Monastery of Salzedas (Portugal): Intervention in the cloister and information management

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ABSTRACT: Anyone involved in the conservation of cultural heritage buildings is aware of the enormous amount of information generated by the different specialists, which is generally not handled adequately by owners and/or authorities involved in the process. The consequence is that valuable information is lost in a complex process of reaching a decision that involves many different experts and information tends to get forgotten or misplaced in the course of time. A case study with extensive damage, which recently suffered significant conservation works, is described in detail, so that the adopted remedial measures are justified. Then, the case study is also used to develop an application for the efficient management and visualization of the information related to interventions of cultural heritage buildings.

1 INTRODUCTION

Monastery of Santa Maria de Salzedas (Portugal) recently suffered major works in one of the cloisters. This case study is addressed here from a comprehensive perspective, including aspects of the intervention project and aspects related to information management.

The first part of the paper describes in detail the Monastery of Santa Maria de Salzedas and the conservation works in the cloister. This includes survey and characterization of the damage, together with in situ and laboratory testing, which allowed to gather the information necessary to establish the need of an intervention and to bound this intervention. The obtained information allowed obtaining a computer simulation of the building, which resulted in clear information on its structural behavior. The details on the consolidation project and the execution works are also provided.

The second part of the paper addresses a database created for the management of the information generated during the intervention process and the historical information collected, which has been produced along the time and has been selected by different areas of study. The information is accessible via intranet for practitioners and is planned to be accessible on the monastery for visitors, in way that a non-specialist and a team specialist can obtain information with different contents. The paper discusses the underlying principles in which the application is based on and details the main characteristics of the application.

2 BRIEF HISTORICAL REVIEW

The Monastery and Church of Salzedas are located in Salzedas, Tarouca and the church was recently classified as a National Monument. The church is essentially set in an urban environment, whereas the monastery is set in a more rural environment (Fig. 1a). The plan dimensions are very large, 75 × 101 m². The monastery and church possess a longitudinal irregular plan with different volumes, typical of a Cistercian Abbey (Fig. 1b). The conservation works addressed here focus in the cloister dated from the 17th century (Main Cloister, in the picture).

2.1 Previous documented works in the main cloister

The main cloister is regular and substitutes part of the primitive cloisters (Fig. 2a). It possesses cross vaults in the 1st level and barrel vaults in the 2nd level. The walls, brackets and ribs are made of granite and the vaults are made of brick masonry with clay or masonry filling. After repeated statements of the pre-collapse status of the cloister, Leitão (1963) and Cocheril (1978), the former General Directorate for National Buildings and Monuments (DGEMN) carried out remedial works in 1980/1981 and 1983 (Figs 2b-d), including: (a) Demolishing and replacing the vault of the 2nd level of the West wing by a reinforced concrete vault; (b) Dismounting and
3 VIRTUAL RECONSTRUCTION

The majority of the monastery disappeared after the extinction of the religious orders in the Age of Enlightenment without letting any vestige. A 3D CAD model of the virtual reconstruction of the medieval monastery of Santa Maria de Salzedas was made in order to allow visitors to better understand the monument and to assist the conservation works.

3.1 The ideal plan of the Cistercian abbeys

The Cistercian Order did not ever define a unique model for the monasteries, in which a formal model was defined and repeated at each monastery. However, the similarities among abbeys, especially in the distribution of spaces, put in evidence a common or ideal plan for the monasteries (Fig. 3), see also Leroux-Dhuys (2006).

Although the plans were very similar among abbeys, they are more different in elevation. The monastery followed a basic square structure; where one of its sides, aligned along the East-West axis, was formed by the church, always in the highest part of the property. The other parts could be constructed oriented to the North or to the South, according to local relief. This is the largest variation observed in the “replication” of the ideal plan among monasteries. It is noted that the disposition of divisions was such that the kitchen and the refectory were located in the lowest part, near to a water-course.
The church was oriented in the East-West direction, with the apse to the East. The plan was a Latin cross, with three naves, being the aisles lower than the central nave. Usually the body of the naves was preceded by a narthex and the transept was formed by a single nave. The naves were divided by square pillars with engaged or truncated columns and were covered by barrel vaults, oriented perpendicularly.

