

Case Study of the Cathedral of Aveiro - Defects, Structural Analysis and Rehabilitation Strategies

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Abstract

This paper is a result of a dissertation developed with the main objective to study the interaction, defects and constraints that arise from the solutions of different construction periods and technology, particularly when dealing with constructions of architectural and heritage importance.

The Cathedral of Aveiro was the case study used throughout this research, since during almost six centuries of its existence it has suffered several accidents (due to natural hazards) and constructive interventions (alterations, expansion, etc.). The structural solutions adopted within the interventions over time accompanied the evolution of the construction technology from masonry stone, wood and iron structures to recent reinforced concrete.

Within the research several tasks were carried out: i) gathering of historical and chronological information on the several interventions on the Cathedral (natural phenomenon, suppression and growth of parts of the structure); ii) recording and diagnosis of the main construction defects of the building, organized and subdivided, whenever possible, by materials and construction period; iii) analysis of simplified numerical models of the structures, with resource to finite element method.

Due to the dimension of the Cathedral structure and to the diversity of existent structural typologies, smaller local models were used to interpret and understand different problems for the roofing system, masonry walls, etc. For each particular structural model, results attained in terms of displacement and tensions are presented and discussed. From the analysis, alternative solutions for structural retrofitting and strengthening are also proposed.

Keywords: pathology, defects, rehabilitation and strengthening

1. Introduction

1.1 Description of the building

Aveiro Cathedral (Sé Catedral) has been classed as a Building of Public Interest since 1996 and it has undergone several interventions, accidents and extensions during its lifetime.

It consists essentially of three sections of different ages: the central nave, the church tower and the altar. The central nave dates from 1423. It is built in traditional stone masonry with a wooden covering structure. The church tower is 19th century and built in traditional stone masonry. The altar is 20th century (1976) and is constructed of reinforced concrete.



Figure 1: Frontal view (left) and lateral view (right) of the Sé Catedral de Aveiro.

Initially the cathedral was divided into three longitudinal naves by two stone walls. During the 16th and 17th centuries lateral naves were subdivided by buttresses, which created the devotional chapels we see today.

In the mid 17th or 18th century oval openings were introduced into the longitudinal walls of the central nave and the roof was also altered.

In 1843 a fire and an explosion of a storeroom reduced the convent to ruins. The cathedral survived this explosion. The high choir and the bell tower were built in the 19th century. A new presbytery was built and the front of the cathedral was changed during the second half of the 20th century.

1.2 The motivation

In 2000 the building presented several constructive abnormalities. These were mainly in the cladding/coverings and due to the lack of maintenance and the inefficient solutions used for the

interface of the constructions built in the 15th century and those built in the 20th century. These abnormalities led to the appearance of other pathologies, both structural and thermal.

The structural pathologies in the vertical elements worsened with the construction of a road tunnel that was built parallel and less than 10 metres from the cathedral, which changed the course of the water within the foundation soil.

2. Description and analysis of the problems

This chapter will detail the main pathologies observed in the building. Figure 2 presents a plan with the location of the different areas of the building where the main problems were observed.

