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# History, situation and reinforcement of the bell towers of the basilica of Penha-Recife-Brazil

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## ABSTRACT
This paper presents and discusses the history, current situation, original techniques and strategies used in the development of structural reinforcement design of both towers of the Basilica of Penha Church. Repair techniques poorly designed, conducted in 1981, along with lack of preventive maintenance, leaks and even the growth of bushes embedded in the masonry led to the instability of the towers of the Basilica of Penha Church.
**Keywords:** reinforcing masonry; historic monuments; reinforcement techniques; execution strategies; carbon fibers.

## RESUMO
Este artigo apresenta e discute a história, situação atual, técnicas e estratégias utilizadas no reforço estrutural desenvolvimento design original de ambas as torres da Basílica da igreja de Penha. Mal concebido técnicas de reparo, realizada em 1981, juntamente com a falta de manutenção preventiva, vazamentos e até mesmo o crescimento de arbustos embutidas na alvenaria levou à instabilidade das torres da Basílica da igreja de Penha.
**Palavras chave:** reforço em alvenarias; monumentos históricos; técnicas de reforço; estratégias de execução; fibras de carbono.

## RESUMEN
En este trabajo se presentan y discuten el histórico, situación actual, técnicas y estrategias originales empleadas en el desarrollo del diseño de refuerzo estructural de ambos campanarios de la Basílica de la Iglesia de Penha. Técnicas de reparación mal diseñadas, llevadas a cabo en 1981, junto con ausencia de mantenimiento preventivo, filtraciones e incluso el crecimiento de arbustos incrustados en la mampostería, llevaron a la inestabilidad de los campanarios de la Basílica de la Iglesia de Penha.
**Palabras clave:** fortalecimiento de albañilería; monumentos históricos; técnicas de refuerzo; estrategias de implementación; fibras de carbono.

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# 1. INTRODUCTION

The Basilica of Our Lady of Penha, Order of Capuchin Friars Minor, is an imposing building in the urban landscape in the district of San Jose - strongly marked by the presence of towering tall towers and a huge dome with cruise, symbols a strong religiosity - Urban environment of the initial formation of the city of Recife. Between the beginning of construction (1656) and the completion of his work, which spent more than 200 years, due to the expulsion of French Calvinists from Recife, by order of the Portuguese court (CECI, 2014).
Figure 1 shows the historical record of the early 20th century building. The building has a central nave and a pair of towers (Epistolary and Belfry), each with eight columns called "minarets". In these columns a number of cracks and detachments of coatings were observed, due to the oxidation of the internal reinforcement, as well as pathologies due to the action of shrubs that grew on the outside and branched into the masonry of one of the towers.
In 1981 reinforcement interventions and filling the windows with cobogos (Araujo 2010) were made, in the reinforcements were identified with the inclusion of some columns and bars of steel in elements of reinforced concrete.
In 2010, due to the aggravation of pathological manifestations in the openings fissures in some columns and loss of internal and external lining, reinforcements in wood structure were inserted in the windows between 8 columns of towers of structure of masonry.


Figure 1. Historical image of the Penha-detail Basilica of the bell tower without cobogo.

Figures 2 and 3 show of one of the towers as well as details of the type of reinforcement used in the columns the towers.

Figure 2. Current view of the tower

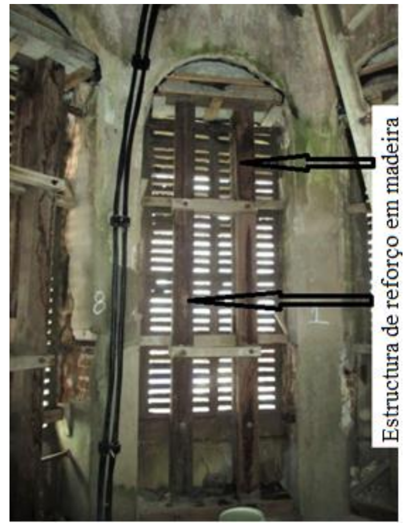



Figure 3. Reinforcement in tower columns

In Figures 4 to 6 it is possible to observe aspects of large cracks in columns generated by the oxidation of the reinforcements incorporated.


Figures 4 to 6. Fissures caused by the oxidation of the iron clamps inserted in the columns

## 2. INVESTIGATIONS

Aiming to support the reinforcement project for the two towers, activities were carried out to characterize the compressive behavior in samples taken from the building and a numerical analysis to determine the actions that work in the towers.

