Bull Earthquake Eng (2017) 15:2939–2980
DOI 10.1007/s10518-016-0073-7

ORIGINAL RESEARCH PAPER

Damage assessment of three medieval churches after the 2012 Emilia earthquake

Marco Valente[1] · **Gaia Barbieri**[1] · **Luigi Biolzi**[1]

Received: 26 August 2016 / Accepted: 13 December 2016 / Published online: 29 December 2016

Abstract The architectural heritage was severely damaged by the seismic sequence that occurred in Emilia (Northern Italy) in May 2012. This paper investigates the seismic behavior of three masonry churches that were damaged by the 2012 Emilia earthquake. The analyzed churches are located in the South-East area of the province of Mantua: they are representative of some churches, denoted as “Matildic churches”, belonging to the territorial area between Lombardia, Emilia Romagna and Toscana and built during the Matilde di Canossa domain, between the X and the XI centuries. The study was based on detailed field surveys, in situ tests, visual inspections and existing archives in order to obtain an accurate knowledge of the churches and a proper evaluation of the damage caused by the earthquake. Then, detailed finite element models of the churches were developed and non-linear dynamic analyses with different peak ground accelerations were performed. The numerical simulations provided a deep insight into the seismic behavior of the analyzed churches, identifying the damage patterns and the main collapse mechanisms for different seismic intensity levels. The obtained results appear to be in a good agreement with the damage experienced by the churches during the earthquake. This study can be considered as a first step to assess the seismic vulnerability of the “Matildic churches”, extremely important for their historical and architectural value.

Keywords Masonry church · Field survey · Crack pattern · Damage · FE model · Non-linear dynamic analysis

---

✉ Marco Valente
marco.valente@polimi.it

[1] Department of Architecture, Built Environment and Construction Engineering, Politecnico di Milano, Piazza Leonardo da Vinci 32, 20133 Milan, Italy

1 Introduction

The seismic sequence that occurred in Emilia (Northern Italy) in May 2012 was characterized by two 5.9 and 5.8 Mw earthquakes and it struck a very large area, including the provinces of Modena, Ferrara, Rovigo and Mantua. Different typologies of constructions were damaged and in many cases an extensive collapse of the structures was detected (Andreini et al. 2014; Penna et al. 2014). As it is well known, unreinforced masonry structures belonging to the cultural heritage were conceived to withstand gravity loads (Foraboschi 2016), but they are very vulnerable to seismic actions: for this reason, several analytical and numerical studies have been developed in literature to assess their performance and their strengthening (Betti and Vignoli 2008; Foraboschi 2013, 2014; Lagomarsino and Cattari 2015; Preciado et al. 2015; Valente and Milani 2016a, b). Moreover, innovative efficient non-destructive methods have been proposed to investigate the structure of a masonry and accuartely define the geometry of its internal elements (Lualdi and Lombardi 2014a, b). The 2012 Emilia earthquake also caused severe damages to a huge number of historical masonry buildings (Cattari et al. 2012; Parisi and Augenti 2013). In particular, churches were highly affected by the earthquakes, as already emerged during past severe seismic events (Lagomarsino 2012). The high seismic vulnerability of churches can be related to their very specific architectural structure, such as their complex geometry and the low tensile strength of masonry (Sorrentino et al. 2013; Milani and Valente 2015a; Barbieri et al. 2016).

This paper aims at providing some insights into the seismic performance of historical masonry churches located in the Mantuan Oltrepò region and damaged by the 2012 Emilia earthquake sequence. The stretch of land in the South-East area of the province of Mantua, near the Po river and the border with Emilia, is known as “Mantuan Oltrepò region” or the “lands of Matilde”. This region provides a number of examples of Romanesque architecture, such as churches called “Matildic” in memory of the countess Matilde di Canossa, surely one of the major figures of the Italian Middle Age (Golinelli 2004).

