THE PIANURA PADANA EMILIANA EARTHQUAKE

Following the earthquakes of May 20th and 29th,2012, which involved an extensive part of Emilia territory (the Western part of Emilia–Romagna), ENEA has been involved in the operations of usability testing and post-earthquake safety interventions on the various construction typologies existing on the territory.
This paper is focused on cultural and artistic interest constructions, only. After the seismic event, many churches and historic buildings have suffered significant damage. Some of these have undergone devastating and permanent damage.
Others can be restored if immediate safety interventions will be realized before carring out the appropriate retrofitting interventions, in order to preserve the historical construction from worsening the damage.
The example presented below, concerns the Visitazione di Maria Santissima Church in Reno Finalese (Modena). ENEA proposed a safety intervention, which has been approved by the Regional Directorate for Cultural Heritage and Landscape in Emilia-Romagna

Post-earthquake safety interventions on the Visitazione di Maria Santissima Church in Reno Finalese

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The church history

The Reno Finalese parish was built because the faithful could not reach the town of Finale Emilia when the Reno River flooded. It is datable before 1487. Information comes to us from the date when the baptismal font was placed, in 1465.
The oldest bell tower, rising on the West side, dates back to 1506, and was equipped with two bells and a clock. On the East side, in 1933 a modern bell tower was built and completed in 1948. It was 38 meters high and hosted three bells.

Damage analysis

Due to the earthquake that affected the Emilia-Romagna region in May 2012, the Visitazione di Maria Santissima Church in Reno Finalese (Modena) (Fig. 1) has

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FIGURE 1 Geographical context of the Visitazione di Maria Santissima Church on a GIS map

FIGURE 2 The main façade

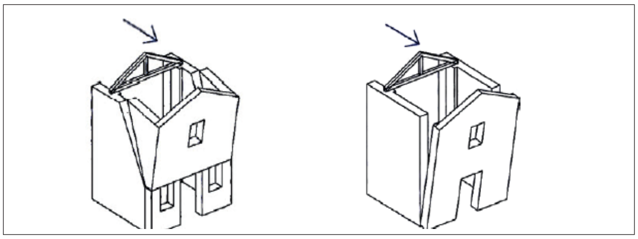


FIGURE 3 Overturning of the façade

suffered widespread damage, in terms of both structures and inside decorations. A group of engineers and scientists of ENEA has carried out a series of checks and on-site surveys, which allowed to identify the damage mechanisms and, thus, to propose a plan of post-earthquake safety intervention for the ecclesiastical building, while waiting for its overall consolidation.

The damage of the building is due to mechanisms typical of this type of construction, being evidenced in other churches located in the area affected by the earthquake, such as Buonacompra, Mirabello and San Felice sul Panaro.

The most evident effect of the seismic action is the collapse of the upper portion of the main façade of the church, due to the lack of connection with the transversal walls. The occurred mechanism is the vertical overturning of the Façade and the collapse of the top one. The non-collapsed part of the façade is separated from the transversal walls and greatly inclined towards the churchyard. The two façades of the lateral naves are connected to the transversal walls and are lower than the main one, therefore they are less damaged (Figs. 2-3).

Both the portion of the roof directly connected to the main façade and the façade itself collapsed at the same time. The timber trusses appear to be connected to the walls, with the "*capochiave*" (anchor plate) clearly visible outside. It is a light pushing structure, 16-18° inclined. Recently, the roofing completion elements located on the secondary frame timber structure, are restored by substitution of the damaged elements with hollow fine bricks.

The central nave has a painted false ceiling made of canes, on which a layer of stucco provides the base of the painting. It is connected to the upper timber trusses and is severely damaged (Fig. 4). On the contrary, the frescoed ceiling of the lateral naves, which are made of "*in sheet*" arranged bricks, have collapsed in many parts, especially in the left nave (Fig. 5). In addition, the cracks' distribution and their depth outline a dangerous condition for the entrance.

