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Structural Damages in the S. Francisco Church (Évora-Portugal)

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ABSTRACT: The gothic church of S. Francisco in Évora (Portugal) shows, along the vault of the nave and on the façade, significant full thickness cracks inspiring insecurity in the users and concern among the responsible institutions. The phenomenon is not new since it was detected and described in the 19th century. According to historical information, the cracks on the vault were repaired and reappeared years latter. The localization, dimension and extension of the present cracks are similar to those detected in the 19th century. Numerical analysis, using linear and non-linear finite element models, enabled to reproduce the phenomenon and the cracks seem to be due to the widening of the distance between the vault supports. A finite element model with interfaces modelling the existing cracks showed that the structure has found, after the occurrence of cracking, a path for stresses which guarantee its equilibrium. Nonetheless, despite this interpretation of historical and numerical data, it is essential to understand if the structure is moving and the crack widths increasing. For that purpose, a monitoring system with temperature and humidity sensors and displacement transducers was installed and a rigorous geometric survey of part of the building was executed. The paper describes the studies for the diagnostic and the monitoring system.

1 INTRODUCTION

1.1 Building description

The church of S. Francisco in Évora, one of the most important Portuguese monuments, was built in the 15th century over a previous gothic church from late 13th century. Although different alterations have occurred, the original magnificence of the building was not lost. This is manly due to the dimensions of the single nave covered by a gothic vault. The building is oriented in the West-East direction, with the main entrance facing West. The main gothic vault surface is intercepted close to the supporting walls and between arches by orthogonal secondary surfaces (double curved surfaces) (Fig. 1). Six arches or vault ribs divide the nave into six bays (each one corresponding to a pair of chapels) and a transept. The vault is supported by granite columns and massive double longitudinal walls connected by transversal (buttress) walls and buttress vaults. Granite was used for the columns, arches, ribs, internal longitudinal walls and in the lower part of the transversal walls; rubble stone masonry with lime mortar in the other walls; and marble for ornamental elements. The vault is made of brick masonry with the inner face covered in lime plaster painted to resemble stone masonry.

1.2 Structural damages

The S. Francisco church in Évora shows, symmetrically, along the nave, full thickness cracks in the intrados of the vault (Fig. 2 and 4). An extension of these cracks is visible on the façade, where two symmetric cracks could also be seen (Fig. 2). The vault cracks (in the doubled curved surfaces, near the longitudinal walls), and on the façade (on both sides of the central opening) were detected in several inspections during the 19th and 20th centuries [LNEC 1998] and seem to have a slow evolution. The most important historical document about the building damages is a 1884 report by the civil engineer Adriano da Silva Monteiro, describing the cracks which are visible today. According to this report the cracks were already visible in 1834, before to the repairing works of 1860 done by a British architect, John Bouvie Junior. During these works the plaster of the inner face of the vault was repaired and the present appearance, with painted joints to resemble block masonry, is apparently of that time. In July of 1876 Adriano Monteiro did his first inspection and detected the vault cracks which had apparently been repaired by John Bouvie. In May of 1884 he verified no evolution on the width and length of the cracks and stated that there were no signs of threatening danger. However, he recommended to follow the evolution of the phenomenon and to reconstruct the cloister close to the church's south external wall. This recommendation was intended to increase the lateral bracing of the church, since he believed the vault fracture was connected with the outwards movements of the church's external walls. None of the recommendations were not followed and the cloister was completely demolished years later. According to the Adriano Monteiro's report, the existing cracks on the inner face of the nave vault and on the façade, and the cracks detected two hundred years ago have similar localization and dimensions. He also described cracks, aligned with the vault cracks, in the external loading walls which were demolished in 1937 during works on the church's roof (Fig. 3).

