Mileto et al., 2011b). In addition, these centuries of abandonment bear witness to the strength of the original building. The Carbon-14 test carried out in 2010 (Villafranca Sánchez, 2010) on samples of wood from the putlogs of the formwork of the rammed earth revealed that these elements were approximately 750 $\pm$ 60 years old, indicating that the Tower could have been built between 1200 and 1320. These dates were cross-referenced with the historical data on the Christian conquest of these territories in 1238, as this would have been the last possible date of construction for an Islamic tower, as well as with the ceramic fragments found in the course of the excavation (Burriel and Ruiz, 2009). This suggests that the tower was built between 1210 and 1220 CE.

The sides of the square tower are 6.15 m, reduced to 5.20 m at the crown, so that the profile is that of a truncated pyramid. The walls are up to 1.20 m thick at the base of the tower but the external tapering and the internal staggering of the wall reduce this to 56 cm in the upper part. The survey suggests that the tower was probably built by

Fig. 2. Bofilla Tower, inner sections, before the conservation work (C. Mileto and F. Vegas).

Fig. 4. Imprints of formwork in walls of the Bofilla Tower (C. Mileto and F. Vegas).

Moorish residents on an existing farm, considering the simplicity, local materials, and the domestic formwork employed, similar to those used in the farmhouses, as established by the archaeological excavation. These assumptions are confirmed by the numerous imprints of the formwork which are still visible on the surfaces of the building, which is made up of 21 rammed earth courses, each with a height of between 83 and 92 cm, totalling 18 m in height. The materials used for the walls, which can be found near the tower and the neighbouring torrent of Carraixet, primarily consist of earth with natural aggregates (90%), lime (10%) and rough stones (approx. 15 × 30 cm) used as reinforcement in regular layers inside the formwork (Kroner et al., 2009).

3. Presence and traces of wood in the Bofilla Tower

As mentioned earlier, the Bofilla Tower was built with rammed earth, although wood was also a major part of its construction and was used in three different capacities. Firstly, as an essential material for executing the formwork (with planks, boards, putlogs, wedges…). Remains from these elements currently include putlogs (Fig. 3) in the walls, which could be seen and accessed to extract samples. Other partial remains of this formwork are seen in the negative imprints on the rammed earth wall surfaces (Fig. 4). Secondly, wood was also present as reinforcement in the earthen structure (especially as sleepers in the walls). These elements embedded in the mix are visible in some parts due to the deterioration of corners or other parts of the tower (Fig. 5). Finally, wood was used as an element to build the floors of the different accessible levels of the tower. As stated earlier, these elements were almost lost following centuries of abandonment of the tower, and it is only possible to speculate based on the negative imprints of the holes of beams and joists inside the tower. These imprints allowed us to identify the position of floors, ceilings and stairs, as well as the number and position of the elements (Figs. 6 and 7). Wood samples were obtained from broken remains of heads still found in the walls. The study and analysis of the wooden remains in the tower allowed us to accurately expand the knowledge of the role of wood in the construction and the completion of this type of towers in Moorish Spain.

4. Sample extraction and analysis

For further information on the use of timber in this particular type of construction, seventeen wood samples were collected from different wooden parts of the tower. These samples were collected from the different remains found: thin putlogs, lintels and sleepers in the walls, heads of beams inside the tower. The identification of the wood species was made following the guidelines for the identification of species found in (UNI 11118, 2004). The sampling called for the removal of a small sliver of wood (a cube measuring approximately 1 cm on each side), identifying the element of origin. The macroscopic characteristics of the wood (uniform grey colour, poor visibility of grain) did not allow a macroscopic identification of the timber, so it was necessary to identify it by evaluating its anatomical characteristics by observing a thin section with an optical microscope. The sample results were obtained from the three anatomical directions of the wood (transverse, longitudinal radial, longitudinal tangential).

The types of wood cells and their distribution along the plane of observation allow the identification of the timber, with the help of comparative terms offered by specialized anatomical atlases (such as (Schweingruber, 1990; Nardi, 2006)) as well as the collection of thin sections kept at the CNR – IVALSA (Trees and Timber Institute).