The cracks' pattern (Figs. 6-8) related to the façades shows a rather critical situation: in addition to the overturning mechanism, many other deep cracks are visible, which are particularly severe. Moreover, a passing through vertical crack located between the second and third arch has been surveyed, also by using a thermal imaging camera (Figs. 9-10).

Other evident cracks are located between the central nave and the apse, where the walls seem unconnected to each other. A horizontal crack at about 2 meters from the ground level is surveyed on the pilaster on the right of the apse, in addition to a slight rotation. Moreover, diagonal cracks on the doors and separation of the corner have been evidenced on the wall located on the right of the apse (Fig. 11). On the contrary, on the left side of the apse, the presence of the oldest tower has provided a connection function between the two walls. In any case, the sacristy wall has been damaged because of the hammering action of the more rigid structure of the oldest tower on it (Fig. 12). Cracks are also present at the bottom wall of the apse.

An overturning mechanism is located on the right nave (Fig. 13), in addition to several diagonal cracks. An arch separating the naves shows a severe crack and a relative translation between the two realized parts, despite the presence of the metallic tie (Fig. 14). On the left nave, no mechanism has been evidenced.

Very serious damage have been surveyed on the two towers of the church. The oldest tower – which is the original bell tower nowadays substituted from the more recent one – is about 16 meters high. With masonry structure and equipped with metallic ties in both directions, it shows a very critical situation. The separation and expulsion of the corners (cantonal) occurred, which predicts a potential global collapse of the tower and the subsequent increasing in the damage of the structures below it (Figs. 15-16).

