Remedial measures for the Cathedral of Porto: a post-modern conservation approach

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ABSTRACT: The present paper presents the works recently carried out at the Cathedral of Porto as a case study of a difficult intervention that challenges current recommendations for the architectural heritage. The historical information is briefly reviewed and the general conservation approach for the different works is addressed. Afterwards, the aspects regarding the strengthening of the towers are treated with more detailed and the diagnostics of a chapel, incorporating the usage of limit analysis for safety evaluation, is presented.

1 INTRODUCTION

The cathedral is not a beautiful building, it does not surrender to love at first sight. In fact, stronger feelings and emotions can only result from a comprehension of the building’s nature.

The works being carried out also fail to provide immediate adhesion. In the framework of a “restoration in continuity”, the works resemble a “no-intervention” or a sort of zero level of architecture. Nevertheless, the authors believe that such a superficial impression is erroneous. The intervention is rooted in options clearly belonging to the disciplinary field of architecture, with an approach that evolved as a result of the knowledge of the building and not an a priori posture. The vanishing appearance of the intervention is not equal to a facing approach, because several levels of remedial measures co-exist, and some of them are profound.

2 THE INHERITED BUILDING – FROM THE EVOLUTIONAL TO THE RETURN TO ITS ORIGIN

The origin of the building is the middle of the 12th century. In this period it is possible to witness the construction of cathedrals in the main cities, across Europe, as a token of a renewed confidence within the urban communities.

The settlement is conceived as an answer to a program that can be referred to as the church where the bishop celebrates, and where an elite of the clergies meet and advise their bishop in the administration of material and immaterial assets of the diocese.

For 800 years, the settlement was a repository of added parts. From this state of a continuous construction yard, the main fabrics are: romanesque and proto-gothic, gothic, renascence, mannerist, baroque, neoclassic, contemporary works from the first half of the 20th century and, finally, the present intervention.

Although the works until the end of the 19th century can be identified by the style and the building techniques, all of them possess a severe common transforming attitude, that is, they add, superimpose, rebuilt, change or render. While the campaign of the 20th century, which lasted from 1918 to 1938 and was carried out after expropriation and classification of the settlement as a national monument, did not aim at transforming the building, but at restoring it, as a sort of time regression, performed with works aiming at bringing back the original style – the medieval.

During this period, the country kept itself at a distance from the industrial progress of the rest of Europe and, between modernity and tradition, Portugal chose the latter. The Medieval Age and Art, celebrated in the official culture as ethical and aesthetical patterns, participated in the construction of the imaginary associated to the valuation of a national identity, being particularly exalted in the public building, built from scratch or restored when historical.

This ideal identity incorporated values such as austerity, purity and trueness, which were then attributed to the “Portuguese race” and were present in the Medieval Art, especially the Romanesque.

In the process of declaring an identity and pursuing their values, styles and periods of the historical buildings were mutilated. In particular, the contribu-
tions of the baroque and neoclassic were aimed at, because their decorative heritage was not in agreement with the “austerity” of the architectonical shapes and the “trueness” of the building materials.

Figure 1 illustrates some of the aspects of the Cathedral of Porto, before and after the restoration works of the first half of the 20th century.

2.1 The surroundings as a frame

After restoration of the building itself, also the surroundings were subjected to modifications. The narrow and labyrinth urban fabric that grew side-by-side with the cathedral was demolished, see Figure 2a. In its place a square was set up, see Figure 2b, and defined by straight alignments and monumental perspectives, see also Figure 2c, featuring a kind of frame aiming at isolating and stressing the importance of the monument, a syntax as inspiration to the way the cities were planned in the Illuminist period. The baroque was removed from the building but references to the baroque period were recreated in the surroundings, see the pillory in Figure 3. At the southwest limit of the square, a tower-house with medieval appearance was built from scratch in 1940, with the purpose of hosting the Museum of the History of the City.

