Analysis of the structural functioning of the church of San Pedro de los Franos in Calatayud (S. XIV)

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ABSTRACT: The Gothic church of San Pedro de los Francos (Calatayud, Zaragoza, Spain) is going to be restored in order to preserve and bring to new uses an antique building of the Spanish Architectural Heritage.

The presence of a provisional wall of brick masonry acting as a huge shoring inside the church to prop up five of the arches, has led the architect responsible for its restoration, José María Valero, to look for a previous structural analysis, consisting on a computer simulation with a finite elements based software. This study is meant to find out the behaviour of the building after the removal of that provisional wall.

In this sense, an analysis of the arches before and after the removal of the wall is done to get the necessary information for the structural repairs using the real geometry of the building. In order to make it, mechanical and geometrical data have been previously taken from the building. The tower of this church, which shows a dramatic inclination towards the street, is also studied with the same computer tool.

As a consequence, a complete set of data about stress and strain at every point of the structural solid model has been obtained, which let us reach a more accurate knowledge of the structural behaviour of the building.

The present study has helped us to evaluate the stability of the building and decide on structural reinforcements.

1 OBJECT

Arches and vaults structure of San Pedro de los Francos church is studied in order to analyse its structural situation and mechanical behaviour, taking account of the elimination of the brick masonry shoring existing under five of the arches. A study about the belfry tower that shows an inclination towards the street of about 4º, it is also intended.

To do that, computer simulation of both models for arcades and tower in two diferent basic situations for the arches, propped up and free of shoring, always based upon real geometry. In this way, the behaviour of the arches are studied, calculating stresses generated on their elements, as well as their deformations and stability, evaluating the need of a reinforcement before setting the shore off.

As a first result of this analysis we can say that it would be necessary to tie up the upper spandrels as well as reinforce the external wall butress. This lead us to simulate a modified model that incorporate the new stabilizing elements, checking their structural performance.

The tower is also studied in two simulations, corresponding to its current state and after a structural reinforcement.

2 STRUCTURE DESCRIPTION

We are dealing with a gothic structure made of columns, arches and vaults from the XIVth century, consisting on three parallel naves, the main one and two adjacent minor ones, a cross aisle at the fourth section with a single nave, similar to the main one, and a group of three poligonal apses corresponding to the three longitudinal naves (Figure 1). We can point out the following elements:

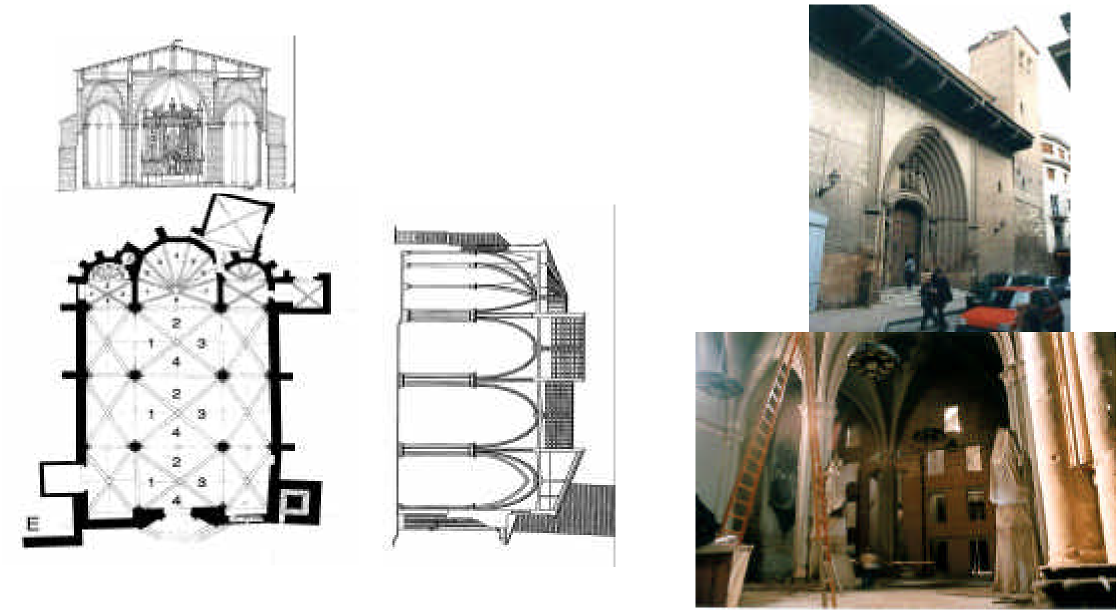

Figure 1

Foil shaped columns, made of brick masonry taken with plaster mortar; the six central ones are original and remain untouched.

Interior reinforced concrete columns, corresponding to the first section, in sustitution of the original ones, erected during an unfinished restoration of the church carried out about 1985.

Perimetral pilasters, made of brick masonry taken with plaster mortar, completing the transverse arcades in their arrival to the external walls.

Two diferent type of external walls, made of brick masonry taken with plaster mortar some of them, and natural gipsum balls masonry also taken with plaster mortar the others.

Arches, both transverse and longitudinal, made of brick vousoirs, starting from the capitals of the columns and pilasters above mentioned, being all the columns of the same height.

Crossing vaults, among arcades, composed by arches of foil shaped brick vousoirs taken with plaster mortar, and the mass between them made of brick masonry all-rowlock (bizantine vaults) with a plaster mortar lining on their back.

Roof, made of a wooden frame of log trusses and purlins leaning either on transverse cob walls or on wooden beams, which moreover lean on small brick masonry pillars taken with plaster mortar, that start from the keys of archesand vaults indistinctly.

The belfry tower, built before the church, made of brick masonry taken with plaster mortar. The wall thickness of the tower is about 1,20 metres, housing in its inner space a staircase and a central pillar of brick masonry too. The inclination of the tower is about 4º towards the front façade. The base of the tower is made of stone masonry, with a starting part of Roman origin. The front of this stone wall has no inclination, perhaps because originally it had positive pitch.

3 FINITE ELEMENT COMPUTER SIMULATION

3.1 Arcades

The present computer simulation of arcades stress status, currently propped up by a brick masonry shore, and that of the belfry tower, of San Pedro de los Francos Church in Calatayud, has been achieved with the help of ANSYS program, release 5.3.

It is intended to study stresses in arches before and after the removal of the brick shore. It is then asumed that the shore is currently loaded. Next it is analysed how the arcades work with the proposed reinforcement.

In the same way it is proposed to be made a simulation of the tower with its current state and after the proposed tie down.

Considered loads are self weight and transmitted loads from the wooden frame of the roof, acording to their real distribution, that is to say, with the colaboration of all the small pillars existing in the roof chamber.

In adition, lateral forces due to the thrust of the vaults must be introduced in the simulation of the arcades. These forces are obtained throught a simulation of simplified models of the vaults.
It is also asumed that foundation is undeformable, so that the removal of the shore will not cause any foundation settlement.

3.1.1 Approach and asumptions

For this simulation is accepted that:

- Roof loads are uniformly distributed over transverse arcade
- Concentrated loads coming from the small pillars actuate on keys of longitudinal arcades
- These loads are obtained as a result of the delivery on every pillar of the corresponding surface load, applied over each ones influence roof area
- Deformations will occur inside the plane of arcades
- Settlement in foundations will be zero
- Brick wall shore is undeformable

Other mechanical data for the brick masonry are:

Young Modulus: $1{,}38\times10^{9}$ N/m^2
Poisson´s ratio: 0,2
Density: 1.800 kg/m^3
Roof surface load: 5.000 N/m^2

The lack of symetry in the crossing vaults creates unbalanced thrust, resulting in horizontal forces on top of internal columns towards lateral naves; In the same way, thrust of lateral nave vaults is acting on the external wall butress.

Magnitude of resulting thrust provoques the observed deformations; these forces reach the following values:

- 2,8 T on the central capitals of the transverse arcade
- 4 T on the lateral pilaster capitals of the same arcade

Every data is expressed on S.I. units.