In fact, from the point of view of results, it is not always possible to establish the taxonomic level of wooden species (Macchioni, 2010), due to the frequent overlaps in anatomical features found in types of wood that are taxonomically very close. In this case, the identification stopped at a higher level of the taxonomic scale, that of genus. Therefore it is not always possible to speak of a specific species of wood, but rather of timber, that is to say, a group of species within the same genus whose wood has fully comparable technological characteristics.

5. Results of the characterization of wood for historical and constructive knowledge

The samples identified are listed in detail in Table 1. Four different timbers are identified: *Fraxinus* sp. (ash, anatomical sections in Fig. 8),

Fig. 5. An example of wooden sleepers in the corner of the northwest wall (V. Cristini).

Fig. 6. Mapping of the wooden traces of the floors and stairs in the walls of the Bofilla Tower (C. Mileto and F. Vegas).

Olea europaea L. (olive, anatomical sections in Fig. 9), *Morus* sp. (mulberry, anatomical sections in Fig. 10), and *Pinus pinaster* Soland (maritime pine, anatomical sections in Fig. 11 and Fig. 12).

As can be seen in Table 1, showing the results of the identification, different timbers were used for different types of elements. The choice does not seem to have been random, but rather dictated by the availability of the timber around the area of construction and also certainly by the technological characteristics of the different timbers employed according to specific use. Similar situations are described in the scientific literature regarding historic timber structures (Macchioni et al., 2013; Palanti et al., 2014; Cruz et al., 2015), where we can find most of timber structures made only of one principal timber, while others in which different timbers were used in order to reach agreement on certain uses due to their peculiar characteristics. E.g. in a single truss

Fig. 7. Study of the imprints that the original floors left on the internal walls of the tower. It has been possible to understand the location of the girders and joists in every floor and the place where the ladders were placed (C. Mileto and F. Vegas).

Table 1
Results of the timber identifications.

Sample	Localization (level)	Identification	Exposure	External	Internal
Timber joist	2°	*Olea europaea*	South	X	
Supporting beam	3°	*Olea europaea*	East	*X*	*X*
Beam, burnt inside the wall	3°	*Olea europaea*	West		*X*
Lintel	0	*Olea europaea*	South		*X*
Thin putlog	2°	*Pinus pinaster*	South	*X*	
Lintel	2°	*Olea europaea*	East		*X*
Lintel	0	*Olea europaea*	East		*X*
Single circular putlog	1°	*Morus* sp.	West		*X*
Rectangular slat putlog	2°	*Pinus pinaster*	South/West	*X*	
Rectangular slat putlog	2°	*Pinus pinaster*	South	*X*	
Embrasure lintel	2°	*Olea europaea*	West		*X*
Single circular thin putlog	2°	*Morus* sp.	West	X	
Embrasure lintel	0	*Olea europaea*	South		*X*
Thin putlog		*Fraxinus* sp.			
Beam 2nd floor		*Olea europaea*			
No indication		*Olea europaea*			
Corner connecting element between 2nd and 3rd floor		*Olea europaea*			

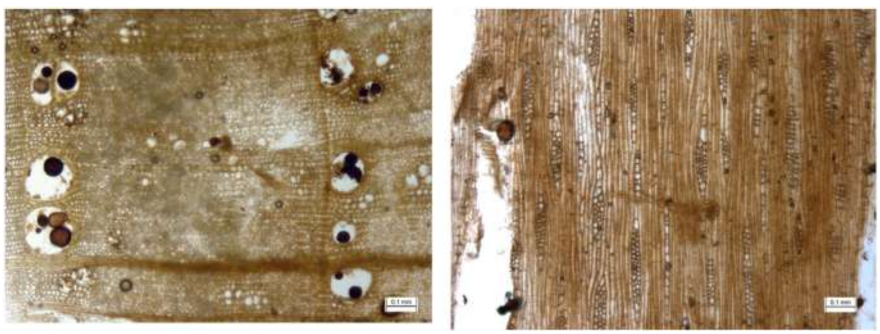

Fig. 8. Cross section on the left, tangential section on the right (*Fraxinus* sp).

fir for long elements and elm for specific compressed elements. Or, also, the use of different conifers in alpine structures according to their natural durability: spruce for less exposed members and larch for riskier parts.

