Structural Analysis of Historical Constructions, New Delhi 2006
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Structural Intervention in a Historical Chapel

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ABSTRACT: The chapel of "S. Jorge de Aljubarrota" was erected in 1393, after the victory in the battle of Aljubarrota, one of the most important battles in Portuguese History because it settled the national independence in relation to Castile. The chapel was built exactly where, on the 14th of August of 1385, the standard of general D. Nuno Álvares Pereira was positioned. Since the foundation, the chapel has experienced several interventions and morphological changes, accurately registered from 1872 to the present time. During the most recent inspection, in 2003, it was observed that the vault of the main altar was severely deteriorated. It was decided to perform a research to identify the possible causes of the observed anomalies; to evaluate the structural safety of the construction; and to propose a solution. Taken into account that consolidation of stone blocks is not possible and that the structural safety of the vault is not assured, minimum intervention is not a choice and a reversible action presents major disadvantages. As a result, the total substitution of the vault is the projected intervention.

1 INTRODUCTION

Interventions on monuments should be performed with the only objective of its preservation. Frequently, non-intervention or, at least, minimum intervention is considered to be the best option to achieve that purpose (Aguiar 2001). The diagnosis of the state of conservation of the monument and the correct assessment of its structural behaviour are, for this reason, extremely important, even more than for common constructions.

In this article, the case study of the chapel of "S. Jorge de Aljubarrota" is presented, being described the studies performed to: justify the anomaly detected at the vault; characterize its state of conservation; evaluate its structural stability; and define the intervention that best safeguards the monument.

2 HISTORICAL SYNOPSIS

On the 22nd of October of 1383, Portuguese king D. Fernando dies. Being his daughter married to the Castilian king, it is inevitable that Portugal looses its independence. Following this event, the people entitle D. João, "Mestre de Avis", protector of the kingdom. Several battles take place until the mythical battle of Aljubarrota where, on the 14th of August of 1385, Portuguese troops, commanded by general D. Nuno Álvares Pereira, defeat the Castilian troops (Monteiro 2001). With this triumph, D. João becomes the uncontested king of Portugal and, to celebrate this victory, he orders the erection of the monastery of "Santa Maria da Vitória" and founds the village of Batalha. D. Nuno Álvares Pereira orders the erection of the chapel of "S. Jorge de Aljubarrota" on the local where his standard was placed, before the confrontation.

3 DESCRIPTION OF THE CHAPEL

The typology of the chapel consists on the volume of the rectangular plant nave with a two slope wooden roof, connected to the volume of the quadrangular plant main-altar with a cross-vault. The main façade is represented on Fig. 1a. The door is located over the symmetry axis, presenting a triangular pediment. The lateral façades (Fig.s 1b and 1c) have loopholes. The North façade also has a door with a gothic vault. The head of the chapel, where the main-altar is located, is a compact turret, of military aspect, with only a small opening on the South façade, crowned by chamfered merlons. On the vertexes thick buttresses with three floors present on top animalist gargoyles.

(a) (b) (c)

Figure 1 : (a) Main façade; (b) North façade; (c) South façade.

Since the construction, the chapel has experienced several interventions and morphological changes. The most recent ones are well documented (Mendonça 1991). Before 1872, although not registered, the interventions left behind revealing elements. The key stone of the vault of the main-altar, richly ornamented with a pelican, symbol of D. João II, witnesses an intervention performed during this period.

4 RECENT INTERVENTION ON THE CHAPEL

In 2003, due to a high state of degradation of the chapel, an inspection and diagnosis of the situation was performed by IPPAR (Portuguese Institute of the Architectural Heritage). It was concluded that the state of the roof allowed the infiltration of rain water, justifying the moisture spots visible at the vault (Fig. 2a), as well as at the chapel walls (Fig. 2b).

Also in 2003, IPPAR began conservation works on the chapel. Starting the removal of a cement based mortar that covered the vault, for subsequent substitution by a lime based mortar, it was observed that the stone blocks of the vault exhibited a high state of degradation, showing a viscous consistency and a saturated humidity state in depth. It was decided to abort this operation and to cover again the zones where the cement mortar had been removed.

(a) (b)

Figure 2 : Moisture spots – (a) at the vault; and (b) at the chapel walls, in 2003, before the intervention.

