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WHEN THE STRENGTHENING OF HISTORIC MASONRY BUILDINGS SHOULD BE CARRIED OUT IN DIFFERENT PHASES: THE STRUCTURAL REINFORCEMENT AND MONITORING OF THE LOMBARD-ROMANESQUE CHURCH OF SAINT BASSIANO, IN PIZZIGHETTONE (CR), ITALY

G. Cardani*and G.E. Massetti**

* Department of Civil and Environmental Engineering, Politecnico di Milano
e-mails: giuliana.cardani@polimi.it

** Studio Ingegneria Strutturale Massetti, Cremona
e-mails: ing.massetti@studiomassetti.it

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Abstract. *An adequate approach to study the historic masonry buildings must begin with the knowledge and understanding of its structural logic with all its specific peculiarities and vulnerable points, given first by its historic constructive evolution and transformations and then to external causes. Also the global survey of the damage can highlight part of those transformations together with the localization of the most damaged areas. Monitoring selected cracks over time can be very useful to assess the evolution of the damage, avoiding collapses, and to understand the damage causes, useful to design the conservation plan. The accurate intervention of repair and strengthening of the parish church of San Bassiano in Pizzighettone, Cremona, Italy is here presented, where the crack monitoring was carried out to evaluate the partial structural intervention plan, to organize the next intervention phase, anticipating the urgent ones and delaying others, in order to leave open the church to the faithful.*

1 INTRODUCTION

The analysis of historical archive documents and, often, careful visual observations are able to detect if the historic masonry buildings has been subjected to numerous repairs, alterations and extensions of different materials or if a portion was rebuilt due to a partial collapse.

These events leave indelible traces in the walls, often affecting the local or even global structural behavior of the building and providing performance far from those designed and implemented at the time of its construction. As a consequence, often historic buildings turn out to be intrinsically weak and those weaknesses represents their scars, that should be recognized, analyzed and cured. The greater is the number of such scars in the historical buildings and the greater is their vulnerability, mainly to traumatic events such as earthquakes.

Serious mistakes can be made not considering this structural weakness before carrying out repairs, strengthening, insertions of new structures or structural changes, especially in earthquake zones.

In this sense, an adequate approach to study the historic masonry buildings must begin with the knowledge and understanding of its structural logic with all its specific peculiarities and vulnerable points, together with a global survey of the damage. Monitoring selected cracks over time can be very useful to assess the evolution of the damage, avoiding collapses, and to understand the damage causes, useful to design the conservation plan.

Looking at the earthquake that shocked the central Italy in 2016, one of the main causes of historic masonry buildings collapses should not be attributed only to the buildings age or to their poor construction quality of the masonry, but to the high vulnerability acquired over the centuries. The risk becomes higher if transformations or repairs are realized with modern materials and techniques, too different from the traditional ones and so incompatible from the structural point of view.

It must be remarked that the value of an architectural heritage is not only related to its appearance, but also in all its material and structural integrity, as a single product of a constructive technology of a specific historical period and place. Preserving the material component means therefore also understanding the logic of its structural system, repairing it with compatible techniques and allowing to be used without changes or substantial additions or substitutions that relegate the original structural material only to an historical backdrop.

In the second half of the XX century, several historic masonry buildings, also architectures of great value, were subjected to structural strengthening through the introduction of modern materials and techniques. The rash use of such techniques, sometimes without rational analysis that simply validates their efficacy and compatibility, turned out to be damaging over time, both for material and for the structure [1, 2, 3]. The conservation of the structures materials means therefore maintaining their role inside the building, removing, reducing or controlling the causes that have damaged them.

As an accurate intervention of repair and strengthening of a masonry church - based on *Anamnesis, Diagnosis and Therapy* - the case of the parish church of San Bassiano in Pizzighettone, Cremona, Italy is here presented: a church in Lombard-Romanesque style built in XII century and so seriously damaged as to be closed to the faithful. The strong economic burden allowed to carry out only one part of the total designed works, following the logic of the minimum necessary intervention, and, waiting for new funds, the church should have been open to faithful. At this step, it was extremely important to open the church in safety without leaving scaffolding and other obstacles. Cracks monitoring of the area still not repaired can become a useful tool to evaluate the efficiency of the structural intervention already done – *Control* -, as well as become a fundamental support for the planning of the next restoration interventions phases, anticipating the urgent ones and delaying others, helping in the necessary and sometimes onerous funds raising.

Crack monitoring techniques can be an efficient support in maintenance of architectural heritage, both for professionals, before, during and after work and for owners in order to plan the interventions over time. Nevertheless, without a deep knowledge of the historical construction, monitoring can provide data which are difficult to be analyzed, regardless of the context in which they are generated, and no intervention of strengthening will have the rational basis that will ensure their success.

2 THE CONSTRUCTIVE EVOLUTION OF THE CHURCH

The parish church of Saint Bassiano has been significantly transformed over the centuries, before showing its current aspect. (Figure 1).

a) b)

Figure 1: Saint Bassiano church: a) external and b) internal view.

The church is located in the center of Pizzighettone, a small city in Northern Italy called in Latin language *Piceleo*, along the Adda river, with a historic port very important for trading. During the middle age, Pizzighettone was long disputed between Milano and Cremona and this last one in 1133 built a fortress on the river side, which became later part of the Milanese domain under first the Visconti and then the Sforza family, who built the masonry town walls [4]. In the beginning of the XVI century, the walled town was invaded by French and then by the Spanish. In th XVIII and XIX centuries was gained by the Austrians, and in between by Napoleon's troops, till the unification of Italy in 1861.