Sometimes, on the side of the transept, engaged to the exterior wall, a bell tower could exist, built in stone or wood. The construction of towers similar to traditional secular churches was forbidden. The church’s facade was simple and divided in three parts. A detailed summary description on the arrangement of Cistercian abbeys can be found in Amado et al. (2006).

3.2 Medieval vestiges in the actual monastery

Parts of the medieval construction could still be found in the actual monastery. Most of the vestiges were found in the church, while very few elements of the medieval period could be found in the cloister. This is probably due to the continuous changes made in the 16th to 18th centuries in the cloister. In fact, it is possible to find masonry ashlars from the medieval monastery that were reused in the new structural elements.

The church conserves the medieval walls up to the openings of the lateral naves with the exception of the main façade, which was rebuilt in the last campaign. The church conserves an apse chapel from the primitive construction in the northern side of the transept (Fig. 4). It is semicircular and built with granite stone blocks, with two engaged columns that divide the exterior wall in three parts. In the central part, a rectangular window provides light to the interior. In this same part of the transept, in the western interior wall, there is a spiral staircase that certainly conducted to the ancient tower. In the outside, in the wall of the northern side of the transept, there are two closed openings (Fig. 4). The central and larger one should be Door of the Dead, now leading to the cemetery. From prospecting pits, it was possible to conclude that the outside walls of the cloister were constructed on top of the medieval foundations.

3.3 Definition of the modeling unit

The modeling unit is the base of the system of proportions, which was an indispensable element to provide the composition of the entire building. The Cistercian buildings were based on the composition principle of “ad quadratum”, Virgolino (1997), in which a simple generating mesh gives the proportions of the elements.

In the Portuguese constructions from the beginning of the second millennium, the units of measure commonly used were the Roman palm (0.223 m) and the Roman foot (0.296 m). However, it is very likely that the Cistercian Portuguese constructions had used the “pied du Roi” or king’s foot, equivalent to 0.32484 m, since it was the standard measure used in France in that time, Virgolino (1997). It is possible to observe that the modeling unit used in Salzedas was equal to 8 king’s feet, since the main elements of the church present values very close to integer multiples of this modeling unit. The reference module mesh is depicted in Figure 5.

3.4 Model of the medieval monastery

The church, the cloister and the three wings (monks, refectory and lay-brothers), which together constitute the five main bodies of the monastery (the abbey’s buildings), were built at different levels, in order to adapt to the morphology of the location. Perpendicularly to the body of the church, the bodies of the cloister are built aligned with the direction of the slope of the ground.

The model prepared for the medieval monastery only presents part of the abbey’s buildings (Fig. 6). The construction has a Romanesque solution, in which the building compound was composed by simple parallelepiped, massive and juxtaposed volumes. The walls, foundations and pillars were built with large ashlars, while the top and intermediate floors were usually made with barrel or quadripartite vaults, in stone or brick masonry. The roofs were of two slopes, with timber structure and tile covering. The cloister should be
supported on double flat and round columns. The chosen solution is similar to the French cloisters: Romanic with a heavy and massive clean style. Details of the model are shown in Figures 7 and 8.

4 IN SITU SURVEY

4.1 Visual inspection

The condition of the cloister was quite poor, including biological colonization sometimes associated with moisture stains, deterioration of the bricks in the vaults, cracks with variable thickness, crushing of stones and excessive movements in walls and vaults.

Large cracks could be observed in the cloister (Fig. 9). The largest and widest set of cracks occurs in the barrel vaults of the South and East wings of the 2nd level, as well as the SE and NW corners. The cracks occur mostly in the longitudinal direction up to a crack opening of 40 mm, even if some transversal cracks also occur. The vaults of the 1st level exhibit cracks in the South and West wings, up to a crack opening of 15 mm. The West wing was supported on temporary wooden poles.

The walls exhibit well distributed cracking at the 2nd level and almost no cracking at the 1st level. With the exception of a few localized areas, cracking is minor (crack openings in the range of 1 to 5 mm).