5 DESCRIPTION OF THE STUDIES PERFORMED

Following the previously described situation, it was decided to perform studies to determine the cause of the observed anomaly; to characterize the state of conservation of the vault; and to evaluate the structural stability of the latter. The information provided by IPPAR and a visual inspection of the chapel, where moisture spots and efflorescences were observed on the walls, point towards the infiltration of water by the damaged roof (until 2003) as the most probable cause.

Electromagnetic prospecting and electric resistivity prospecting were performed to analyse the presence of water on the soil (Júlio et al. 2006). These works indicated that the chapel is situated on a clay layer that, being impermeable, facilitates water accumulation on a superficial layer of clayey sandstone with coble stones. It was also concluded that the geological layers in this place present a semi-horizontal position that makes difficult underground water to flow. These facts associated with the use of high porosity materials in the walls promote the presence of rising damp by capillarity in the monument.

Considering the relative humidity as a decisive factor for the presence of efflorescences and stone degradation, in situ testing of temperature and moisture were performed (Fig. 3). Although measurements were made in summer, the value of environmental humidity inside the chapel varied between 70 and 82 %. Temperature measured inside the chapel did not suffer significant differences, assuming values between 22 and 24 ºC, whereas the temperature measured on the walls surface was fixated on 21 ºC. According to (Henriques, 2001), for these values of relative humidity and temperature, water condensation on the walls is possible to occur, for a temperature reduction to 18-19 ºC.

Figure 3 : Temperature measurements inside the chapel.

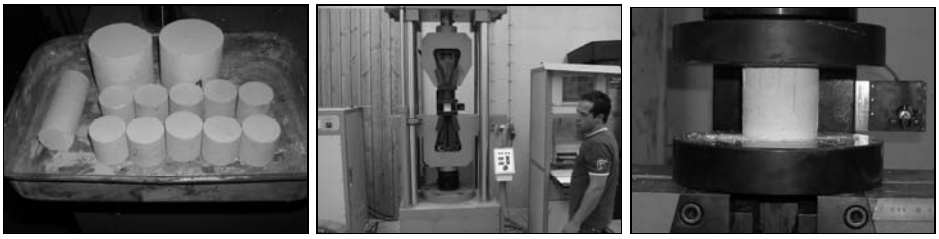
To analyse the state of conservation of the vault, three soundings were conducted at the base (Fig. 4a), followed by a visual inspection using an endoscope (Fig. 4b and c). The level of humidity was measured at the laboratory from samples obtained at different depths and varied between 9 and 12%. The material collected presented a viscous consistency and exhibited a bright color indicating the possible rocky origin.

It was not possible to analyse thin plates of the removed material since it did not present the necessary cohesion. For this reason, only a mineralogical analysis by X-ray diffraction of this sample was performed (Júlio et al. 2006). To obtain a reference for comparison of this rocky material with other in the chapel, a sample was removed from the main door pediment (Fig. 4d).

Figure 4 : (a) Sounding at the vault base; (b) and (c) Inspection with endoscope; (d) Collect of sample from the main door pediment.

Comparing samples it was possible to conclude that limestone of identical composition was present in both, composed by Calcite ($CaCO_3$), Quartz (SiO_2) and traces of clayey minerals. There was not found any salt in both samples. The macroscopic analysis of the samples allows to state that this material is a white limestone, dominantly oolitic.

Since it was verified that the stone material removed from different elements of the chapel – vault, walls, and main door pediment – are limestones of identical composition, it was decided to mechanically characterize this material by determining the compressive strength of samples obtained from healthy blocks placed near the chapel during the intervention in 2003 (Fig. 5a). Tests were performed with a universal testing machine (Fig. 5b and c), registering an average value of 58 MPa compressive strength.



(a) (b) (c)

Figure 5 : (a) Samples obtained from a limestone block; (b) and (c) Compression test of a sample.

The structural stability of the chapel was analysed with a commercial finite element software, considering the structure subjected to the static action of its dead weight and also when subjected to a seismic action, determined according to the Portuguese safety code (RSA 1983). Due to the objectives of the analysis and to the uncertainty in relation to important parameters such as soil and walls mechanical characteristics, a non-linear numerical analysis (Lourenço 2002) was not considered justified. Therefore, it was assumed a linear elastic material behaviour in this analysis. The structure was modelled using shell elements for walls; main altar vault; and nave roof; beam elements for columns; visible parts of the nervures of the main altar vault; and linear elements for the steel cables of the nave roof (Fig. 6).

