Monastery of Salzedas (Portugal): Intervention in the cloister

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ABSTRACT

A comprehensive program involving inspection, diagnosis, safety assessment and remedial measures of a Cistercian cloister is 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.

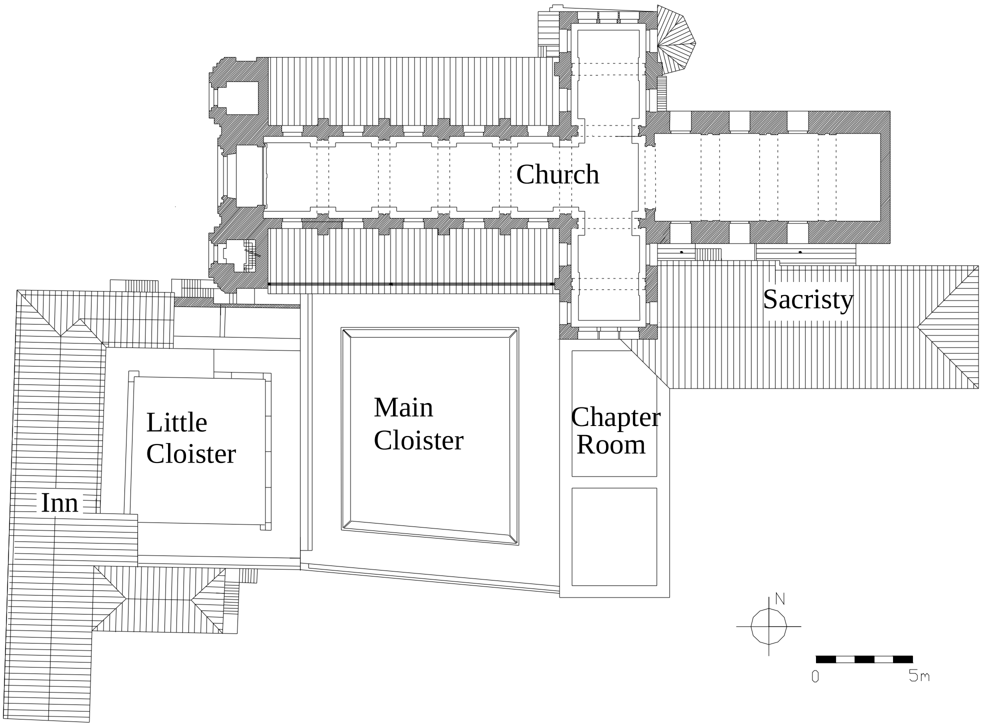
1 INTRODUCTION

Monastery of Santa Maria de Salzedas (Portugal) recently suffered major works in one of the cloisters. The paper describes 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 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 x 101 m^2. 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 17^{th} century (Main Cloister, in the picture).

The main cloister is regular and substitutes part of the primitive cloisters. It possesses cross vaults in the 1^{st} level and barrel vaults in the 2^{nd} 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, the former General Directorate for National Buildings and Monuments (DGEMN) carried out remedial works in 1980/1981 and 1983, including: (a) Demolishing and replacing the vault of the 2^{nd} level of the West wing by a reinforced concrete vault; (b) Dismounting and reassembling the wall separating the large and small cloisters, between the 1st and the 2nd levels. The works do not comply with modern theories of intervention in historical structures and would be, today, very debatable.


(a)



(b)

Figure 1. Monastery and Church of Salzedas: (a) aerial view; (b) plan and spatial units.

2 IN SITU SURVEY

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, see Fig. 2. Vertical displacements up to 35 mm were measured at the key of the crossed vaults of the 1st level. 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. 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. 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, due to frost-thaw cycles and water infiltration. 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

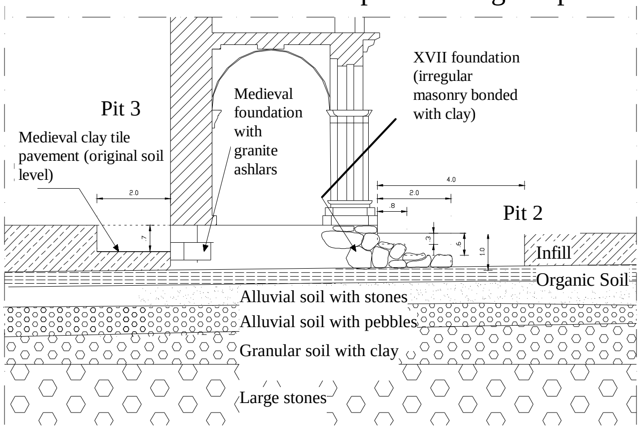
(a)