In particular, this study investigates three Matildic masonry churches damaged by the 2012 Emilia earthquake: (1) San Benedetto Abate church in Gonzaga, (2) San Fiorentino Martire church in Nuvolato, 3) Santa Maria Assunta church in Felonica. Figure 1 shows a general view of the three churches under study. These buildings have been selected because they are representative of the architectural and constructive practice of a significant number of churches in the Po valley area. They are unreinforced solid clay bricks masonry structures that were built between the X and XI centuries; the buildings underwent several interventions and transformations over time, but they present clear references to their Romanesque origin.

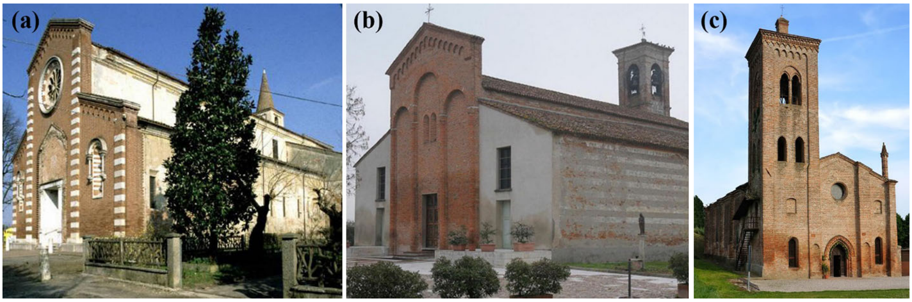


Fig. 1 General view of the three churches under study: **a** San Benedetto Abate church in Gonzaga, **b** San Fiorentino Martire church in Nuvolato, **c** Santa Maria Assunta church in Felonica

All the three case studies are characterized by a similar structure: the main body consists of a large hall closed by a semicircular apse (sometimes there is the choir) and covered by a wooden roof system; the aisles are characterized by cross vaults with an *in foglio* arrangement, consisting of flat laid bricks with the broad faces exposed so that the thickness of the structure is equal to the height of the brick (about 6 cm); round arches characterize almost all the openings; high bell towers integrate the principal structure; the exterior is characterized by a massive structure (with a thickness ranging between 40–100 cm and small openings) scanned by important pilasters; the façade presents a gabled profile. The three churches suffered different levels of damage, which highlight the most vulnerable elements of this typology of buildings. In particular, Santa Maria Assunta church in Felonica presented moderate damage, San Fiorentino Martire church in Nuvolato underwent serious damage and San Benedetto Abate church in Gonzaga suffered very serious damage.

The analysis of each church has been carried out developing the following parts: (1) historical analysis; (2) definition and description of the geometrical structure; (3) identification of the masonry quality; (4) evaluation of both the damage state and the crack pattern; (5) development of numerical models in order to explain the damage due to the 2012 earthquake.

A preliminary historical research is a fundamental requirement for the analysis of the three churches. It allowed obtaining valuable information for the definition of a reliable structural model, with reference to original design and construction, architectural and technical phases, as well as transformations that occurred over the centuries.

An accurate geometric survey of the actual configuration was performed in order to detect the complex three-dimensional geometry of the structure. Moreover, a visual inspection allowed the analysis of the employed constructive techniques, the structural constructive details, connections between elements and the identification of the degradation state of the materials. Some experimental tests were carried out on materials and structures in order to identify the conservation state of the churches and to obtain a qualitative assessment of the material.

An extensive field survey of the crack pattern was conducted after the 2012 earthquake. Based on both a Terrestrial Laser Scanning (TLS) geometrical survey and a visual inspection, the presence of several cracks was detected. The damage observed during the field surveys was analyzed with reference to typical local collapse mechanisms of macro-elements. In the majority of the cases, the outcomes of the post-earthquake inspections on the masonry churches evidenced a poor seismic performance with the occurrence of significant damage in different macro-elements.

The evaluation of the seismic vulnerability of the structures was carried out through refined numerical models. The same masonry material was assumed for all the churches in order to have an insight into the dynamic behavior of the structures only as a function of their geometries. Detailed three-dimensional finite element (FE) models of the churches were developed and non-linear dynamic analyses were performed with different peak ground accelerations (PGA) in order to detect the main parts of the churches characterized by severe damage and stress concentrations. The non-linear dynamic simulations were useful tools to show the evolution of damage for different levels of seismic intensity.