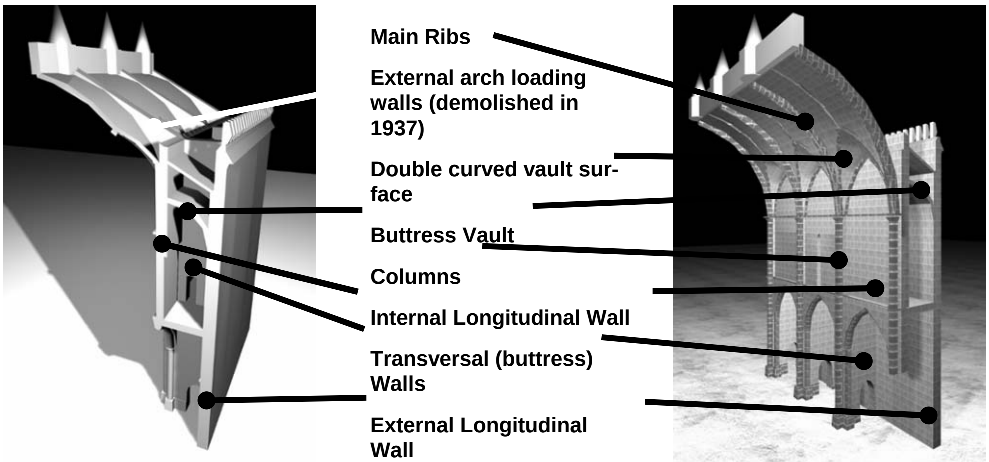

Figure 1 : S. Francisco Church in Évora – Building description

The plaster near the vault cracks exhibits signs of a reparation (Fig. 4), which was apparently done after the 19th century inspection. After this repair the cracks reappeared. In the same way, the façade cracks repaired in 2001 are reappearing today. According to the historical data, the phenomenon seems to be due to the reactivation of old cracks and not to the formation of new ones. On the other hand, since they correspond to those described in the 19th century this suggests a stabilisation of the cracks after some dimension has been reached. Despite this interpretation, it is essential to understand the origin of the phenomenon and to know what is happening on the building. Is the structure moving? Are the crack widths increasing? For that propose a monitoring system was installed, with displacement transducers, in order to record any possible movement of the structure.

2 NUMERICAL MODELS

2.1 *Preliminary finite element models with elastic linear behaviour*

For a first approach, in order to identify the general lines of the structural behaviour, simple numerical models and few material variables were used: a simple linear elastic finite element model with curved shell elements (Fig. 5). As shown later, this model was able to qualitatively simulate the structural behaviour of the vault and allowed the understanding of the origin of the cracks. In order to reduce the number of degrees of freedom, boundary conditions appropriate to simulate the apparent symmetry of the structure were used. A vault module with pin connections at the base was first analysed (Model I in Fig. 5). The objective was to investigate if the origin of the cracks could be related to the simple behaviour of the vault under self weight. The distribution of tensile stresses obtained [Gago&Lamas 2001] suggests a crack pattern different from that observed in the building. This led to the conclusion that the cracks did not appear as a consequence of the structural behaviour of the vault itself.