(b)

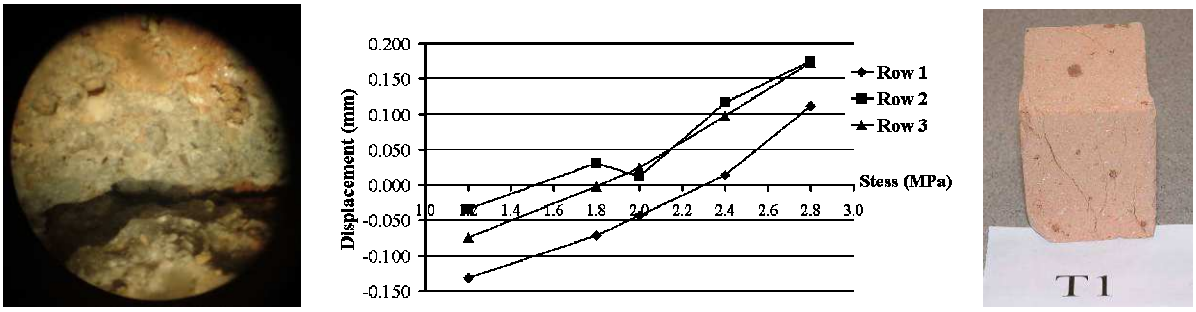
Figure 2. Examples of observed damage: (a) cracks; (b) large movements; (c) material damage and deterioration.

3 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, see Fig. 3. The soil and foundation 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. 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.



(a)



(b) (c) (d)

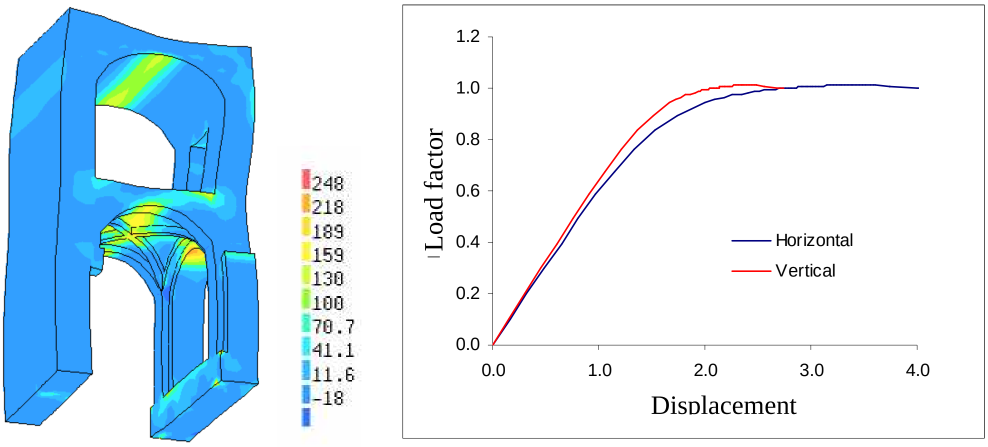
Figure 3. Some results of in situ survey and laboratory testing: (a) soil survey; (b) rigid boroscope observation; (c) flat jack testing; (d) sample for testing the brick compressive strength.

In order to characterize the inner constitution of vaults and walls, a few bore holes and several cracks were inspected with a rigid endoscope. 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. As a result of the inspection with the rigid endoscope, it was concluded that the granite walls of the cloister are adequate and there is no danger of collapse due to desegregation under vertical loading. Coring and other techniques to estimate the strength of the walls were considered not necessary and it was decided to carry out two simple flat-jack tests. In order to confirm the internal constitution of the vaults and to characterize the mechanical behavior of the brick masonry, three ϕ75 mm cores were extracted from the vault. The cores confirmed the borehole observation.

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. 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 non-durable, with an absorption in cold water around 20% and a volume mass of 1560 kN/m^3. The obtained Young's modulus and strength for the bricks were 7300 MPa and 5.2 MPa, respectively. The obtained Young's modulus and strength for the mortar were 8600 MPa and 3.8 MPa, respectively. With these results it is possible to estimate the strength of the brick masonry.

4 SAFETY ASSESSMENT

The objective of the structural analysis carried out was the safety assessment of the cloister and the definition of remedial measures, see Fig. 4. The results 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. 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. The obtained deformation for the self-weight indicates a movements inwards to the court of the cloister, as observed in the actual structure. Thus, the structure seems to presents insufficient buttressing in the internal walls.