### 2.1 Physico-mechanical characterization of the building

The physical and mechanical characteristics of the building were obtained through inspection by prospecting in areas in the region of the tower of the Epistle, through drill and double disk cutter, with the samples sent to the laboratory of the ITEP-Institute of Technology of Pernambuco.

Attempts to obtain samples using a 4" diamond drill bit were not efficient, since the need to cut with hydraulic lubrication favored the solubilization of the mortar and the brick itself, since both the lime-based mortar and the Not completely burned brick suffered with action of disk movements and water action. In order to obtain samples of the masonry, it was necessary to use a double diamond disc cutter, as shown in figures 7 and 8.

Figure 7. Sample removal process using double diamond disc.


Figure 8. Sample removed from masonry sent to the laboratory.

Samples were cut and rigged in four specimens for achieving the compressive behavior tests, being used press with displacement control, with capacity of 300kN, allowing register the post rupture behavior.
For the determination of the longitudinal and transverse modulus, deflectometers with precision of thousandths of a millimeter were installed in the cross section of load application and LVDts were used in the measurement of longitudinal and transverse displacements. The composition of Figures 9a-d shows characteristics of the tests on the compressive behavior of the samples.

a) sample 1 b) sample 2 c) sample 3 d) sample 4

Figures 9a-d. Compressive behavior of the assays in the samples

From this evaluation, on analysis of determination of the characteristic resistance, according to the recommendations of ABNT NBR 15182-2 was obtained

$$f_{pk} = 1{,}15\ MPa$$

**2.2 Active stress**
The tensile stresses were obtained based on numerical modeling based on the finite element method (Mamaghani, 2004). The masonry structure was modeled with solid elements of various shapes, the floors in plate elements combined with membrane elements and the arrow covering the towers in bark elements. The SAP2000 computational system was used to obtain tensions, and the densities and characteristics of the compressive behavior (modulus of elasticity and Poisson's coefficient) were reported.
Figure 10 shows aspects of the solid elements used and the results of the tensions in the various elements that make up one of the towers.