Pizzighettone shows the unique ring of walls almost complete in Cremona province and is the most important one among the surviving ones in Lombardy. It is under those complicated historic events that the church of Saint Bassiano underwent constantly significant changes [5].

- **1st phase**

In the late Romanesque time, the local historiography ascribed to Lodi people, after the village destruction by Milanese, the reconstruction of a preexisting church starting from 1158 and dedicated to Saint Bassiano, the patron saint of Lodi city. Its façade was probably smaller and those traces are still visible (Figure 2). The building should have already had three naves and two towers at the place of the two lateral apses. The bell tower was on the South side and a second tower was on the North side but different from the one visible now, that shows traces of a demolished vault.

- **2nd phase**

In medieval time cross masonry vaults are added over the three naves and the façade was elevated to cover the larger height of the central nave.

- **3rd phase**

In 1456 the Milanese Sforza family radically transformed the architectonical aspect of the church: the façade was elevated adding a brick decoration under the eaves, two brick arched windows above the lateral doors and a beautiful rose window with twisted columns and multifoil small arches, surrounded by polychromatic tiles with heraldic symbols of the family and that cut a preexisting window.

Two rows of chapels were added on the external sides of the aisles. A new roof covered Northward the nave and the chapels with only one single roof pitch, hiding the single lancet windows of the nave. In the same period, the single lancet windows of the South side may have been enlarged and substituted with double lancet ones, now visible only from the inside of the church.

- **4th phase**

In late Renaissance time, between 1525 and 1580, additional changes occurred: a) in 1525 the present sacristy was added North-West of the church; in 1533 the bell tower was moved from South to North side of the apse and the first part of the present tower was built (Figure 2); between 1540 and 1543 a large fresco depicting the crucifixion, made by Bernardino

Campi [6], was added on the counter façade with the resulting internal covering of the rose window. In 1578 the first elevation of the tower bell took place to add a clock.

- **5th phase**

In XVIII century the elevation of the old bell tower on the South side was demolished and the entrance portal seems to be added at those time.

- **6th phase**

In XIX century the facing South chapels were demolished and probably the facing South windows of the main nave were re-formed. At this time, iron tie rods were added to the masonry vaults. In 1820 the tower bell on the North side was further elevated and in 1835 the internal church was fully depicted with the present visible style.

- **7th phase**

In XX century the last elevation of the tower bell with octagonal shape was added.

In 1963 a restoration made by the architect A. Edallo, changed the roof, partially also with modern materials, and the long single pitch Northward was demolished. The hidden single lancet windows facing North side became visible again and were so restored. Two chapels on the North side were rebuilt in modern style.

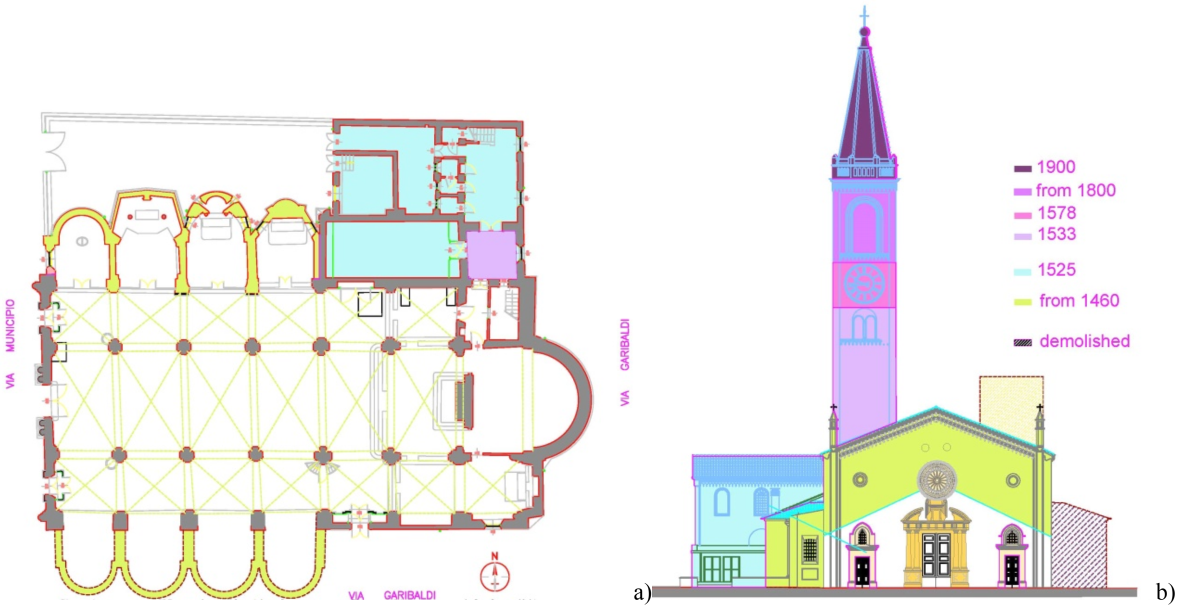


Figure 2: Historical evolution of the St. Bassiano church: a) plan and b) West facade view.