Vertical displacements up to 35 mm were measured at the key of the crossed vaults of the 1st level. But all the walls of the cloisters exhibit large horizontal movements that lead to the separation between the vaults and the walls, in a clear lack of verticality (Fig. 10).
The out-of-plumb displacement of the internal walls reaches values of 0.18 m, 0.14 m, 0.09 m and 0.07 m in the wings West, South, East and North, respectively.

The brackets supporting the crossed vaults of the first level show signs of compression/shear damage, particularly in the West wing (Fig. 11a). This can be explained by the tilting movement of the walls. The absence of connection between the infill of the crossed vaults and the walls resulted in a much localized area to transfer the load, i.e. only the brackets. Also, a significant number of bricks show deterioration, particularly around the cracked areas (Fig. 11b). This occurs at both floor levels and can be explained by frost-thaw cycles and water infiltration, as the amount of rainfall per year in the region is high and the temperatures in the winter are excellent for ice formation (daily cycles with ±0°C).

Other perturbing signs, less relevant from the structural point of view, include damage of the stone due to freeze-thaw cycles, effloresce and biological colonization (Fig. 12). A detailed survey on stone deterioration and salt effloresce in the cloister are given in Alves & Pamplona (2006, 2007), see also Figure 13.

5 IN SITU TESTING AND LABORATORY INVESTIGATION

In order to better characterize the materials, to justify the observed damage and to define corrective measures, an experimental in-situ and laboratory testing program was carried out.

5.1 Soil and foundation survey

This survey consisted of seven boring holes and three pits to define the mechanical and physical
characteristics of the soil and foundations. It was possible to define a layered soil consisting of an infill of clayey nature (1.1 m), organic soil (0.30 m), alluvial soil with medium large stones, naturally wounded and worn by the action of water (0.60), alluvial soil with pebble (0.50 m). Between 2.5 and 2.7 m depth, the soil is granular with some clay and below 2.7 m depth large stones, with a size of 0.30 m to 0.40 m are found (Fig. 14).

The foundation soil exhibits moderated resistance and large heterogeneity for depths between 1.0 and 1.8 m, were supposedly all the cloister foundations are set. The foundations for the walls seem to be medieval and of good quality, but the foundations of the cloister columns are inadequate. These irregular masonry foundations are unable to distribute the loads over a significant soil area and the foundations depth around 1.0 m seems to indicate that the foundations were built on top of the original pavement level, directly on organic soil.
5.2 Internal characterization with rigid endoscope

In order to characterize the inner constitution of vaults and walls, a few bore holes and several cracks were inspected with a rigid endoscope (Fig. 15). The inspection allowed several conclusions, among which: (i) vaults are made with clay brick masonry with 0.22 m thickness. Infill material in the 1st level is soil and infill material in the 2nd level is a sort of rubble masonry. Separation between the two materials was not found; (ii) walls are made with large granite stones, with dry joints or a thin clay joint. The clay joint seems to be washed out around the cracks and in the external part of the wall due to weathering. An internal core of weaker mechanical characteristics was not found; (iii) internal longitudinal cracks that would compromise the stability of the walls under vertical loading were not found.

5.3 Flat-jack testing

The results of one test are shown in Figure 16. The average in-situ stress obtained is 1.2 MPa and no indication of bending in the walls was found. The value expected is around 0.6 MPa. The difference between these values might be due to the irregular shape of the masonry blocks, indicating that only half of the stone block is active. It is stressed that the value of 1.2 MPa obtained can be considered as relatively low for the particular type of masonry.

5.4 Coring

In order to confirm the internal constitution of the vaults and to characterize the mechanical behavior of the brick masonry, three $\phi$75 mm cores were extracted from the vault (Fig. 17). The cores confirmed the borehole observation.

5.5 Chemical, physical and mechanical characterization

The plaster, vault infill and mortar from the brick masonry of the vaults were characterized with X-ray diffraction, non-soluble residual and burn loss tests (Fig. 18a). The bricks were characterized with absorption tests and uniaxial compression tests.
The mortar from the brick masonry was also characterized with uniaxial compression tests. The representative samples were extracted from the construction or the cored samples.