2 Historical survey

This section provides a short historical description of the churches under study. The knowledge of ancient buildings involves a historical review that should be considered as integral part of the seismic assessment procedure.

2.1 San Benedetto Abate church in Gonzaga

The church of San Benedetto Abate is located in Gonzaga, a small city in the province of Mantua in Lombardia region, about 25 km south of Mantua.

A first historical document, which proves the presence of an ancient religious chapel in Gonzaga, probably in the same site as the present San Benedetto Abate church, dates back to 967. Probably at the end of the XI century, Matilde di Canossa rebuilt the ancient monument in a Romanesque style and established a new Benedectine monastery, which was constituted under the dependence of the nearby Benedictine monastery in Polirone (San Benedetto Po). Recovery materials of Roman origin were used for the new Matildic building. According to the historians reconstruction, the Matildic structure presented a Latin-cross plan and it was composed of three naves, the principal one closed by a presbytery and a semicircular apse. Other two apses were in correspondence with the two arms of the transept. Nevertheless, only a small part of the original structure is currently still existing (two apses, the presbytery and a part of the transept). In fact, a partial important reconstruction of the church was performed before 1534, probably after the damage caused by the 1501 earthquake in Reggiolo, and mainly involved the restoration of the three naves and of the coverings and the creation of a new first counter-façade on the existing one. The bell tower placed against the north side of the presbytery dates back to the end of the XV century. The annexes on the north-east side of the church were surely built before 1663. The annexes on the south-east side of the church, with the *Sala Confratelli*, were added between the XVIII and XIX centuries and caused the demolition of the original apse.

In the second half of the XIX century, San Benedetto Abate church was in a precarious state of conservation. Some interventions are documented to have been carried out in this period: the ceiling wattle of the main nave, the sacristy and a new floor were realized in 1868.

During the XX century, some works were performed to counteract the overturning of the façade, due to the thrusts of the arches of the aisles and to the inadequacy of the foundations (some inspections revealed that, in correspondence with the façade, the foundation thickness was smaller than the thickness of the overlying wall). In 1925 the creation of a new counter-façade in a false-Romanesque style was conducted and the demolition of the original prothyrum was realized.

In 1981 some restoration works were carried out at the roof level, mainly at the wooden structures. The restoration of the presbytery and apse was conducted in 1983: the main idea of the project was to bring out the different construction phases of the church, which seemed to be the result of a mixture of different architectural styles. After the filling of the cracks, five original single windows of the apse and the presbytery were re-opened while the most recent openings were re-closed, the plaster was removed, the roof structure was replaced and the tympanum was strengthened. Some diagnostic inspections were carried out and revealed some information about the original structure (i.e. the existence of an old floor under the presbytery and the central nave, probably revealing also the presence of a crypt, the proofs of a gabled roof in the transept, the ruins of the right Romanesque apse demolished between the XVIII and XIX centuries). In 1985, the plasterwork of the internal walls was realized and some evidences of the ancient connection between the transept and the lateral naves emerged. Some strengthening works were performed too. In 1986 the filling of the cracks in the south arm of the transept was performed. In 1988 the strengthening of the cracked ceiling wattle of the central nave was realized using epoxy resin injections; then, in 1989 some interventions concern the openings in the main façade.

During the Eighties, some concerns regarded also the structural conditions of the bell tower, which showed important cracks and a significant leaning toward east. In 1986 some strengthening interventions were performed on the bell tower walls and the cracks were filled.

In 2001 additional works were conducted on the bell tower (the retrofitting of the masonry structures and of the floors), the basement of the apse and the north portion of the roof.

Since 2012 a monitoring system was set up in order to detect the bell tower and the façade deflections.

Figure 2 illustrates the construction phases of San Benedetto Abate church.

