THE 2012 EARTHQUAKE: AN ABACUS OF SURVEYS AND INTERVENTIONS IN MANTUA CHURCHES

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ABSTRACT:

After the earthquake of 2012, the ecclesiastical heritage of Mantua was so damaged to render unusable many buildings. Especially churches show a higher vulnerability in relation to their architectural features. From a recognition after the seismic event, more that 40% of the churches of Mantua were damaged with different intensity.
After the first phase of expeditious damage detection, a methodical analysis has allowed to know the real state of conservation of many architectures.
The Diocese of Mantua commissioned to the Mantua Campus of Politecnico di Milano the survey and digital documentation of 25 churches differently affected by the seismic event. The goal of the survey was double:
a) realize the documentation necessary for the shoring and protection of damaged structures;
b) prepare the drawing for the following interventions on the buildings such as restoration, reconstruction and retrofitting.
Five years after the earthquake, many interventions of those identified were completed and concluded. Numerically, 129 churches were damaged and, nowadays, 115 have been restored and now they are fully open.
The paper aims to illustrate the operational criteria used in the survey activity and repair operations carried out in order to identify guidelines that can direct operators in cases of new consolidation measures.
All these directions were based on this premise: for historic structures, it is appropriate to accept a level of awareness with seismic risk higher than for ordinary structure, rather than act in the manner contrary to criteria of preservation of cultural heritage.
In these years, we tried to identify the forms of dependence between observed damages, construction types and the conservative state before the earthquake. The goal in fact is to understand the cause of the wide loss of ecclesiastic heritage. The reason can be searched in the unfamiliarity of construction practices, techniques and materials with earthquakes or the inability of existing building to resist the seismic stress because badly maintained.
These two possibilities conditioned the repair choices applied on the churches. The interventions regard different techniques which were optimized not only to be applied on buildings damaged by the earthquake but also on those that gradually show the necessity of accommodation measures. It is important, in order not to miss the operational experience gained in these years, to maximize the economic resources deployed by focusing the results achieved and verify if the followed path has been consistent and, if not, adjust the direction followed.
In summary, the solutions adopted are for example: ties and anchor elements, repair works on vaults with mesh and plaster, repair works on vaults with addiction of lightweight ribs; repair works on cracked vaults with wood, steel wedges and injections of natural hydraulic lime, filling in the gaps of the masonry structure to reduce vulnerabilities.

1. INTRODUCTION

1.1 The recovery after an earthquake

The effects of the seism that, in 2012, hit Emilia Romagna and Lombardy, were very serious, as well as unexpected, because the area is located in an area classified as a low seismic risk (for a more detailed discussion, see Stucchi et al, 2012).
The earthquake caused significant damage to rural and industrial buildings, works of water canals, along with buildings and historical monuments and the civil old buildings in stones, bricks or pebbles. Most of the monuments and places of artistic interest including a wide area, from Mantua to Modena to Ferrara to some municipalities in the province of Bologna, were severely damaged or partially collapsed
The damage was estimated (in a report sent to the EU Commission) for 13 billion and 273 million euro. For instance, in Emilia-Romagna the estimate is 12 billion and 202 million euro including: emergency measures, recovery damage to residential building, productive activities, historical-cultural-religious heritage buildings and public services and infrastructure.
After the earthquake, the activities of safety and reconstruction has been greatly increased. Five years from the earthquake, the newspaper tells about the success of the recovery of historic and artistic heritage, especially the sacred building, managed personally by the Diocese of Mantua.
The goal of this article is to study the working conditions and the choices that allowed to reopen 115 buildings for worship and community to after 5 years (over 89% of the damaged assets). The study cases are made of 25 building that were surveyed by the Politecnico di Milano and restored under the control of Diocese of Mantova. The attention is not focused on the individual technical choices, but on the whole process from survey, through damage analysis until the definition of interventions, to study also the model of management in case of post seismic emergency.

1.2 The earthquake of 2012 in Lombardy

The seismic crisis that hit the Emilia-Romagna, Lombardy and

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Veneto in May 2012 consisted of a series of seismic shocks located in the district of Emilia's Po Valley, but felt in a much wider area including Central Northern Italy and part of Switzerland, Slovenia, Croatia, Austria, southeast France and southern Germany.
The most intense shock occurred May 20, 2012 at 04:03 hours Italian time with Richter magnitude 5.9, and May 29, 2012, with 4 significant shock: at 09:00 Italian time of Richter magnitude 5.8. More tremors were recorded in the following days.
The region of Lombardy was mostly damaged by the shocks recorded on May 29, 2012, both for its proximity to the epicenter, and because the already damaged structures (20 days before) suffered, in this second occasion, the so-called "coup de grace".
In Lombardy region, the affected area was recognized in 47 municipalities
In July 2012, the Lombardy Region has carried out a survey activity that quantified more than 900-million-euro total damage, divided on the different types of structures as reported in the table below (Lombardy Region, 2016):