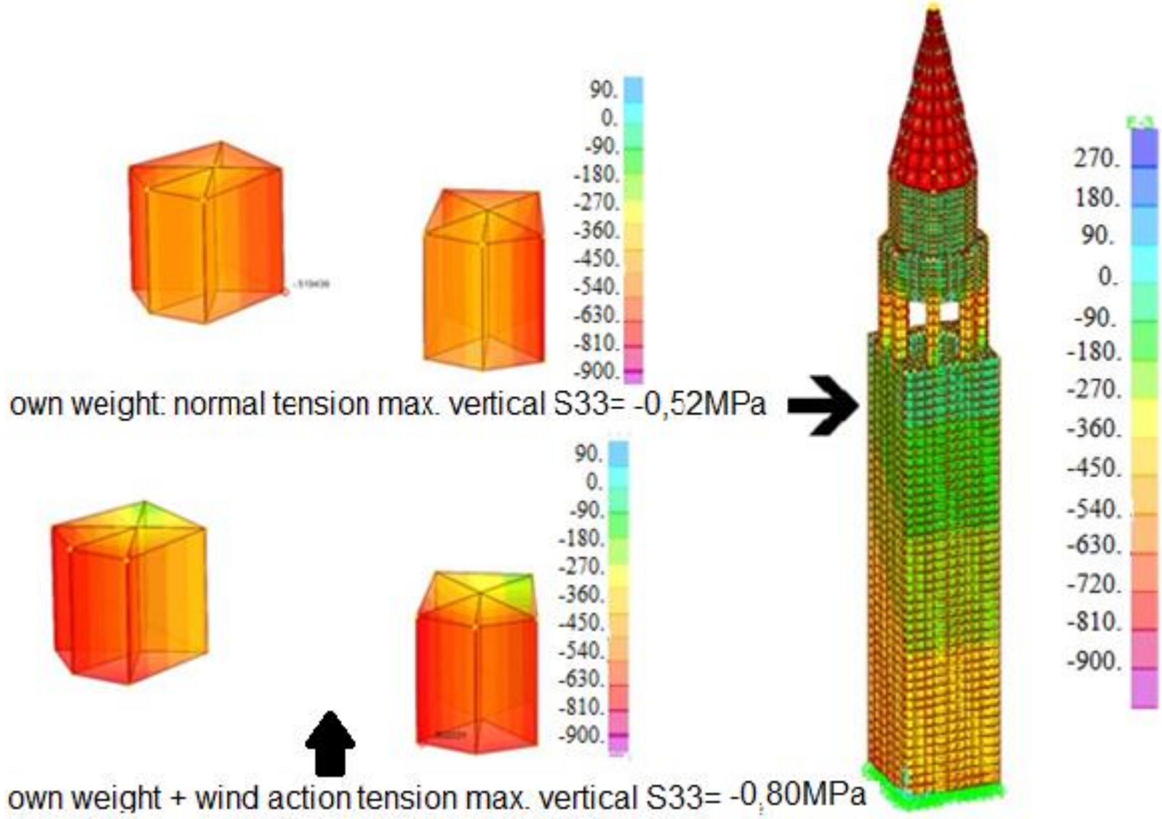



Figure 10. Results of the numerical analysis of the tower of the Basilica

The images in figure 10 show that the most critical regions of stress concentration are located at the base of the columns, reaching a value of 0.52MPa due only to its own weight and of 0.80MPa when considering the combined action of weight and wind action.

### 2.3 Structural security analysis

Considering the results of the requesting tensions, especially in the region near the bases of the columns, reaching maximum values were between 0.52MPa to 0,80MPa and considering that the characteristic resistance of the samples was determined at 0.63MPa.

These values show that in the performance of the wind the tensions surpass the resistant capacity of the columns, even without considering the safety factors, normally existing when proceeding to a dimensioning. In this way the temporary reinforcement structures, built with wooden structures in the windows of the towers are acting decisively, avoiding collapse in this region.

The results of these analyzes are very coherent with the situation that presents the columns of the tower of Basilica, presenting a high state of cracking and indicative of localized ruin.

Thus, it is concluded that it is extremely necessary to use reinforcement that allows to raise at least twice the resistant capacity, thus meeting the normative principles of structural safety.

## 2. STRUCTURAL REINFORCEMENT PROJECT

### 3.1 Principles of reinforcement design

Composite systems structured with carbon fibers are efficient for the absorption of tensile stresses, avoiding, through the confinement of the section of the axially required pieces, the growth of the transversal deformation of the materials, resulting from the action of the axial load.

The effect of the confinement pressure is to induce a triaxial stress state in the masonry and under these conditions masonry, or other fragile material, substantially alters its compressive behavior, both in strength and ductility (Fiorelli, 2002).
Figures 11 and 12 show the difference in compressive behavior of a concrete element, which could be masonry, without and with transverse confinement.

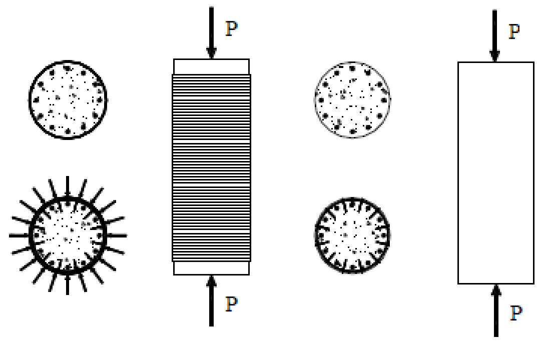


Figure 11. Tensions and strains in confined and unconfined systems

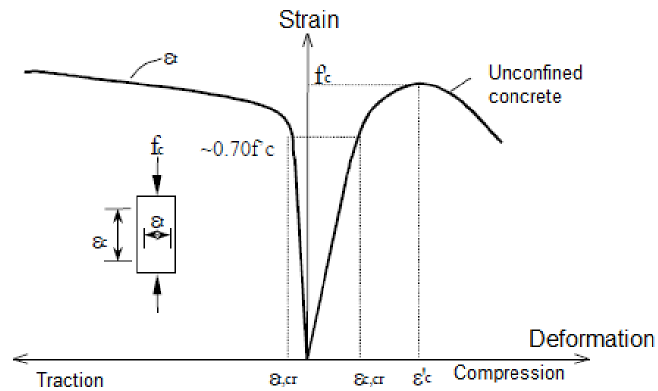


Figure 12. Typical configuration of a piece of concrete confined and unconfined

In addition to the effect of confinement promoted by the use of a carbon fiber and epoxy resin system, the lime-based mortar coating will be replaced with cement-based polymer mortar based coatings and chemical additives.

## 3.2 Determination of the influence of reinforcement

The compressive characteristics of polymer mortar in relation to the lime mortar are substantially larger, being able to overcome the compressive strength by 15 times and the value of the longitudinal modulus of elasticity by more than 35 times, see table 1.