3.1.2 Modelizing Criteria

Given that bidimensional simulations of each arcade are going to be carried out, it is necessary to define plane models for them.

Each model is built in the following way:

- Getting the proper shape of the arcade, eliminating minor details, but keeping the keypoints needed to identify main elements such as columns and arches. This shape is defined in a CAD file created from the real dimensions taken at the church
- Conversion of the CAD file to an IGES (format) file, which is compatible with ANSYS. Then, in meshing the model using structural plane elements (PLANE 42 with thickness). For this case and for smplicity, it´s been taken a thickness of 0,25 metre.

This model has a structural behaviour under its self weight absolutely independent of its thickness, since its variation affects at the same time to self weight and to the resistant section. However the value of thickness does affect to mechanical behaviour under roof loads that remain unaltered.

3.1.3 Information obtained throgh simulation

Two simulations are carried out for each arcade, transverse and longitudinal, correspondent to the state of the arcades before and after the removal of the brick shore.

The results of simulation give us information about the stress and strain status of the model under the applied loads. In this way, not only compression and tension stresses at every point of the model are obtained, but also deformations and displacements.

Six diagrams are obtained from each simulation:

- Horizontal stresses (sx), expressed in Pascals, which ANSYS shows in a colour code, maximum stresses in blue and minimum in red
- Vertical stresses (sy), with the same code
- Principal stresses (s)
- Displacements (u)
- Horizontal displacements at significant points
- Vertical displacements at significant points

3.1.4 Transverse arcade (propped up)

Its current status can be seen in this simulation, confirming that stresses and strains are acceptable for the constituent materials.

3.1.5 Transverse arcade (free of shore)

Two interesting observations can be made:

- First, there is an unavoidable deformation that tends to "open" the arcade, making the central arch "wider". Vertical elements show a batter towards the outside of the church and extreme tension stresses in the zone of keys of the arches indicating the appearing of inverted "v" cracks into the upper cob wall.
- Second, the removal of the brick shore may produce additional movements and progress of deformation of the whole arcade, with a serious risk of collapse.
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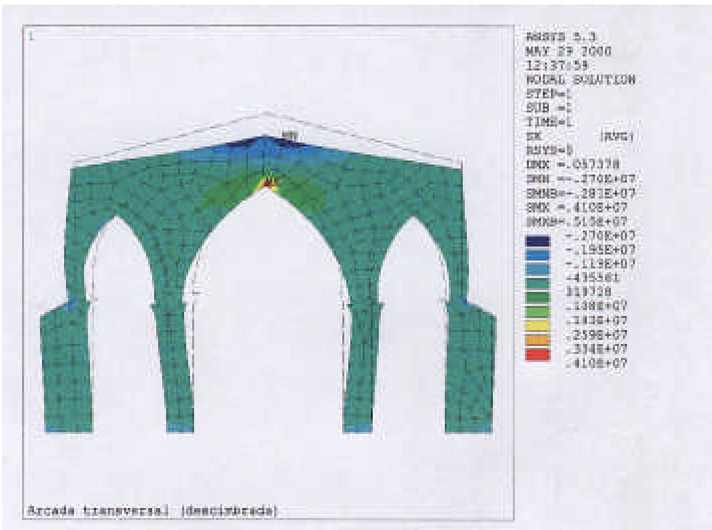