5.1. Timber structure

Olive wood (*O. europaea* L.) seems to have played a leading role in the tower. In fact, the availability of this material is certainly compatible with the Mediterranean climate of the area and with the activities typical of the rural communities living around the tower (Terral and Arnold-Simard, 1996). Its use in construction is considered to be rare and infrequent, but apparently olive wood is well suited to direct contact with earth. Vitruvius (Vitruvius Pollione, 1992) already mentions the peculiarities of this raw material in numerous passages of *De Architectura* in Book 1/Chapt.5. "Construction of walls and towers", specifying that it is a very durable wood, suitable for these buildings because "*… it is not damaged by pests, nor by the climate, nor with the passage of time, on the contrary, even if we cover it with soil or water it retains its force for many years without any kind of imperfection…*". In other

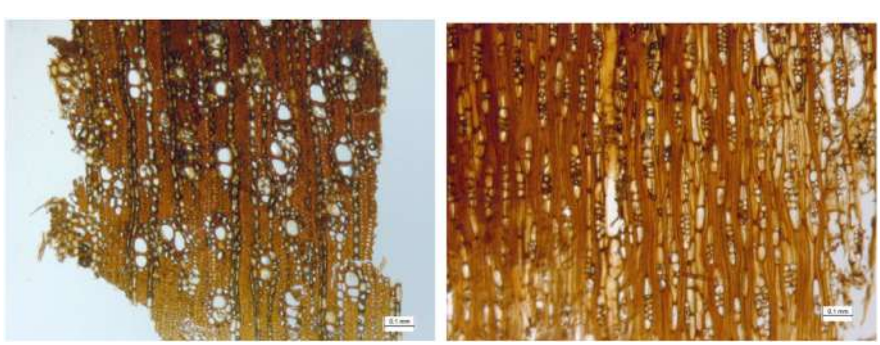

Fig. 9. Cross section on the left, tangential section on the right (*Olea europaea*).

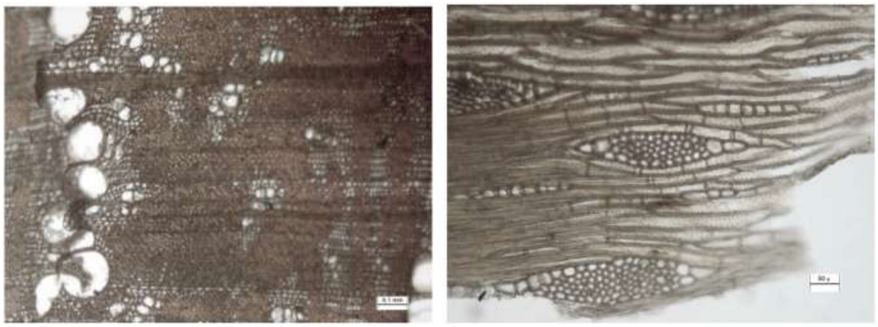

Fig. 10. Cross section on the left, tangential section on the right (*Morus* sp.).

passages (Book 3/Chapt.4 and Book 5/Chapt.7) he even speaks of establishing systems of stilts in the swampland with "*… poles of olive wood aged and hardened by flame…*" or of making tie rods (Book 7/ Chapt.3) "*… with a wood that is not threatened by termites, the passage of time, rot or moisture, such as boxwood, juniper, olive, oak or cypress…*".

Current scientific knowledge regarding olive wood confirms the good natural durability of this timber, which has always been considered a secondary product compared with that of its fruit and as such has been used for equipment relating to agricultural production such as handles, vehicle parts, or containers (Meiggs, 1982; Giordano, 1981). The Islamic construction site of the Bofilla Tower (associated with a farm and with extensive agricultural areas) took advantage of the availability of this timber, capable of providing technical performances linked to the free development of tree crops and unthinkable even today. The dimensions of the samples examined are not compatible with the present availability and standard size of different varieties of olive tree. Very little is known about the cultivation practices of olive trees in Spain in Moorish times. It is certain that the cultivation of olive trees in Spain for fruit production started during prehistoric times and increased during the Roman domination (Terral, 2000). From the beams of the Bofilla Tower it appears that in medieval times olive trees were not pruned or cared for as much as current standards of olive harvesting require today. During this period agriculture in small rural communities could probably not envisage the intensive cultivation and monocultures to which we are accustomed today: fruit trees had to be combined with other productive activities such as annual crops, wheat for example, or grazing (McGregor et al., 2009). In North Africa olive leaves were still recently used for livestock feeding (Le Houerou and Froment, 1966). Olives were harvested by beating the tree with a pole and/or harvesting the fruit from the ground, and some forms of productive activities led to the development of very tall trees and a less dense distribution of plants compared with current standards of olive monocultures; a good example of this is the picture in Fig. 13 showing tall olive trees in the countryside near Fez, in Morocco. For this reason, the logs used in the construction of the tower are not limited to the normal length of today's trees, as the trunks