Typology	Total estimate of damage	Damage on public property	Damage on public property	Damage on productive activity
Public infrastructure, cultural heritage, and places of worship	299	157	141	
Residential buildings	141		141	
Touristic activities	4			4

Table 1: the estimates are in millions of euro. Some typologies are not inserted in the table (industrial, handmade, agricultural activities)

The earthquakes caused heavy damage to buildings rural and industrial, works of water canals, as well as to buildings and historical monuments and buildings of civil old stone or pebbles. Most of the monuments and places of artistic interest in a wide area, from Mantua to Modena to Ferrara to some municipalities in the province of Bologna, was seriously damaged or partially collapsed.
Many damaged buildings consisted of churches. In fact, designed to withstand vertical loads, churches in general present slender walls, lack of horizontal structures, weak or non-existent connections among structural elements, absence of effective tie-rods to absorb arch thrusts, and irregular stone texture. These aspects, added to poor material performance especially in tensile stress mode, are among the reasons for the structural collapses of historical monumental buildings when subjected to seismic forces (Castellazzi et al, 2013).
The Diocese of Mantua made a detailed report about the effects of the seism. It found that 125 building were damaged by the seism. After a classification based on the seriousness of conditions and the economic damage estimate, the buildings were divided into three groups:
-red code: uninhabitable buildings, partially collapsed with danger for public safety and an estimate between 5 and 2 million of euro;
-orange code: uninhabitable buildings, partially collapsed with danger for public safety and an estimate less than 2 million of euro;
-blue code: uninhabitable buildings, damaged with no danger for public safety and an estimate less than 500.000 euro.
In the early stages after the seismic event, the diocese of Mantua asked the Mantua Campus of the Politecnico di Milano, for a cooperation in the survey and analysis of 25 buildings among those listed, according to the necessity of safety measures or the restoration project (for the complete list see Adami et al, 2016).

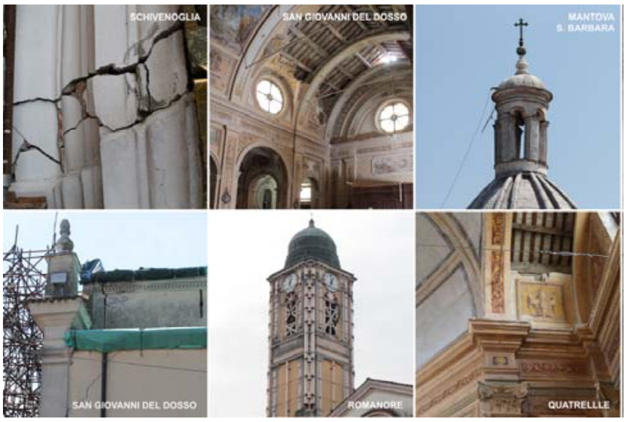

Figure 1: some photos of different damages in the churches of Diocese of Mantua

2. THE SURVEY

2.1 *The knowledge of building: from survey to state of damage*

In case of a seismic event, immediately after the phase of emergency, it is necessary to come to the aid of people with speed and efficiency. The first step of this process, usually managed in Italy by Protezione Civile (Civil Defense), must be a rapid and effective survey campaign of damage and evaluation of compliance with safety standards. Usually it is carried out by technicians and by using the AeDES forms (*Agibilità e Danno in emergenza sismica*) which allow an immediate knowledge of the building. Specific AeDES forms exist for cultural heritage to identify the building, the state of damage, the cultural values and contained the pieces of art (Di Marco, Eva, 2009)
According to the outcomes of this survey, the first activity has to guarantee the safety for inhabitants and volunteers who are working in the area by using also temporary structures, such as the perimeter activities, the provision of barriers, shoring, using rods and hoop buildings. In extreme cases, you can proceed to the dismantling of the buildings or to partial or complete demolition of buildings not covered by the protection.
The step of reconstruction starts immediately after this and the primary activity is concerning a complete knowledge of the building, considering its history, geometry and state of damage. This operation requires a long time and can be afforded by specialists in different fields. The architectural survey plays an important role in this context as it can give information about the geometry of the building, but also it can be used to make interpretative models of the buildings to be used in analytical studies such as structural analysis (Milani, Valente, 2015) or to set-up a BIM for conservation purposes (Achille et al, 2015b)
Geomatics allows to carry out this operation in different ways and with different techniques, but, at any rate, all the methods have a common outcome which is the 3d point-based database. Obtained by photogrammetry or laser-scanner, the 3D database allows to make observations and measurements and to integrate the existing documentation, but in a safety way. All techniques aim at diminishing the survey time on site, and to allow to obtain detailed information during the post processing stage and