Table 1. Mechanical characteristics of materials.

| **Materials** | **Compressive strength (MPa)** | **Elasticity module (GPa)** | **References** |
|---|---|---|---|
| Masonry bricks and lime mortar | 2,0 | 0,40 | Ensaios em amostras (ITEP) |
| Polymer mortar | 30,0 | 15,0 | Product characteristics (Viapol,2015) |

The effect of the confinement, promoted with the use of a system composed of carbon fibers and epoxy resin, can take up to 30% the resistant capacity of a compressed part.
Thus combining the effects of coating replacement with confinement on the outer cross sections of the columns provides an increase in the resistive capacity of these elements that make up the towers.
Figures 13 and 14 show the positioning of the columns that present the most critical situations in terms of stress concentration.

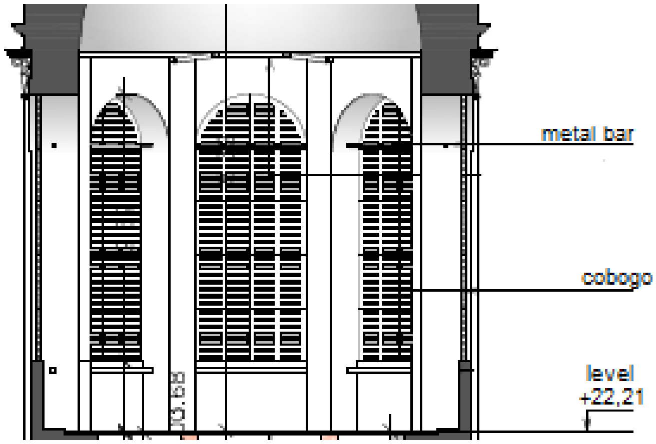



Figure 13. Drum region

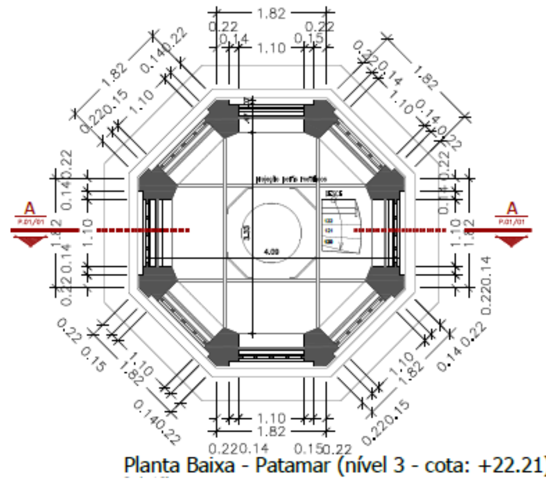
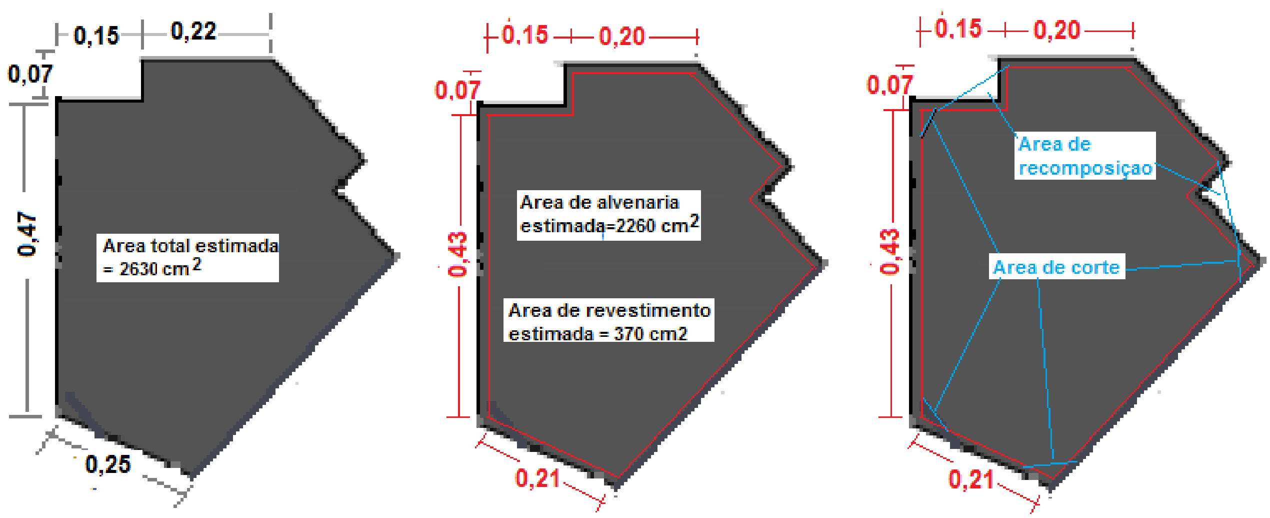



Figure 14. Low plant at the base of the columns

The evaluation of the cross-sectional areas of one of the columns to be reinforced is considered in figure 15.

