Survey on the main defects in ancient buildings constructed mainly with natural raw materials

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ABSTRACT: Many of the existing buildings constructed mostly with natural raw materials, in European sites, are frequently lacking proper maintenance and, therefore, a high degree of degradation is verified in these buildings compromising their integrity and reducing their lifetime probability. Often in the rehabilitation or reconstruction of old buildings the solution adopted is the partial or integral demolition and substitution of several building components. The aims of this study are to describe the most common constructive solutions in Portuguese buildings constructed with raw natural materials, to specify the principal problems that affect each building component, and to present possible solutions to correct each defect. This study is focused on the principal elements that compose the building structures in Portugal, including load-bearing walls, wooden floor and roof structures. The corrective solutions presented and studied privileges the adoption of materials and techniques similar and most compatible with the original ones.

1 INTRODUCTION

In Portugal, the main traditional construction techniques that make use of earth are rammed earth, adobe and half-timbered. These techniques fell into disuse upon the appearance of reinforced concrete and ceramic bricks (Carvalho et al, 2008).

An expressive amount of the existing Portuguese buildings reveals a certain lack of maintenance or conservation and the main reason for this fact is inherent to cost reasons. It is almost symptomatic to observe pathologies even in recent buildings. The cause of these premature pathologies may be building error, design error, inappropriate building conception, inappropriate or deficient building materials, among others. On the other hand, the degradation tends to increase with the age of the construction and it may be considered as a natural degradation related to natural pathologies.

The presence of undesirable water during a long period of time frequently deteriorates the materials properties which decreases the stiffness of the structural elements and may result in partial or total collapses of the constructions.

A regular maintenance or conservation work is required to avoid undesirable unexpected building construction deterioration. The occurrence of a pathology may lead to others and, in the limit, may results in a progressive structural collapse (Pinto et al, 2002).

In this context an early 19th century Portuguese watermill building is used as a study case to show how a roof leaking may lead to a progressive building collapse.

A brief description of the building is done followed by an identification/characterization of the building materials. In particular, an experimental study of the structural mortar was done in the Microscopic Electronic Unit of the Trás-os-Montes e Alto Douro University (UTAD) in which the chemical elementary composition was studied by scanning electron microscopy/energy dispersive spectroscopy (SEM/EDS) and the mineralogical elementary composition was studied by X-ray tests. The experimental identification of wood specimen was done at the Laboratory of the Forest Department of UTAD.

The chronological partial roof structural failure sequence is presented and described in which a pathology cause/effect link is also done. Meanwhile, the analysis of this failure sequence may give evidence for achieving better robust timber structural roof solutions and also reinforcement repairing structures proposals for traditional Portuguese buildings.

The building used as a study case may be seen a real experimental model of a traditional Portuguese building which are in general sustainable.

2 BUILDING UNDER STUDY

2.1 *Historical and geographic context*

In this research work, the building adopted as a study case is an early 19th century watermill which its main function was to provide the neighborhood and the surrounding villages of flour. Its activity ended by the mid 70`s with the boom of the supermarket networks which started to offer pre-packed cereals and flour. The death of the owner plus the above described situation were the main reasons why the watermill building has been without any use and maintenance from that time. The Fig. 1 shows the watermill building in 2000 in which it is evident that a partial roof collapse has occurred (Fig. I, detail I).

The building is located in Portugal continental central region, on the coast, in the district of Coimbra, in the municipality of Figueira da Foz, in the village of Carritos (Fig. 2).

Figure 1. Watermill building's condition in 2000

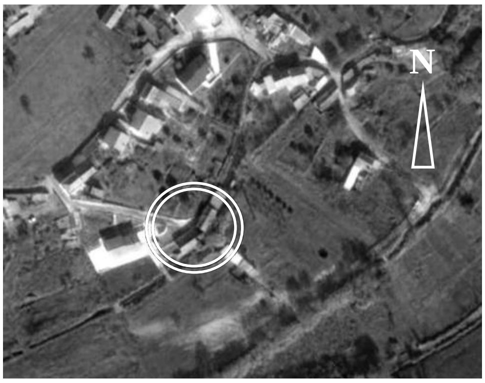

Figure 2. Location (http://maps.google.pt/)

2.2 *Architectural and construction conditions*

An expressive amount of the existing Portuguese buildings reveals a certain lack of maintenance or conservation and the main reason for this fact is inherent to the related cost. It is almost symptomatic to observe pathologies even in recent buildings. The course of these premature pathologies may be building error, designs error, impropriated buildings conception, impropriated or deficient building material, among others. Of course that the degradation tends to increase with the age of the construction and it may be considered as a natural degradation.

