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Non conventional solutions for the consolidation of bell towers

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ABSTRACT: During 2003, the authors of this paper achieved the first phase of the consolidation of the XVIII century bell tower of the monumental parish church at Vistabella del Maestrazgo (Castellón, Spain). For this first intervention, a very precise survey study was carried out on the structural problems of the bell tower through the analysis and interpretation of the cracking and deformation maps. Nevertheless, in this occasion only a few restoration works could be done due to both financial problems and the emergency character of the intervention. In 2006, after two years of detailed monitoring of the bell tower movements, the same authors have been able to design a second phase of restoration aimed to solve the serious and still existing structural problems.

1 INTRODUCTION

1.1 *Description of the church*

The parish church of Nuestra Señora de la Asunción at Vistabella del Maestrazgo (Castellón, Spain) (fig. 1), a monumental temple built during the 17th century, was a compulsory last stop for the pilgrims going to the famous sanctuary of San Juan de la Peñagolosa (Fernández 1995). The church with its three naves has a bell tower thirty meters high that is located at the foot of the church, over the first vault of the right hand nave, supported at the corner of the South and West walls of the church and the inside first buttress of the lateral nave (fig. 2).

The bell tower is built with ashlar work in the most conspicuous areas of the exterior facade combined with masonry walls in the rest of the exterior and inner facades. It has three levels in height: a first level with the same height of the temple where the secondary access to the church is located; a second level, between the bell tower's lower cornice or temple cornice and the bell tower's middle cornice, where the facade clock is inserted; and a third level that forms the crowning of the tower and houses the tower bells. These three facade levels correspond respectively to three inner spaces, each one covered by a crossed vault (fig. 3). The vertical access to the bell tower takes place through a round stairway located inside the Southwest corner that ascends from the ground floor of the church till the roof of the bell tower.

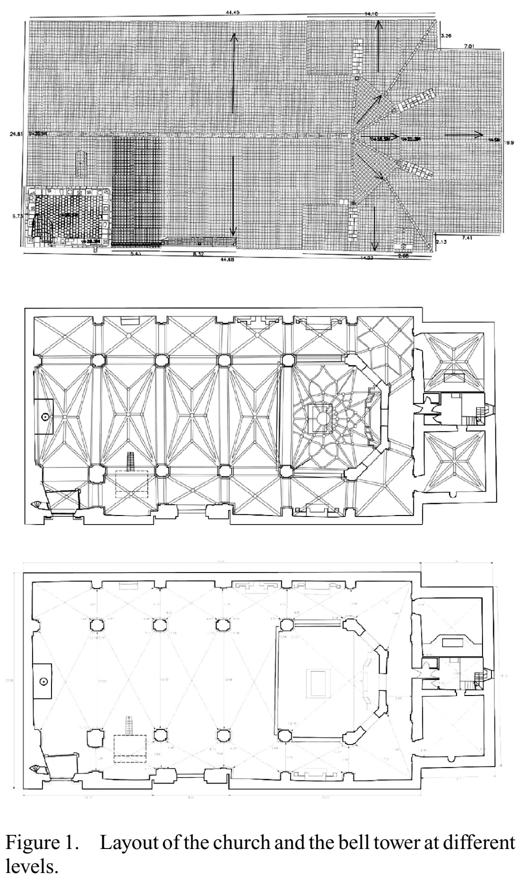

Figure 1. Layout of the church and the bell tower at different levels.