The tests indicated the composition of the plaster and mortar (1:3 in volume) and the composition of the vault infill. The bricks are of low quality and nondurable, with an absorption in cold water around 20% and a volume mass of 1560 kN/m$^3$.

The uniaxial compression tests were carried out in samples of 45 × 45 × 45 mm$^3$, tested with greased Teflon layers to avoid the plate confining effect. The obtained Young’s modulus and strength for the bricks were $E_b = 7300$ MPa and $f_b = 5.2$ MPa, respectively. These values are quite low and confirm the poor quality of the bricks. The obtained Young’s modulus and strength for the mortar were $E_m = 8600$ MPa and $f_m = 3.8$ MPa, respectively. This strength value can be considered normal for the mortar composition.

With these results it is possible to estimate the strength of the brick masonry as:

$$f_c = K \times f_b^{0.65} \times f_m^{0.25} = 0.60 \times 5.2^{0.65} \times 3.8^{0.25} = 2.4 \text{ MPa}$$

(1)

according to ENV 1996-1-1. The Young’s modulus of the composite might be obtained from homogenization procedures as:

$$E = \frac{t_m + t_u}{t_m + t_u + \rho} \times \frac{E_m + E_u}{E_m + E_u} = \frac{0.02 + 0.04}{0.02 + 0.04} \times \frac{8600 + 7300}{8600 + 7300} = 3800 \text{ MPa}$$

(2)

where $t_m$ represents the thickness of the mortar, $t_u$ represents the height of the brick and $\rho$ represents an efficiency factor associated with the deficient bond between the two materials (assumed equal to 0.5).

6 SAFETY ASSESSMENT

The objective of the structural analysis carried was the safety assessment of the cloister and the definition of remedial measures. For this purpose, two models of...
Figure 19. Linear elastic analysis with a 3D model of the periodic cell of the cloister: (a) finite element mesh; (b) deformation in axonometric view and cross section showing the inwards movement; (c) maximum (tensile) principle stresses; (d) minimum (compressive) principle stresses.

the periodic structure of the cloister were considered, namely a three-dimensional model and a plane stress model.

The results shown above from the survey and testing were adopted to define the geometry, constituents and properties. Different materials were used for the vaults, walls and infills. For the actions, only the self-weight of the structure was considered.

6.1 Three-dimensional model

Figure 19 shows the results of the periodic part of the cloister using linear elastic analysis. Appropriate periodic boundary conditions have been added along the longitudinal direction, whereas no boundaries were added in the transverse direction, as a lower bound representation of central part of the South wing, see Lourenço et al. (2000) for details.

Twenty-noded elements with quadratic interpolation were used in the model (Fig. 19a) and the obtained deformation for the self-weight indicates a movements inwards to the court of the cloister, as observed in the actual structure (Fig. 19b). Thus, the structure seems to presents insufficient buttressing in the internal walls.

The maximum tensile principal stresses are found at the key of the barrel vault of the 2nd level, at the key of the cross vault of the 1st level and at the key of the door arch in the 1st level. The maximum value of the principal stresses are +0.25 MPa and –0.6 MPa, which are relatively moderate values.

Figure 20. Adopted 2D model for the 2nd level: (a) thickness in different parts; (b) deformation and boundary conditions.

6.2 Two-dimensional model

In order to better understand the structure and its damage, a plane stress model has been used for the barrel vault, calibrated with the 3D model. Figure 20 shows the thickness adopted and the sliding clamping supports considered for the inner wall. It is noted that four different boundary conditions of the inner wall have been tested and this has a major impact on the vertical displacement of the key of the barrel vault, on the maximum horizontal displacement and on the maximum tensile stress.

A non-linear analysis has been made with the 2D model, incorporating interface elements for the deformability of the soil and a maximum tensile strength of 0.1 MPa. Figure 21 presents the results in terms of load-displacement diagram and maximum tensile strains (as damage indicators). The model replicates the most significant damage observed in the structure, including separation between vault and walls, and longitudinal cracking in the vault.

Also the model predicts no remaining capacity of the structure in terms of additional vertical load. It is stressed that this statement holds only in the case of the weak foundation found. If the foundations are assumed as rigid, the ultimate load of the structure increases considerably.