Practically after the cutting interventions (corners roughing) and rigging, necessary to enable cross-sectional casting of the columns, the estimated areas of masonry and cladding do not change.




a) cross section of a column

b) masonry sections and coating

c) treatment and recomposition of areas

Figure 15. Evaluation of areas after interventions required for treatment to strengthen

The evaluation of the active and resistant loads at the base of columns can be estimated in:

a) Total active load, due to its own weight, considering the numerical modeling

$$\mathbf{S_{pp}=5{,}20*2630=13{,}676\ ton}$$

b) Total active load, due to the combined action of own weight and wind

$$\mathbf{Spp=8{,}00*2630=21{,}040\ ton}$$

c) Resistance of the current masonry, considering the characteristic resistance obtained in the test.

$$\mathbf{Ra = 6{,}30 * 2630 = 16.569\ ton}$$

d) Estimated strength for reinforced masonry with replacement of lime mortar coating by polymer mortar

$$\mathbf{Rr1 = 6{,}30 * 2260 + 300 * 370 = 127{,}569\ ton}$$

e) Estimated strength for reinforcement with the use of the carbon fiber belt

$$\mathbf{Rr_2 = 127{,}569 * 1{,}20 = 153{,}082\ ton}$$

In this way, it can be considered that the proposed reinforcement allows a resistance increase of the columns in 7 times its resistant capacity and if compared to the load acting on the base of the columns due to combined action of own weight and wind action. In this way, the proposed reinforcement presents a security coefficient of the order of 7.0, well above the 2.0 recommended by masonry standards.

## 4. REINFORCEMENT PROCEDURES

Following are the procedures for implementing structural reinforcement.

**4.1 Basic procedures for strengthening masonry structures.**
The basic procedures to be followed for execution of reinforcement in masonry:

**4.1.1 Demolition and removal of the existing coating, with thinning of the corners and cleaning of the areas to be reinforced**
In the areas to be reinforced, the existing coatings must be removed, using corodur grinding wheel coupled to a rotating sander, in this way there will be no significant impacts on the masonry structure, as shown in figure 16a.
After skirting the corners and removing the entire coating, the areas should be clean and free of dust and can be used with slightly moist air, as shown in the diagram of figure 16b.
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Figure 16a. Roughing process with grinding wheel

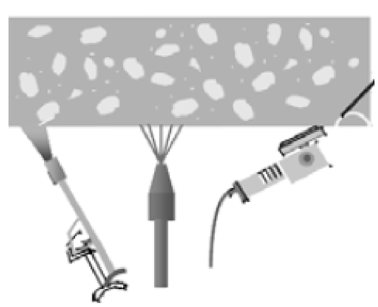

Figure 16b. blasting scheme and thinning of the corners

#### 4.1.2 Surface preparation and rigging

In the areas that will receive reinforcement, outlined by the project, they must prepare the surfaces receiving application of primer to make it possible to fill the voids to receive the layer of polymerizing mortar, as indicated in figures 17a and 17b.

This mortar should have adequate consistency with its application with a metal trowel on the primed surface.

The final surface must be smooth and compact.

After 3 days of application of the mortar, a new primer coat is applied.

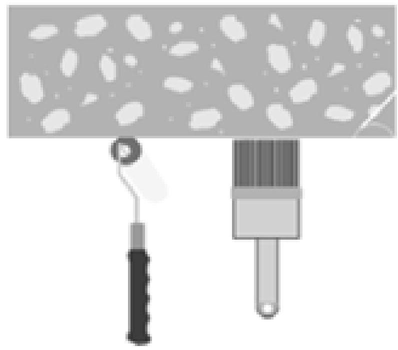

Figure 17a. Scheme of the preparation process

Figure 17b. Primer application as surface preparation

#### 4.1.3 Procedure for applying carbon fiber blankets

The surface of the masonry already prepared an epoxy resin layer is applied with a roller. Typically, this product has a low viscosity - which facilitates its penetration into masonry. The function of this layer is to provide adequate adhesion to the surface of the structure (Grande 2011).