![Figure 1](image1.png)
![Figure 2](image2.png)
![Figure 3](image3.png)

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Figure 2. Aspects of the restoration work in the surroundings of the compound, carried out in the first half of the 20th century: general view and plan (a) before and (b) after the works, and (c) detail of the narrow street and square in front of the main façade.

![Figure 2](image2.png)
![Figure 3](image3.png)

Figure 3. Details of the baroque pillory in the center of the square.

The scenic effect that resulted from the restoration produced a kind of representation of the past and the past in this way represented understated the representation. A kind of an alternative past or a commemorative allegory.

3 BASIS FOR CURRENT WORKS

3.1 The rehabilitation of the restoration as a program

The building, as it is found today, is hybrid and frozen in a perpetual past, where re-combinations or ar-
chitectural redesign seem hardly acceptable in the near future. It is with the signs of anomalies and the absence of formal borders that the memory of the building is found and that the violation of authenticity, which is lacking, is understood. This process of learning is also a process of increasing identification and love between the authors and the building. Only then, it is possible to understand that the fake self of the cathedral, as a result of the previous restoration, is today the real self of the cathedral, transformed into a monument. This is a forged identity that cannot be considered a minor representation of the strength of a specific cultural period.

Therefore, the governing thread of the program of the current intervention is to rehabilitate the restoration. The aim is to reactivate, rehabilitate and upgrade the competence, where competence is understood as the performance capacity of the structures, the materials, the shapes and also the space, assumed as a support for functionality.

The intervention in the building was organized around five operations: removal of infestations, consolidation, water-tightness, ventilation and protection. And, finally, also monitoring.

From the functional point of view, the use was strengthened, which can be summarized by more “cathedral” and less “museum”. In fact, several rooms had lost a meaning, either due to degradation or because they were changed into a kind of “museum” without a clear program, where loose artifacts of sacred art were exposed as an ornamentation of openings and empty spaces. Therefore, where possible, the aim was the rehabilitation of the function for which the spaces were created and the reintegration of the artifacts in their context. This program did not reduce but even increased the part of the compound open to the visitors.

3.2 Dialogue as a methodology

A constellation of professions has been mobilized and the dialogue has been applied as a methodology to carry out the Works, which are only superficially from an author and much more from the collection of professionals.

Preliminary diagnosis was very brief and, therefore, the design project was not conceived in detail. On the contrary, the project was a directive kept open and continuously adapting to the unforeseen, which is often the case in historical buildings, where the anatomy is processed by successive approximations and under the lens of different disciplines. Of course, dissection as a knowledge tool cannot be a part of a modern intervention.

In this case, the lack of adequate preliminary diagnosis, which is in opposition with modern methodologies, was compensated with an intense multidisciplinary activity during the execution period (2002-2004), supported by research, consultancy and expertise in various fields. In the contingency of works that had started already, the reunion of efforts resulted in a process of effective cooperation, with the advantage of permanent in situ approaches and discussions.

4 SELECTED ASPECTS OF THE INTERVENTION

The restoration carried out in the first half of the 20th century used traditional construction techniques. Some of the structural deficiencies encountered were then solved with the dismantling and rebuilding of unstable parts, and with the replacement of deteriorated or damaged granite, with poor mechanical performance.

The sole concession to the industrial technology is the use of Portland cement, used as a common binder for repointing masonry joints, rendering walls and several reparations that during and after the restoration works, aimed at solving the following issues, without success: waterproofing of surfaces, glue and reconstitute volumes, stabilize cracks and stop movements.

It is precisely with respect to the above-cited issues that deeper interventions have currently been carried out, some without visible effects and other with the addition of parts, as in the strengthening of the towers. Therefore, the architects in charge of the works tend to joke about the fact that the only intervention being carried out is the strengthening of the towers.

Next, see Figure 4 to Figure 12, some of the aspects of the works being carried out are briefly reviewed. The works are mostly concentrated in the towers, and the roofs and façades in the west and south wings. Diagnosis and strengthening of the towers and the Saint Vincent Chapel are addressed in a separate section.