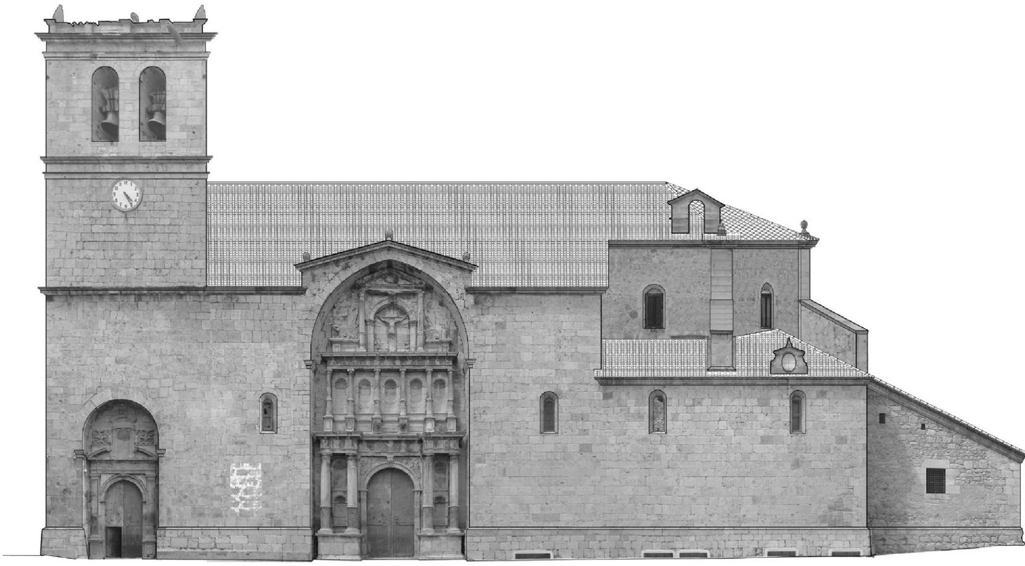

Figure 2. South elevation of the church with the bell tower.

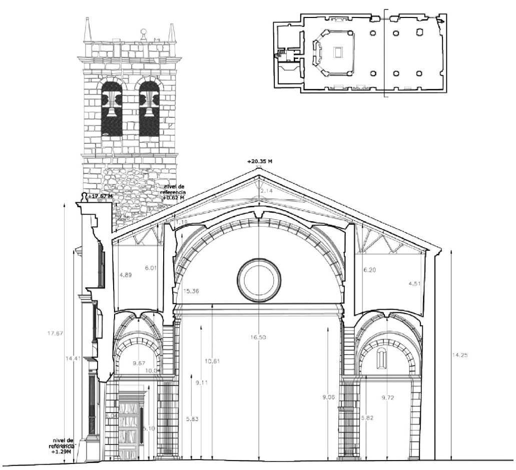

Figure 3. Church's section and East elevation of the bell tower.

2 THE 1ST INTERVENTION PHASE

2.1 *The bell tower study developed during the 1st intervention phase*

During the first intervention phase that took place between 2002 and 2003 (Vegas & Mileto 2005), an accurate study of the bell tower was made in order to detect its structural and material problems. First, a very precise survey with both traditional and technological methods was done to draw the layouts, sections, facades and deformations. Second, a study of the materials and constructive techniques was developed. Third, a detailed map of the cracking situation and deformations of the bell tower was drawn. Besides, deepening studies were conducted: the study of the subsoil of the bell tower and the surrounding area (geo-radar explorations, archaeological surveys and geotechnical surveys), a structural analysis, mortar characterization and lichen studies (Vegas & Mileto 2005).

The detailed study of the bell tower detected structural cracking, tilting and overhang that could be attributed to several causes. The complex cracking pattern of the facades showed cracks that sometimes arrived up to 25 cm wide. Besides, the bell tower presented an overhang of 22 cm at the top of the Southwest corner and convex and concave deformations up to 4 cm in the horizontal sections of the upper part of the bell tower. A stone flattening phenomenon was detected at the base ashlars of the Southwest corner, with little vertical fissures, due both to the tilting of the tower towards the Southwest and the weakening of the Southwest corner because of the presence of the round stairway.

The movements of the bell tower had also caused deformations, and cracking of the bell tower vaults, till the point that the roofing vault showed up to three previous collapses and reconstructions. The opening of the crowning walls of the bell tower had caused the dislocation of several upper bell tower arches, where several voussoirs and ashlars had lost support and stability. Besides, the arches of the lateral nave of the church where the bell tower is standing on were completely deformed under the weight of it. Last, the

untimely insertion of the clock in the South facade without creating an arch in the wall perforation, either on the outer or inner side of the facade or the filling, had caused the settlement of the ashlars over it.