After application mass regularization is then applied an epoxy mass + carbonates to correct and eliminate surface defects that can detract from the application.

After perfect regularization, the first layer of resin is applied. The surface of the structure is covered with epoxy resin saturation. This resin, high viscosity, helps to maintain the CFC and the correct position. The impregnated saturation in the blanket being applied, it also helps in the efforts of the fibers and abrasion protection.

The application of the carbon fiber blankets cut into the size of the surfaces and the area geometry is applied to the epoxy resin saturation.

Continues with saturated resin application of the reinforced top layer are made throughout the entire area so that the system is hidden.

After all CFC layers have been applied, regularization with polymer composite and plastic fibers is promoted.

Figure 18 shows the procedures for the application of carbon fiber blankets.

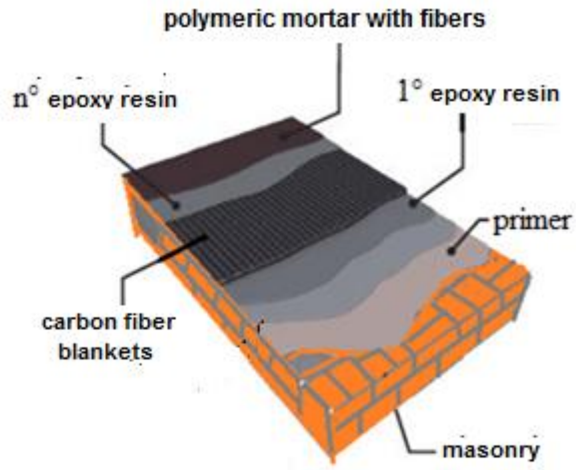


Figura 18. CFC System

**4.1. Strategy for recovery of towers**

Considering the critical situation of the elements that make up the towers, from the loss of coating of the copper pieces on the cover of the arrows, causing rotting of structural elements of this cover, from the degradation action of bushes of grew and branching in the drum of the tower to and the signs of ruin at the base of the columns. In order to proceed with the recovery of the towers, a strategy must be developed to carry out the reinforcement steps of the towers.

**4.2.1 Procedure for cleaning and injection of cement paste into fissured columns**

In the fissured columns there is a need for cleaning and filling with epoxy resin for recovery of the moniliticity, shown schematically in figure 19 [5].

A) Cleaning of cracks with compressed air blasting;

B) removal of parts of impregnated reinforcements inside the cracks, so as not to cause major damage;

C) Drilling of holes along the fissure and placement of masters, filling the outer side with cement grout tix;

D) Injection of cement paste, with low pressure, in the pugadores, from bottom up, in order to fill the fissures.

Figure 19. Injection process: placement of masters and injection through injection pump

**4.2.2 Procedures for removing the copper plates from the cover of the arrows.**
Preparation of an auxiliary structure to support a scaffolding platform: Insert into the bases of the wooden elements 4 transverse metal profiles, which supported the scaffolding lines.
A) Mount the 8 columns of scaffolding until reaching the edge of the base of the arrow, securing them against the walls of masonry;
B) Place a grid / net of protection on the scaffolds in order to avoid falling objects of the arrow;
C) With the aid of a boom crane coupled to a protective structure, remove the copper pieces from the cover of the arrows.