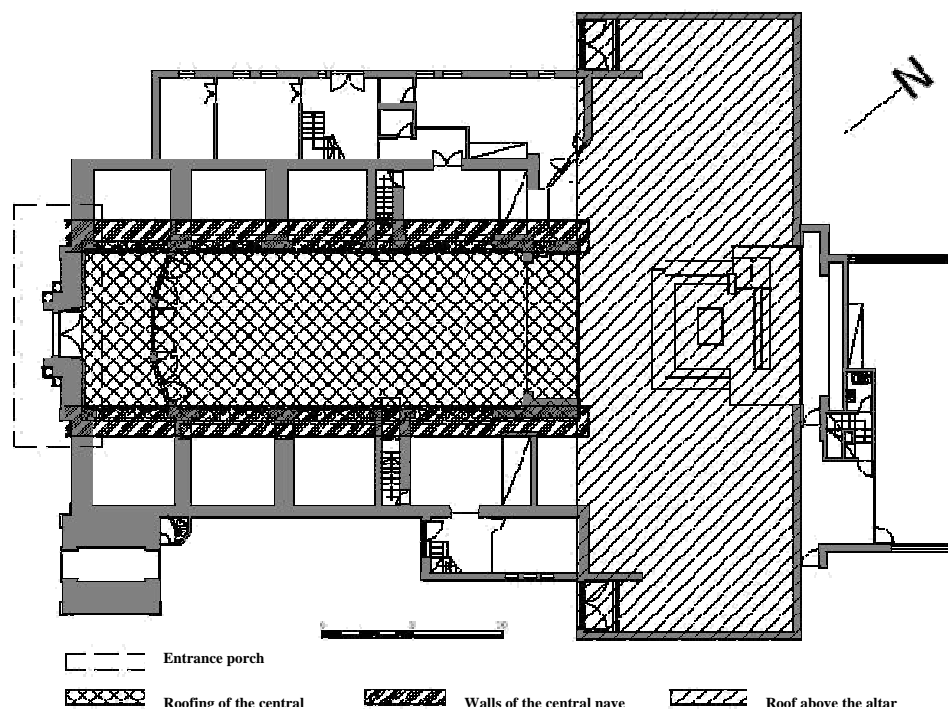


Figure 2: Plan of the building Roof above the Altar entrance porch

A) Roofing of the central nave

The roofing structure of the central nave consists of two timber trusses that support a timber platform. The platform and its support bars were seriously affected by xylophagous attack, as shown in Figure 3 and so they had to be completely replaced.

The xylophagous attacks were less serious and more sporadic in the shear bars and some cracks running parallel to wood fibres could be seen. The attacked zones of these bars were treated and all the elements exhibiting cracks were girdled with metal straps. The straps were introduced during

maintenance work and treatment of wood trusses (Figure 4). The supports of the shear plates showed no signs of decay, so it was not necessary reinforce or replace them.



Figure 3: Loft of the covering of the central nave (XV century). Distortion of the base of the shear



Figure 4: Metal straps

Some parts of the upper side of the platform had lost the stucco finish and from time to time we could see some decay caused by water infiltration. Some pieces of the timber roof had suffered slight xylophagous attack.

B) Walls of the central nave

Both of the longitudinal walls of the central nave had interior vertical cracks located between the top of the arcade and the bottom of the oval openings, (see Figure 5). There was a diagonal crack above the high choir door.



Figure 5: Vertical cracks in the interior face of the central nave wall

The outer face of the wall had no paint. Part of the wall between the top of the oval opening and the cornice had vertical cracks and exhibited weakness in the upper arches. The fixation zone of the stretcher in the outer face of the walls had several cracks and the mortar had detached, as shown in Figure 6.



Figure 6: External envelope of the central nave.

C) Entrance porch

Some damage was found in the masonry mortar bed joint in the stonework of the entrance porch, and because of that there are gaps and cracks in the stones' finishing mortar. There was some other damage in the sculpted stone.

Those constructive anomalies in the petrous elements of the stonework can be triggered by the structural movement of the building as it constantly adapts to the foundations.

Various pathologies associated with several elements of stonework could be seen. These could be caused by atmospheric pollution, biological colonisation and to actual aging.

D) Roof above the altar

The roof of the altar is formed by two 0.15 cm thick slabs of prestressed concrete beams with ceramic tiling supported by inverted beams 11.60 metres long with a section of $0.30 \times 1.20 \text{ m}^2$. The two beams of the central porch support two other transversal beams. Those two transversal beams support a reinforced concrete structure shaped like an inverted box. This is 1.35 metres high with slabs and walls 0.20 metres thick. The upper slab has an oval opening in the centre that supports a conical wall made of solid brick which also supports a metal and glass dome.