Figure 2

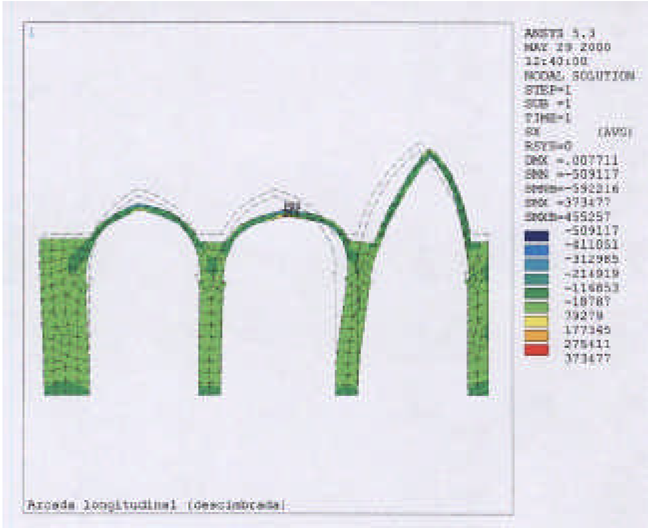

Figure 3

3.1.6 Longitudinal arcade (propped up)

The current reality can be also be seen, with enough stability in the propped arches, and the appearing movements in the cross aisle that can provoke cracks such as the ones already existing parallel to the arch.

- Por otra, en el momento de eliminar el apeo actual se pueden producir nuevos movimientos que hagan progresar la deformación del conjunto, con el riesgo de su colapso

3.1.7 Longitudinal arcade (free of shore)

Again, the following can be remarked:

- Tendency of the whole arcade to deform towards the altar, basically due to its structural system, with the arch of the cross aisle higher than the rest (but same span) and so, less stable in the horizontal direction considering thrusts coming from the other arches and crossing vaults.
- Thre is a remarkable risk of deformation progress during removal of the brick shore, and the possibility of reaching structural collapse if adequate repairs are not executed.

3.2 Belfry tower

From a structural and mechanical point of view, the behaviour of brick tower and stone masonry base can be considered separately. While stone base does not present any inclination (see photo on figure 1) the upper brick tower has about 4º of inclination towards the street (Rua de Dato).

Therefore, to analyse separately the part of the tower constituted by brick masonry could be acceptable as an approach to the problem of tower stability, which in fact suffers destabilizing effects of inclination.

In order to do that, three-dimensional simplified model of the tower is created, eliminating details such as the roof, the windows, etc.

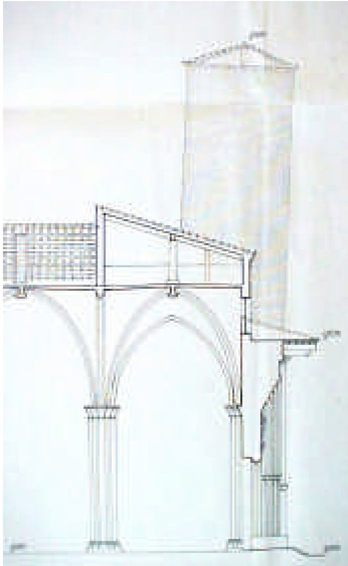

Figura 4

3.2.1 Modelling criteria

A three-dimensional box-shaped model is used, reproducing the main dimensions of the brick walls of the tower. Inclination is introduced by turning gravity's direction aside the adequate angle, resulting the following Cartesian components:

X axis "g" component: 9,8×sen4º

Y axis "g" Component: 0

Z axis "g" Component: 9,8×cos×4º

In addition, wind loads are introduced, according to NBE-AE Spanish standards, applied as surface loads over the appropriate faces.

3.2.2 Information obtained from simulations

Two simulations of the tower are carried out, in its current state and after the incorporation of tie down stays.

In the present situation, it can be clearly observed that stresses are distributed as in a cantilevered beam. However their value goes from a maximum of 0,63MPa, in the front façade, to a minimum of 0,14MPa, in the back façade, being both walls in compression (figure 5). The resultant displacement on top of the tower in this simulation has a value of 7mm.