Figure 4. Remedial measures in the roof structures included cleaning, application of biocide, application of preservation products, consolidation, strengthening and local replacement. Experts were responsible for diagnosis and structural assessment.
Figure 5. Replacement of the ceramic tiles including new anchors, traditional eaves, strengthening in the corners, introduction of under-roof sheeting and walkways.

Figure 6. Remedial measures for stone, including removal of biological activity, dry and low pressure water cleaning, localised consolidation, application of water repellents, reconstitution of voids, crack closure and injection, replacement of iron ties, and, exceptionally, replacement of stone pieces. Experts were responsible for diagnosis and specific treatments.

Figure 7. Repair of grilles included control of anchors and new anchors, and measures for proper rainwater flow.

Figure 8. Physical protection of the granite stone include sheeting in the external horizontal planes and installation of an electrical anti-pigeon system.

Figure 9. Repair of finishings included repointing of masonry joints with lime mortar and repainting of wood with traditional oil paints.

Figure 10. The historical survey aimed at study existing documents, drawing and bibliography to define the evolution of the cathedral. The archaeological survey included in situ excavation and stratigraphical records of the faces of the masonry walls.
5 INTERVENTION IN THE TOWERS

5.1 Introduction

A key aspect in the behaviour of ancient towers is that the collapse process usually excludes the possibility of ductile behaviour. In fact, there are hardly any possibilities of internal force redistributions between different critical sections, and failure of a single section is usually sufficient to provoke the entire collapse of the structure. This intrinsic feature leads to a high structural risk in tall masonry towers, because increasing height means large vertical loads and high compressive stresses at the base. Therefore, it seems easy to accept that masonry towers should possess a higher safety margin than the values normally found for other historical structures. But this is not often the case, see Binda & Anzani (1997).

A tower is usually a result of the need to create a symbol or the need to challenge structural stability (and nature itself). The interpretation of this desire to build higher, and simultaneously to reduce the safety of structures, was left to ancient builders in the context of almost no scientific basis. It is striking that the majority of the ancient high towers in Italy, e.g. in Pavia and Bologna, are no longer present, Macchi (1998). The reality is that only a few of these structures survived until today, due to collapses, destruction due to lightening and even demolitions (often by precaution and concern of eminent collapse). In the recent history, there are well-known cases of collapse, namely the Campanile in Venice (1902), the Civic Tower in Pavia (1989) and the Santa Maria Magdalena Bell-Tower in Goch (1993). In the case of Venice, collapse was gradual, with signs of distress two days before collapse. Also, 20 minutes elapsed between the fall of the first bricks and collapse. In the other cases, collapse occurred without previous warning. In Pavia, the collapse occurred in a few seconds and provoked four casualties, Macchi (1992).

Therefore, it seems unquestionable that the high structural risk of high masonry towers justifies detailed studies and carefully planned remedial measures in case of doubt about their behaviour. Several recent case studies have been reported, Modena et al. (2001), Valuzzi et al. (2003) and Lourenço (2004).

5.2 Description

The main façade was built between 1176-1200 (central part) and 1229-1325 (towers), see Figure 13. The towers evolved into a Bell-tower (North) and a Clock-tower (South). In 1552, damage due to lightening is reported in the South tower. Between 1665-1669 the South tower was demolished up to mid-height and rebuilt. In 1717, it is recorded that the South tower was in the verge of collapse and, in 1727, buttresses were added, similarly to the ones that already existed in the North tower. Pinnacles were added in 1732. The construction of the Chapter House, contiguous to the South tower, also aimed at consolidating the tower. Also in this period, the two small windows in the main façade (South tower) were replaced by a single large window, similar to the one that existed in the North tower. Before 1841, a new lightening stroke the South tower.
As addressed above, the structure suffered several major modifications through time, which resulted in a very complex internal structure with different load bearing internal elements at each level. The structure of the towers cannot be understood from structural reasons and several openings are closed, facing staircases or vaults. The entrance for both towers is located at mid-height, with a connection between both towers from the top of the main vault. But the two towers have a rather different structure. The South tower possesses an internal core with a staircase shaped helicoidally, see Figure 14a,c. The North tower (presently with the bells and clock) features a horizontal mid-level with stone slabs and architraves apparently supported in columns and stone struts, see Figure 14b.