2.2 *Restoration works done during the 1st intervention phase*

The 1st intervention phase (Vegas & Mileto, 2005) was focussed to solve the most serious problems of the bell tower as well as to avoid the worsening of the degradation phenomena. First, the voussoirs of the dislocated upper bell tower arches were either jacked up or dismantled and rebuilt to the former position. Second, a tightening system for the bell tower crowning with six stainless steel cable braces was installed on the bell tower's upper cornice to avoid its continuous opening caused by the V-shaped cracks coming from the base.

Other works aimed to the conservation of the bell tower were made, both from a structural and material point of view: the parapets' ashlar work in the bell tower upper arches was dismantled, relocated and sewed with fibreglass to the existing buttresses to prevent them from collapsing; a new layer of lime mortar and a new ceramic layer was applied to the existing roofing flat vault in order to thicken the vault supporting section; a structural metallic arch was designed and installed in the clock hole to hold the wall above it and simultaneously permit the clock machinery to function normally; the empty joints of the stone wall were injected and filled with mortar to restore lost strength to the stone wall and to prevent rainwater from entering and the ensuing formation of ice; and the cornices were cleaned and consolidated, especially where they were threatening to come loose and collapse (Pita 2002).

3 EXTENSION OF THE STUDY

3.1 *Extension of the survey*

The development of a second project during 2006 for the consolidation of the bell tower has brought the extension of the already done survey to the whole of the church in order to deepen in the structural pathologies of the bell tower, partly linked to the connection with the church itself.

3.2 *Monitoring of the cracks in the stone wall*

After a visual examination and an accurate recording of the cracks of the bell tower done during the first phase of intervention (Vegas & Mileto, 2005), nine movement monitors were installed on significant cracks, plus another one that exclusively measures the variation of temperature, all in order to obtain a two-year record of the possible movements of the bell tower cracks (Serna 2004). At the moment of writing this paper, measures that correspond to two and a half years' monitoring have been already collected.

3.3 *Conclusion of the monitoring of the cracks*

The measures taken during this period confirm in general terms the first provisional conclusions made during the first phase of intervention (Vegas & Mileto 2005). Bigger or smaller movements are to be observed in practically all the cracks of the bell tower. Among all of them, attention should be paid to the crack with the monitor number 6 that could worsen the flattening phenomenon on the Southwest corner, and the crack with the monitor number 1, because of the settlement of the arch of the interior nave under the East facade. The thrust of the vault of the main nave at the foot of the church is causing the closing of crack with the monitor number 7 and, therefore, an accurate study of the adjacent vaults and arches to the bell tower of the church should be done in order to better solve these movements.

In any case, it seems at first sight necessary to give back strength to the bell tower through the after the 1st intervention still to be done repointing and injection of mortar in the two lower levels of it; the insertion of tightening braces to restrain the further opening of the cracks; and the repair of the flattening phenomenon at the Southwest corner. The facades walls show a deformation map that helped understand some of the movements of the bell tower. The arch under the East facade had settled in such a way that it had dragged the upper masonry wall down with it.

The arch under the North facade has also suffered deformation, settling and leaning towards the West wall at the foot of the church, accompanying the movement caused by the thrust of the last vault in the central nave on the closing wall at the foot of the church.

3.4 *Cracking in the stone walls*

The cracking picture of the stone walls is complex and due to multiple reasons. The general causes of cracking that can be found in the bell tower are fundamentally: settling of the stone wall, opening because of unequal sinking in the foundation, flattening and opening of the walls because of the settling and horizontal thrust of the arches and vaults, those inside the bell tower and those adjacent to the central nave of the church. All these cracks have been enlarged by everyday weather, particularly, rain and ice.

