Post-earthquake Recovery of Architectural Heritage: Diagnostics, GIS Documentation and Restoration
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1. The 2012 Emilia earthquake
An important seismic sequence hit the Emilia-Romagna Region and its surroundings in May - June 2012, causing 27 people killed, some hundreds injured, thousands of homeless, damage and some collapses to strategic and residential buildings, factories and infrastructures. Because of its peculiarity, cultural heritage suffered widespread and heavy damage, being surely the most affected by the earthquake.

The interested area is the Southern portion of the Po Valley, characterised by vast sedimentary deposits submerging several tectonic structures, whose configuration and activity are not very well known. As it occurred several times in the past, one of them, the Ferrarese Dorsal (part of the buried Apennines, moving forward North-East), originated the Emilia-Romagna seismic crisis [Toscani et al., 2009]. The principal event, Mw 6.1, focal depth about 10 km and epicentre near Finale Emilia, has been recorded on May 20th, followed by other shocks on May 29th, Mw 5.8, two strong aftershocks, Mw 5.3 and Mw 5.2, epicentre near Cavezzo-Medolla-Mirandola and on June 3rd, Mw 4.9, epicentre near Concordia sulla Secchia-Nov di Modena. Data taken from RAN recording stations interested by the seismic events show that ground characteristics probably generated widespread local amplification effects of the ground motion. This earthquake evidenced that also the Po Valley is prone to seismic risk, although the area has been included in the Italian seismic zonation only after 2003 [Formisano, 2013; Indirli et al., 2013].

Immediately after the first event, an ENEA team of experts has been involved in the operations of usability testing and post-earthquake safety interventions on the various construction typologies existing on the territory, including historical and artistical buildings and monuments.

2. GIS documentation
Among the centres afflicted by the earthquake, Finale Emilia, in the district of Modena, is one of the most affected, suffering great losses and widespread damage to its Cultural Heritage, which offers art and environmental testimonies dating back to a rich and fertile past.

A Geographic Information System (GIS) has been used in order to get an accurate analysis of the damage in a territorial scale, which allows the collection of accurate information related to their geographical position [Geremei et al., 2013]. As first step, the dwg/dxf vector file maps of the town, procured by the Technical Office of the Finale Emilia Municipality, have been geo-referenced, linking a geographic coordinate system to the territory by recognition of some
known points on it; to this aim, the PROJ and GDAL/OGR libraries have been used through an appropriate programming. The geo-referenced maps have been compared with both geo-referenced orthophotos of the area and Google maps, giving a perfect pattern matching.

The used GIS software is the open-source platform QGIS\(^1\), a very powerful and adaptable tool to manage any type of project. The software allows the import of various file formats, including those of technical drawings, and particularly it allows the integration between vector and raster files with different coordinate systems; in this case, orthophotos have been included with the WGS84 UTM Zone 32 coordinate system. Then, historic buildings such as palaces, castles, towers, churches and monuments have been identified within the GIS and included in a separate layer: later, these new “objects” have been integrated with previously acquired data, e.g. name, type and year of construction, suffered damages etc.

As result, a GIS database of the territory of Finale Emilia and its suburb Reno Finalese has been realized in a very short time, with a set and time-tested very quickly and efficiently route [Travierso, 2012]. Figure1 shows a typolo-
gical classification of the analyzed historical assets, while Fig.2 presents the Visitazione di Maria Santissima church with very detailed scale orthophotos.

3. The case study of the Visitazione di Maria Santissima church in Reno Finalese
The Visitazione of Maria Santissima church, datable before 1487, was built in the suburb of Reno Finalese, on the opposite side of the Reno river from the town of Finale Emilia, in a location reachable from the faithful also during the river floods. The first information is related to the placement of the baptismal font inside the church in 1465; the oldest bell tower, rising on the West side, dates back to 1506 and was equipped with two bells and a clock, while on the East side, a modern bell tower was built in 1933 and completed in 1948.

The earthquake caused widespread damage to the church, in terms of both structures (Fig.3) and inside decorations (Fig.4): 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, therefore, to propose a plan of post-earthquake safety intervention for the ecclesiastical building, while waiting for its overall consolidation [Carpani et al., 2012].

3.1. Damage assessment and diagnostics
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 [Indirli et al., 2012; Formisano et al., 2013].

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 chuchyard. The two façades of the lateral naves are connected to the transversal walls and are lower than the façade of the main one, therefore they are less damaged. 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, have been 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. 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. In addition, the cracks distribution and their depth outline a dangerous condition for the entrance. The cracks pattern 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 clearly observed by using a thermal imaging camera (Figs.5-6, respectively).

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. 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. Cracks are also present at the bottom wall of the apse.
An overturning mechanism is located on the right nave (Fig.7), 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.8). On the left nave, no mechanism has been evidenced.

Very serious damages have been surveyed on the two towers of the church. The oldest tower - which is the original bell tower nowadays substituted by 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 (cantalonal) occurred, a fact that predicts a potential global collapse of the tower and the subsequent increasing in the damage of the structures below it (Fig.9).

The more recent tower, being made of solid bricks, is more than 38 meters high and is connected to the right side of the church through a structure of brick 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. Finally, a minor rotation occurred. Further damage has not been observed above the horizontal crack, at least from the outside. The steeple, which has been subjected to a shear stress and rotated at the base, has been quickly removed in order to ensure the passage through the adjoining 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.

3.2. Proposed safety intervention

According to the surveys carried out on site and the documentation provided by the Engineering Department of the City, we suggested and signed an appropriate safety intervention. The planned measures can be listed as follows: safety of the overturning mechanism of the façade; ringing of the perimeter walls; removal of the cover; ringing of the original bell-tower; ringing and inser-
tion 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 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.10): 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 located at the windows’ position, aiming at avoiding additional damage to the frescoed ceiling (Fig.11).

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 horizontal ties, made of high-resistance 20mm-diameter steel cable, anchored to the masonry walls by employing the Bossong system (Figs.11 and 13). 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 the access to 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 brick, 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 (Figs.12 and 13). 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, performed under the scientific supervision of ENEA [Indirli et al., 2001]. 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.

In series with the ties, four 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 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.

4. Conclusion
In the framework of a restoration intervention on Cultural Heritage, a multidisciplinary approach is certainly suitable. In fact, the preliminary knowledge of the whole construction history, of the environmental peculiarity and conservation condition is essential in the definition of the appropriate intervention. The presented case study followed this kind of approach, with the effective collaboration among GIS experts, conservators, diagnostic test specialists, art historians and structural engineers. All the data acquired during the surveys have been managed using a Geographic Information System, that allows not only the data storage, but also their subsequent processing, interpolation and representation on thematic maps of the territory, providing a very useful tool for monitoring, to correlate and to share the information.

The proposed safety intervention design has been based on the results of a preliminary in depth damage assessment, which is necessary in order to correctly plan the intervention strategy. Moreover, it has been developed taking into account the subsequent retrofitting and restoration phases. In fact, the design of a safety action should be considered as the first step towards the global restoration intervention, therefore, it should be useful and not an obstacle to it. The so planned intervention performs this dual function: it realizes a safety system which preserves the structure and the internal decoration from the worsening of the damage due to other seismic events and exposition to weather agents; moreover, it provides a safe work place for the subsequent restoration phases. Finally, it is completely reversible and recyclable.

The proposed safety intervention measures for the Visitazione di Maria Santissima church have been evaluated and approved by the Regional Directorate for Cultural Heritage and Landscape of the Emilia-Romagna region, in full compliance with imposed deadlines.

Notes

References