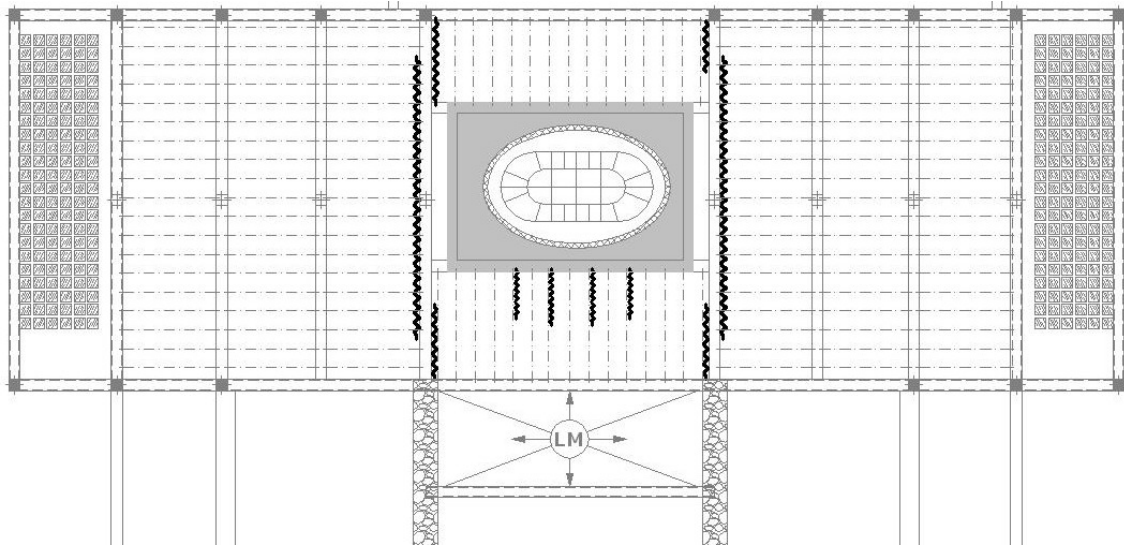


Figure 7: Structural pan of the roof above the altar - indication of the cracked areas

There were some longitudinal cracks at the point where the slabs and the two beams of the central porch intersect, near the lower edge of the beams, as we can see in Figure 8. Those beams exhibited considerable deformation and we could see that the area of their longitudinal framework is around 44% less than the area needed (66.03 cm^2) to withstand the applied forces.

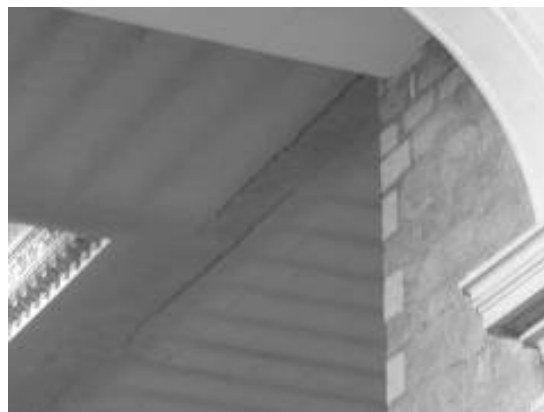


Figure 8: Roof above the Altar (XX century)

3. Assessment of structural safety

The overall assessment of the structural safety was carried out for different structural elements by resorting to numerical simulation using the finite element method. The timber roof structure and the massive masonry stone walls simulation have produced valuable information, on one hand to interpret the structural problems, and on the other to support retrofitting strategies.

In respect to the behaviour of the roof system, the structure was simulated by essentially modelling the timber shear plates and structure of the arched roof (see Figure 9). The size of the structural elements was reduced by 1 cm for modelling purposes in order to account for the loss of strength due to the xylophagous attack. To take into account the loss of rigidity of the timber elements through aging or decay, the Young's modulus was reduced by 10% ($E=10\text{GPa}$; wood strength class D40)

The safety of the shear plate elements was analysed and verified for both the reduced section and the carbonised section (simulating fire attack). The sections of the legs of the shear plates, mainly in the zone between the purlin support and the shear line, presented compression stresses between 90% and 110% of its ultimate resistant capacity.