The evolution of this building is rather complicated and all these signs, like scars, are clearly visible on the building, as well as those leaved on the façade by an explosion of a powder-magazine in 1967. In 1989 many cracks and moisture penetrations are reported since a long time. The seriousness of the structural damages and the needs to substitute the damaged roof led then in 2013 to a new general structural strengthening intervention together with an improvement of the seismic performances.

3 THE DAMAGE OBSERVED IN THE CHURCH

The crack pattern survey highlighted the seriousness of the damages both in the vertical structures, weakened by the continuous alterations over the centuries, and in all the vaults. The bell tower and the sacristy are seriously damaged too (Figures 3,4 and 5). The past interventions on the roof, with its thrust, have burdened on the nave vaults and subsequently on the aisles, causing many structural cracks and detachment from the arches of the central nave.

The main arch between the apse and the nave showed a serious sliding over 2 cm (Figure 6), whereas the nearest barrel vault toward the apse, showed a large slope.

The different elevations of the Northern tower bell, with its poor basement (in the 1st construction phase it was probably a portico) caused a relevant out of plumb of about 12 cm towards the North-East side, with resultant crushing on one side and dragging on the other side, with consequences on the sacristy (Figure 4b). Many cracks due to discontinuity are present along the chapels and a soil settlement effect is recognizable on an internal pillar of the main nave in South-East direction. The Western façade showed an out of plumb of the gable outwards, probably as a consequence of the strong explosion of a powder-magazine located nearby. The surrounding area had a military vocation for a long time and vibrations can still been caused by the motorable road along the South-East side of the church.

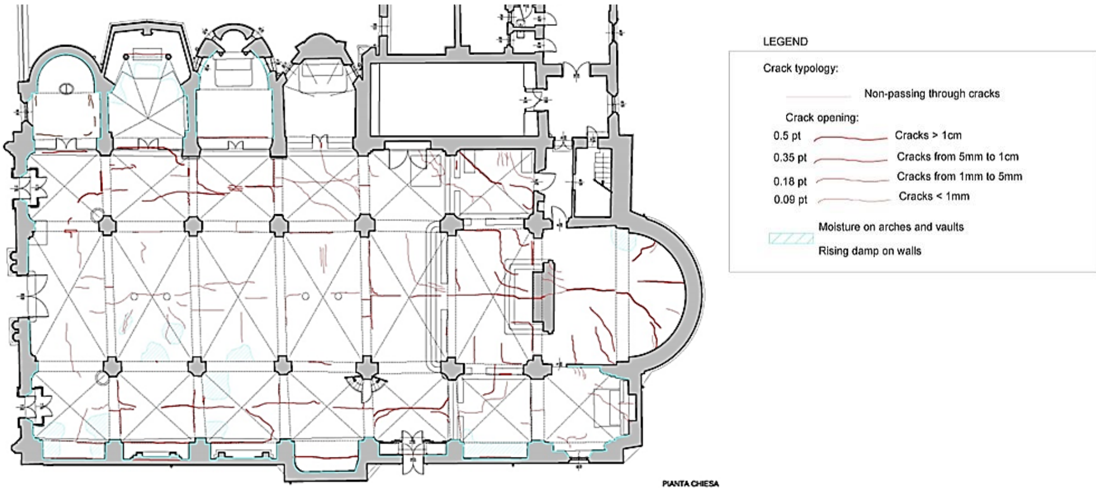
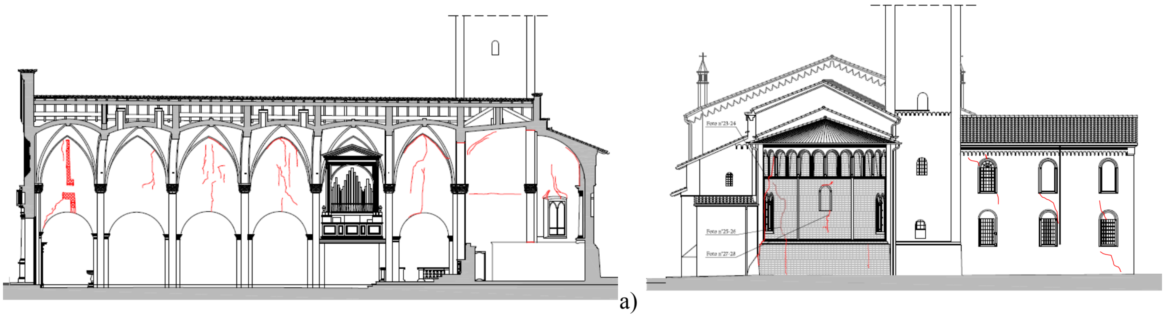
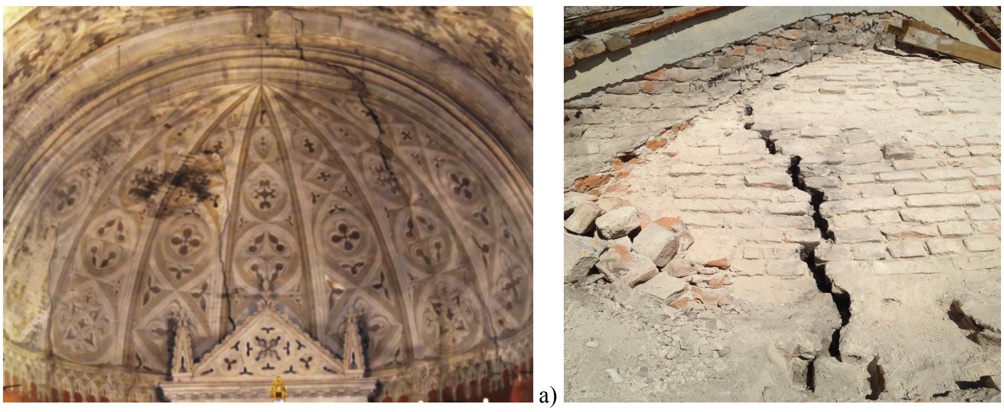