to elaborate drawings, plans, sections and elevations in a very safe way.
The survey after the earthquake presents quite a number of difficulties or problematic elements related mainly to safety aspects. The biggest risk for the operator is to stay at the presence of unsafe parts that can fall because of successive shocks or stresses of the structure. This kind of risk is very relevant in structures as churches where the height of the room is high and there are many elements that can break down such as vaults, beams, moldings and decorations.
There are no absolute solutions to these problems, so the strategy is to reduce the time of survey on site or use a movable structure, scaffold, which constitutes a sort of safety shell (as we did in San Giovanni del Dosso).
An alternative is given, especially to investigate the roof and the upper structures, by the use of UAV for monitoring and for capturing photographic needed to build three-dimensional models (as we did in Santa Barbara and S. Andrea in Mantova).
The debris and temporary structures are additional difficulties because they make longer the acquisition stage and they imply also a time-consuming operation to delete all those structures from the point cloud.

2.2 Classification of interventions and examples

The survey experience of Politecnico di Milano can be classified into three different groups according to many aspects such as the accessibility of places and buildings, the time, the objectives of the survey and types of graphic restitutions and the difficulties inherent to every building, including the geometric complexity and the artistic value (Adami et al, 2016).
According to all these needs and criteria, the survey activities were classified into different levels of complexity of the actions involved and importance of the damage.
Case 1) low complexity: low-risk people, survey for the implementation of small or medium-sized interventions, short acquisition time and time processing, topographic network and laser scanner.
Case 2) average complexity: moderate risk, survey for final restoration and seismic improvement of buildings to medium complexity, complete drawings of the building, using topographic network and laser scanner
Case 3) high complexity: high-medium risk, survey for final restoration and seismic improvement of buildings in high-complexity, full drawings, use and integration of various methods such as laser scanning, photogrammetry from the ground and from above, or UAV aerial platform with a topographic network.

From a geomatic point of view, this kind of acquisition did not require new methods and instruments, but only to rationalize the exsting ones in order to reduce the safety risks and ensure to acquire as data as possible for the next step of data processing.
We used the terrestrial phase shift Leica Geosystem HDS7000 laser scanner, that allows to detect 1 million points per second with a precision of 0.3mm rms at 10m (80% white surface). The speed of acquisition (from 3 to max 12 minutes for each single scan), long-time batteries and the possibility to work with a remote control (by Wireless LAN) made this instrument very suitable in an emergency context. All scans were registered in a single reference system using a total station which allowed to work also with not overlapping pointcloud and, at the same time, gave us a guarantee about the verticality of the reference system.

Churches classified in "case 1" (Sarginesco (figure 1), Angeli and Pietole) have a low level of complexity for the risk, the problematic to be addressed in the operational phase, the architectural configuration and the amount of documentation to be produced for the design of interventions.
These building were surveyed by laser scanner in a very short time. Time required for the entire survey (acquisition stage, data processing and drawing editing) was about 1 week.
The processed products were architectural plans and sections. To give more information to the designer, we enriched the classic drawings with the orthographic projection of the point clouds, as a background. They allow a better comprehension of the architecture and the designer can extract the cracks, the gaps, the degradations by himself.

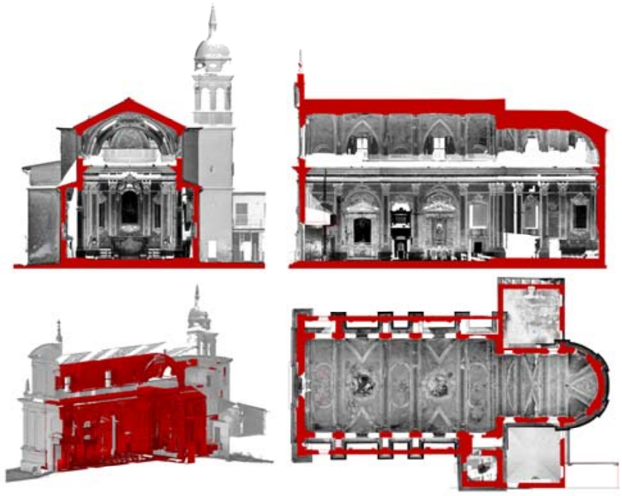

Figure 2: Church of Surcinesco: view of the pointclound (interior in red, exterior in grey) and the outcomes of the survey. The photographic content is given by an orthophoto extracted from the point cloud.