FIGURE 4 The false ceiling of the central nave

FIGURE 5 The collapsed vaults of the left nave

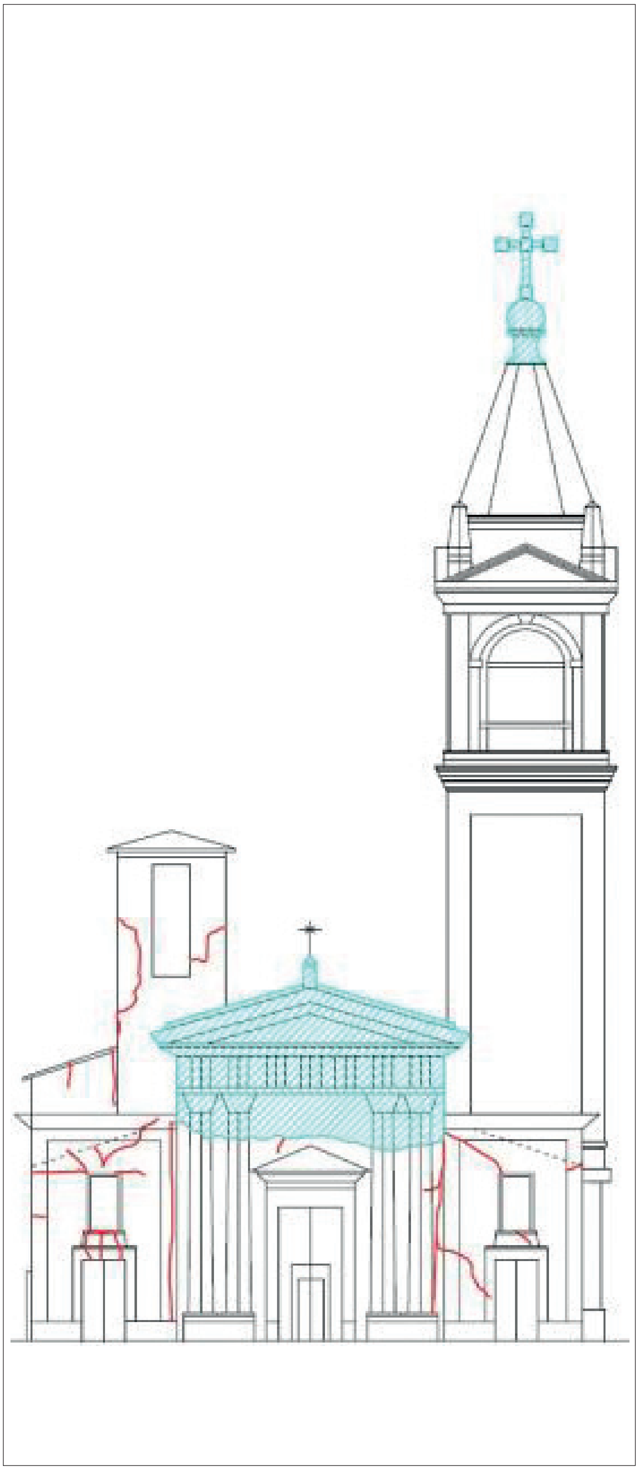


FIGURE 6 Cracks on the main façade

FIGURE 7 Cracks on the east side

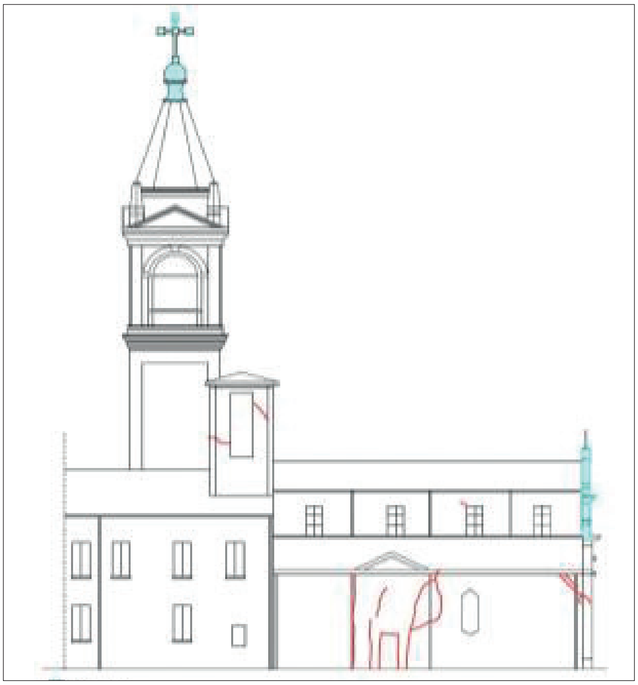


FIGURE 8 Cracks on the west side

FIGURE 9 Passing through vertical crack

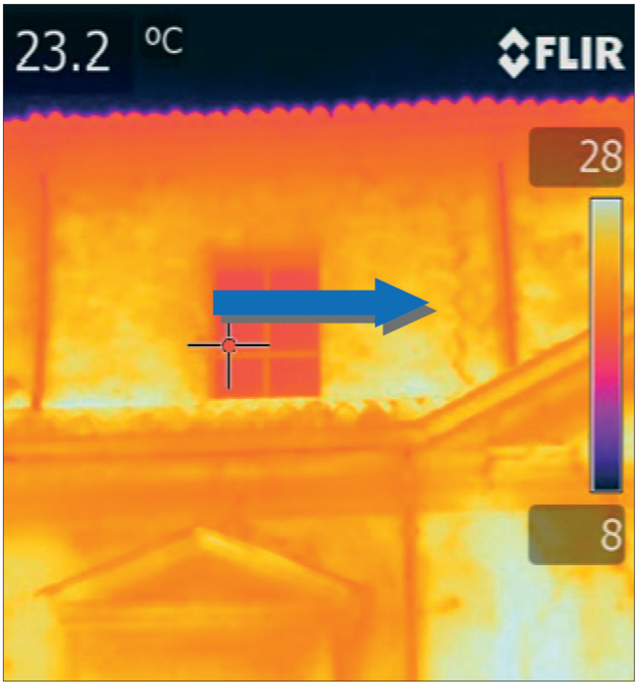


FIGURE 10 Passing through vertical crack (thermal imaging camera)