Figure 3: Crack pattern survey of the vaults of St. Bassiano church.



a) b)

Figure 4: Crack pattern survey of St. Bassiano church: a) central nave longitudinal section and b) external view of the East side.



a) b)

Figure 5: Crack pattern of St. Bassiano apse: a) internal and b) external view under the roof.

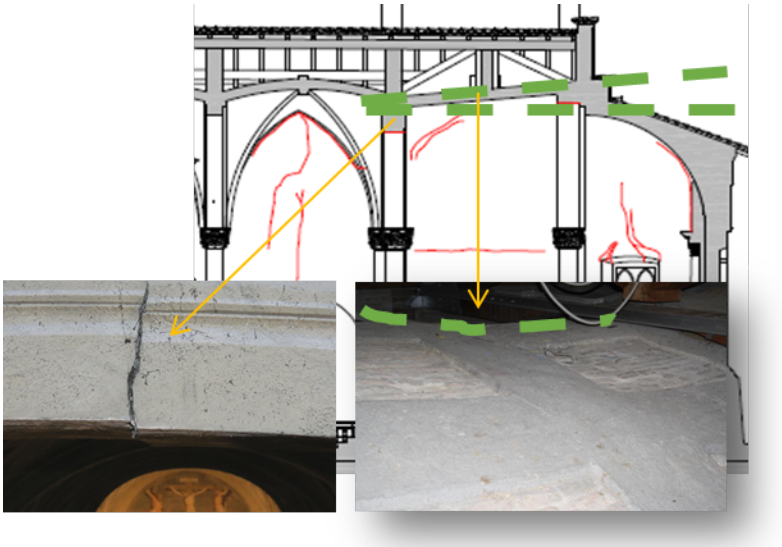


Figure 6: Crack pattern of St. Bassiano apse: the sliding of the main arch between apse and nave, on the left, and the curved profile of the barrel vault after the half-dome on the right.

4 THE DIAGNOSTIC PLAN INVESTIGATION

Due to the seriousness of the surveyed damages, a complete diagnostic investigations campaign was firstly carried out on the church structures together with a short time monitoring of few selected cracks on the apse.

The diagnostic investigations previewed: a) soil penetration tests on the South and East sides; b) installation of a piezometer to monitor groundwater level in front of the bell tower; c) foundation inspection near the three apses; d) sonic tests by direct transmission on all the internal pillars, sonic tomography and borescope inspection on 2 internal pillars on the North side; e) inclination measuring of the internal pillar through laser scanner; f) 8 single flat jack tests on West and East sides (from M1 to M8 in Figure 7) and 6 double flat jack tests; g) out of plumb evaluation of the bell tower with topographic (laser scanner) and measuring (laser centering pendulum) devices; g) automatic monitoring of the bell tower and apse cracks; h) tension evaluation in all the iron tie rods of the central nave; i) masonry coring and borescope on the apse and bell tower.

The single flat jack tests showed the uniform load distribution along the façade and confirmed the non-uniform load distribution along the bell tower, higher toward North-East

Sonic tomography on the two pillars highlighted their non-homogeneity mainly due to a different decay (moisture penetration for a long time) instead of different constructive techniques

5 THE STRENGHTENING OF THE CENTRAL NAVE

The common criterion for all project choices refers to punctual and, when possible, reversible interventions following the principle of the minimum intervention and respect of the building history and authenticity. The original materials were preserved as much as possible, without changing the original structural behavior and making recognizable ex-post the intervention areas (Figures 9 and 10).

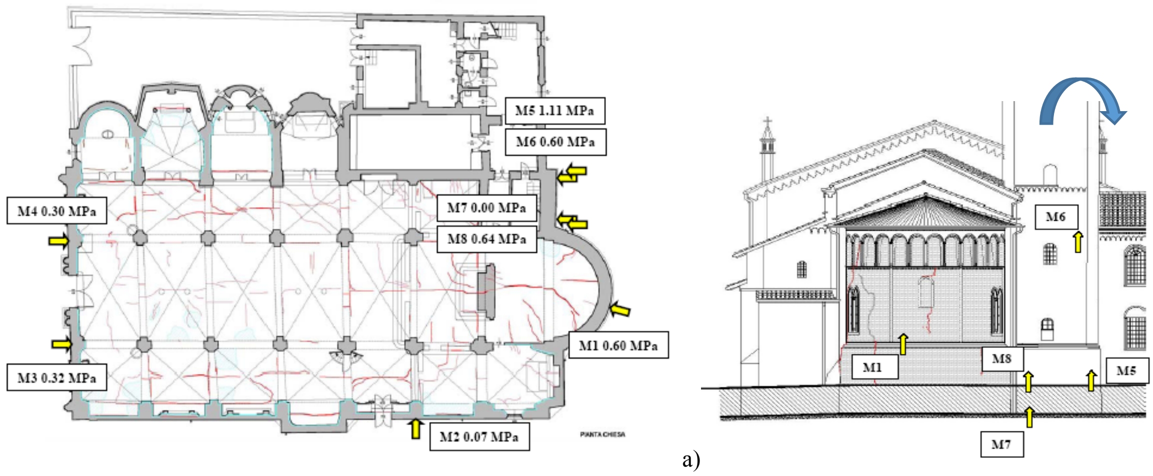


Figure 7: St. Bassiano church: state of compressive stress measured through single flat jack tests: a) in plan and b) on the East side view.