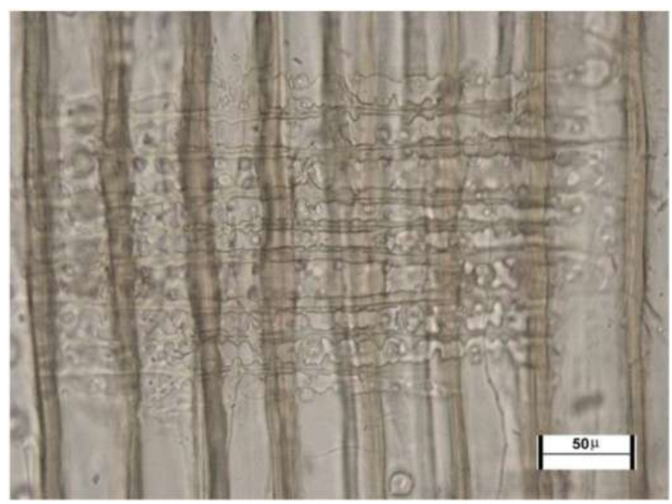

Fig. 12. Radial Section (*Pinus pinaster*).

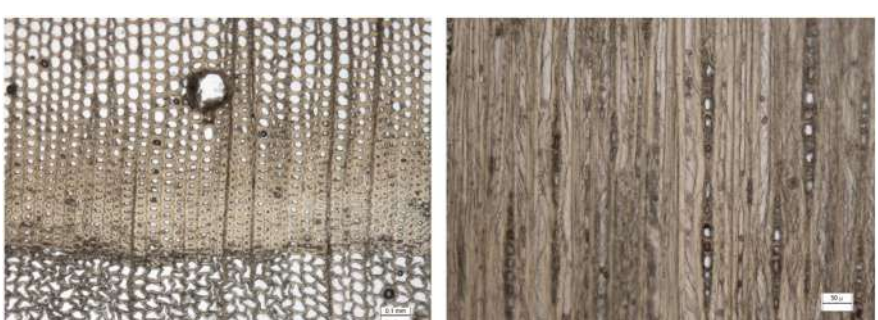

Fig. 11. Cross section on the left, tangential section on the right (*Pinus pinaster*).

Fig. 13. Tall olive trees near Fez in Morocco. Similar trees were possibly used to obtain the beams for the Bofilla Tower.

of these medieval olive trees usually reached and at times exceeded a height of 8 m.

5.2. The formwork

In Spanish, the rammed earth walls are called *tapia*, a name associated with the term *tapial*, which refers both to the construction technique and the formwork used to build a rammed earth wall. Indirectly, this etymological closeness reflects the importance of the formwork, its implementation and characteristics. Hence the need to use specific timber, possibly maritime pine (*P. pinaster*) for the formwork of the tower, consisting of panels with five planks, ranging between 13 and 17 cm in height. Moreover, these measures reflect the thicknesses of the layers of rammed earth inside the formwork, combined with the regular spacing of rough stones, used as reinforcement.

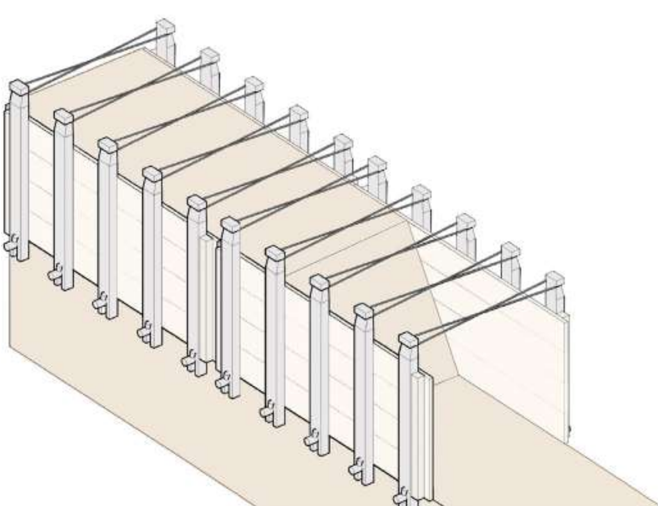

Fig. 14. Schema of the formwork used in Bofilla Tower (C. Mileto and F. Vegas).