This category "case 2" includes most of the churches. The purpose was to provide a 3D database as complete as possible of the building to extract key information on the state of damage of the structures.
All 2D representations of the building were required: ground floor plans, sections and elevations (internal and external). In most of the cases, there were no available and reliable surveys, printed or in digital form, which architects and engineers could use to design the executive restoration project and seismic strengthening.
The churches of this category were more complex because of their geometries, architectural dimensions and the presence of high detailed decorative apparatuses.
Therefore, it was necessary to acquire a greater number of scans than in case 1 to get the right level of resolution and overall coverage.
Usually three or four operators made the acquisition (laser scanner and topography) in 1 or 2 days. The deadlines to complete the drawings was about 30 days (figure 2).

The complexity and importance of the architectures of case 3, together with the logistical aspects determined by the collapse and damage reported after seismic events, required for these buildings the coordination between the authorities and those involved and a careful planning of the survey. These conditions proved much longer times. In all the churches, the Protezione Civile intervened only on the facades and on roofs to avoid collapses to the external public spaces. Nevertheless, they did not make shoring or support structures inside the buildings and

left a critical situation as after earthquakes.
In some cases, such as the bell tower of the church of Santa Barbara (Achille et al, 2015a) or the lantern of the dome of the Basilica of St. Andrea in Mantua, the survey had to consider the height of the structures (h = 53mt for S. Barbara, 73mt for S. Andrea). In addition, the density of the ancient urban context made it difficult to find good positions on the ground from which to acquire measures.

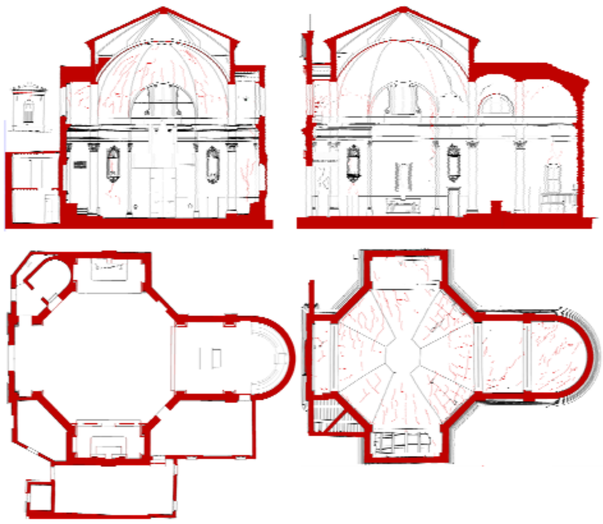

Figure 3: Church of Natività Beata Vergine Maria in Quatrelle. In the results of the survey stage, there are not only the geometric information, but also the description and localisation of cracks.

Therefore, for all the above-mentioned reasons, in case 3 the laser scanner acquisition was integrated with a 3D photogrammetric survey based on automated 3D image modeling and conducted by Agisoft Photoscan.
It gave the opportunity to have a point cloud from which to extract profiles and sections and to have true orthophotos in short times or to produce texture models. In both cases, it is possible to obtain information about the damage and cracks present, essential for the design of the restoration project.
The digital camera used in the surveys from ground and aerial platform (survey of the roof of the church of S. Apollonia in Mantua) was the Canon EOS 5D Mark III (22 Mp) with lenses 24 and 35mm.
The aerial surveys have been performed instead, for the two cited cases Lantern of St. Andrea and the bell tower of Santa Barbara, with an octocopter equipped with digital camera Canon EOS 650D from 18Mpxl, 2 gyroscopes, GPS and barometric altimeter for the flight control.
In the survey of these churches, we were employed five operators for two days of acquisition. Deadlines to complete the drawings and delivery of the documents with 2D orthophotos: 40 days.

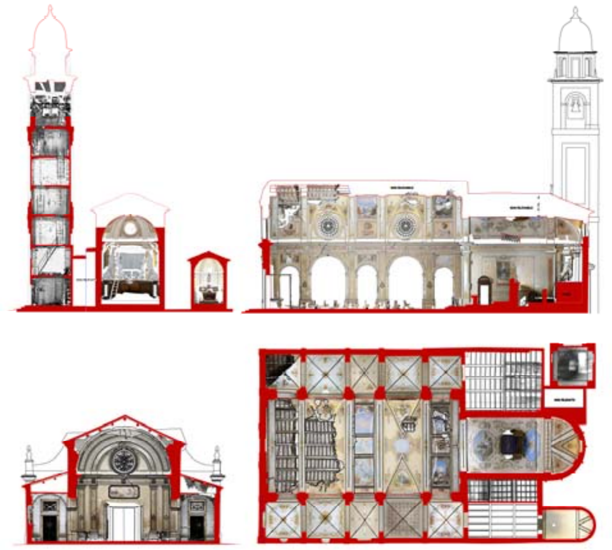

Figure 4: San Giovanni del Dosso, one of the most damaged churches. It was necessary to do a photogrammetric survey to survey not only the geometry, but also the decoration (frescoes, vaults, etc.)