FIGURE 11 Horizontal crack on the pilaster

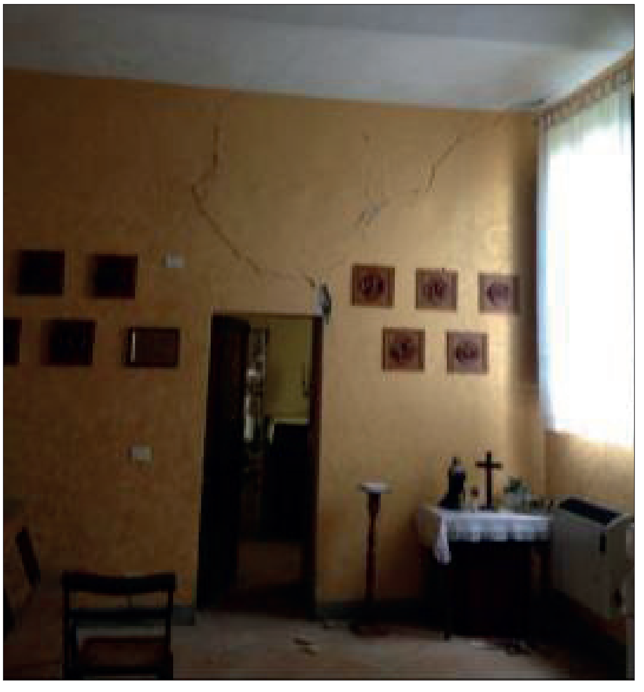


FIGURE 12 Diagonal crack on the sacristy wall

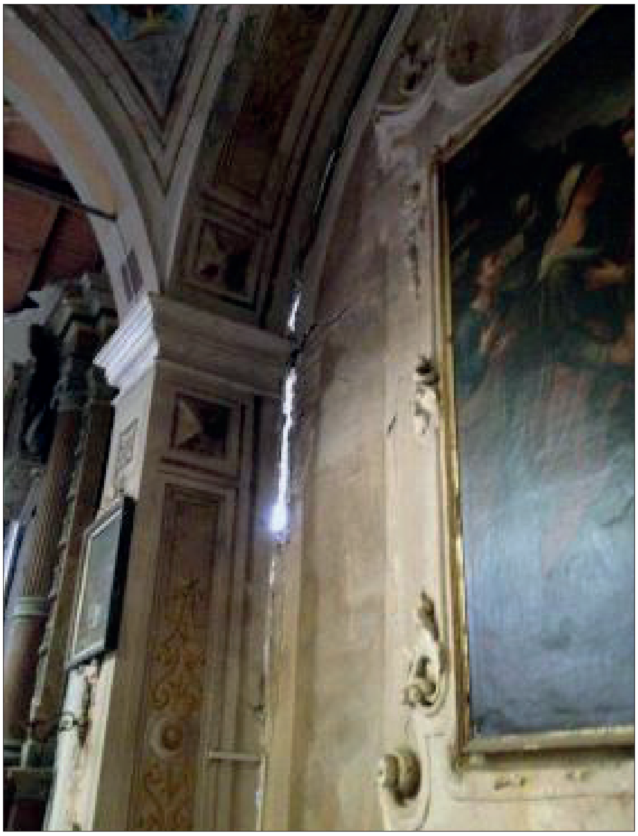


FIGURE 13 Overturning mechanism f the walls on the left nave

FIGURE 14 Crack and translation on the arch

The more recent tower, being made of solid bricks, is more than 38 meters high and was built adjacent to the right side of the church using bricks and concrete. The earthquake caused the twisting of the whole structure, cutting it at about 2 meters from the ground, in correspondence of a discontinuity in the material of the basement. In addition, a minor rotation occurred (Figs. 17-18).
Further damage has not been observed above the horizontal crack, at least from the outside. The steeple, which is also cut and rotated at the base, has been quickly removed in order to ensure the passage through the nearby street. Finally, the more recent bell tower is dangerous for the street users and surrounding buildings in case of collapse, in addition to the potential danger for the whole adjacent structure of the church.