![Figure 14](image)

Figure 14. Partial sections of the towers: (a) horizontal section of the South tower, (b) horizontal section of the North tower and (c) sections A-D for the South tower.

### 5.3 Constitution of masonry walls

The constitution of the masonry walls from the towers was characterized using visual inspection, both by removing smaller stones of the outer leaves and by using a boroscopic camera inserted in cracks or in holes drilled in joints, see Figure 15a. From the inspection, it was possible to conclude that the three-leaf walls have external leaves of granite ashlar with a thickness ranging from 0.30 to 0.70 m, while the middle leave is made from loose smaller stones and / or silty soil, see Figure 15b and Figure 16. The combination of heavy rain in Porto, strong winds in the top of the hill where the Cathedral is located, and the open joints in the external masonry face, results in a wet infill even in the summer and the continuous washing out of the infill, see Figure 15c.

![Figure 15](image)

Figure 15. Visual inspection to define the constitution of masonry walls: (a) boroscopic camera, (b) opening up the structure (c) loss of material through central cracks in the openings.

![Figure 16](image)

Figure 16. Typical cross section of the masonry walls.

### 5.4 Existing damage

The towers exhibit distributed cracking and significant out-of-plane movements. The existing damage resulted in the past addition of three iron ties (date unknown), see Figure 17a. Tie T₁ presents a severely deformed anchorage, see Figure 17b, and tie T₃ is corroded and broken, see Figure 17c. It is stressed that the separation between the East and West façades of the South tower continued after tie T₃ was broken. It is also noted that the masonry walls in the vicinity of the anchorages are also deformed, as expected due to the application of a large point load.
Figure 17. Ancient tower ties: (a) Deformed anchorage of tie $T_1$ and (b) details of broken tie $T_3$.

The South tower is more damaged than the North tower. Figure 18 exhibits the location of severe cracks and out-of-plumb walls in the South tower. Also the East façade of the South tower presents out-of-plane movements to the exterior. It is noted that the internal walls of this tower are straight, indicating crumbling or desegregation of the walls, with major cracks and voids in the interior, see Figure 19a. The separation between the internal and external leaves of the walls is further confirmed by the longitudinal cracking observed in most of the openings. Figure 19a illustrates such cracking, with a maximum width of some centimetres. Finally, it is noted that the North tower presents severe distributed vertical cracking at the base, see Figure 19c.

This cracking is only visible in the internal (medieval) face, while the external face seems undamaged. Moreover, the very large thickness of the walls are not replicated in the South tower, see Figure 20. For these reasons, it is believed that the damage is not recent and the helicoidal staircase belongs to the structure of an older tower.

Figure 18. Location of most severe cracks and out-of-plumb walls, in the South view and main façade.

Figure 19. Details of the cracks in the towers: (a) cracks up to 0.20 m width in the South façade / South tower; (b) typical active cracks parallel to the walls at the openings; (c) vertical cracks at the base of the North tower.

Figure 20. Plan of North tower at the base.
Additionally, also the following damage is noted:

- Steel structure in the cupolas of the towers with advanced corrosion, see Figure 21a;
- Balustrades and pinnacles under deficient stability conditions and with significant movements due to corrosion of dowels and ties, see Figure 21b;
- Misconception of the structure supporting the bells and clock in the North tower, see Figure 21c.

Figure 21. Other damage: (a) Corrosion of the steel structure of the cupolas; (b) corrosion of dowels and ties in balustrades and pinnacles; (c) deficient structural system to support the bell stone level floor.

5.5 Remedial measures

As it arises from the history and survey, the towers seem to have been damaged in the past and rebuilt (particularly the South tower). The (re)construction seems to have been carried out under deficient execution conditions, no particular well defined structure and using improvised construction details. In addition, different remedial techniques were already used in the past aiming at correcting and strengthening the towers.