Other churches of this group needed some specific approaches. In many cases, it was necessary to acquire the real RGB values of the surfaces for the documentation of preservation status of frescoes, decorations, furniture elements and altars in stone and marble. We applied different approaches: in some cases, we worked with Agisoft Photoscan, and in others we decided to acquire data color through the automatic acquisition of spherical panoramas (figure 3).

3. DAMAGES AND RESTORATION

3.1.1 Analysis of damage

The proposed restoration activities of the phases after survey, showed that the main approach was towards a conscious use of technology and materials compatible with the historical context. This address was seconded mainly by the Superintendent of architectural heritage in accordance with the Italian regulations. It should be added that the logic at the base of the activated choices wanted to satisfy a definition of seismic improvement which aims to accommodate an increase in the overall security without modifying the constructive idea of the artifact.
These assumptions have found a good knowledge, guaranteed by the architectural survey that provided not only the geometry but also the situation of underway instabilities.
In particular, with reference to seismic damage mechanisms, it had to be noted how the same behaviors were common and uniformly spread in several of the investigated churches. In particular, the most common damage mechanisms are linked to the overturning of the façade (mechanism n.1 as described in Papa, Di Pasquale2013), mechanisms in the top of the façade (n.2), mechanisms in the facade plane (n.3), transverse hall response (n.6), shear sidewall mechanism (7), longitudinal response of the columns (n.7), hall vaults, central and lateral naves and apse(n. 8, 9, 18), overturning of the transect (n. 10), transept shear mechanisms (n.10), vaults in the transept (n. 12), triumphal arches (n. 13), apse shear mechanism (n.17), hall covering elements, transept, apse (n. 19,20,21), interaction in the vicinity of irregularities (n. 25), overhangs (spires, pinnacles, statues) (n.26), bell tower (n.27) and the steppler (n.

28).

Through the reading of the mechanisms of damage, it emerged that the vulnerability of the ecclesiastical heritage was linked to the lack of curbs in roof and lack of relevant connections at lower levels, which are necessary to ensure the box-behavior of the architectural complex.

Even if in some cases irrecoverable phenomena were recorded with the complete loss of architectural elements portions (vaults, gables, steeples top), the types of identified lesions are essentially two.

First, crossing cracks, where we observed the fall of plaster and/or clay fragments and the breakage of some architectural elements (frames, capitals, projecting decorations). Secondly, there were many diffuse cracks that have affected only the layer of plaster or intrados surface, without structural repercussions. It should be noted that, often, the difference in crack pattern that has been detected on the inner surfaces with respect to the external of the masonry itself is linked to the type of the existing masonry. The existing one is, in fact, a rubble masonry that is composed of two outer facings in solid brick and lime mortar disconnected from each other, with the presence of a large inner core composed of masonry in disorderly stones. For this reason the survey of the interior lesions was not corresponding to the external crack.

Along the main fronts, damages was tied to the beginning of collapse mechanism in the plane and in the top of the facade, shear breakage of the dividing walls with the formation of detachment wedges. On the side walls, there were crossing cracks which were probably due to a reaction to the overturning of the main facade and crazing linked to the behavior of masonry incorrectly clamped during its construction. Along the exterior elevations, the crack patterns were particularly pronounced in the higher parts of the walls and near the eaves, where the masonry appeared generally irregular and not very cohesive. The previous lesions, poorly repaired, fostered a collapse of the masonry, characterized by irregular joints, poor mortar, and in any case made with powder mortar and mediocre consistency and binding capacity.

Additional problems were caused by the plano-altimetric discontinuity of architectures or due to the seismic action associated with the height difference of adjacent volumes at different heights and discontinuous between them.

Regarding the interior, the most significant evidences of damage were present on arches, vaults and the supporting walls. The most significant crossing cracks were localized on the boundary walls of the nave and apse and in the proximity of the main facade. The first were related to the high difference in stiffness and different geometry that exists between volumes. Important losses occurred on the vaults whether they were built in bricks without structural functions (single leaf vault), both constituted by wooden ribs with lattice of strips of wood or cane.