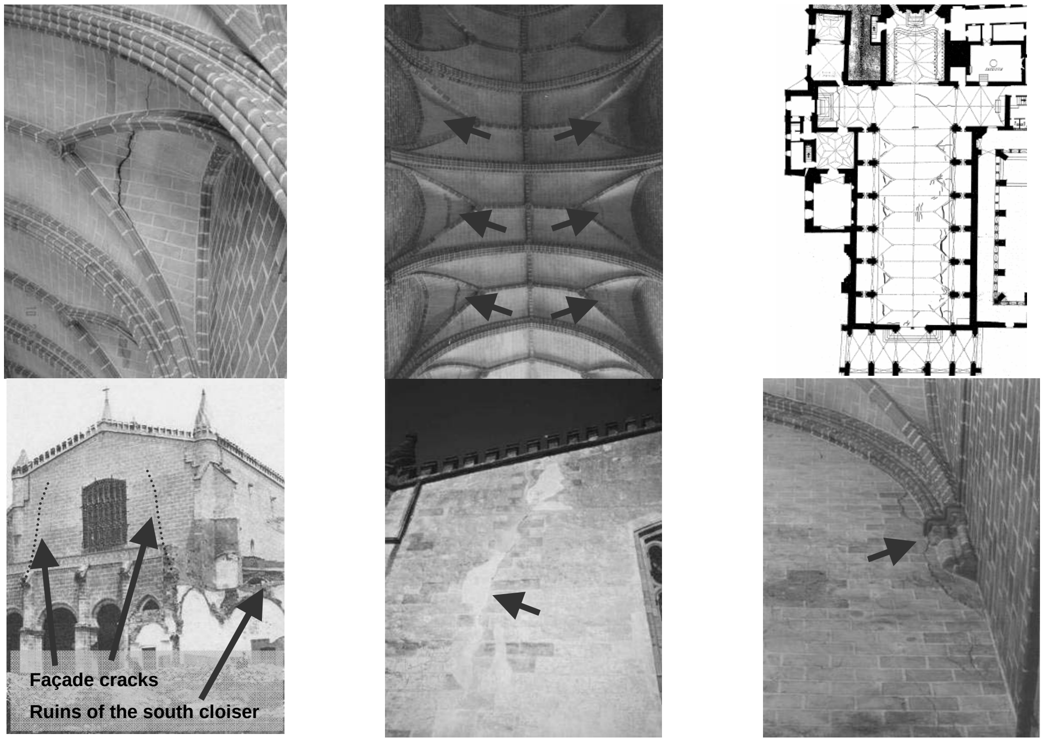

Figure 2 : Top: cracks in the nave vault; Bottom: cracks in the façade [left: view of the church during the works in the square in front (1873) where the façade cracks and the ruins of the southern cloister can be seen; centre: external face of the façade wall in 1998; right: present internal view of the façade].

Figure 3 : Views of the church's roof [left: old view with the external loading walls; centre: works during 1937; right: present view]

A second finite element model of the vault and the vertical adjoining structure was then analysed (Model II in Fig. 5), assuming pin supports at the base of this structure. The consideration of the deformability of the vertical structure results in a stress distribution with high tensions developing in directions in agreement with the observed crack pattern. This indicates that an outwards movement of the supporting structure can produce tensile strains on the upper face of the vault and generated cracks. Since the compression stresses on the lower face of the vault are parallel to the cracks, they do not produce any restriction to crack opening, and so the cracks can propagate from the upper to the lower face. This mechanism of crack generation is similar to the mechanism described by Heyman for "Sabouret" cracks [Heyman 1996]. If the cracks were formed on the extrados of the vault and propagated to the inner face, crossing its thickness, wider cracks should be visible below the roof covering. This was confirmed when the roof over the area of the biggest crack in the vault (about 6 cm wide) was partially uncovered. In fact, after removing the tiles a large crack, about 12 cm wide, crossing completely the vault thickness, was visible (Fig. 6) confirming the described assumption.

Figure 4 : Details of the cracks in the inner face of the vault, where signs of previous reparation of the plaster (darkest areas) can be seen.

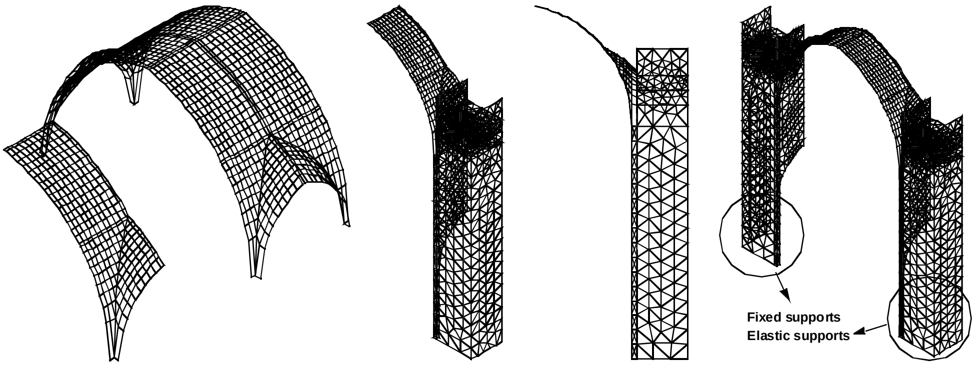

Figure 5 : Preliminary finite element models with elastic linear behaviour [Gago&Lamas 2001]. Left: Model I; Centre: Model II; Left: Model III