Proposed safety interventions

Basing on the surveys carried out on site and the documentation provided by the Engineering Department of the City, we suggested and d signed an appropriate safety intervention.
The planned measures can be listed as follows:

1) Safety of the overturning mechanism of the façade;
2) Ringing of the perimeter walls;
3) Removal of the cover;
4) Ringing of the original bell-tower;
5) Ringing and insertion of vertical ties on the more recent bell-tower.

The intervention should be articulated in two phases and should be realized from outside of the church, in order to guarantee the safety of the

FIGURE 15 Separation and expulsion of the corner

FIGURE 17 The more recent bell tower

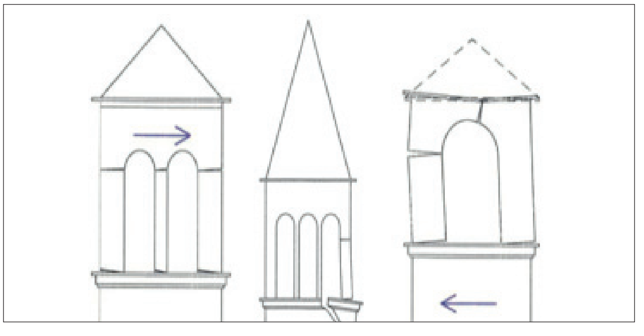


FIGURE 16 Typical damage mechanisms for bell cells

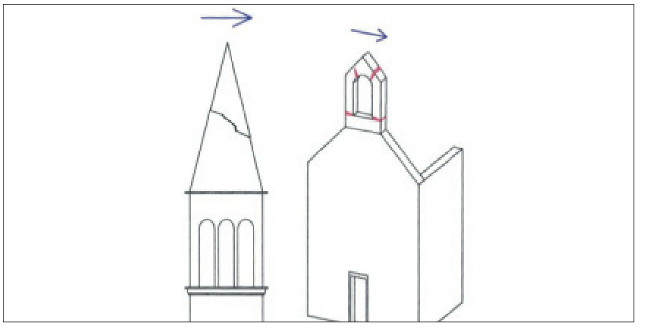


FIGURE 18 Typical damage mechanisms for projections

operators. In particular, the first phase consists in blocking the overturning mechanism of the façade and ringing the perimeter, in order to give a box behaviour to the whole complex structure. The second one consists in removing the cover and ringing the more recent bell-tower.

Afterwards, the existent covering structure, which is severely damaged, should be removed by means of a telescopic mobile platform, on which workers can operate safely from the external side. A new temporary steel structure will be realized, which accomplishes three functions (Fig. 19): it realizes the temporary cover of the church, protecting it against both rain and snow; it provides the upper protection plan and allows to enter the church for the subsequent consolidation phases; it provides the work plan support below the ceiling, when the latter is being restored. In particular, both vertical and horizontal structures are realized by coupled C profiles, while the inclined one consists of a reticular structure made of box profiles. The horizontal working floor is realized by wooden planks, which are light and of easy realization. The whole structure is reversible and easy to assemble and dismantle. It is worth noticing that the vertical structures are Y-shaped and are located at the windows' position, aiming at avoiding additional damage to the frescoed ceiling (Fig. 20).

With reference to local safety interventions, all doors and windows of the façade should be ribbed. The elimination of the overturning mechanism of the façades is realized by ties made of high-resistance, 20mm-diameter steel cable (Fig. 21), anchored to the masonry walls by employing the Bossong system (Fig. 22). At the corners, the cables are anchored to the corner-shaped, 50x40 cm steel plates, in order to adequately distribute the actions on the masonry walls.