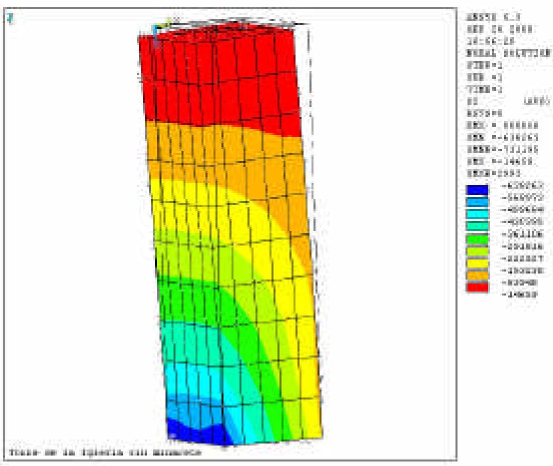

Figure 5

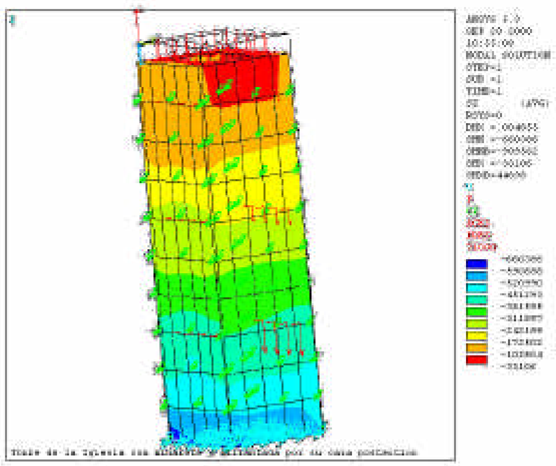

Figure 6

A model of the tower incorporating the tie down at three different heights is also been simulated, what permits to reduce to almost zero the difference between stresses at both, front and back, façades.

It is also possible to reduce to minimum the displacement on top of the tower (figure 6).

4 CONCLUSIONS AND PROPOSED REPAIRS

The two simulated arcades can be considered as enough representative of the church, due to the symmetry of its plan, so that, from the obtained results we can reach the following conclusions:

4.1. Structural stability of arches and vaults

Assumed the absence of foundation settlement, and taking account of the work of the existing brick shore, it's proved that the dimensions of the structural elements are enough to resist stresses generated by current loading; tension stresses tend to provoke cracks (which in fact have already appeared) without a serious danger of collapse; otherwise compressive stresses are perfectly absorbed by the constituent materials of the structure.

On the other hand, simulation of the arches without the current shoring indicates a series of descents of the keys of the arches and displacements to the outside in the starting points of the arches that drag capitals, columns and pilasters with buttress along with them, with an evident danger of collapse, specially thinking of their progress along time.

All of this makes sense by analysing the structural situation, with the following factors:

4.1.1 Arches with different dimension starting at the same height:

The existence of arches of different dimension at the same arcade creates an important structural problem since their different thrusts over one single capital remains always unbalanced, appearing as a result, horizontal forces that push apart the smaller arches causing its deformation (figure 7).

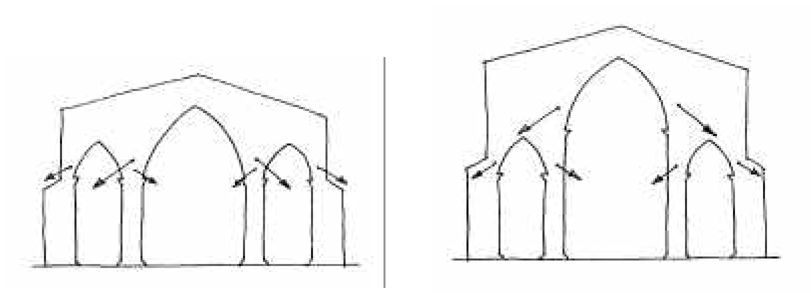

Figure 7

4.1.2 Roof wooden frame leaning over keys:

The existence of small pillars over keys of arches and vaults that transmit vertical loads coming from the roof structure, generates punctual forces that easily produce stress concentration which become in cracks and descents of the keys, as a first step before collapse.

4.1.3 Poorly dimensioned buttress:

External wall buttress adjacent to pilasters at the ends of the transverse arcades, are scarcely scaled and of low height. This makes that buttress cannot balance horizontal thrusts coming from the arches, provoking the inclination of the columns.

4.2 Tower stability

The data obtained through simulation indicate that the tower is actually stable, with small displacement towards inclination.

The concentration of compressive stresses on the front façade is not alarming, since its maximum value of 0,812MPa can be transmitted without problems to stone base and be distributed properly through this base to foundation.