4 THE 2ND INTERVENTION PHASE

4.1 *Generally adopted methodology and criteria*

The second consolidation phase of the bell tower, to be implemented during the year 2008, has been

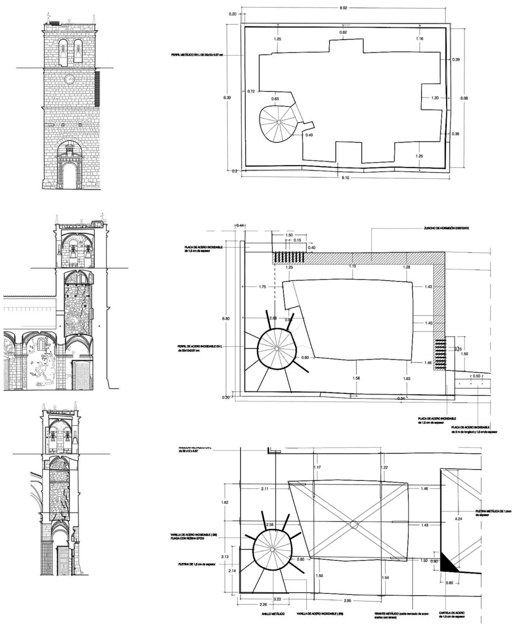

Figure 4. Projected braces for the bell tower at levels 1, 2 and 3.

designed with the collaboration of the structural engineers Giulio Mirabella Roberti from the University of Pavia, and Adolfo Alonso and Arturo Martínez of the Universidad Politécnica of Valencia. The consolidation will use stainless steel braces, reinforcements and profiles that adapt themselves to the shape of the bell tower and the complex connection between the bell tower and the church. These elements will be installed in most cases in non visible places (like the interior of the round stairway, under the roof eaves of the church, in the hidden space between the vaults and the roof of the church . . .), will be reversible and inspectionable. Each element has been specifically studied and designed to fit the existing bell tower and solve the structural requirements and stresses.

4.2 *Injection and repointing of the two lower levels*

During the 1st intervention phase, the empty joints of the stone wall in the upper lever of the bell tower were injected and repointed to restore strength to the stone wall and to prevent rainwater from entering. The 2nd intervention phase previews the extension of this action to the rest of the bell tower to give the bell tower better strength and further waterproofing. In any case, the injection and repointing will respect the original existing mortar joints wherever they present a good state of conservation. This selective repointing to be made with hydraulic lime mortar in a similar proportion as the historic walls, i.e. 1:2 or 1:3, is therefore to be implemented only in the existing voids and gaps of the joints, setting itself slightly back and not overlapping the historic mortar of the joints.

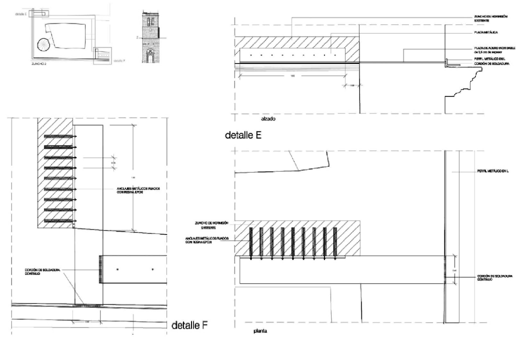

Figure 5. Constructive detail for the brace at level 2 (lower cornice).

4.3 *Installing of the structural restraint systems of the bell tower*

During the 1st intervention phase the opening of the bell tower's crowning was tightened by means of the insertion of stainless steel cable braces at the upper cornice. During the 2nd intervention phase, other braces at three different levels are to be inserted to tighten the bell tower and stop its opening (figs. 4–5). Given the diversity of the characteristics of the bell tower, the proposed solutions are different and specific for each case.