6.3 Conclusions

The conclusions of the numerical analyses together with the inspection allowed to conclude that: (a) the non-symmetry between the internal and external walls of the cloister result in inwards movements in the direction of the court, as observed in the construction; (b) a linear elastic analysis of the construction results in very limited displacements (in the order of one millimeter) and moderate stress values (maximum tensile stress of +0.25 MPa and maximum compressive stress of −0.6 MPa). The large displacements observed in the construction require a geometrical and physical non-linear analysis; (c) in order to obtain horizontal
displacements of magnitude comparable to the values observed in the structure, it is necessary to consider the soil-structure interaction. It seems therefore that the foundations play a key-role in the observed damage; (d) the large movements recorded in the construction and the deterioration of the brick vaults indicate that the safety level of the structure is not compatible with any use and immediate intervention was necessary.

7 REMEDIAL WORKS

The cloister required consolidations works and the proposed solution included repositioning the walls in plumb, elevation/re-centring vaults and arches, and hidden tying of the walls as an additional strengthening. This strategy resulted from the inspection, diagnosis and safety assessment, and from the previous experience of the stone master in charge of the works (Humberto Reis de Sousa), as a joint decision by the authors and the technicians in charge of the monument (Architects Angela Melo and Jorge da Costa from the Cultural Property Service, Porto). The option not to intervene in the foundations was made from the beginning, as: (a) the intervention would need to be very invasive; (b) it would lead to the destruction of the buried remainings; (c) the authors believe an intervention in the superstructure is sufficient to stabilise the structure. In the modern spirit of a step-by-step minimal intervention, the owner was alerted to the fact that a (possible, but unlikely) intervention in the foundations might be required in the future.

The viability of the proposed works depended on the possibility of cracked masonry to accommodate movements and the technical capability of the contractor, as the structures would be moved but not dismounted. The operation entails some risk due to the precarious stability, significant weight and non-monolithic behaviour of part of the structure. The operation was made possible only by the careful execution of the stone mason Humberto Reis de Sousa, who knew how to straighten and move structures walls using hydraulic jacks, cable tensioning tools and adjustable props.

Figures 22 and 23 illustrate the proposed structural remedial measures. All metallic elements are in stainless steel AISI 316, which provides the highest corrosion resistance. The ties are applied only in the wings that exhibit larger damage, possibly due to the lack of external transverse walls: South and East, and South and West. The ties are placed in the vault infill, meaning that the horizontal thrust from the vault is not aligned with the tie. This non-alignment produces a bending moment, which is balanced by vertical stitching (or reinforcement) for the 2nd level and an uneven vertical distribution of stresses for the 1st level. This uneven distribution of stresses, which does not provoke any tensile stresses, is possible due to the weight of the upper structure.

It is noted that other possible solutions were initially considered for the 2nd level, and a final solution remained to be decided during execution and clarification of the composition of the vaults. It was found that the masonry infill of the vaults from the 2nd level was extremely hard and impossible to remove without significant loss of fabric and possible damage to the structure. This contributed to the conception of the adopted solution for the 2nd level.

All ties possess a coupling element capable of adjusting the tie. In the 2nd level, the ties are connected to a vertical bar inserted in a fabric sock, capable of containing the injected grout. As the masonry in the internal walls is made of large ashlars, additional anchorage is provided with a transverse element. For the internal walls, sufficient bond occurs in the contact with the irregular masonry. In the 1st level, vertical
bars are not needed, and the ties are directly anchored to the walls at a 30° angle.

Figure 24 shows images of the preparatory works for protection and for propping and lifting the vaults. Details on the installation of the ties are shown in Figure 25 and several complementary works are shown in Figure 26.
Figure 25. Execution of consolidation: (a, b) removal of infill from wings in 2nd and 1st level; (c) openings to remove debris and lift barrel vaults; (d) coring for vertical reinforcement and tie anchorage in 2nd and 1st level; (e, f) installing ties, repairing brackets and final view in 2nd and 1st level ceiling.