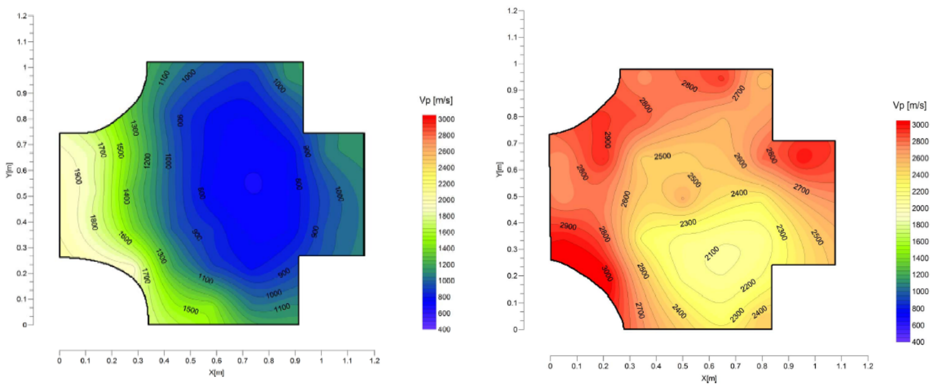


Figure 8: St. Bassiano church: sonic tomography on two close internal pillars of the North side.

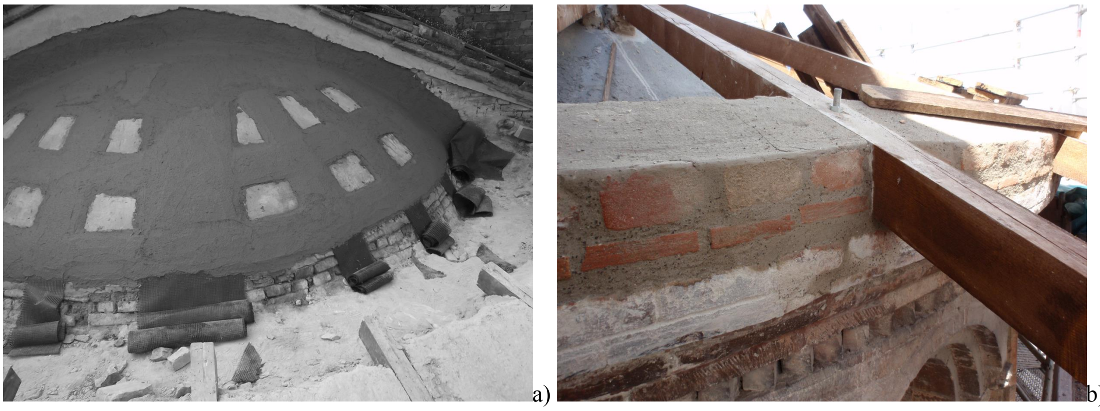
The structural intervention was not only economically important but required the closing of the main church of the town for many years. The decision to subdivide the intervention in different phases became so a necessity: a first phase was considered urgent, allowing the temporary reopening of the church at the end of this step; a second and a third phases were postponed to recover the necessary funds and to conclude the works.

The first phase included the complete substitution of the main nave roof from the façade till the apse, with a new wood structure not loading vaults anymore and with wood trusses, removing the horizontal thrust on the bearing walls (Figure 12). Such intervention stopped the main damage cause affecting the apse, the cross vaults and the main masonry arches of the nave, which were consolidated with FRCM (Fiber Reinforced Cementitious Matrix) composite system, made with a bidirectional mesh of poliparafenilenbenzobisoxazolo (PBO) fibers, offering high temperature protection, and a stabilized pozzolanic inorganic matrix, specially formulated for masonry substrates.

The groin brick masonry vaults of the main nave has been fully cleaned, after the backfilling removal, then replaced after the end of the strengthening works, realized with bedding mortar repointing and FRCM application on the extrados along stripes with pozzolanic mortar (Figure 10). Pozzolanic hydraulic mortar was preferred to epoxy resin because it is more compatible with the masonry substrate. This reinforcing system was preferred in order to fulfill the mechanical performance as well as the durability performance, according to the climatic variations and allowing continuous transpirability in the repaired areas, for the better conservation of the internal decorations. Also the arches between the groin vaults were reinforced as well as the damaged ribbed walls above the vaults, which were disassembled and then fully rebuilt with the original bricks and connected to the longitudinal nave walls (Figure 11). Longitudinal iron tie rods were inserted to fix the rotation outwards of the façade.