Figure 6 : Crack on the external face of the vault

Although the cracks are visible on both sides of the vault along the nave, the cracks on the South side are slightly more pronounced. To understand this difference a complete model with fixed supports on one side and elastic supports on the other was analysed (Model III in Fig. 5). It shows that the tensile stresses are much higher on the side near the fixed supports, indicating that asymmetry in the stiffness of the soil foundation or in the stiffness of the vertical wall can produce asymmetry of the crack pattern. The comparison between the small asymmetry of the existing crack pattern with the strong asymmetry of the results obtained with this simulation makes less credible the hypothesis of differential settlements between the North and the South walls.

Once a possible origin of the cracks was found, the safety of the structure remains to be assessed. For that purpose, a simple linear model with an artificial joint along the zone where the cracks are visible was analysed [Gago&Lamas 2001]. According to this model the stability of the structure does not seem to be compromised by the presence of that joint, which only perturbs the path of the compression stresses.

2.2 Non linear finite element models

After a first set of numerical simulations with the linear elastic finite element model, two more sophisticated models were analysed. They assumed the masonry to be non tension resistant using a multi-directional fixed crack model with tension softening and shear retention. In the first model triangular curved shell elements were used [Gago&Lamas 2003] and in the second pyramidal solid elements [Apostolov et al. 2005]. To build the mesh, as it happened in the linear elastic model, the geometry data obtained from drawings in public archives was used. A rigorous geometric survey performed later [Falcão 2005] confirmed that the disagreement between the drawings and reality, is not sufficiently expressive to invalidate the models. In booth models, the existing external loading walls over the arches, demolished in 1937, were considered and a representative part of the vault was analysed, using appropriate boundary conditions to simulate the remaining structure.

To corroborate the interpretation that the cracks are due to the widening of the distance between the vault supports, horizontal displacements with a linear distribution in height were imposed in the shell model, to simulate a rigid body rotation of the vertical supporting structure around its base. The results (Fig. 7) showed damages in the connection between the vault and the wall for small rotations of the longitudinal wall. As it can be seen in Figure 7, those damages were also detected during the inspections. Increasing the lateral displacements, a progressive redistribution of stresses occurs and damages appear on the upper face of the vault, on the external loading walls and, finally, on the lower face of the vault. The maximum horizontal displacement imposed to the model was 10 cm. During the first inspection (using a crude method) a 10 cm vertical displacement of the top of the southern external wall was measured. This magnitude corresponds to a wall average inclination of 0.4%, which is consistent with that detected during the rigorous geometrical survey. Although the finite element model did not consider second order geometrical effects the results are sufficiently accurate from a qualitative point of view, namely for the prediction of the damages (location, relative intensity and development), and can be used to explain the building behaviour. As it can be seen in Figure 7, the damages simulated by the model and the present visible cracks have similar locations, confirming the preliminary diagnosis: the cracks are due to the increasing of the vault span and they have appeared first on the upper face of the vault and later propagated to the lower face.

In the solid finite element model a representative part of the structure was simulated (Fig. 8), considering for the different parts (rubble masonry, ashlar granite masonry) different mechanicals characteristics. Non linear behaviour (non tension resistance) was only assumed in the vault elements. The results (Fig. 8) have confirmed those of the previous models: cracks on the upper face of the vault appeared when 30% of the self weight was applied, confirming that this load has an important role in the initiation of cracking in that area. As happened in the previous non linear finite element model, with the increment of the dead load the cracks on the upper face of the vault spread to the lower face and damages on the external loading walls appeared.

3 GEOMETRIC SURVEY, INSPECTION AND MONITORING SYSTEM

The numerical models were built using geometric information obtained from drawings, which could have some differences from the real structure. On the other hand, regarding the preliminary diagnostic, it was important to measure the inclinations of the columns and walls. A rigorous geometric survey of the building was consequently executed and marks were positioned to topographically follow eventual building movements [Falcão 2005]. The topographical geometric survey detected disagreements between the drawings and the reality, namely in the orthogonality of the nave (Fig. 9). However, the detected differences in the dimensions are not sufficient to compromise the validity of the numerical models. The topographic measurements indicate an average inclination (outwards) of the longitudinal walls around 0.5%. The geometric survey is being interpreted but the available results suggest an outwards movement of the longitudinal walls, as predicted by the numerical models.