The walls of the towers seem not to possess adequate connection between the external leaves and severe water infiltration in the walls contributed to the existing damage and to the loss of material in the rubble infill. Here it is again stressed that the Cathedral is located at the top of a hill, the masonry joints have lost all mortar and it was found that the rubble infill was wet by the end of the summer.

Besides other damage, the most relevant feature is that the North tower is divided in two similar U-shaped parts, from mid-height to the top, with full cracks along the West-East direction (in the other direction, the existing ties kept the tower together), and the South tower is bulging outwards both to South and to East (the existing West-East tie is broken).

The solution adopted for strengthening consists mostly of a steel ring in both towers, aiming at confining the structure along the two orthogonal directions, in the sole location possible, see Figure 22a,b. The rings are made with welded stainless steel plates (class AISI 316L), connected to the towers using long, inclined stainless steel anchorages inside of a cloth duct to prevent generalized injection, see Figure 22c-e. The length of the steel profiles is defined so that the elements can be transported to the location through the existing doors and can be easily assembled in situ, without any further welding.

In the North tower, the ring also aims at providing a support for the stone pavement for the bells. The reason being that the stone columns are very deteriorated and possess presently no structural function and the stone struts have very deficient conception, see Figure 22c. Here it is noted that it was decided not to recuperate the structural function of the columns (e.g. using injection) because the lower level seems to indicate insufficient strength of the inner core, see Figure 20c and Figure 21. The steel ring is made of U profiles (240 × 120 mm and 200 × 100 mm height).

In the South tower, a set of two ties was provided to the ring, because it was possible for aesthetic reasons and they are a witness of the ancient broken tie. The ring must cross the staircase at a selected location because the complex internal structure of the tower does not allow otherwise. Due to the lack of internal stiffening elements, a much more stiff steel frame is needed and the steel ring is made of I profiles (180 × 180 mm). Due to the bulging outwards of the East and South façades, and the severe cracks in the corners, several short ties have been added to the structure to stitch the East and South façades, and two long ties through the core of the South façade have been added to connect the West and East façades, see Figure 22f. Figure 22g presents details of the two types of anchorage plates adopted (circular plates and specially designed crosses).

Figure 23 illustrates the aspects related to repairing the pinnacles and balustrades, which consisted of replacement of iron dowels and ties by stainless steel. The large pinnacle in the top of the North tower cupola was totally loose at the time of the works and was jacketed with steel plates at the top and bottom necks.

The other works carried out include injection of the main cracks with lime based mortar grout, repointing all joints with two selected lime mortars (a traditional mortar for the filling and a more
traditional mortar for the filling and a more durable lime mortar for the finishing), protect against corrosion (the two ties in the North tower were kept in place) or replacing all existing iron.

Figure 22. Aspect of the strengthening of the towers using stainless steel rings and long inclined anchorages: (a) plan of the ring for the North tower; (b) plan of the ring for the South tower; (c) North-South section for North tower; (d) West-East section for North tower; (e) typical section for South tower; (f) additional ties placed in the West and South façades of the South tower; (g) details of the anchorage plates.

Figure 23. Pinnacles and balustrade removal and placement with stainless steel dowels and ties: (a) general view; (b) removal of the centre pinnacle; (c) aspect of stainless steel elements and placement.

5.6 Monitoring Plan

Given the cultural importance of the building and the significant damage in the South tower, a monitoring system was planned and installed.

The system includes four waterproof crackmeters in the largest cracks, two strain gages for the new ties, two biaxial clinometers to measure the tilting of the tower, as well as temperature, humidity and wind sensors. The system includes a GSM interface for remote monitoring.

6 SAINT VINCENT CHAPEL

The Saint Vincent Chapel is located next to the South wing of the Cathedral cloister. During the restoration works of the roof, it was found that the extrados of the chapel vault was filled with rubble resulting from old demolitions see Figure 24. Also, and as usual in several historical constructions, the timber roof was partly supported by the vault, using later added struts.