A regular maintenance or conservation work is required to avoid unexpected building deterioration (Faria et al, 2008). The occurrence of a pathology may led to others and, in the limit, may result in a progressive structural collapse.

The presence of undesirable water during a long period of time frequently deteriorates the material proprieties which decreases the stiffness of the structural elements and may result in partial or total collapses of the construction.

The watermill building was thought of only working purposes which may explain the very simple but efficient architectural solution adopted (Fig. 3 and 4).

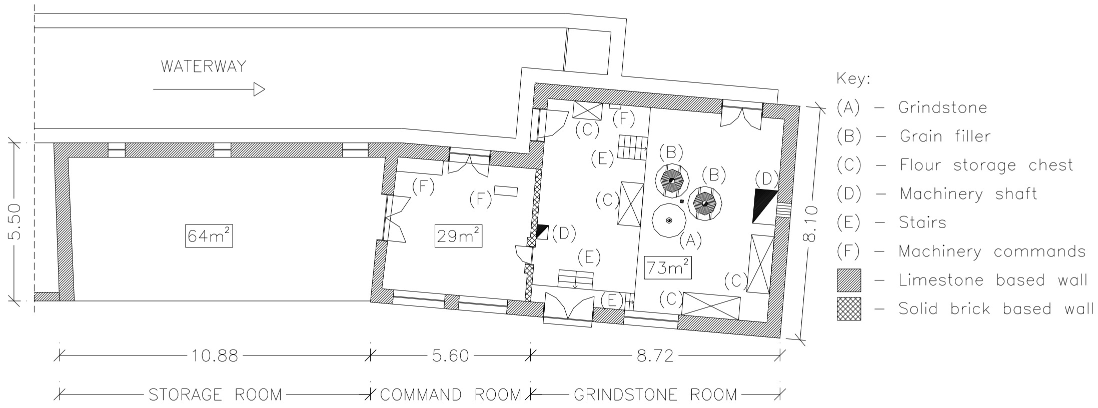

Figure 3. Ground floor Plant, 2009 (m)

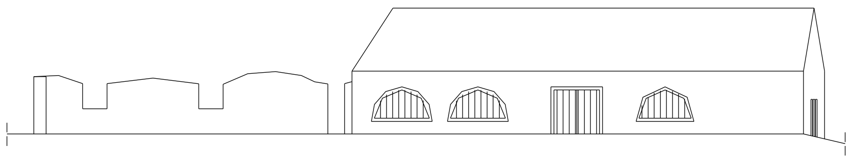

Figure 4. Frontal view, 2009

The building has basically three rooms located in the ground floor. These rooms are the grindstone room, the machine command room and the storage room, Fig. 3. The grindstone room has a 73 m^2 area in which exist the grindstone, two grain filers and massive wooden chests to retain the flour. The machine command room has a 29 m^2 area where the turbine's switching levers are located. Finally, the storage room has a 64 m^2 area and its purpose was for storing the grains and flour. Thus, the building has a total area of 166 m^2.

3 IDENTIFICATION AND CHARACTERIZATION OF THE BUILDING MATERIALS

The used building materials are limestone, structural mortar, timber, solid and hollow ceramic bricks, finishing plaster and ceramic tiles.

Since this region is sparse in stones, the structural stone masonries walls (exterior and interior) had been built up using irregular and small sized limestone pieces (Fig. 5, detail I) agglutinated by a structural mortar (Fig. 5, detail II). The average thickness of these walls is 0.40 m.

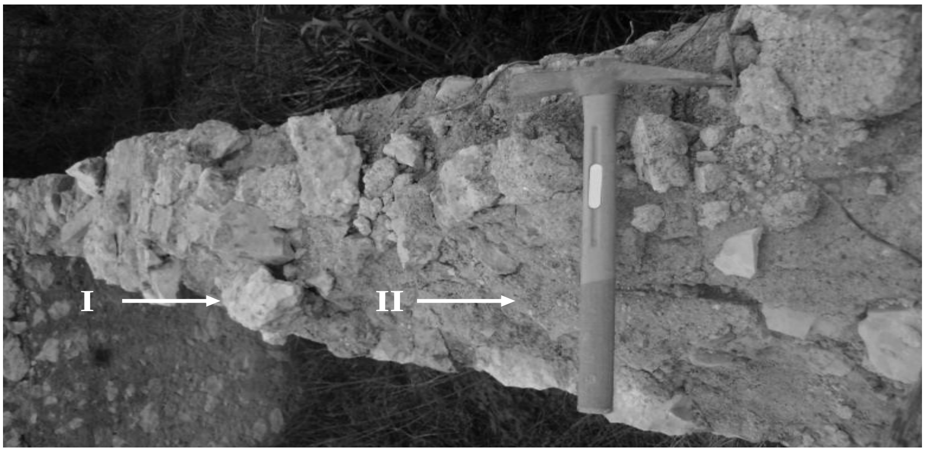

Figure 5. Detail of the structural stone masonries walls

Timber was highly used in this building. The floor, the purling, the beams of the roof structure and over the openings (windows and doors) and the ground pavement are timber. Since the building is next to a watercourse we suspect that its foundation system includes also timber piles to reach good capacity resistance soil. However, this last fact needs to be further confirmed through an excavation.