The damage on the bell towers, when they have not led to the collapse of the summit cells, reached very dangerous situations. For safety reasons, it was proceeded to increase the level of safety through the bandage of the summit structures with steel cables and wooden elements, to embrace the tower in order to avoid the structure of the summit cell both to implode or "bulge".

3.1.2 A new culture for interventions

The management board of the Diocese of Mantova has set a methodology of intervention on artifacts that has supported some homogeneous operational strategies declined in different architectural reality. These methods were aimed at achieving adequate levels of design quality, synonymous with safety in interventions, proposing technical reference tools that provide guidance in the choices to be placed at the base of the building rehabilitation project hit by the earthquake.

The experience of the Diocese of Mantua can be considered as an opportunity for synthesis and verification of operational solutions activated and shared between designers and builders. In an emergency, the number of designers involved increases suddenly, including those who do not have adequate experience in the field of seismic repair: the goal of this paper becomes also to spread the "culture" needed to reach the quality and effectiveness of the interventions required in similar predicaments.

Even if an approach based on knowledge of the artifact is more sharing (in theory), the appropriation of effective and timely methods, designed on the basis of extensive case studies and showing the performance of the old buildings (Della Torre, 2016), is still a subject not completely widespread, but only the part of the background of knowledge and skills of designers and contracting companies who experienced such operations. In fact, it is not uncommon that important designs have a high-quality knowledge support at their disposal which is not reflected in the design phase. This limit also stems from the relationship, even distant, between universities, protection institutions and professional associations. Professional figures dedicated or specialized in the areas of cultural heritage are growing, but the additional training is not always recognizable in design competitions and work management.

This also applies to companies: in situations of emergencies, residential construction builders are working on ancient artifacts, without knowing the constructive logic of religious architecture (in our case), which are the most suitable materials and the installation techniques (we think of the difficult use of lime in repairs), not to mention the lack of understanding of the architectural significance of constructive elements that have their own value because materially historians and not for their shapes (in fact the reconstruction of portions is economically advantageous and the repair is absurd especially if it keeps the signs of the damage occurred).

The Diocese of Mantua, thanks to the presence of an independent technical office, has got to monitor over time the evolution of the construction site from the survey stage to the design, check the status of permissions and maintain control during construction till planned conservation of buildings (Bossi, 2016). The unified management, while maintaining the specificity of each parish institution, has acted as guarantor to prepare executive procedures. After developing the analysis of the seismic vulnerability of the building, we have defined some interventions aimed at achieving an improvement of the seismic behavior of the structure that have had a methodological and executive repetitiveness in many analyzed churches, although divided into the specificity of had damage.

This article is intended to illustrate some repair procedures that have found a positive deferral in churches that were investigated immediately after the earthquake from Politecnico.

3.1.3 The roof

The roofs are the key architectural element to the preservation of the building, but frequently there are no routine maintenance operations, making this part of the building more fragile than others.

In addition to structural problems, the earthquake also affected on several architectural aspects as the roof coverings, provoking the slippering down of the bent tiles due to the vibrations of the seismic shocks. The consequence of this problem, added to the widespread rot in the floorboards and joists, suggested to carry out the work by completely opening the roof. The choice has allowed to realize a perimeter curb of "reinforced masonry" and the remaking of a rigid floor covering, allowing to bind and connect the longitudinal walls in a flexible, but resistant, way the and to "hook", when necessary, the facade and the 'apse.

The structural function of masonry curbs has three basic static advantages:

- absorb the axial forces spreading them on the masonry of the arch impost,
- to share the vertical concentrated loads so as to facilitate its introduction into the underlying masonry;
- counter the dangerous damage mechanisms of out the plane

In the investigated cases the brick curb has fulfilled its primary function of vertical load distribution. It created the conditions for a mutual cooperation between the walls and allowed to counteract the overturning of the out of plane walls. Because of its flexibility, it realized a good adhesion with the masonry even in dynamic conditions.

Figure 5: nailings of the wooden planking to the joists and securing the steel perimeter curb.

The reinforcement of masonry at the summit level was obtained with the laying of unidirectional fabric in steel fiber impregnated with structural mortar natural hydraulic lime between the last brick courses.

The homogeneity of the new wall profile has allowed to place joists and planking in such a way that the wooden planking would guarantee to be uniform and homogeneous, to further stiffen the floor by the laying of multilayer phenolic type OSB / 3 panels with a thickness of 35 mm. The panels were appropriately fixed, by means of self-tapping screws, to the underlying joists for the whole thickness of the latter. The panels were connected to each other with the use of perforated tapes (80 x 2.0 mm) steel and self-tapping screws. The guarantee of anti-seismic coverage was carried out through the attachment of the floor to the underlying masonry by means of vertical threaded rods in stainless steel or metal taproots. Besides, through the connection of the wooden beams in correspondence with the ridge means of suitable steel plates.