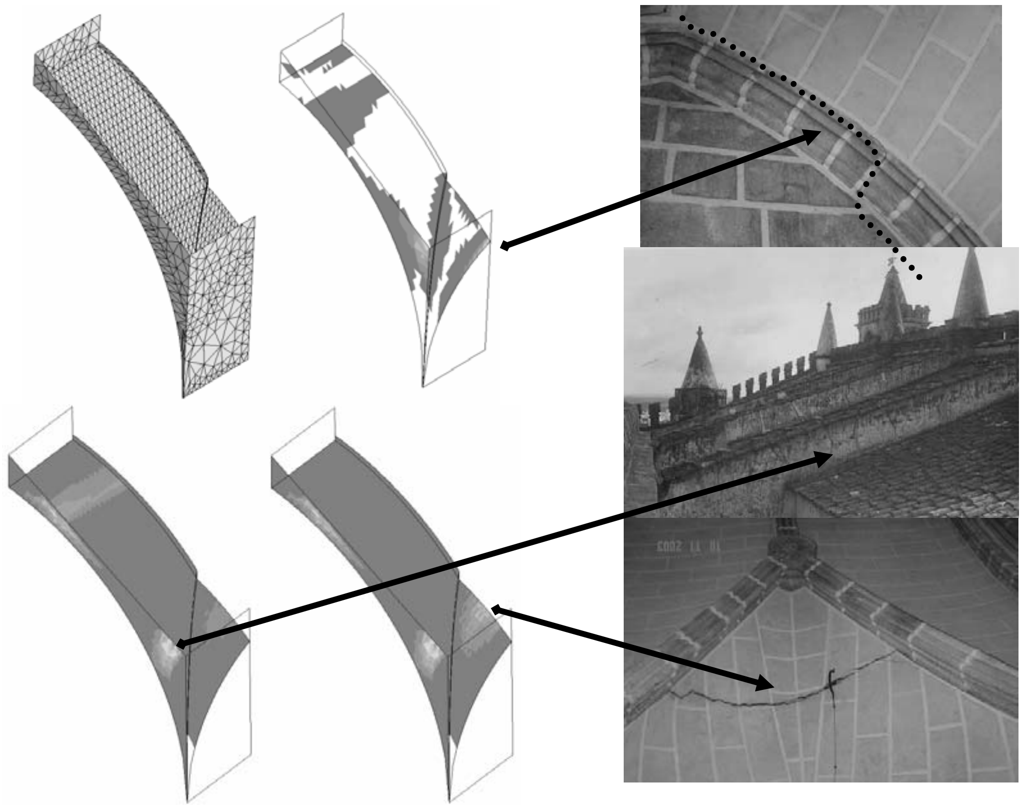

Figure 7 : Non linear finite element model with curved shell elements. Top: finite element mesh (left), damages on the lower face for a low level of imposed horizontal displacements (centre) and damages in the connection between the vault and the vertical wall (right). Bottom: damages on the upper face (left) and on the lower face (centre) for an imposed 10 cm top displacement and cracks on the roof walls and on the vault intrados (right).

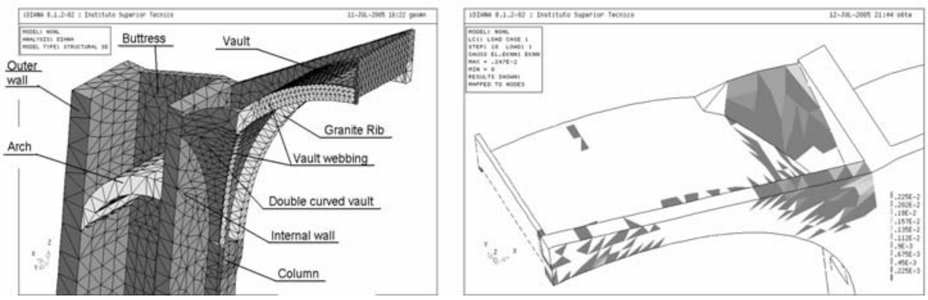

Figure 8 : Non linear finite element model with solid elements. Left: finite element mesh Right: damages on the numerical model [Apostolov et. al., 2005].