(a) (b)

Figure 4. Examples of the results of the structural analysis: (a) maximum (tensile) principle stresses from a linear elastic analysis with a 3D model of the periodic cell of the cloister: (a) load-displacement diagram in a non-linear analysis.

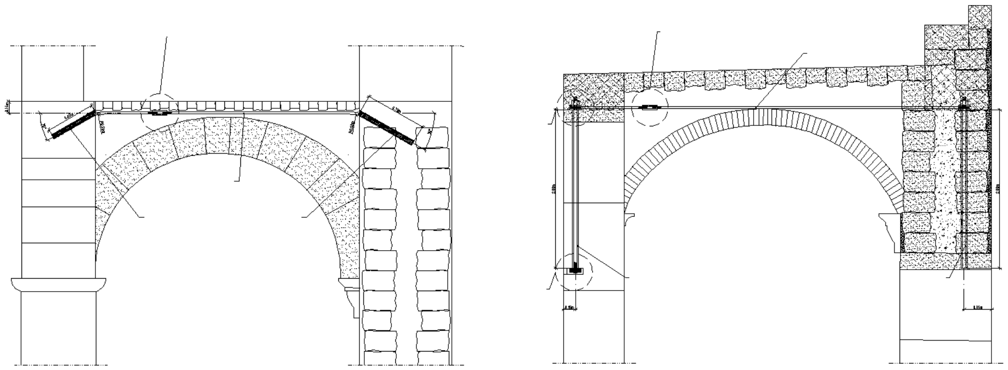
The maximum tensile principal stresses are found at the key of the barrel vault of the 2nd level, at the key of the cross vault of the 1st level and at the key of the door arch in the 1st level. The maximum value of the principal stresses are +0.25 MPa and – 0.6 MPa, which are relatively moderate values.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

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 and moderate stress values. 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.

5 REMEDIAL WORKS

The cloister required consolidations works and the proposed solution included repositioning the walls in plumb, elevation / re-centering vaults and arches, and hidden tying of the walls as an additional strengthening, see Fig. 5. 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 stabilize 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 behavior of part of the structure. The operation was made possible only by the

careful execution of the stone mason Humberto Reis de Sousa, which knew how to straighten and move structures walls using hydraulic jacks, cable tensioning tools and adjustable props.
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. 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 2^{nd} 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.



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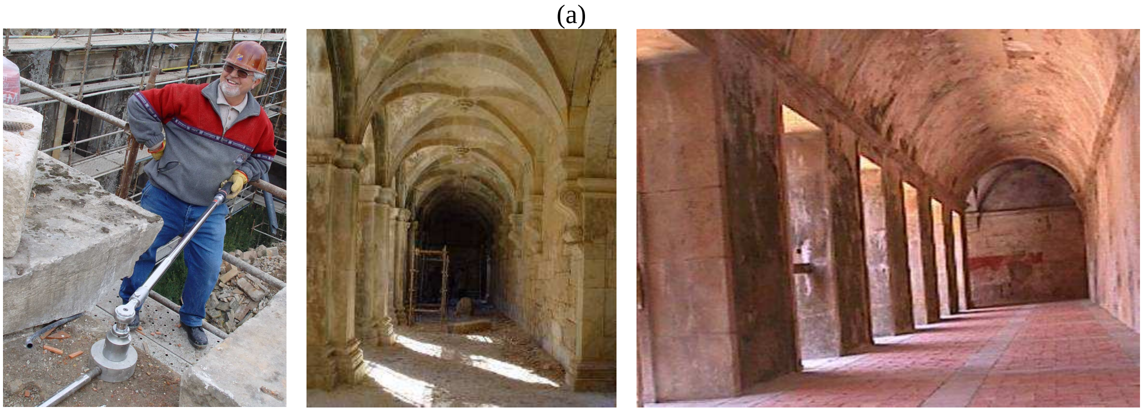

(b)

Figure 5. Examples of consolidation works: (a) strengthening adopted for 1^{st} and 2^{nd} level: (b) applying torque and final aspect after the intervention.

All ties possess a coupling element capable of adjusting the tie. In the 2^{nd} 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 1^{st} level, vertical bars are not needed, and the ties are directly anchored to the walls at a 30º angle. Besides the works shown, protection against rainwater infiltration and drainage of rainwater were also carried out. A PVC membrane was installed in the 2^{nd} level roof and new gargoyles were designed. The final aspect of the cloister, with the exception of the 2^{nd} level roof is of the previous untouched antique.