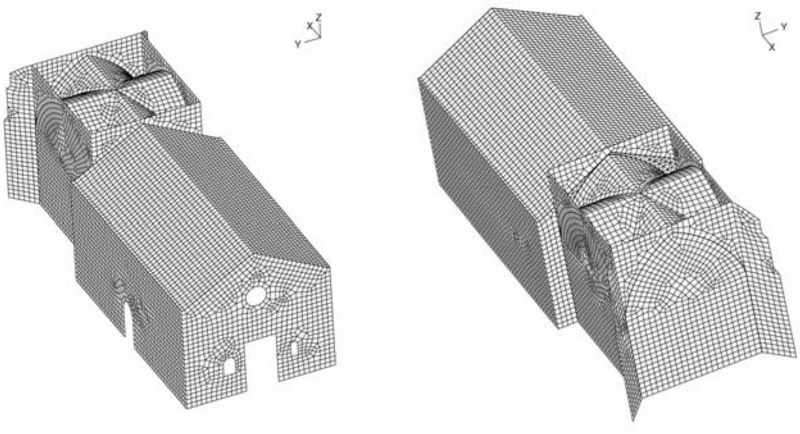
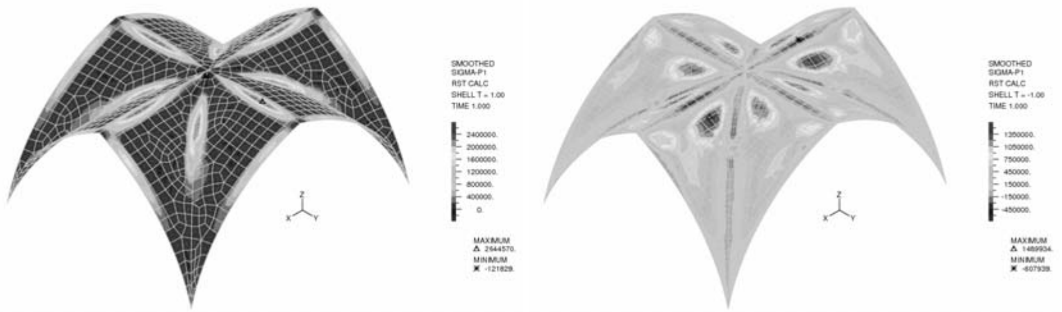


Figure 6 : Finite element model of the chapel.

The most conservative scenario was considered, corresponding to total lost of cohesion and strength of the stone blocks of the vault. Therefore, the analysis of the structural stability of the vault was performed only considering the cement based mortar, covering the intrados of the vault with an average width of 30 mm, and the visible part of the stone nervures as structural material. As support conditions of the structural model, it was assumed that all displacements of ground nodes were restricted and all rotations were free.

The structure response was analysed for its dead weight acting alone and for the combination of this action with the seismic action. The latter has been considered separately according to the three directions of space, N - S, E - W and vertical, associating to the seismic action acting in each direction adequate percentages of the seismic action acting in the remaining directions. In this analysis the actions were assumed with nominal values, i.e. not affected by partial safety coefficients. Therefore, results can not be interpreted as an ultimate limit state situation but corresponding to a possible short duration occurrence during the structure life-time.

Results, in terms of principal stresses, obtained from the static analysis, i.e. considering the isolated action of the dead weight of the structure, indicate that the level of stresses is, generally, of small importance (Fig. 7). In the case of the highest compression stresses, of approximately 2.5 MPa, this can probably be assured by the mortar layer. However, for the maximum tension stresses, the registered value of 1.5 MPa, especially at the intrados of the vault, should indicate cracking that can not be observed, until now, in place. This fact leads to the conclusion that, in spite of the high level of degradation of the stone blocks of the vault, the self-sustaining capacity of the latter is, so far and somehow, assured. It should be noted that, however, if a decrease of strength and of cohesion of the stone blocks is registered, due to an evolution of the degradation process and/or the change of the conditions of temperature and relative humidity, it will be predictable a progressive disorganization of the mortar layer with eminent collapse of the vault.



(a) (b)

Figure 7 : Principal stresses σ_1 at the vault - (a) outer faces; and (b) inner faces.