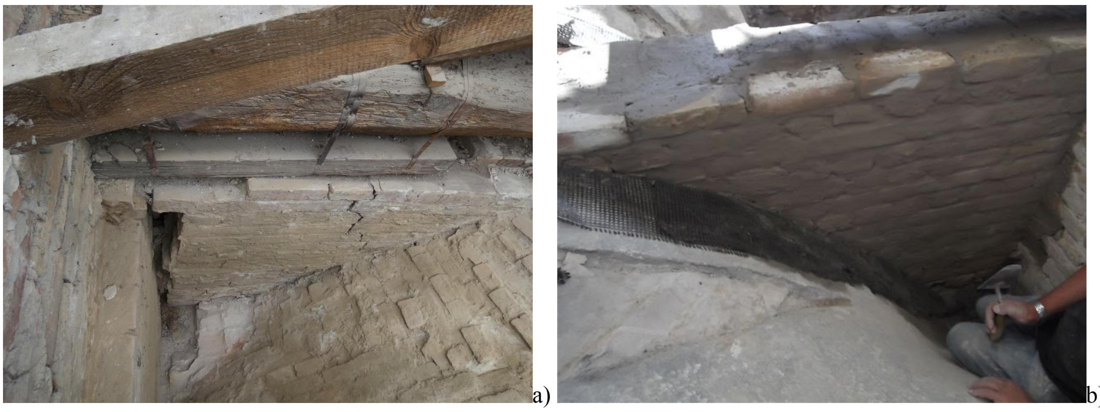
a) b)

Figure 9: St. Bassiano church apse: cracks repair with “scuci-cuci” technique (literally, a technique of unstitching/stitching the damage masonry); before (a) and during (b) reparation



a) b)

Figure 10: St. Bassiano church apse: a) FRCM matrix application and b) timber beams fixing



a) b)

Figure 11: St. Bassiano church nave: a) damaged ribbed wall above a masonry vault and b) repaired ribbed wall and interlocked with the lateral walls

Figure 12: St. Bassiano church nave: a) old wood roof structure loading the masonry vaults and b) new wood roof structure with trusses

The vertical sliding of the arch between the apse and the nave was repaired with a dense series of props with adjustable length and helpful to slowly move the arch in the original position. The FRCM was then applied on the arch extrados and connected to the arch with joints placed at regular spam in order to avoid detachments and future vertical sliding (Figures 13 and 14).

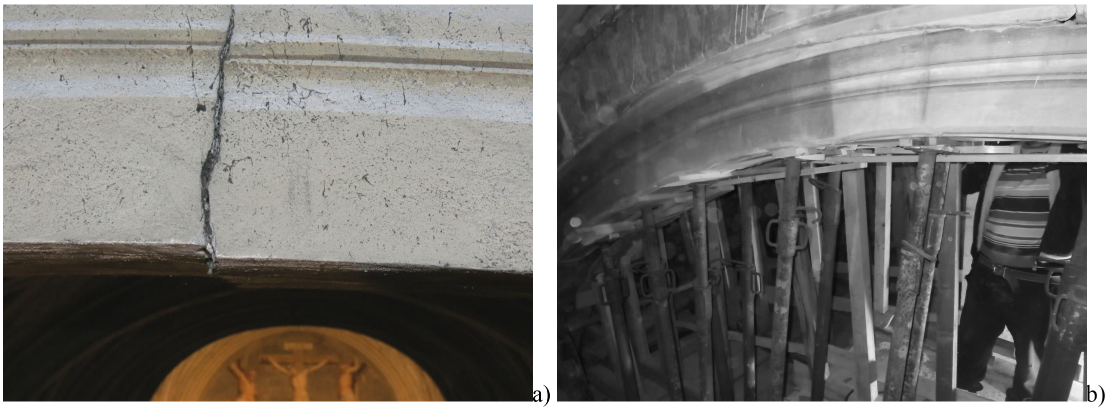


Figure 13: St. Bassiano church main arch between the nave and the apse: a) vertical sliding in the key before intervention and b) displacement in the original position with props

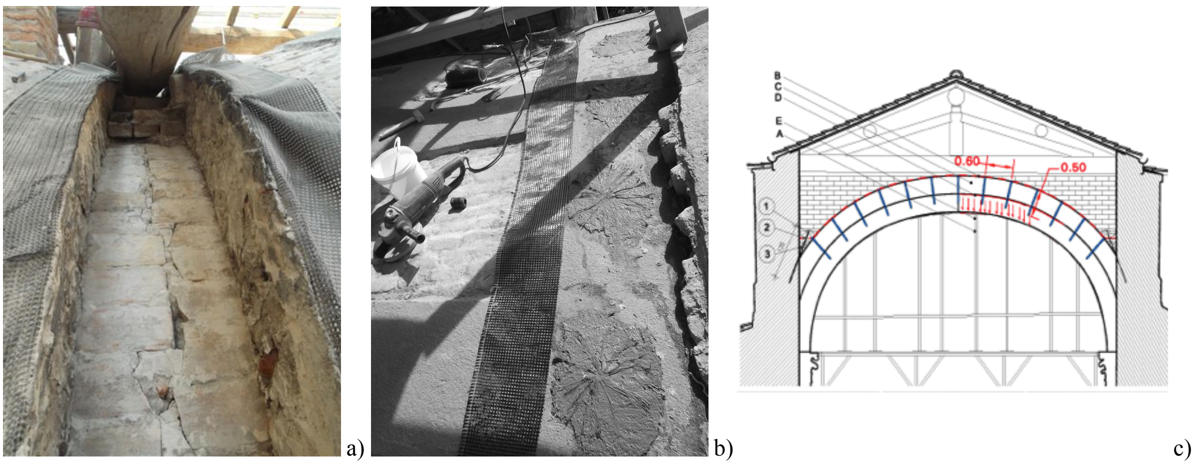


Figure 14: St. Bassiano church main arch between the nave and the apse: a) reinforcement with FRCM; b) and c) connection joints with masonry arch and lateral walls

The second and the last intervention phases refer to the reinforcement of the bell tower and of the foundations with deep driven piles along the side-wall.