Although historical information indicates a slow evolution of the phenomenon, it is important to confirm if the cracks are or not increasing. For that purpose a monitoring system was placed in the building. During the installation of the displacement transducers, using a special platform (Fig. 9), a detailed survey of the intrados vault surface was done. The cracks were measured, photographed and filmed and the crack pattern recorded in sketches. Each crack in the inner face of the double curved vault, as well as the façade cracks, was instrumented with a displacement transducer (0.1 mm precision). Five devices to measure the temperature inside the walls (10 mm deep) and 4 devices for registering the environmental temperature and humidity were installed at different levels of the church. The system is connected to two data loggers which can daily record the readings. The first results indicate a reduced level of deformation, which can point to a stabilization of the phenomenon. However, the recording must be extended to a longer time period in order to dissociate climatic influences and have secure conclusions.

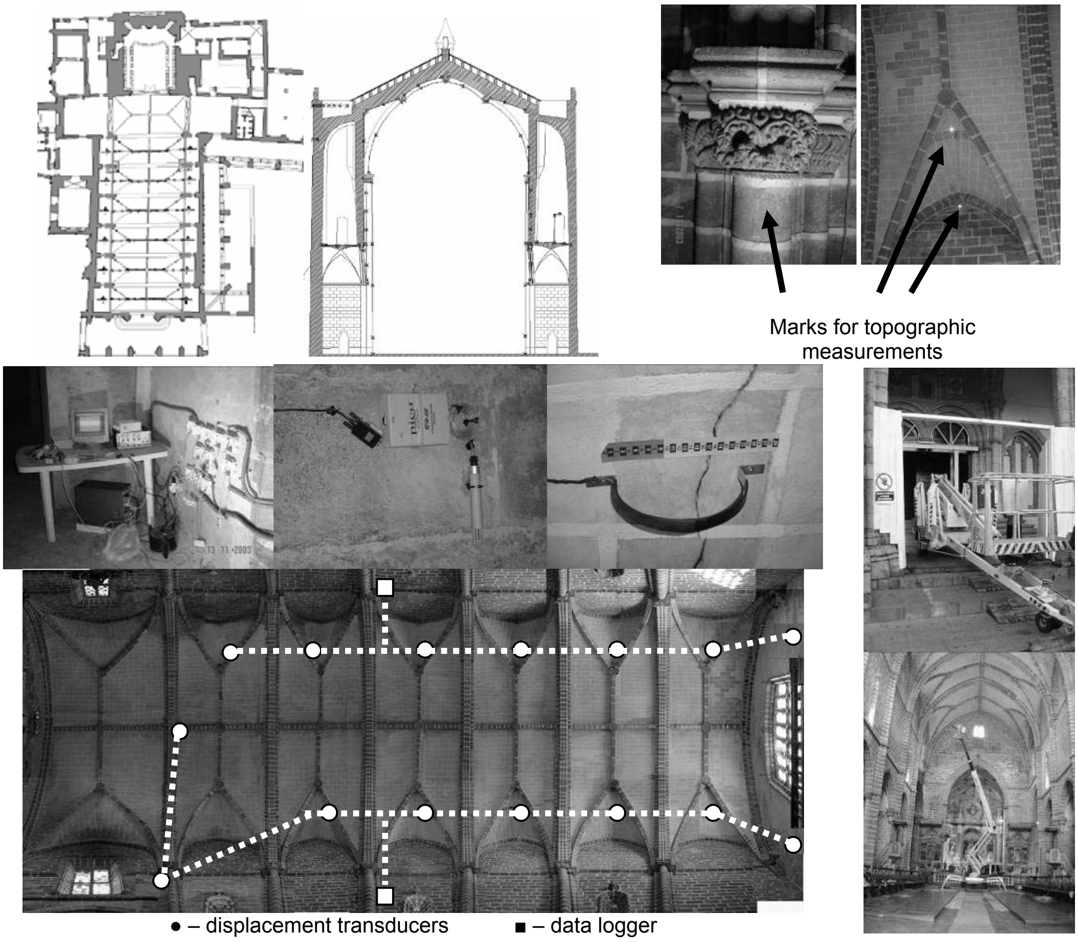

Figure 9 : Survey of the S. Francisco Church. Top: drawings of the geometric survey and topographic marks; bottom: monitoring system and platform used for inspection and installation.

4 DIAGNOSIS

The numerical models show a connection between the cracking phenomenon and the widening of the vault span, due to the vault's horizontal thrust, confirmed by the geometric survey which indicates an outwards inclination of the longitudinal walls. This can be due to the deformation of the vertical structure or to soil consolidation under the foundations. On the other hand, the cracks are less visible near to the transept (Fig. 2), where massive transversal walls limit the horizontal movement of the vault's supports, and more visible in the middle part of the nave, where the transversal bracing is less effective. They are again less visible near the main entrance, where the façade wall limits the horizontal movement of the supporting structure. Near to the façade crushing cracks on the vault crown are visible (Fig. 10). All this can be explained by an increasing of the vault span. It is possible that tension stresses in the upper face of the vault were generated in the first years of the building, when the scaffolding was removed, or years