At the envelopes of principal stresses, σ_1 and σ_3, for the combinations of actions considering the seismic action, it can be observed, as expected, significant increase of the maximum values of tension and compression principal stresses comparing to the situation of isolated action of the vault self-weight. For instance, it can be observed that tension stresses of around 5 MPa can occur at the inner layer of mortar, which, evidently, can not be resisted by this material.

6 DIAGNOSIS OF THE STATE OF CONSERVATION OF THE VAULT

Based on the inspection performed, as well as on the elements given by IPPAR, it is possible to conclude that the chapel was subjected to rain water infiltrations through the nave roof and the vault of the main-altar during long period(s) of time. The geophysical study indicates that the chapel is erected on a little permeable ground, facilitating the accumulation of rain water at the surface, which is favourable to the presence of rising damp by capillarity at the chapel walls.

The cement based mortars, applied in previous interventions on the walls and on the intrados of the chapel vault, contributed probably to prevent these elements to expel the water infiltrated or adsorbed. The removal of this mortar layer from the walls and the subsequent substitution by a lime based mortar, during the most recent intervention, explains, due to its constitution and its higher permeability in relation to the cement based mortar, the presence of the salt efflorescences protruding from these surfaces.

With the geologic study it is possible to conclude that the limestone of the degraded blocks of the vault is identical to that used in the main door pediment and that of the healthy blocks removed from the chapel during the last intervention. The mechanical characterization of the stone material, carried out with compression tests on specimens extracted from a healthy block, indicated that the average value of compressive strength is approximately 58 MPa. It was not possible to determine the compressive strength of the degraded blocks of the vault because of their reduced consistency that turned unviable the extraction of specimens.

The numerical modelling of the structural behaviour of the chapel, subjected to the action of its dead weight, was performed assuming the most unfavourable situation: null strength and cohesion of the vault blocks, i.e. considering only the nervures and cement based mortar layer with 3 cm of width as structural elements. From the maximum values of tension in the mortar layer of the intrados of the vault and taken into account the inexistence in situ of these, it is licit to conclude that: (1) the vault has not reached yet the extreme state considered, still having, at least, part of its self-sustaining capacity; this situation is confirmed by the written elements given by IPPAR, referred to the last intervention performed, where it is mentioned that part of this mortar layer was removed and the collapse of the vault has not occured; (2) in the case of changes in the hygrothermic conditions of the vault, the state of degradation of the stone can develop and approach a critical situation, i.e. a decrease of strength and cohesion of blocks can occur reaching the limit situation assumed in the numerical simulation, which would imply the collapse of the vault. From the dynamical analysis, it also results evident that the stress increase introduced by an intense earthquake will imply the collapse of the vault.

7 INTERVENTION PROPOSAL

It has been proposed, on a first approach, the opening of “windows” to perform a visual inspection on the cement based mortar of the intrados of the vault, allowing to characterize the general state of degradation of the stone material, followed by soundings, including the observation with endoscope, to evaluate the state of degradation in depth and also the extraction of samples to be analysed in laboratory.

On a second phase, if proved that degradation is not superficial, nor localized, the consolidation of degraded blocks is unviable. In this case, as in other cases (Macchi 2003), alternative solutions must be confronted: (1) addition of a strengthening structure; or (2) substitution of the existing structure. The first solution does not appear to be the best for several reasons: (a) the degraded material would remain in the structure and, due to the level of moisture still present, it would continue to cause the occurrence of humidity spots and efflorescences; (b) substituting the cement based mortar layer by a lime based mortar, the degraded material could loose the already reduced cohesion and, consequently, it could become acting like a load instead of acting as a structural element; (c) last but not least, the simple aesthetic of the gothic chapel would become seriously menaced to assure the reversibility of the strengthening structure, a condition actually generally accepted as essential in the case of interventions on monuments (ICOMOS 2003).

In the case of generalized degradation of the stone, at the surface and in depth, the substitution of the blocks of the main-altar vault is, in this case, the correct option, i.e. the one that best safeguards the monument.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude to: Professor Fernando Henriques (UNL), for his comments concerning the correct conservation methodology; Professor A. Elena Charola (WMF) and Dr Delgado Rodrigues (LNEC), for their remarks related to stone consolidation; and to Eng.ª Margarida Lagarto, for her collaboration by compiling all relevant elements concerning the last intervention performed at the chapel.

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