However, given the plasticity of this masonry, due to plaster mortar and its special sensibility to moisture, long term deformations may occur because of the stress unbalance.

5 RECOMMENDED REPAIRS

The actions to correct the observed defects must be oriented to recover stability of structural elements, taking in account their mechanical function, their constituent materials and the structural system as a whole. Let's see which of them we consider more important, following the same sequence than in precedent exposition:

5.1 Starting point of arches at the same height

Since it is an inherent character of the building itself, intervention must be oriented to mitigate this defect by other compensations that reduce unbalanced horizontal thrusts to the outside, or compensate them either. The following can be considered:

Horizontal tie of cob walls over transverse arcades; with this solution horizontal tension stresses on the keys of the arches could be reduced, especially on the central ones. In fact it is quite similar to tie stays that appear in Renaissance buildings tying together the start of many arches. Anyway it would be a partial solution, which cannot be used separately but in combination with the following:

Reinforcement of buttress on the six pilasters of transverse arcades.

5.2 Small pillars over keys of arches

To avoid punctual load concentration transmitted by that pillars, the most suitable solution is to eliminate them and substitute this leaning by another, not introducing anomaly loads on arches and vaults. In this way we consider a roof structure that leans uniformly over arcades, in the same way that the upper cob walls do now on the transverse arcades.

5.3 Simulation of proposed solutions

After introducing on transverse and longitudinal arcades the boundary conditions correspondent to proposed repairs, such as tying cob walls and eliminating the influence of roof pillars, with the consequent load centring over internal columns, new simulations are carried out. The metallic ties are introduced in the model as pairs of opposite forces acting in their ends (figures 8 and 9).

The results of this simulation shows that these solutions allow to reduce drastically the observed displacements in precedent simulations, so in transverse arcade as in longitudinal one.

5.4 Tie down of the tower

Incorporation of tie stays that compress the back face of the tower is a guarantee of drastically reduce inclination progress (figure 8).

The simulated stays represent tension loads of 4×10T, at the highest level, 4×20T at the intermediate and 4×30T at the lower one. At the same time the tower is tied horizontally with 4×10T at every level, to compress it in horizontal direction too, so to eliminate possible tension stresses deriving from side effects of vertical main stays (figure 10).