6 EFFICIENCY EVALUATION OF THE PARTIAL INTERVENTION

After the first intervention phase and waiting for the two subsequent phases, the crack pattern is controlled with a remote structural health monitoring [7], in order to: a) control the remaining unrepaired portions during the necessary time for recovering funds; b) evaluate the efficiency of the first phase intervention over the time and its effect on the remaining damaged portions; c) open the church to the faithful in safety conditions without leaving props or other obstacles, giving the important signal to close the building as soon as movements are measured over a certain risk level threshold.

Some cracks have been selected among the surveyed ones, reported in figure 15, and located in the unrepaired areas, as the groin vaults of the aisles. Some monitored cracks are located also in the apse both internally to verify the efficiency of the realized intervention and externally to verify the effect of the continuous traffic vibrations.

Cracks are monitored with linear displacement transducers, sending signals to a data logger, which converts signals and sends them constantly through the phone line. Measurements are recorded every minute and averaged to half an hour, since 2014. The period is long enough to evaluate the active movements, their velocity, the effects of additional damage causes still not arrested, as the soil settlements, and of the daily thermo-hygrometric vibrations.

In Figure 16 some significant measurements are reported, showing the cracks movements in the apse both internally and externally: although the large oscillations on the external side, the cracks are stable and confirm the strengthening intervention efficiency, as well as the internal cracks, which are constantly rather flat, as well as the aisles ones. On the contrary S9 measurement base, located near the South-Eastward first pillar, is showing a constant opening increase over the time mainly due to a differential soil settlement.

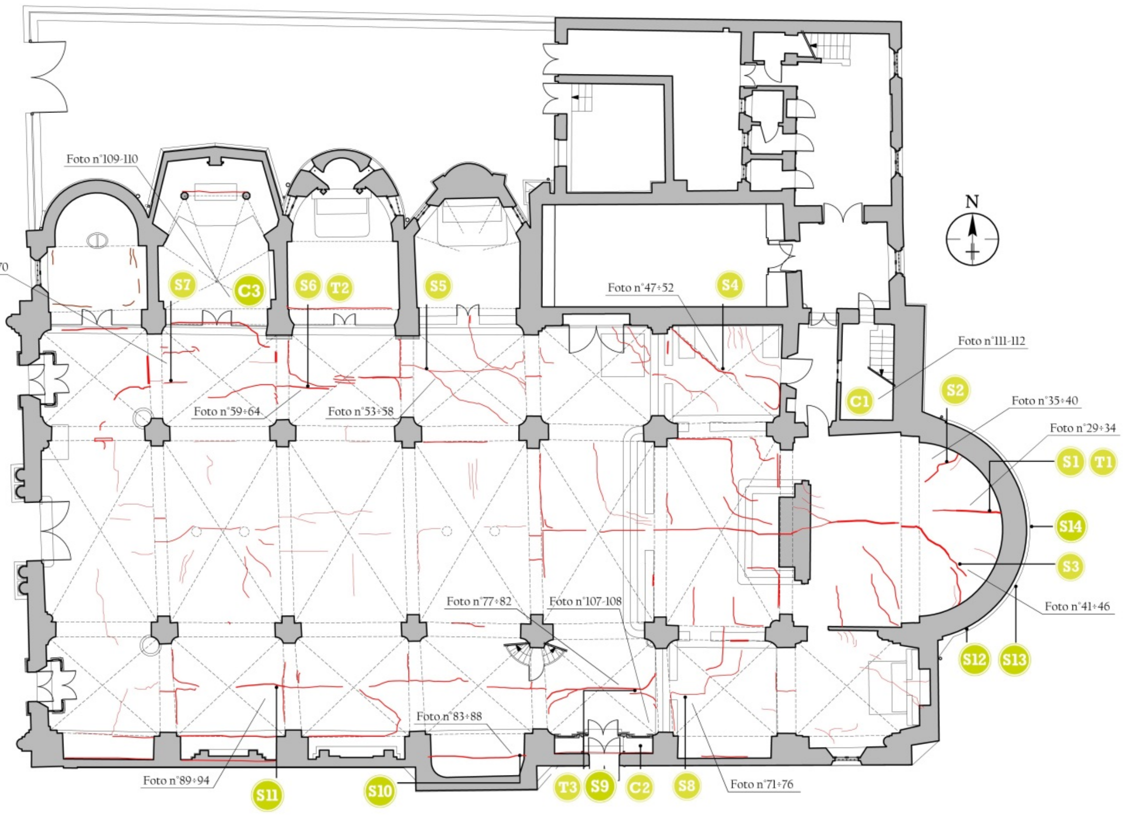


Figure 15: ST. Bassiano church: localization of the sensors on selected cracks of the aisles groin vaults and of the apse.