It is also possible to find ceramic hollow bricks punctually on the top of the timber boards located on the windows. At the same time, there is an interior partition wall that was built using solid ceramic bricks. The mortar attached to these bricks seem to be different of the used in the structural walls and may indicate that this wall is earlier than the others and may be related to any renovation work.

A finishing plaster material was used in most of the walls excluding the ones of the storage room. The exterior covering of the roof is ceramic tiles.

In order to identify the type of mortar, the type of finishing plaster and the specimen of timber, experimental tests were done.

The identification/characterization of the chemical and mineralogical elementary compositions of the mortar and the finishing plaster materials was done by scanning electron microscopy/energy dispersive spectroscopy (SEM/EDS) and X-ray tests which were performed in the Microscopic Electronic Unity of the UTAD. Similar tests have been already done in the framework of other research projects (Pinto et al, 2009), (Silva et al, 2009) to characterize the available and used materials for the local traditional constructions.

Four mortar material samples (sample 1, 2, 3 and 4) were collected and tested. It was also tested a lime sample and a hydraulic lime sample since they are the more common binding material used in these traditional buildings.

The preparation of the mortar material samples required a triturating process because only the thinner portion is used.

The chemical elementary composition results obtained by the SEM/EDS test are presented in Table 1.

Table 1. Chemical elementary composition results of the SEM/EDS (%).

Chemical element	Sample 1	Sample 2	Sample 3	Sample 4	Lime	Hydraulic lime
Oxygen (O)	52.01	51.44	52.07	49.06	56.06	39.85
Sodium (Na)	--- --	-----	-----	0.90	-----	-----
Magnesium (Mg)	-----	-----	-----	0.68	2.01	0.50
Aluminium (Al)	6.37	6.11	8.74	6.68	3.40	0.38
Silicon (Si)	13.84	9.45	17.48	15.01	7.42	-----
Chorine (Cl)	-----	-----	-----	0.58	-----	-----
Potassium (K)	1.90	1.09	3.45	1.65	0.99	-----
Calcium (Ca)	24.92	31.17	17.36	22.51	28.01	59.26
Iron (Fe)	0.96	0.74	0.90	2.94	1.4	-----

The mineralogical elementary composition results of the X-ray test shown in Table 2.

Table 2. Mineralogical elementary composition results of the X-ray test

Sample 1	Mineralogical composition
Sample 1	Quartz, Calcite, Muscovite
Sample 2	Calcite, Kaolinite, Quartz
Sample 3	Calcite, Quartz
Sample 4	Calcite, Quartz, Plaster
Lime	Calcite,Calcium Oxide
Hydraulic lime	Calcite, Quartz, Plaster

Mortar material samples 1, 2 and 3 have very similar elementary composition in particular in terms of chemical (Table 1).

On the other hand, the mortar material sample 4 seems to be slightly different of the others (5^{th} column, Table 1 and 5^{th} line, Table 2) and shows a lot of mineralogical elementary composition similarities with the hydraulic lime (Table 2).

At the same time, this sample was gotten from the above described interior partition wall which is earlier than the others.

Based on these results and the above analyses we may consider that the mortar material samples 1, 2 and 3 are a mixture of local earth and lime and the mortar material sample 4 is a mixture of a local earth and hydraulic lime.

All the samples have an expressive amount of Ca. Taking into account that it is a limestone geological region, the earth must be also limestone based. Thus, further experimental work is required using local earth samples in order to confirm if samples 1, 2 and 3 are earth based mortars.

The experimental identification and characterization process of the six timber samples was done at the Laboratory of the Forest Department of UTAD. Two timber samples of the timber structural roof were experimentally identified as being *Pinus pinea* specimens. One timber sample of the ground floor pavement was experimentally identified as being *Pinus pinaster* specimen. These are both local trees specimens.

Based on the above building material description it is possible to realize that most of the used materials are natural and local and, the building itself is associated to building techniques that require small amount of energy consumption and releases an unexpressive amount of noxious gases to atmosphere (Murta et al, 2009). Consequently, we have a remarkable example of a sustainable building solution.