- Level 3 (at the middle cornice). At this height, the bell tower is still free-standing from the church, so that a perimeter restraint for the bell tower to stop its opening is still possible. In this case, this exterior brace will be done with a stainless steel L-profile 20 × 12 cm that will seize the perimeter of the bell tower and will be placed on its middle cornice in order to avoid as much as possible its direct vision from the streets. Given the irregularity of the bell tower's exterior shape this brace will be composed of several shorter profiles to be welded in continuity so that they will be able to adapt to the polygonal bell tower's contour. If necessary, hydraulic mortar will be poured on the back of the profile to fill the little gaps in order to ensure a better contact of the bell tower's whole perimeter.
- Level 2 (at the lower cornice). At this level, the bell tower is not longer free-standing and forms part of the church's body in two of its four facades. The installation of an exterior brace is much more difficult and less evident at this level. First, at the

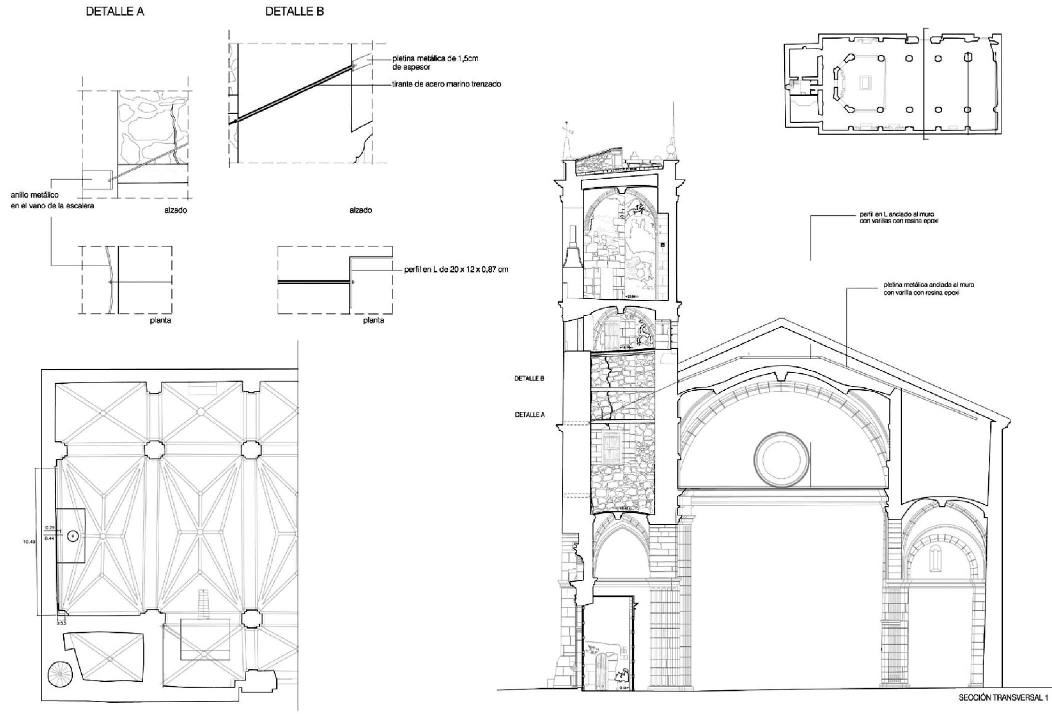

Figure 6. Example of ties between the bell tower and the church.

exterior facades the bell tower has its lower cornice where a similar L-profile as the one installed at the middle cornice may be installed. In a previous intervention of 1992 conducted by other architects with different criteria, a reinforced concrete brace inserted in the masonry fabric was made at this level of the bell tower as part of the consolidation of the whole church that substituted the whole roof old structure. Even not sharing this intervention philosophy already done in the past because of the rigidity and invasive character of the reinforced concrete, in our project we use the unavoidable presence of this concrete brace in order to be able to tie together the bell tower exterior profiles.

Thus, we connect the exterior profiles with the existing reinforced concrete brace with two 40 cm wide plates to be welded to the exterior profiles and anchored to the interior concrete brace. The width of these two plates is due to the necessity of resisting horizontal stresses. At this level, a structural stainless steel ring plate is also inserted in the interior walls of the round stairway that will be connected both with the exterior stainless steel profiles and the rest of the masonry fabric by means of metal bars. This element will serve as contention and reinforcement of the corner as well as an anchorage to the church.