In order to reduce the excessive stress a strut and a tie-rod was inserted at the mid span between the purlin and the tie beam. This retrofitting action also reduces the shear's leg stress, however a slight increase in the tensile stress in the shear line is expected, although within the limit values.

Analysis of the timber structure of the arched roof showed that the stress values (tensile and compression) in the different elements is below the maximum allowed values, apart from one zone in the lower support of the vault. In regard to this situation it was proposed that any timber element that exhibited any weakness should be replaced or strengthened.

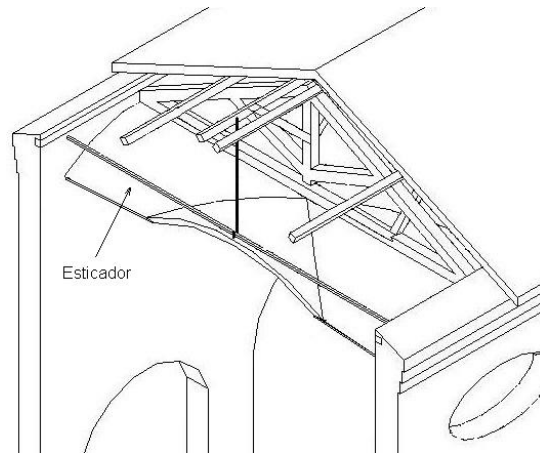


Figure 9: Structural scheme of the roofing system of the central nave

The longitudinal walls composition of the central nave is very heterogeneous. From the bottom up to a height of 2 to 3 metres they are constituted by irregular sandstone masonry. Above 3 metres the masonry is constituted by rubble stone, and there is less sandstone and the quality is poorer.

The upper part of the wall is built of only locally-available stone which is red sedimentary sandstone from the Eirol area, Aveiro. Black ballast stones were also used, that were originally used to stabilise merchant ships that sailed empty to Aveiro to be loaded with salt and ceramic products from the Aveiro region. The geological and mechanical characteristics of the ballast stones vary depending on where they came from (area of the docks).

With respect to the masonry walls, the results of the numerical simulation for a combined vertical load (self-weight and vertical live load) show that the tensile and compression stress levels are below the acceptable maximum (tensile = 0.1 MPa; compression = 0.9 MPa). The compressive stress values computed for the masonry walls vary from 0.4 to 0.6 MPa, less than the yield stress for the stone masonry, while the tensile stresses vary from 0.08 and 0.1 MPa, these values are very close to the yield stress limit computed, as shown in Figure 10.

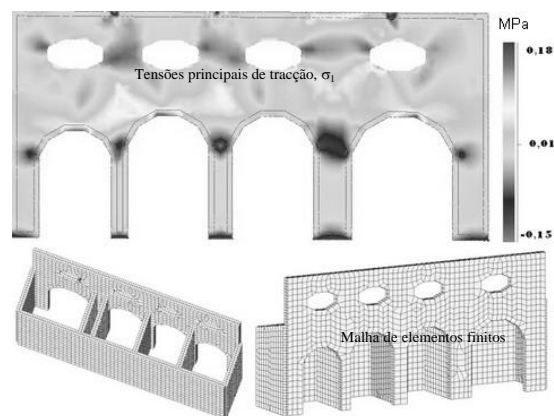


Figure 10: Structural model of the wall

In 2000, the tunnel recently constructed next to the cathedral opened to traffic (about 10 metres from one side of the cathedral). The construction work on the tunnel and continuous traffic could have altered the initial stress state of the foundations of the cathedral by lowering of the water level underneath the cathedral. This was caused by the artificial barrier created during the tunnel construction and continuous drainage through permanent pumping along the whole length of the tunnel. The underground pressure in the tunnel was thus kept low, avoiding the risk of uplift by the underground water level which might induce higher effective stress in the foundation soil. This phenomenon would have increased the settlements of the cathedral foundations nearer to the tunnel, causing to slightly tilt on the tunnel side. This problem has in fact occurred and been confirmed in many similar situations.