Besides the works shown, protection against rainwater infiltration and drainage of rainwater were also carried out. A PVC membrane was installed in the 2nd level roof and new gargoyles were designed. The final aspect of the cloister, with the exception of the 2nd level roof is of the previous untouched antique.

Figure 26. Complementary works: (a) mortar color adjustment; (b) view of the completed external wall of South wing; (c) buried remainings found; (d) local consolidation with new masonry parts; (e,f) view of 2nd and 1st level floor.
8 INFORMATION MANAGEMENT TOOL

Anyone involved in the conservation of cultural heritage buildings is aware of the enormous amount of information generated by the different specialists, which is generally not handled adequately by owners and/or authorities involved in the process. The consequence is that valuable information is lost in a complex process of reaching a decision that involves many different experts and information tends to get forgotten or misplaced in the course of time.

Upon the recognition of this evidence, University of Minho (UMinho) in partnership with Centre of Computer Graphics (CCG) and the former Portuguese Institute of Architectural Heritage (IPPAR) developed an application for the efficient management and visualization of the information related to interventions of cultural heritage buildings. The development was based in a case study with extensive damage and that recently suffered major works in a cloister, namely the Monastery of Santa Maria de Salzedas (Portugal). A database was created for the management of all the information generated during the intervention process of 2005 and the historical information collected which has been produced along the time and has been selected by different areas of study. The information is accessible via intranet for practitioners and, planned soon, to be available on the monastery for visitors, in way that a non-specialist and a team specialist can obtain information with different contents.

8.1 Internet as a tool for information management

Internet is an excellent tool that fulfils the ICOMOS (1996) principles for the management, dissemination and sharing of records, namely: (a) the original electronic version can be safely archived; (b) backups are easily made and can be stored in a different and safe place; (c) updated records can be easily incorporate; (d) the format of the records can be standardized and indexed; (e) information is accessible 24 hours a day, year round, from any point of the world; (f) information can be published, disseminated and be easily accessible and/or restricted depending on the classification of the information and the user; (g) the information can be easily presented in different languages in real time allowing its dissemination around the world.

8.2 Structure of the database

The information about the Monastery is presented using virtual representation (VR), i.e. through multimedia tools, the users will have access to all information stored in the database.

The application, and the database, is structured in three main groups, which define the way in which the information can be accessed, namely spatial units, level of access and thematic areas. The spatial units should be understood as the different areas in which the Monastery has been divided. The level of access defines the privileges of the user. Thematic areas are the options for searching the information contained in the database. The database can be browsed through menus or hotspots in photographs, 360° panoramic views or 3D model (Fig. 27). The thematic areas depend on the level of access. A tree-like structure was thought for the thematic areas (menus and submenus), in which each one can be subdivided in three different levels.

The main menus or thematic areas are shown in a fixed top bar, while the submenus are displayed at the top-left of the screen. The bottom-left area displays the image with hotspots. The hotspots link with some particular information or display files stored in the database. The information is displayed in the main window. The information is presented as image elements (pictures, drawings, movies, panoramic views,
3D models, etc.) in the top, with text elements in the bottom.

The application has been developed in two different parts, including a Backoffice for inserting the information gathered and the Front End, which is the part visible to users as webpages automatically generated from the backoffice. Both parts can be accessed remotely via Internet connection.

Besides the tree menu structure, there is a search bar to find any particular file stored in the database. Figure 28 shows a typical view of the navigation window of the database. This window shows the same fields as the file form associated with each file in the database. The download option will be turn on only if the user has at least the same rights as the file has (level of access).

9 CONCLUSIONS

A comprehensive program involving inspection, diagnosis, safety assessment and remedial measures of a Cistercian cloister was presented. The cloister was in very bad structural conditions and the consolidations works aimed at stopping further degradation and at preventing collapse. With the objective of keeping the abandoned/ruined condition of the cloister, all works have been hidden, while ample information is available to document the intervention.

These tasks are complemented by a virtual reconstruction of the medieval monastery and an information management tool, with the objective of providing simple technical information to the visitor and of managing the significant amount of expert documentation gathered in the process.

The application is based on the creation of a database that makes possible the efficient management of all information related to past, present and future interventions of the Monastery, in way that it is easily accessible by anyone.

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