The issue addressed here is the stability of the vault and the convenience of the removal of the infill.
of the structure is not particularly relevant. Therefore, the influence of the cloister, openings of the walls and ribs of the vault were neglected in order to avoid the need of a three-dimensional model, Lourenço (2002).

The numerical results are given in Figure 26, in terms of thrust-lines and collapse mechanisms, both for the model with and without infill. The ultimate load factor increases 45% if the infill is removed, which seems also natural because it was not originally planned for this construction.

6.1 Survey

The structure consists of a barrel vault with an approximate thickness of 0.25 m and a span of 6.8 m. On the North side, the cloister acts as a buttress but on the South side no buttresses are present. Even if the South wall (1.70 m) is thicker than the North wall (1.30 m), out-of-plumb movements outwards are clearly visible in the former, up to 1.5% (or 0.10 m at the springer of the vault), see Figure 25a.

Nevertheless, as the vault presents only minor cracking, see Figure 25b, it was believed that the vault has been built after the wall deformation. As it will be confirmed next, the vault replaces a previous timber roof at the same level.

6.2 Structural Analysis

A plane model was adopted for the structural analysis of the barrel vault. The analysis was carried out using limit analysis, discretizing the walls and vault as a set of rigid blocks, see Orduña & Lourenço (2003). More complex approaches are available, Lourenço (1998, 2001), if necessary for more detailed studies. The assumed material properties include a tensile strength equal to zero, a tangent of the stiffness angle equal to 0.7, zero dilatancy and a compressive strength equal to 6 N/mm². The actions included consist only of the self-weight of the structure.

As the objective of the analysis is to evaluate the influence of the infill, a sophisticated representation of the structure is not particularly relevant. Therefore, the influence of the cloister, openings of the walls and ribs of the vault were neglected in order to avoid the need of a three-dimensional model, Lourenço (2002).

The numerical results are given in Figure 26, in terms of thrust-lines and collapse mechanisms, both for the model with and without infill. The ultimate load factor increases 45% if the infill is removed, which seems also natural because it was not originally planned for this construction.

6.3 Remedial measures

The infill was removed but, for safety reasons, it was recommended to accompany this task with topographic measurements, see Figure 27a. The targets were read always at early morning to reduce temperature effects, daily during the process of infill removal (one week) and weekly during one month after load removal. Approximately $35 \text{ m}^3$ (7000 kg)
of rubble were removed from the vault and no movements were recorded in the targets.

Figure 27b demonstrates that (a) the vault was never conceived to accommodate infill and (b) a timber roof existed at the level of the vault, before the construction of the vault and the new roof at a higher level.

![Figure 27a](image1)

![Figure 27b](image2)

Figure 27. Infill removal: (a) location of topographic targets for monitoring; (b) aspect of the cleaned vault.

7 CONCLUSIONS

The present paper addresses the works recently carried out at the Cathedral of Porto as a case study. The methodology that governed the complete set of works is addressed and the conservation and repair works are briefly addressed. Two aspects are treated in detail, namely the towers and the Saint Vincent Chapel.

The towers exhibit severe global damage including cracking, crushing and separation between leaves and also local damage in the cupolas, pinnacles and balustrades. The global damage seems mostly due to water infiltration, deficient conception of the structure, ancient damage due to lightening and changes in the structures of the towers. For the purpose of increasing the structural performance, a rigid frame of stainless steel profiles and a set of long, inclined anchors have been designed to provide a confining ring. In addition, new ties and stitching of the external leaves were also included when necessary. The local damage is mostly due to corrosion of iron elements, which have been replaced by stainless steel elements or have been protected.

The chapel exhibits a significant overload due to a rubble infill resulting from previous demolitions and the external wall presents moderate out-of-plane displacements. From the diagnostics, it was possible to safety prescribe the removal of the infill (approximately seven tons). This operation allowed to confirm that the present vault is not contemporary to the walls and the external wall deformation is stabilized.

REFERENCES