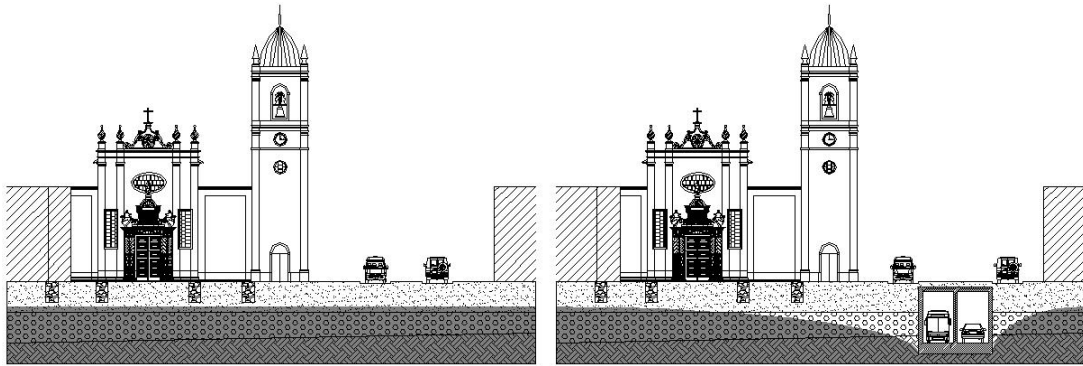


Figure 11: Geological profile

If, for the combination of vertical actions used to evaluate the stress state of the stone masonry walls, a small settlement of 1 mm is added to simplify the simulation of the potential effects of the tunnel construction, it was computed that the compression stresses installed in the walls increase to values close to the yield stress values for compression state of the masonry, while the tensile stresses computed exceed the yield stress limit (see Figure 7). The simulation also confirmed that, due to a possible settlement, a slight out-of-plane movement of the masonry walls can occur.

Therefore, the vertical cracking in the interior face of the masonry wall and in the area between the arch and oval window openings (see Figure 3) is originated by the construction of the tunnel was caused by the combination of high tensile stresses aggravated by the out-of-plane movement of the masonry walls.

At the end of the 19th century, the reception area of the cathedral and the high choir (entrance area) was built, as well as the side access to the bell tower. The masonry access to the high choir balcony was executed in stone, supported on the side chapel vaults and on the cathedral's front façade. The slab level of the high choir is below the top of the arches of the side chapels, so these were lowered as shown in Figure 8. This lowering is of aesthetic nature lead to the change of the Roman arch into a depressed arch, whose design made use of a timber partition system made of layered wooden boards that are rendered on the outside. The existing arches adjacent to the high choir were slightly damaged and concealed by a mortar layer.

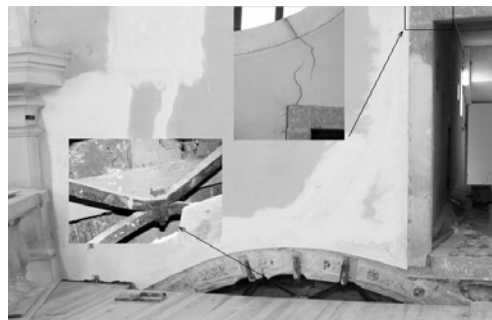


Figure 12: Demotion and structural reinforcement

During the maintenance works on the cathedral a structural reinforcement was found in the arch adjacent to the access to the high choir. This structural reinforcement consists of squared iron bars with a cross-section of about 32 mm fixed by 20 mm diameter screws (see Figure 12).