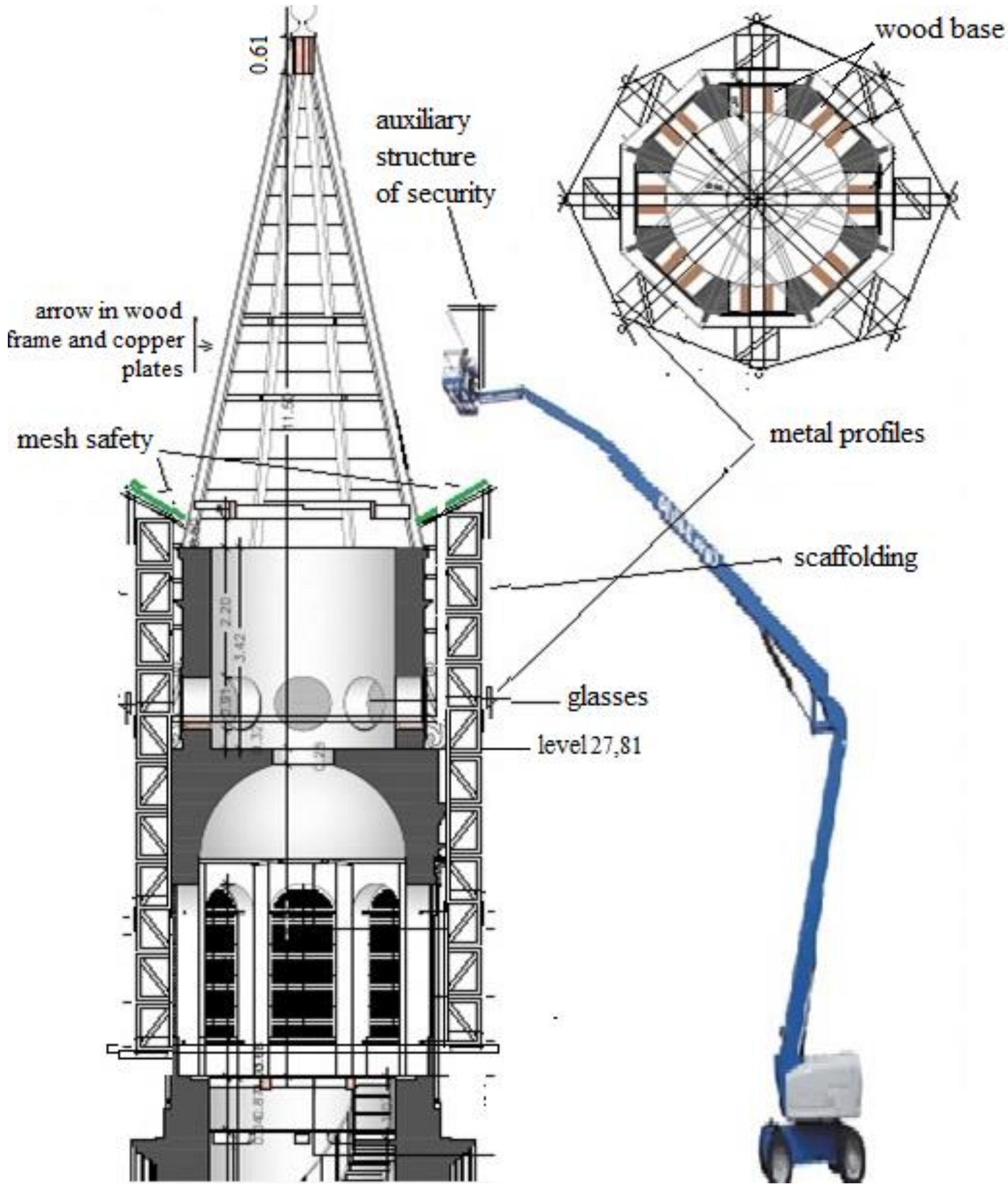


Figure 20. Scheme of the process

**3.3 Procedure for reinforcing tower columns**
The eight columns that make up each one of the towers, are currently with provisional reinforcement fomó by wooden structure and with closure in cobogo.

To promote reinforcement of these columns, in pairs and opposites, the reinforcement technique should be used with replacement of the existing coating and carbon fiber sheeting.

A) It starts soon after the treatment of fissures, according to 2.2.1.

B) It is promoted the cut of the area of cobogó surroundings of the pair of selected columns;

C) The coating and the thinning of the corners are removed, as described in 2.1.1;

D) The reinforcement is promoted as described in 2.1.2 and 2.1.3;

E) Repeat this procedure for other pairs of opposing columns.

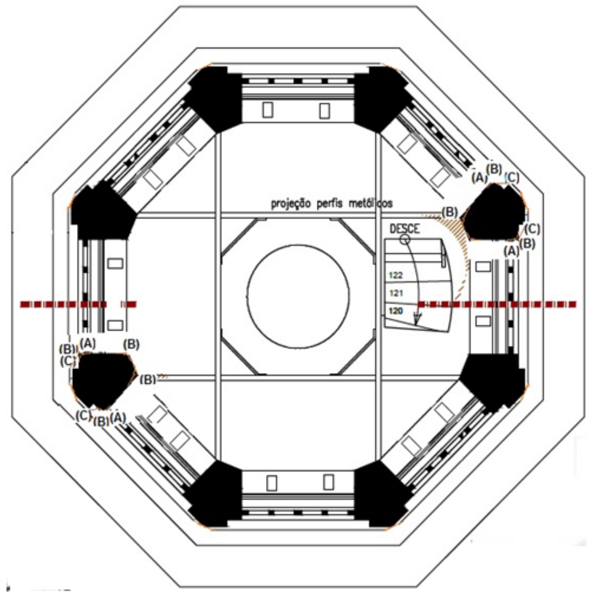


Figura 21. Bottom floor at level 22.21

**4.2.4 Procedure for removal of the rooted shrubs in the tower of the Epistle and execution reinforcement of the wooden structure of the cover.**