On the extrados of the planking a double layer of bituminous sheaths has been laid and the roof tile has been fixed with specific hooks to stop tiles.

3.1.4 The masonry

The perimeter walls have been usually reinforced through the installation of steel rods.

The adopted solutions have many aspects in common, but the tie-bar with rectangular cross section (flat 100x10mm) have been used. They depart from the outside of the walls and continue hidden above the internal frames to the aisles and the facade. Depending on the design of the front they have chosen different shapes of anchoring: tie-plate and/or steel plates hidden under plaster or with internal contrast.

Another frequent solution was the use of "low relaxation strands" to 7 or more wires, placed horizontally in the thickness of the facade and localized in the portion above the lateral cover flaps. The contrasting action has been transferred to the masonry by means of special steel plates positioned on the outside of the masonry itself. Even in the safety of facades, tie-bars were used, after providing perforations in thickness of the wall.

It has been interesting to analyze the enforcement proceedings in cases of straightening of the facades after they are guaranteed against the complete collapse. The recovery of the sensible out of plumb and detachment from the longitudinal walls of the main nave has been made by a procedure that required a meticulous control of the masonry connections even in the smallest displacements during the movement (rotation) and relocation of the facade to its original position. The first step of the process was the removal of the cover and then the cleaning of the cracks in order to eliminate any obstacles and contrast elements to the recovery of the deformation movement. As support of the façade, a provisional structure in joint-tubes has been made immediately after the earthquake in order to prevent further collapses and has been equipped, in a second time, with the special reinforcements in order to use the scaffolding for the breakdown and the transmission of the tension applied on the facade plane. Where necessary, the structure has been reinforced, by doubling of the tubular profiles. In favor of safety, we have positioned steel plates anchored on the angle between the longitudinal walls of the nave and the transverse wall of the nave bottom to give contrast to the pulling action. The steel cables (internal and external) and a system of jacks connected to a control unit were used to monitor the pulling action so as to ensure a uniform stress on the structure; instead crack meters tested the effectiveness of shooting. The rotation of the facade, pivoting on the base, has been performed by operating the jacks in a very slow way up to recover the reached deformation. The masonry has been fixed at the inner molding of the nave and of the eaves. Afterwards it has been necessary to guarantee the static of the façade by reconnection at the coupling of the front wall with the longitudinal ones.

Figure 6: example of hooking of the façade wall to the nave

A very common re-connection system is the one which used helical rods placed in correspondence with the contact between the core walls of the hall and underlying arches in full masonry. The bars have been chosen because of the possibility to be installed in dry condition and oriented in a crisscross pattern to connect the garments.

The binding of the masonry action has been often obtained also by the tie bars.

On the perimeter walls, both internally and externally, we have been performed the reconnections of cracks in different ways:

- closing of cracks with reconstruction of the wall texture with brick and lime mortar;
- stitching of masonry with solid bricks, made dry by stainless steel helical bars installed with dry-fix technology;
- making of armed masonry through improved adherence bars installation in holes drilled with rotary/ roto-percussion drill, immersed in a fluid slurry of binder products;
- repairing of cracks in the walls by inserting hardwood wedges and/or iron and mortar;

- repairing of isolated cracks with a binder mixture made of lime, sand or marble powder or other binder compatible products.

The most invasive operations were those in which you used the stitching techniques.

The operation consisted in the removal, for small parts, of damaged masonry to replace it with new parts and replenish the unitary nature of the wall structure. The difficulty of execution arose when the cracks were larger and the wall structure was very fragmented and heterogeneous.

Because of the severe damage and the crossing cracks, the safety of the apses has been accomplished through the implementation of plates adherent to walls (with the wider section in vertical position) and circular shape to avoid the overturning of the wall. According to the height of the apse, a single or double hoop reinforcement were used.

Figure 7: armed stitching along the mortar joints to close the cracks

3.1.5 The vaults

In the territory of Mantua quite a number of vaults were constituted by wooden ribs which support a lattice of strips of wood. Usually the lattice has been covered by a layer of plaster as the ceiling finishing. When these vaults were not fully collapsed, it was very frequent to operate from above, but with some necessary preparations (shoring) for safety reasons.