Even today, maritime pine wood is used for building structures, sawn timber, secondary woodworking and packaging, as it is easy to saw. Its lower natural durability, particularly due to fungal attacks, means it has always been recommended for temporary use, such as the construction of formwork (EN 350.2, 1994).

In the walls of Bofilla, the 21 overlapping rammed earth courses are especially interesting because of the data relating to the material remains of the putlogs of the formwork, as well as to traces of the studs that held the five planks together (Fig. 14). In the first case, the survey revealed the presence of seven distinct types of thin putlogs (Fig. 15 and Fig. 16). In most of the cases simple sticks and twigs of mulberry (*Morus* sp.) and ash (*Fraxinus* sp.) rather than sawn wooden slats are identifiable, showing the domestic nature of the construction resources. Some of these age-old thin putlogs are still visible in the unsealed holes of the facing, thus contributing to the analysis of the use of wood. As anticipated, another interesting constructive register is the presence of wooden studs that were also used in this case to connect various formwork units to each other. These are clearly visible in the interior walls of the building and can only be deduced in the exterior facings of the tower because of the fresh sealing. The presence of these elements can be deduced and approximated from the regular recycling which was a feature of the continuous assembly of formwork.

Mulberry and ash were widespread in rural areas of the past, the first for feeding silkworms, while ash leaves could be used for livestock, and ash wood was useful for many purposes relating to crops and transport. Where no special properties were needed from the timber, the highly practical use of these plants demonstrates the close links of the agricultural world with the small community found around the tower.

5.3. The reinforcement

The Bofilla Tower shows interesting wooden reinforcement systems, identifiable within the structure. Indeed, as frequently occurs in cases of Islamic defensive architecture, the corners of the walls are made up of continuous modules of rammed earth, which are crucial points for the strategic function and stability of the building. In these areas, thanks to the presence of erosion in the facings, at least 9 sleepers, rough beams, designed to reinforce the angles (Fig. 17), were located. Other wooden logs are embedded in the walls, in this case visible in the access area. The arched doorway of the tower itself was reinforced with a lintel, made of four olive trunks about 14 cm in diameter, whose imprints were perfectly identifiable during the restoration process (Fig. 18).

Finally, the use of lighter systems to improve the mixture of earth, lime and inorganic materials, used in the upper parts of the building is particularly unusual. In these areas traces of olive stones have been found in the mix. These are elements that prove to be excellent granular aggregates, mainly due to their light weight, cost, and availability.

5.4. The floors

As far as the structure of the tower is concerned, it is interesting to note the characteristics of the original floors whose traces are visible in "negative" thanks to their imprints on the walls and indicate the presence of three main levels, with slits and a guard's passage with a gallery (Fig. 19). The imprints found in the walls of the tower made it possible to establish the exact location of the points where the main beams and the floor joists were inserted. The absence of imprints at specific points clearly showed the position of the original ladders, now missing, inside the tower. The original structures, damaged and destroyed by fire, used massive trunks of olive trees found in the countryside around the building and easily identifiable thanks to the imprints of the heads of the planks. With this data, it was possible to establish that a beam (about 22 cm in diameter) was used to support a floor made from juxtaposed thinner log joists (14 to 15 cm in diameter) arranged as regular planks, alternating in direction in the different levels of the building (in this case the presence of a floor every 4 modules of rammed earth and a guard's

Fig. 15. Mapping of the wooden putlogs and the reinforcement in the walls of the Bofilla Tower (C. Mileto and F. Vegas).

passage after the last three modules is recognisable). In addition, the crowning of the tower bears traces of olive beams, put in place to support a gallery and a trapdoor (Burriel and Ruiz, 2009).