The shrubs that have grown and rooted in the tower of the Epistle need to be carefully removed.

After the removal of the coating of the arrows the investigation of the wood structure that composes the covering arrows of the towers is carried out.

A) Identify the damaged wood elements and promote their reinforcement;

B) The reinforcements can use steel plates and stainless steel screws, and it may be necessary to fit new pieces of wood.

Figure 22. Cover situation detail

**4.2.5 Reinforcement procedure for the outer contour of the towers**

In the outer contour regions of the towers, at levels 18.00, 25.00, 27.00, 29.00 and 31.00, reinforcements will be developed, according to the following steps and illustrated in figure 23:

A) Preparation of an auxiliary structure to support a scaffolding platform: Insert into the base of the columns wooden elements that will support 4 transverse metal profiles, which supported the scaffolding lines.

B) Mount the 8 columns of scaffolding until reaching the edge of the base of the arrow, securing them against the walls of masonry;

C) Place a grid / net of protection on the scaffolds in order to avoid falling objects of the arrow; D) With the aid of a boom crane attached to a protective structure, remove the copper parts from the cover of the arrows.

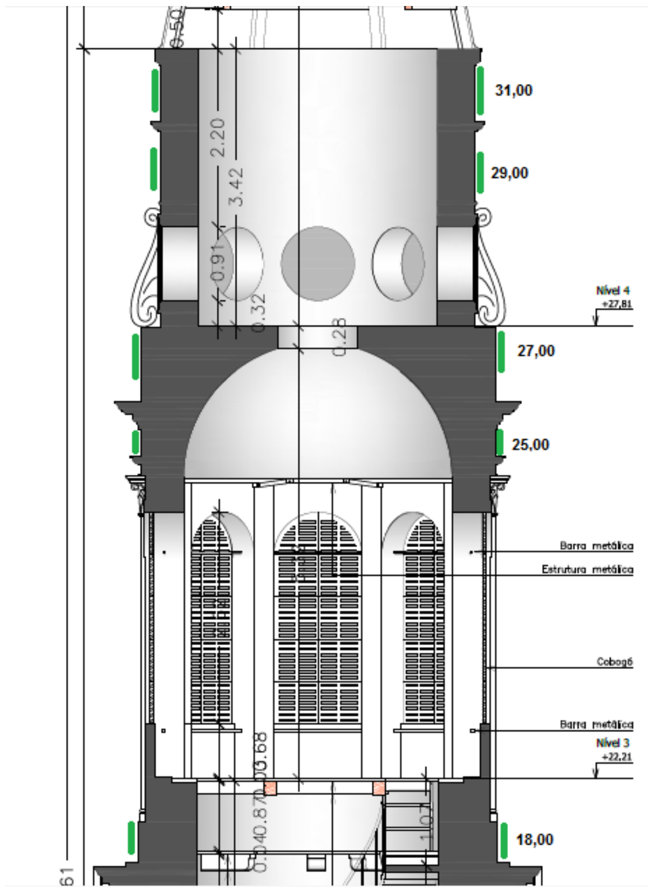


Figure 23. Reinforcing by grating the columns

## 5. FINAL CONSIDERATIONS

The situation of the towers of the Basilica of Penha shows signs of concern regarding structural stability. In the evaluation carried out there is no safety reserve, the temporary reinforcement implemented is acting in an effective and full, but new signs of ruin are on display. The proposal of reinforcement presented makes possible not only the removal of the provisional reinforcement the cobogó closing built after the construction of the basilica in the XVIII century. The use of reinforcement on the basis of replacement of lime mortar by polymer mortar and carbon fiber sheeting, may be covered by a new layer of mortar based on lime with reconstitution of architectural details and frescoes similar to the original ones.

The reinforcement in carbon fibers and polymer mortar does not suffer degradation with the humidity and natural weathering actions, are thus considered durable.

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