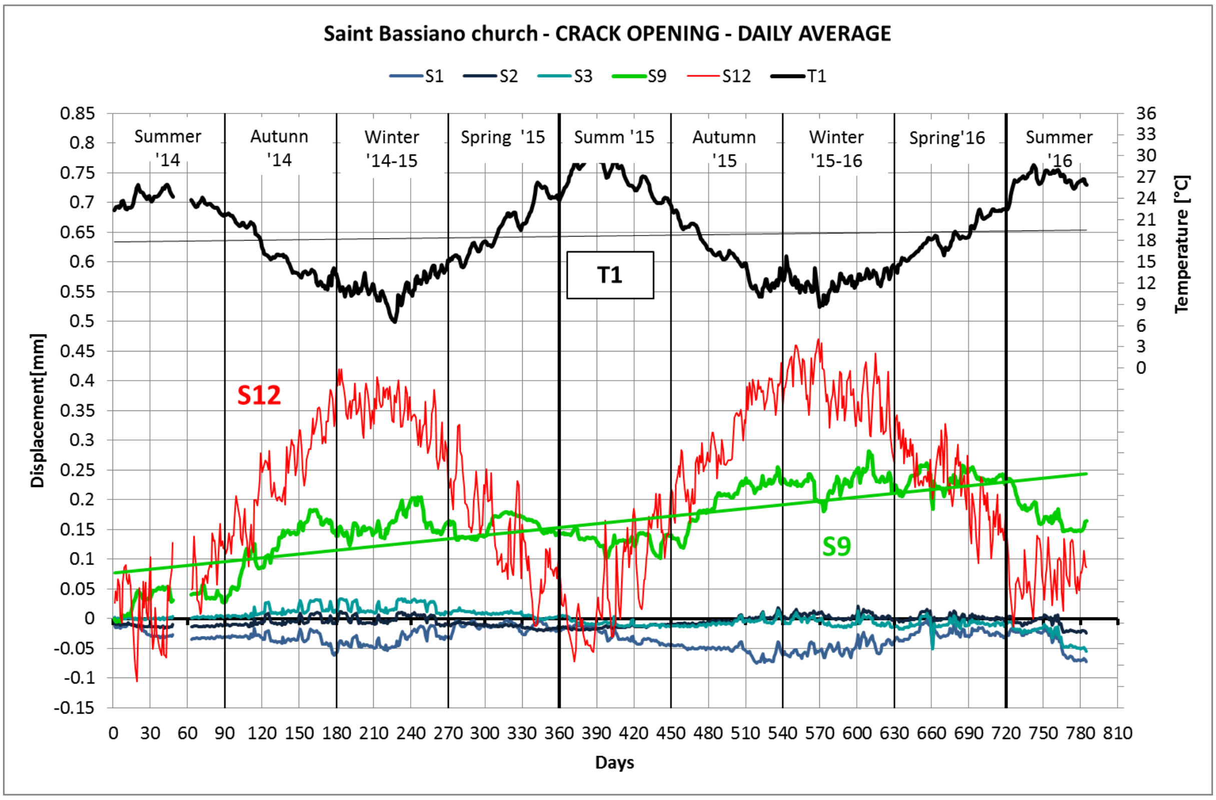


Figure 16: St. Bassiano church: plot of the 2-year crack monitoring, after the strengthening intervention of the nave vaults and roof. After two years, all cracks in the apse (S1, S2, S3 internally) and (S12 externally) are stable, whereas only one crack in the South aisle (S9) shows continuous opening.

Before starting with the second and third intervention phases, some of the stable sensors will be moved to the bell tower and to other areas subjected to soil settlement.

7 CONCLUSION

The case of Saint Bassiano church in Pizzighettone was here presented, an historic masonry building of great historic-cultural value not only for the town but also as a beautiful example of Lombard Romanesque architecture. It is a complex building due to its historical constructive evolution over the centuries but seriously damaged.

The complete interventions required the closing of the church, moving faithful away for a too long time. So the interventions were planned in different phases, solving first the damage occurred in the main nave vaults and roof. Thanks to the evaluation of the local collapse mechanisms through the linear kinematic analysis (i.e. overturning of the apse, nave wall, façade and arches, etc.) and to the adopted strengthening techniques (walls connections with iron tie rods, transversal connections in the arches and vaults with FRC matrix, insertion of new wood trusses, etc.), an acceptable safety level was reached for the local seismic risk, to be improved with the remaining planned intervention phases.

The adopted remote structural health monitoring (SHM) was useful to measure the cracks opening in a hardly accessible area like the intrados of the vaults and to evaluate the acting damages, as well as the efficiency of the strengthening interventions, so to guarantee safety and accessibility of the partially repaired building.

SHM monitoring has now reached a cost level which is competitive with the manual ones and has the undoubted advantage to evaluate in a short period the damaged structures behavior with daily or hourly records, taking into account also the environmental thermo-hygrometric variations. The level of magnitude of the crack movements over the time is so correctly evaluated, allowing to assess the correct choice for the structural intervention.

Diagnostic and crack monitoring techniques can be an efficient support in maintenance of architectural heritage, both for professionals, before, during and after work and for owners in order to plan the interventions over time. Nevertheless, without a deep knowledge of the historical construction, monitoring can provide data which are difficult to be analyzed, regardless of the context in which they are generated, and no intervention of strengthening will have the rational basis to ensure its success.

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