– Level 1 (half way the height of the church facade). Even not existing a cornice to place a brace, the need of tighten the bell tower at this level has forced us to create a different restraint system as the two upper levels. In this first level, we shall use again the same system with stainless steel cable braces that was used during the 1st intervention phase at the bell tower's upper cornice. Six cable braces will be installed, three on each side, that hold the fabric through small stainless steel plates in the exterior facade and a continuous bigger stainless steel plate in the interior side, placed in a hidden space. The two braces that arrive to the round stairway will be connected to a second stainless steel ring plate placed in the interior walls and linked to the exterior plate through metallic bars (fig. 7). This element also allows tightening the bell tower's corner.

4.4 *Connections between the bell tower and the church*

The increasing movement of tilting of the bell tower towards the Southwest corner suggests to tie it with the rest of the church in order to stop this living movement of detaching. Therefore, it has been necessary to tie the bell tower to the church in two directions (along the South and West facades) in order to counteract

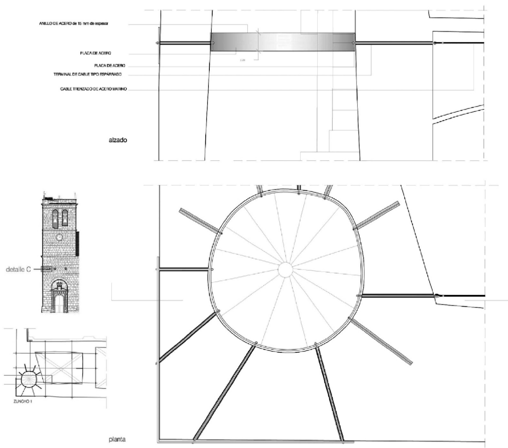

Figure 7. Detail of the round stairway reinforcement at level 1.

its movement (fig. 6). In order to invade as less as possible the interior of the church, the most obvious and direct solution of installing visible cable braces in the first bay of the church nave has been rejected and alternative non visible solutions have been designed in every facade and level.

First, two ties at two different levels have been designed along the South facade. The upper tie will take place at the height of the middle bell tower's cornice where a stainless steel plate 40 cm wide will be welded to the exterior stainless steel brace and placed on top of the church's facade wall in order to be able to hide it under the roof tiles. This element will be connected with the church's wall through 2 meters long metallic bars inserted vertically in it with epoxy resin. The second lower tie between the bell tower and the church will be placed at the level of the bell tower's lower cornice, placed in the interior face of the church's wall over the lateral nave, through a 40 cm wide stainless steel plate that will be fixed with the help of metallic bars and epoxy resin along the South wall and a steel cable brace to the bell tower's round stairway.

Second, two other ties at two different levels have also been designed to connect the bell tower to the church along the West facade. A stainless steel 20×12 cm L-profile is to be placed on at the height of an interior church cornice connected with a metallic cable brace to the reinforcement stainless steel ring plate in the round stairway at the bell tower's level 1. In the upper level, placed in the hidden space between the vaults and the roof of the church, several stainless steel plates welded in continuity and connected at the level 2 to the bell tower's brace have been designed to follow the shape of the church's gable end to be completely invisible for the visitors.

4.5 *Repair of the flattening phenomenon at the Southwest corner*

The bell tower's Southwest corner, at its foot, has a clear flattening phenomenon that should be taken care of. A solution for this corner has been designed after the example of the interventions designed by Prof. Luigia Binda (Polytechnic of Milano) and Prof. Claudio Modena (University of Padua) for some bell towers in Italy (Binda et al. 2001). The proposed consolidation consists of a disseminated reinforcement in all the lower part of the corner affected by flattening little but dangerous cracks, where the tower apparently stands on a single buttress because of the presence of the secondary entrance of the church (fig. 8). This intervention will be done through the insertion of reinforced joints and the connection between the interior and exterior of the masonry fabric with its own nucleus.