latter, due to the consolidation of the soil foundation and creeping of the vertical structure. However, the first report of the crack phenomenon dates about 3 centuries after the building's construction and there is no information about previous interventions related with these damages. In the beginning of the 19th century the building and the adjacent constructions were abandoned and highly destroyed. Particularly the constructions contiguous to the North and South longitudinal walls, which certainly contributed to their lateral bracing, were in an advanced state of ruin. As a consequence, Adriano Monteiro recommended the reconstruction of the cloister near to the South wall as a measure to avoid the aggravation of the vault damages. Instead, it was demolished, as well as other buildings adjacent to the North wall. This may not have initiated the cracks but by reducing the lateral bracing of the church it has contributed to their widening and propagation from the upper to the lower face of the vault. The cracks became probably visible in the vault intrados at that time. In the numerical models it is well shown that compression stresses appear parallel to the crack direction on the lower face of the vault. Filling the cracks with mortar does not change the stress paths and the cracks continues to behave like a joint. After some years, the structural movements (due, for instance, to temperature and humidity changes) make the filled mortar to separate and fall from the edges of the crack, and the crack reapers. This is the possible interpretation of the reappearance of the cracks some years after having been repaired.

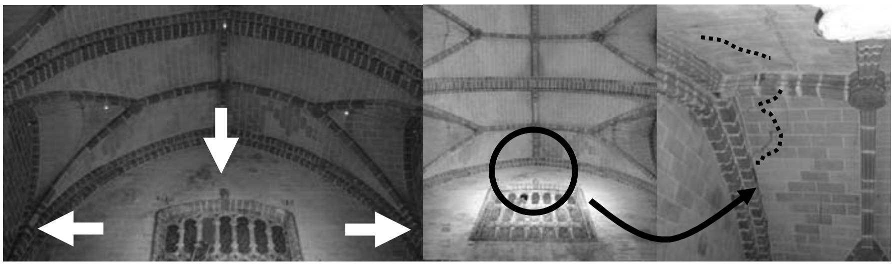

Figure 10 : Crushing of the vault crown due to the vault spam increasing.

5 CONCLUSIONS AND FURTHER WORK

The results of the monitoring system will allow a more solid interpretation of the evolution of the phenomenon. The remedial measures to be implemented are dependent of these analyses. If the phenomenon shows any sign of evolution a drastic intervention should be taken. In any case, the reinforcement solution has to prevent the vault span from increasing, and tie rods (connecting the bases of the main arches of the vault) seems the more effective solution. It has a limited esthetical impact and will confer a better structural behaviour for vertical and horizontal loads.

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