Inside the church a scaffold was built to enable the access and interventions on the ceiling, but above all to create a plan to work on the extrados of the vault. Then all the materials used to fill the abutments of the vault were removed. From a structural point of view, it is proceeded to the consolidation of the wooden ribs with structural deficiencies and/or serious deteriorations of the same. The operation was performed by flanking the existing wooden ribs with other elements connected with nails.

In areas where the plaster was completely detached, the reconstruction was made with mortar of only natural lime. Where the *camorcanna* (reed and plaster ceiling) was destroyed, we applied a layer of reinforcement (jute), fixed with special adhesives, crossed over to the various ribs or arch bricks to create a single body with the same camorcanna. Brass rods with steel rings were placed between the camorcanna and the armature to create attachment points to be hung. On the remaining portion of the vault, we repaired the damages by closing the cracks with strongly adhesive lime mortar until rejection, after having stripped and cleaned cracks to allow the product to penetrate deeper.

In the case of vaults made of bricks “in foglio” (with no structural function) the previous operations were the mending and clogging of the connections. In these situations, on the extrados of the vault, we placed structural bandages with the application of carbon fiber fabric. This operation was particularly delicate. In fact, the improper execution could compromise the validity of the procedure. Therefore, after cleaning the surfaces, we levelled them with suitable mortar. Secondly, the carbon fiber fabric was applied and fixed with mortar.

The masonry vaults affected by small cracks were restored from the intrados. The procedure took place after the cleaning of the edges of the crack with the removal of portions of crumbling plaster and the subsequent insertion of steel wedges and hydraulic lime mortar to complete the stiching. The work was completed with the restoration of the plaster layer of surface finish.

A second solution, for the masonry vaults, saw the laying of an armed hood based on natural hydraulic lime of limited thickness with the use of lightweight aggregates. After emptying the abutment and removed the historical layer of plaster (when present), we proceeded to the stripping of the connections, the cleaning of the surface, and the application of welded mesh anchored to the vault by means of steel connectors with improved adherence fixed with an epoxy resin. Beside the intervention of general consolidation, the crossing cracks were closed through the insertion of steel wedges and mortar based on hydraulic lime.

In general, the aim of interventions on masonry arches aimed to a common objective which was to ensure their stiffening. It is therefore seen, therefore, the laying of high adhesion bars connected to the arch by means of brackets placed below the extrados, specially deformed and made cooperating through a small casting based on natural hydraulic lime.

Figure 8: consolidation of the vault with bandages

3.1.6 Underpinnings structures

In a few cases, it was necessary to proceed with underpinning interventions. This operation was very delicate because it has implicated action directly at the point of connection between structure and high soil which frequently proved to be of poor quality and compactness. The choice of the consolidation system has seen the use of deep type underpinning, excluding the realization of continuous beams. To properly transfer the loads of the building structure to a sufficient compactness ground, we used underpinning poles made to successive segments of tubular metal, driven into the ground using hydraulic jacks.

3.1.7 Moldings and overhangs

Many after-earthquake operations regarded the safety of decoration such as plasters, moldings and overhangs which were damaged, fallen or in an unstable position. The solution is part of the classic interventions of restoration: we realized micro armed stitching with stainless steel rods applied in the gypsum and then plastered the surfaces

4. CONCLUSIONS

From the experience of the Diocese of Mantua, the first learned lesson is the importance to enable a coordination of interventions which should be over-local. This is important

because the choices related to operational priorities and the preservation of artifacts need to combine the material aspects with social and anthropologic ones, ensuring the preservation not only of material culture but also of symbolic meanings that contribute to the connection of local communities, generating enthusiasm and affection, feeling need to take care of the existing buildings.
The structuring of the activities has therefore made it possible to systematically plan surveys, interventions, target resources in relation to the real conservative situation and usage requirements, to optimize the operating timing, in order not to endanger further artifacts and finally concentrate experiences repair.
The restoration interventions showed that there has been an evolution in the repair techniques when compared to procedures implemented after the 1997 earthquake in Umbria, following which it was assumed greater attention to traditional construction aspects, promoting research activities related to technological solutions belonging to the seismic culture linked to local building practice.
Unfortunately, it has also emerged as the operations proposed in the projects belong to an educational background that usually is not common to professionals. Frequently, architects and engineers acquire knowledge of design solutions only after colliding with the negative opinions of the protection institution when approving the project. This situation highlights an educational problem of no small importance.
In fact, the appropriation of knowledge regarding design solutions for use in cultural goods are acquired when it completed the formation of the college student and is transmitted to the professional personnel whose job is not to educate but verify that all aspects of the protection are implemented in exhaustive and correct way. This training gap is not present for the first phase constructed approach, or about prior knowledge, survey, surveys etc. where technology has reached high levels and routinely recognizes the strategic role.

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