The reinforced joints will be done emptying 10 cm of the ashlar work joints in all the length of the corner, inserting three 6 mm in diameter corrugated stainless steel bars or a flexible stainless steel plate 1–1.5 mm wide in the joints, filling the interior with hydraulic lime mortar and repointing the exterior with aerial lime mortar. These elements, both bars and plates, will be welded to perpendicular bars that will connect them to the wall nucleus through holes drilled in the masonry. Being the interior of the round stairway a masonry fabric and therefore not having clear horizontal joints to be reinforced in parallel with the exterior facade, only perpendicular bars will be deeply inserted as reinforcement from the inner side. These bars will overlap the perpendicular bars inserted from the exterior in order to form a continuous reinforced ashlar and masonry fabric that should notably improve the behaviour of this wall against the flattening phenomenon. This little sacrifice and loss of historical mortar bring a great relief to the flattening stresses that affect both the stone and the mortar and is worth as long as allows the bell tower to survive this dangerous phenomenon.

5 CONCLUSION

The previous described consolidation devices such as repointing the walls, bracing the bell tower at different levels, tying the bell tower to the church, or introducing reinforced joints at the bottom of the corner, will help to solve the structural problems of the bell tower and, at the same time, will try to reduce to the minimum the impact of the intervention in the historical structure. Compatibility has been pursued both from the point of view of material, structure and character of the bell tower (Mileto & Vegas 2006). The structural consolidation of the parish church at Vistabella del Maestrazgo has been an opportunity to reflect on the

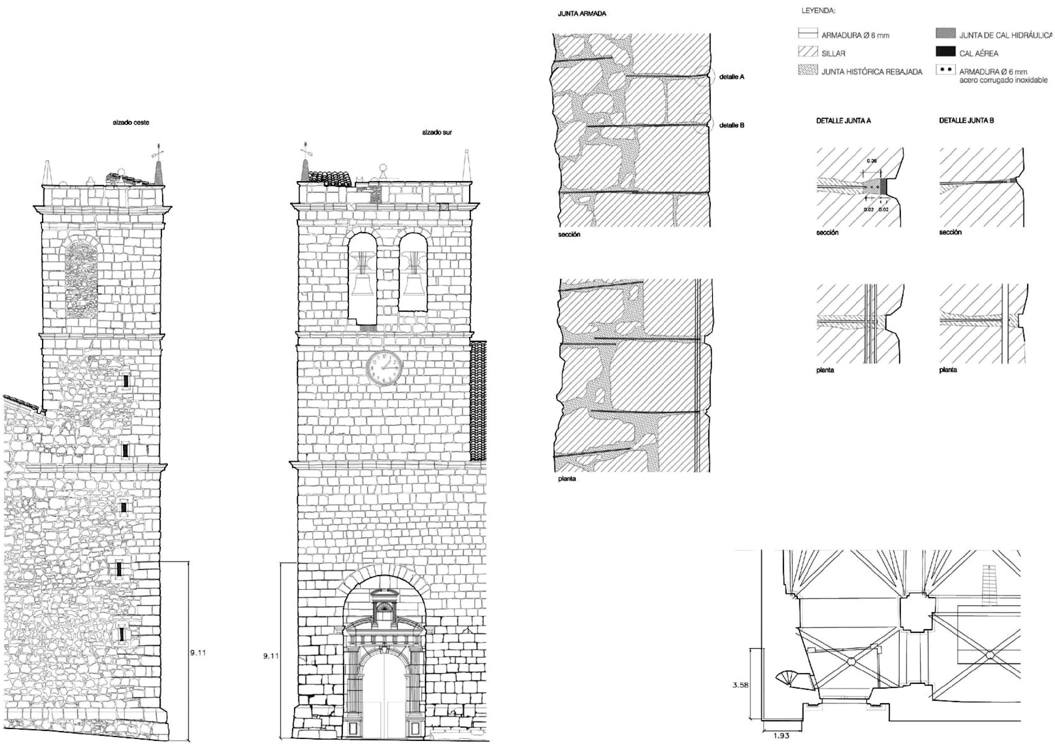

Figure 8. Reinforced joints to repair the flattening at the SW corner.

necessity of conceiving, designing and implementing specific structural solutions for each part of a historical building with the aim of ensuring the maximum conservation of the monument in all senses.

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