This structural reinforcement might have been built when the access to the high choir was built, or it may have been a later structural intervention to correct the deflection of the arch. This problem is still unsolved and continues to cause cracking. A first analysis suggested this deflection is caused by the progressive deterioration of the arch stiffness due to the creep of the iron structure and loss of the cross-section of the iron bars due to the corrosion over time. The typical cracking generated by the foundation settlements of a masonry wall can also be seen near the access door; it consists of diagonal cracks that initiate and spread from the corners of the door openings.

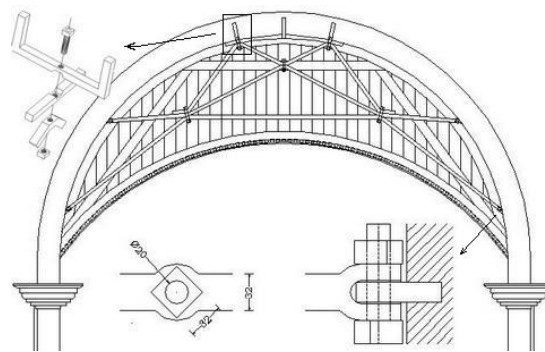


Figure 13: Structural scheme of the reinforcement of the arch of the lateral chapel

4. Hygrothermal behaviour of the cathedral

A simplified analysis of the hygrothermal comfort conditions of the cathedral was carried out. This study was confined to the cathedral's principal nave including the side chapels and altar. All these spaces are connected and considered as a whole zone for the purposes of the study.

The interior comfort conditions were ascertained by characterising the thermal properties of the external envelope and the interior surface coverings and renders. The construction elements that are responsible for the main thermal losses and which limit the interior thermal inertia were identified. These factors were used to define and evaluate the thermal discomfort felt inside the cathedral.

This simplified approach considers neither thermal losses through linear and plane thermal bridges, nor losses through construction elements (floor slabs) in contact with the foundations. These simplifications are justifiable since improvement measures (correction of thermal bridges) are very difficult to implement because they will affect the architectural authenticity; therefore the main principal is solely to identify and arrive at an overall appraisal of the thermal conditions.

The main thermal losses occur through the roofs, terraces and window glazing, which in total account for about 56% of the total thermal losses of the area considered and described above. Since this is a listed building and the major thermal losses occur through the roof, there is now an opportunity to intervene with thermal reinforcement of the roof without compromising the building aesthetics. The use of insulation on the vertical envelope would compromise the authenticity of the construction; therefore the roof is zone on which work can be done.

Applying thermal insulation (35mm of XPS) to the roof and replacing the glazing in the altar skylight reduced thermal losses by one third, leading to their more even distribution: vertical enclosure walls (34%); roof (35%) and window glazing (31%).

5. Conclusions

Some of the retrofitting actions described above in section 3 and 4 have taken place, however the overall assessment and defect analysis of the cathedral revealed that more attention should be given to the load-bearing masonry wall foundations of the masonry walls. The foundations should be thoroughly assessed and inspected; a mechanical characterisation of the masonry walls resorting to flat-jack testing to evaluate the in-situ stress state, as well as a dynamic identification is very useful.

Simple and immediate measures to control and monitor the building are desirable: installation of topographical targets so that the wall displacement, particularly the out-of-plane movements, can be measured over time; crack metres should be installed to measure and control important cracks to check their development so that changes in any tensile stresses and deformations that the wall might suffer can be estimated.

Any maintenance work carried out should both guarantee the watertightness of roof coverings and structural stability of certain areas, should also ensure the accessibility of these areas so that future inspections, cleaning and maintenance can be carried out safely.

This intervention should create conditions and guarantee the conservation of the cathedral - which is completing six centuries of existence. Its functional capacity should be fully restored and improved without significantly changing its materials and architectural features. It will thus continue to be a landmark in the history of the religious architecture of the city of Aveiro.

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