A very important aspect of the intervention concerns the recovery of the decorations, severely damaged by the earthquake. This stage occurs after the completion of the phases described above, in order to allow to access the building under adequate safety conditions. The first step should consist in collecting all the collapsed portions of decorations, storing them in a suitable place for their preservation, and then re-adhering the detached parts to the proper support. With regard to the lateral naves vaults, the collapsed frescoes are still adherent to the surface of the single bricks, therefore a possible intervention could consist in restoring the original painting layout.

Regarding the original bell tower, the new intervention allows for the application of steel cables equal to those used for the church, which ensure the complete ringing of the tower in addition to the existing metallic ties, thus preserving the structure from collapsing.

Finally, with reference to the more recent bell tower, the proposed intervention has been designed as permanent. It consists of four steel ties located at the four internal corners of the structure and fixed to both the upper floor and the ground floor by means of steel plates, each equipped with shape memory alloy (SMA) devices located at their middle length.

A similar solution has already been adopted in another consolidation intervention of the bell tower of the Church of San Giorgio in Trignano (Reggio Emilia), severely damaged by an earthquake in 1996, per-

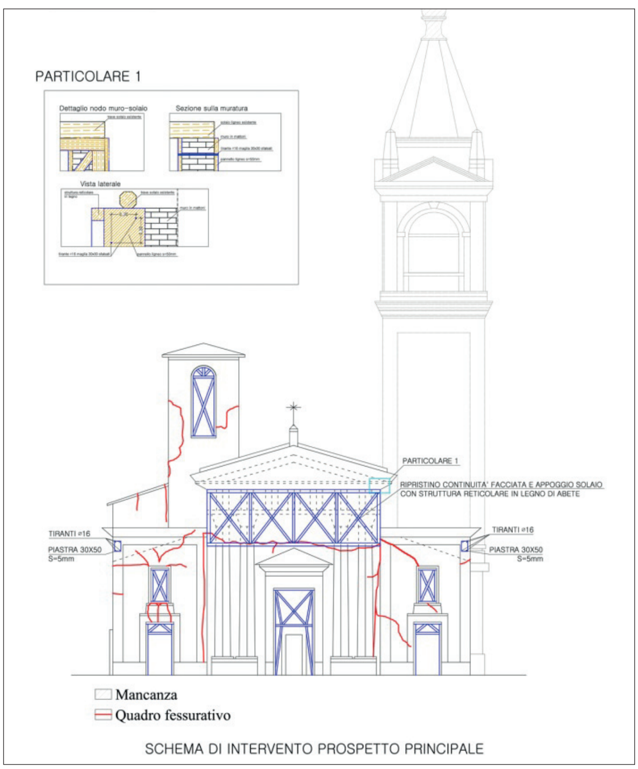


FIGURE 19 Main façade

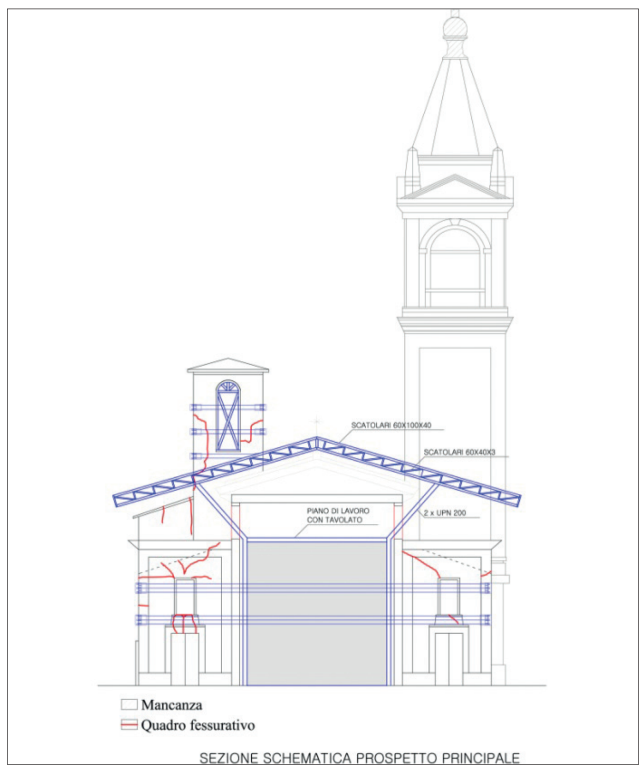


FIGURE 20 Covering protection systems

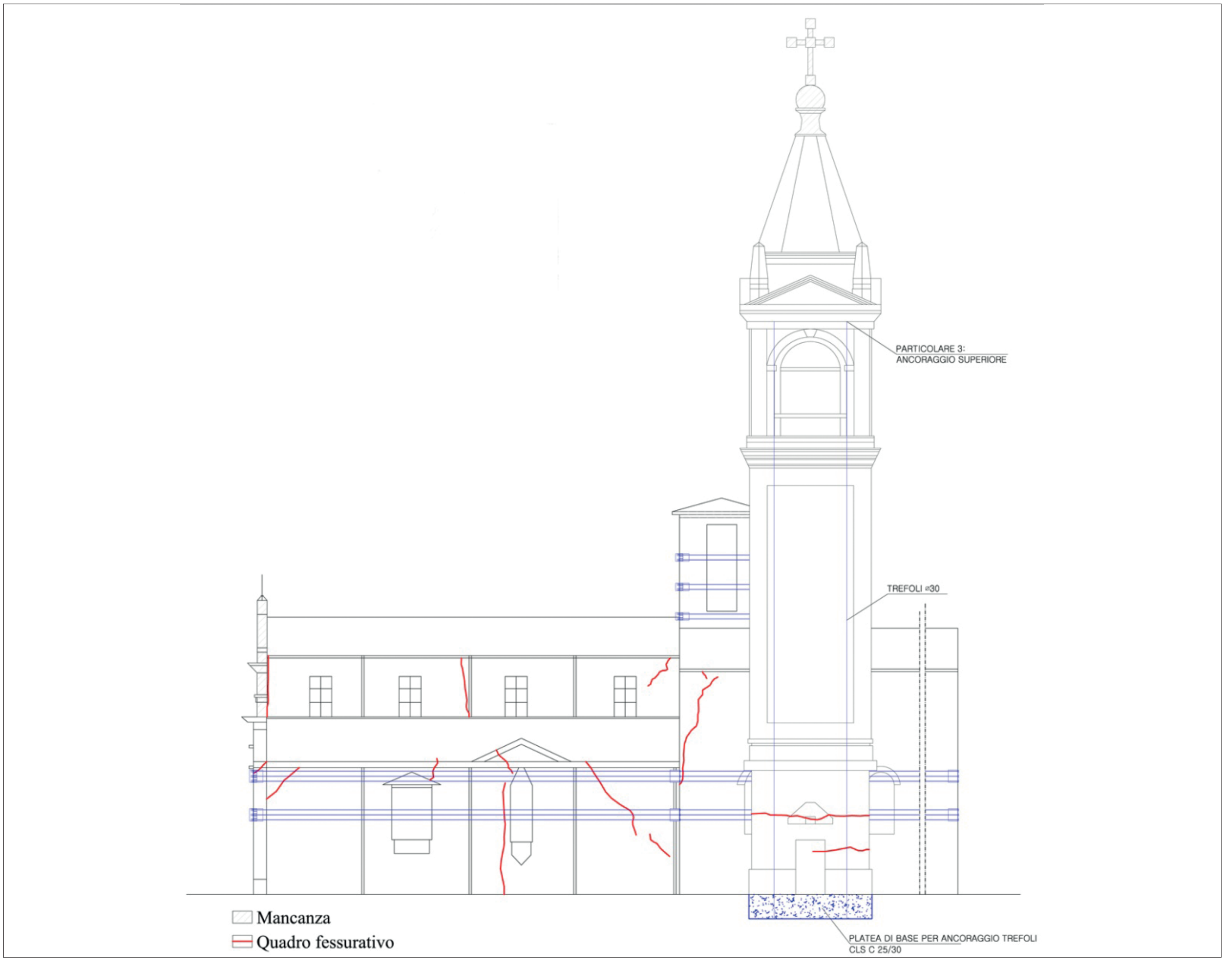
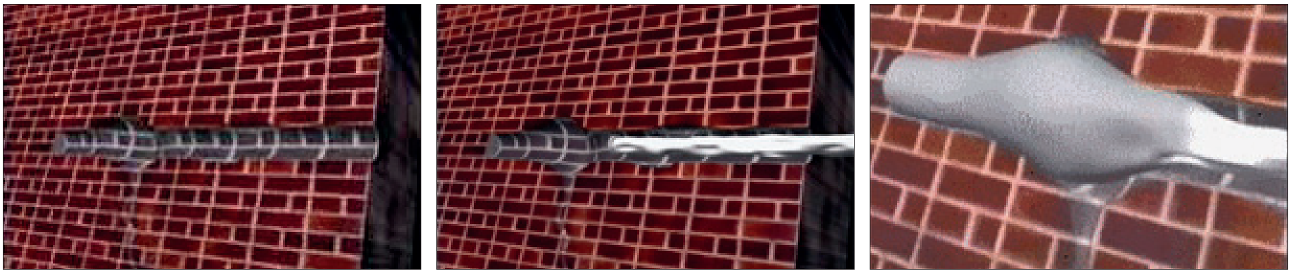