6. The restoration of the Bofilla Tower

The restoration (Mileto and Vegas, 2012) of the Bofilla Tower has aimed to preserve all imprints resulting from its construction process and the passage of time (Fig. 20). During the restoration and

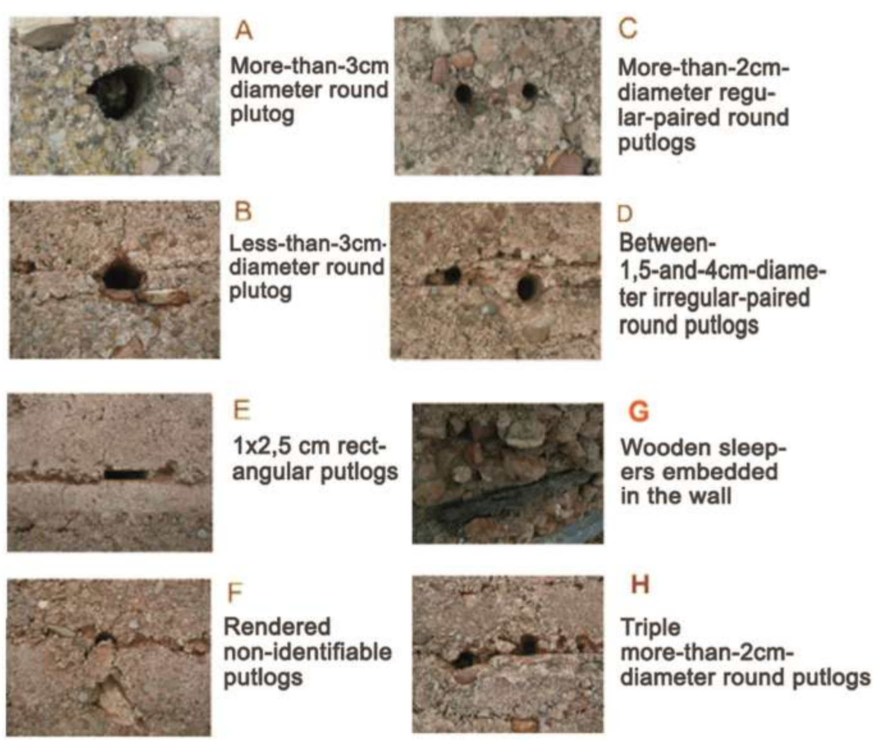

Fig. 16. Mapping of the different types of wooden putlogs (C. Mileto and F. Vegas).