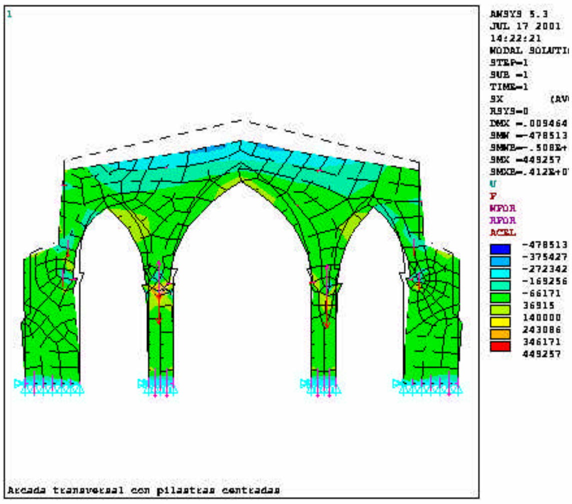

Figure 8

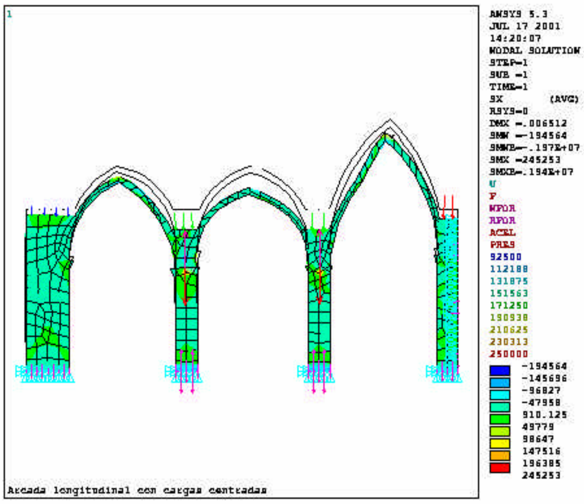

Figure 9

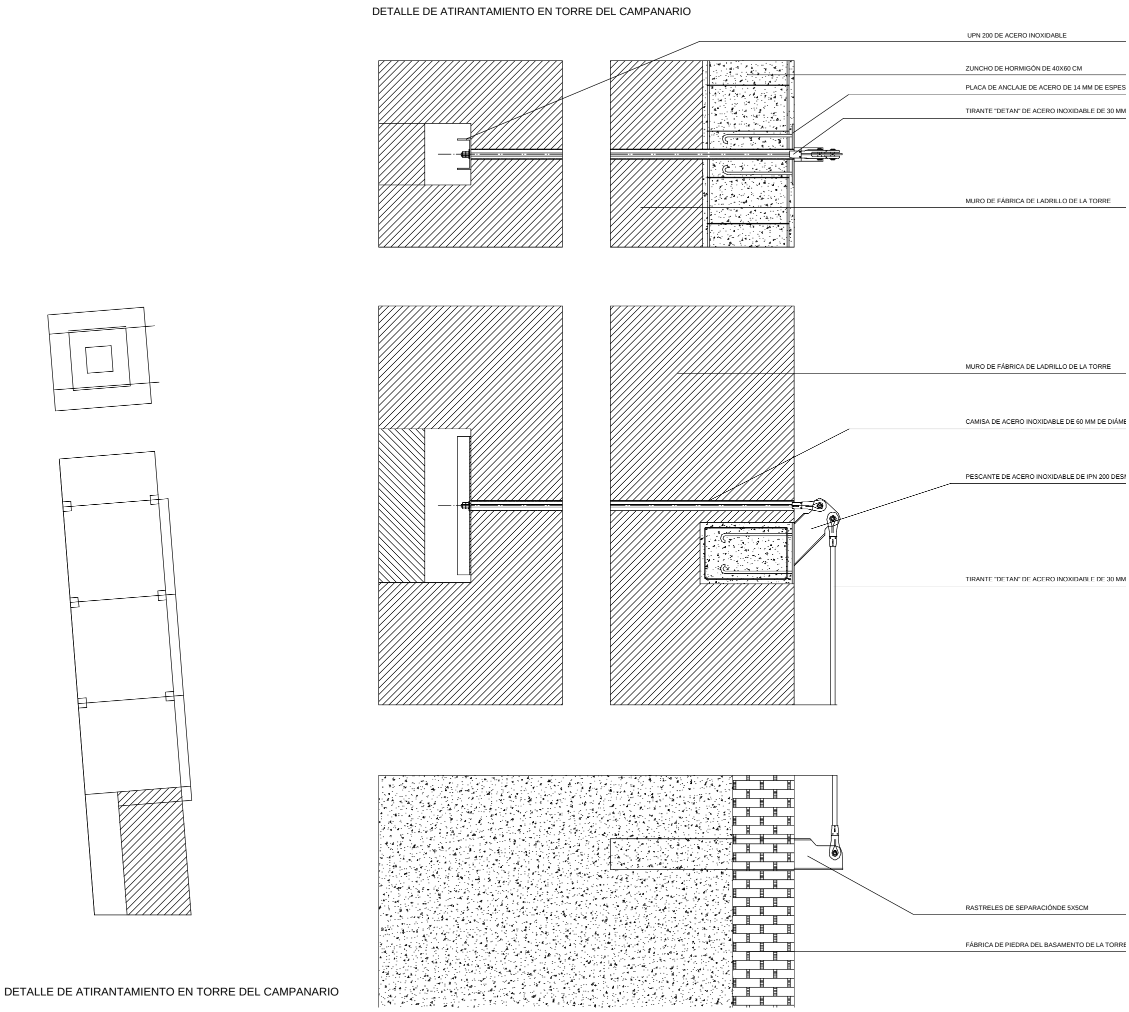

Figure 10