It is important to study the composition of the existing mortar and to identify the wood specimen used for future renovation and conservation works for this building, in particular, and for traditional Portuguese buildings in general. We are also particularly interested of verifying if the mortar is an earth based material

4 STRUCTURAL SOLUTION

According to Fig. 3 there are two types of walls. There are several limestone based masonries walls and one solid ceramic brick based wall. The function of the last one is partition. In contrast, the main ones have a structural function since they support the roof system.

The roof timber structural solution comprises two types. In the grind stone and the command rooms (Fig. 6-a) it was adopted trusses (Fig. 6-a, detail I) directly supported on the limestone based masonries walls (Fig. 6-a, detail II), these trusses support beams (Fig. 6-a, detail III) which are supporting the purling (Fig. 6-a, detail IV). On the purling there are timber boards (Fig. 6-a, detail V) supporting the ceramic tiles.

a. Trussed type roof structural solution b. Beamed type roof structural solution

Figure 6. Roof structural systems

The other type of roof timber structural solution was only applied in the storage room, Fig. 6-b, which includes timber beams (Fig 6-b. detail I) which were structures supported on the limestone based masonry walls (Fig. 6-b, detail II) and a central timber beam (Fig. 6-b, detail III). On these timber beams there were timber boards (Fig.6-b, detail IV) supporting the ceramic tiles.

These are remarkable traditional timber structures built under skills based on experience.

5 FAILURES AND PATOLOGIES

5.1 *Roof structural failures*

The roof timber structure has been facing partial collapses throughout the last 9 years. The first partial collapse occurred in 2000, in which part of the roof of the storage room was lost (Fig. 8-a, detail I). It is important to underline tha the main structural timber elements which are trusses did not get damaged.

The second structural failure of the roof occurred in 2007 resulting in the completely loss of the roof of the storage room (Fig. 8-b, detail I) and part of the frontal limestone based masonry wall (Fig. 8-b, detail II).

The third roof structural failure occurred this year in the roof of the grindstone room (Fig. 8-c, detail I) in which its roof was partially lost. In this case, the purling (Fig 6-a, detail IV) collapsed in the zone of their support (the limestone based masonry wall (Fig. 6-a, detail VI) generating a load redistribution which resulted on the collapse of the beam (Fig. 6-a, detail III). This load redistribution was possible because the roof structural solution works as a structural system (CEN, 1998).

a. 1st Collapse (2000) b. 2nd Collapse (2007) c. 3rd Collapse (2009)

Figure 8. Roof's partial collapses

5.2 *Pathologies*

This section is focused on the pathologies associated to the above described failures.

Figure 8-a in its detail II shows a local permanent deformation of the roof system of the grindstone room in its connection to the frontal wall. Some ceramic tiles were also missing there.

Meanwhile, Figure 8-a illustrates the roof's condition of the grindstone room before the above described third roof's structural collapse occurred in 2009 (Fig. 8-c). Some purling and timbers boards showed an advance stage of deterioration in the contact zone with the structural wall. Through Figure 6-a, detail I, itis also possible to notice that these timber elements had a darker shade than the similar ones located outside of the damaged zone which indicated a leaking problem. By doing a similar analysis, Figure 6-a, details VII, VIII and IX indicated that there were some cracked ceramic tiles or the ceramic tiles/timber board direct contact solution was not the appropriated one because may increase an undesirable water moister in the timber structural elements.

An expressive vertical crack located in the junction of two limestone based masonry wall of the storage room (Fig. 9, detail I) was formed just before the occurrence of the second roof's structural collapse occurred in 2007. The thickness of this vertical crack decreases from the top to the bottom.

Figure 9. Vertical crack, 2007

6 MAIN CONCLUSIONS

The architecture solution, the structure solution, the building material's identification/ characterization, the sequence of structural failures and the main pathologies identification/ characterization related to an early Portuguese 19th century watermill were described and detailed.

This building may be considered as a real scale experimental model which may contribute to the rehabilitation and conservation fields of traditional Portuguese buildings.

Based on the fact that the experimental material study concluded that the building used as a study case is environmental friendly and may also be used as a sustainable building model. The structural limestone based masonry walls adopted solution has the particularity of using small size limestone pieces connected by an earth based structural mortar which is also a sustainable and economic solution.

The reported structural failure sequence has been caused basically by roof leaking problems which has been deteriorating the timber structural elements of the roof of the watermill building. Then, a regular maintenance is required in order to avoid building failures. This fact is much more relevant in traditional buildings.

The trussed timber roof structural solution had shown a better structural behavior than the beamed timber roof structural solution because it avoids total collapse and, consequently, it is more robust. These facts may be easily extrapolated to the repairing of the Portuguese traditional buildings which are in general environmental friendly.

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