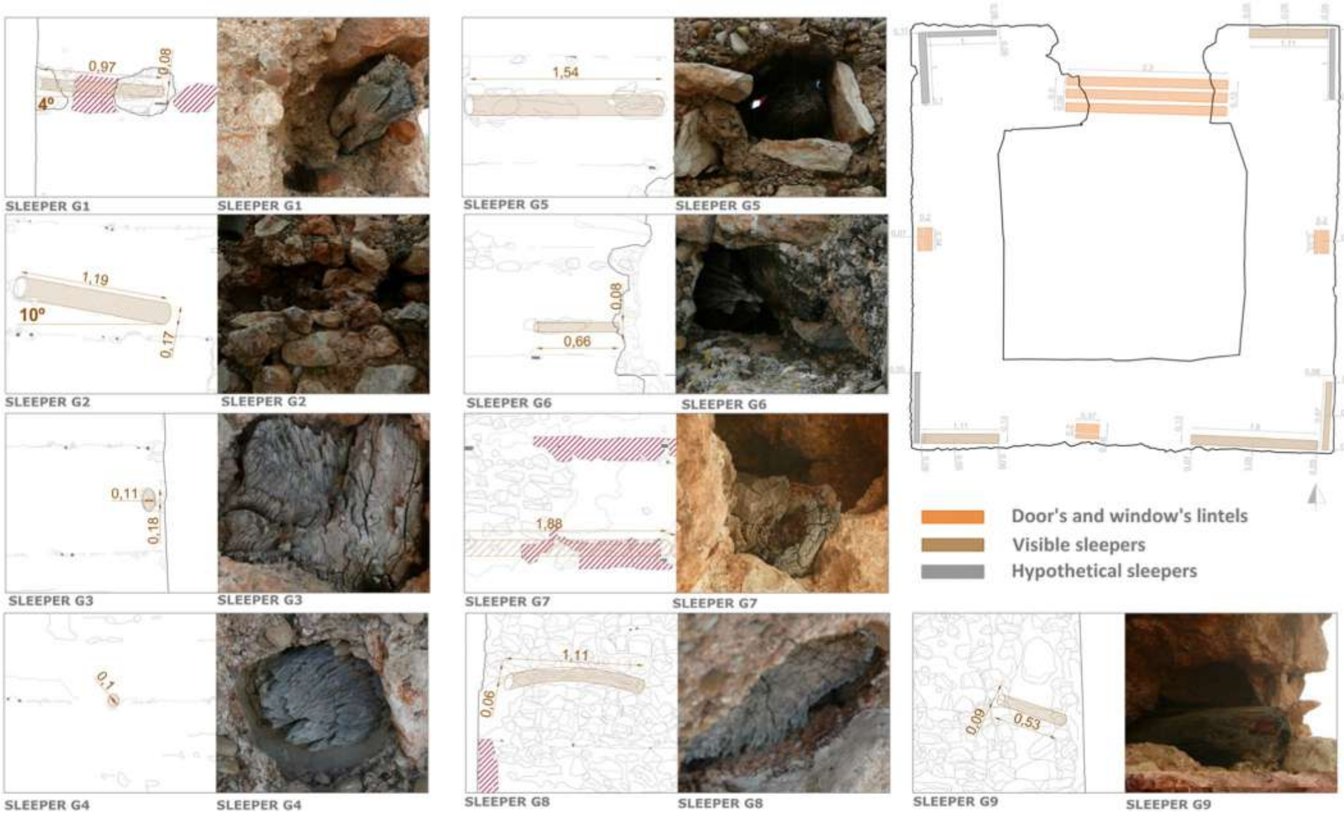

Fig. 17. Mapping and classification of wooden sleepers and lintels inside the walls of the tower (C. Mileto and F. Vegas).

reconstruction of the interior, it was not expected to be possible to imitate the original floors, built with hewn logs, planking and cast earth and lime. The interior floors, ceilings and staircases were built at the same points as the missing elements, following their imprints while respecting modern distinguishability criteria. The new floor and ceiling structures were built from pine wood for two main reasons. Firstly, the abstract shape of these elements cut from clean straight wood favoured the distinguishability of the new structure. As stated earlier, the intervention did not seek to completely mimic the historic structure, but rather to reinterpret the missing elements. In addition, the possible use of olive wood was not feasible either due to the unavailability of olive wood similar to that used originally. As already mentioned, modern olive cultivation does not provide logs long enough to cover the span required. Moreover, the structural characteristics of olive tree trunks are affected by numerous structural defects that would make them unsafe for use. Even the possible solution of using glued laminated olive wood for timber is not feasible because the EU sector legislation does not provide for its structural use, given the deficiencies in gluing olive wood for structural purposes.

In addition to these considerations with respect to the type of wood to be used, the construction of the new structures tried to follow the traces of the measurements and position of the original missing elements, still identifiable in the imprints in the rammed earth wall. The new solid pine wood boards only lean against the original walls, ensuring compliance with the initial finishes and correct access to all levels of the tower at the same time. Whilst respecting the grooves and rhythm tracks of the original floors, it was decided to finish them off with wooden profiles, using contemporary building practice and standard profiles. The floor is made of wooden beams (12×18 cm) and rafters (9×12 cm), carefully inserted into the original positions without modifying the structure, with a 5 cm thick processed plank set in a metal profile and set back from the inside edge of the wall (Fig. 21). Plywood beams and rafters have been put in place with three vertical slats, thus improving control of bending and torsion without sacrificing the simple appearance of the natural beams.

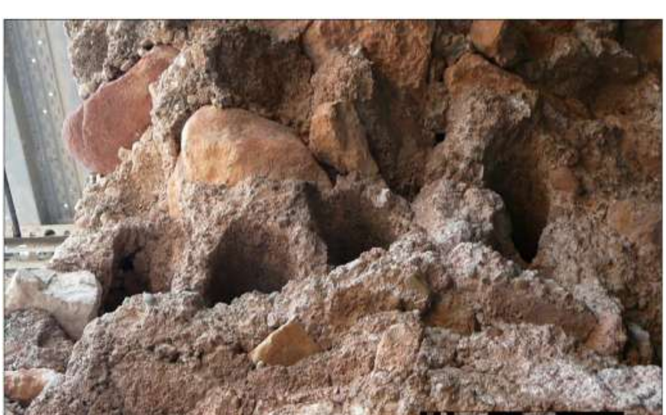

Fig. 18. Imprints of the reinforcement logs for the lintel of the access room (V. Cristini).