FIGURE 21 Ties' positioning on the East façade



a) realization of the hole *b) insertion of the steel bar* *c) injection of fixing material*

FIGURE 22 The Bossong system

FIGURE 23 The San Giorgio in Trignano bell-tower

formed under the scientific supervision of ENEA [1]. The innovative intervention – chosen as the subject of the pilot application of seismic Innovative Techniques (TIA) within the EU project ISTECH (Development of innovative techniques for the improvement of stability of cultural heritage) – consisted in inserting four post-tensioned metal ties formed by six modular units at the inner corners of the tower, in order to increase the structure's resistance to bending without perforating the masonry (Figs. 23-24).

In series with the ties, four shape memory devices (SMAD, Shape Memory Alloy Devices) have been incorporated, tested to ensure the constancy of compression on the masonry, by maintaining the applied force at a set value. Each SMAD is composed

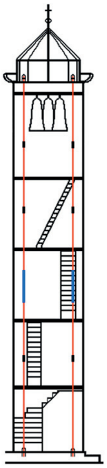


FIGURE 24 The San Giorgio in Trignano bell-tower: consolidation system

by 60 wires (each of 1 mm in diameter and 300 mm in length) made of hyperelastic nickel-titanium alloy. In addition, suitable anchorages have been realized (in the foundations and at the top of the tower) in order to support the concentrated actions transmitted by the ties. Dynamic identification tests have been performed immediately after the earthquake, aiming at the validation of the system. The ENEA researchers have installed an accelerometric pattern to record the behaviour of the structure under the action of 67 earth tremors. The last experimental campaign was carried out when the consolidation intervention was completed.

The proposed safety measures for the Visitazione di Maria Santissima Church were evaluated and approved by the Regional Directorate for Cultural Heritage and Landscape of the Emilia-Romagna region, thus the safety intervention should start by October 2012.

references

[1] Indirli M., Castellano M.G., Clemente P., Martelli A. (2001), "Demo Application of Shape memory Alloy Devices: the Rehabilitation of S. Giorgio Church in Trignano"., *Proc., SPIE's 8th Annual International Symposium on Smart Structures and Materials (Newport Beach, 4-8 March)*, 4330_30