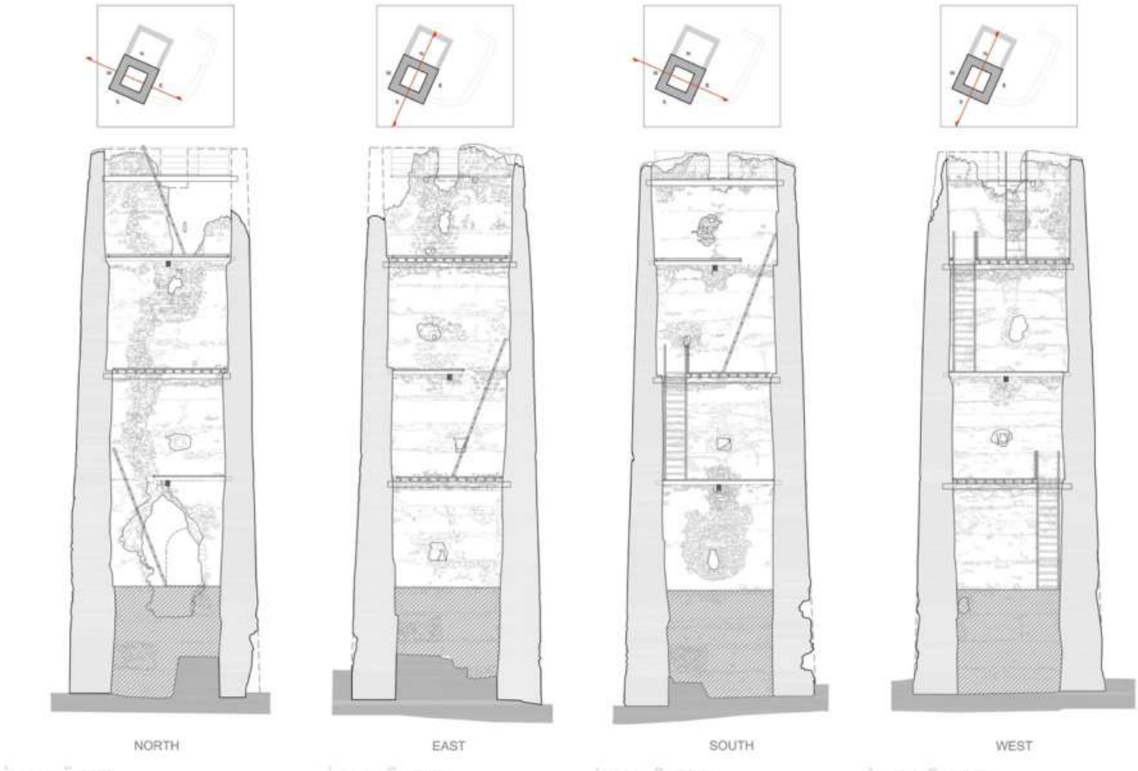

Fig. 19. Project for new floors, ceilings and stairs (C. Mileto and F. Vegas).

7. Conclusions

The meticulous attention to the walls and their historical value has been respected and protected throughout the project of restoration and conservation of the Bofilla Tower. The study and complete survey allowed the leading role of wood in this unique rammed earth construction to be highlighted. The technical and construction use of this material does not assume the role of "background actor" compared with earth and its constructive peculiarities: on the contrary, the perfect symbiosis of the two techniques provides outstanding performance for the building. The detailed study of the imprints of the missing structures and the analysis and characterization of the timber from material traces in the construction (thin putlogs, sleepers, lintels, beams) has provided knowledge of Islamic construction (constructive process and

Fig. 20. Bofilla Tower after restoration (C. Mileto and F. Vegas).

Fig. 21. New floor project, respecting the imprints of original planks (C. Mileto and F. Vegas and T. Baeza).

elements), unprecedented for this type of structure. The study and interpretation of this building will be useful as a basis for the correct reading of other similar buildings.

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