2.2 San Fiorentino Martire church in Nuvolato

San Fiorentino Martire church is located in Nuvolato (municipality of Quistello), a small town in the province of Mantua in Lombardia region, about 20 km south-east of Mantua.

The original church of San Fiorentino Martire was probably built in the second half of the XI century (it was mentioned for the first time in a document dating back to 1059).

From the interpretation of the archeological survey, it can be assumed that the original Romanesque church presented a Latin-cross plan and it was composed of a single nave with three apses containing altars. The main apse was in correspondence with the nave, behind the presbytery.

A first significant structural change is registered in the XVII century: the minor apses were demolished due to the construction of the bell tower and of the sacristy (demolished

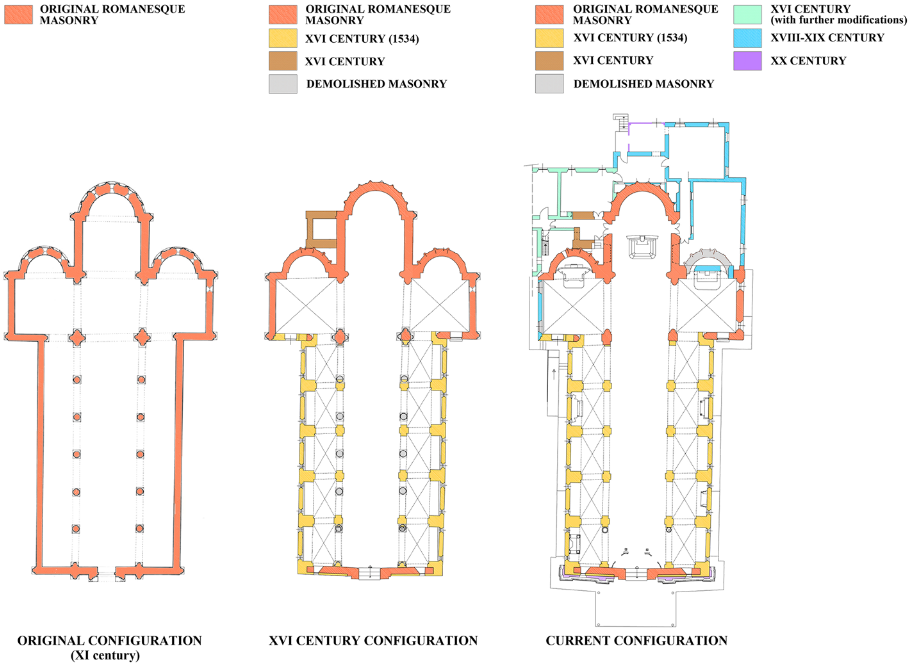


Fig. 2 San Benedetto Abate church: the construction phases

in 1935) on the left and on the right sides of the main apse, respectively. Before 1735, the *Confratelli del S.S. Sacramento* Oratory and the pilgrim guestroom were built against the left side of the original structure.

During the XVIII century, the church underwent a new transformation that involved an adaptation to the baroque style both for the interior space and for the main façade. Between 1776 and 1779, the original structure was enlarged and two aisles were symmetrically added on each side of the external perimeter walls of the principal nave. The new lateral naves were constituted by a sequence of three chapels and they were connected to the principal space by three arches made in breach in the ancient walls. This operation involved also the demolition of the pilgrim guestroom and of the *Confratelli del S.S. Sacramento* Oratory, the latter rebuilt against the north lateral nave in the first decade of the XIX century. In addition, other interventions have been carried out also during the XIX century and completely overturned the church Romanesque identity, which remained visible only in the external side of the apse. Inside the monument, the floor and the walls of the central nave were raised, the wooden trusses of the roof were rebuilt and hidden by a vault, all the walls were plastered. Outside, the main façade assumed a three-lobed shape with semicircular tympani and it was totally plastered; a stairway extending along the entire façade was realized.

In the Twenties of the XX century, the artistic and historical value of the church was re-evaluated. Therefore, between 1970 and 1975, some new interventions were performed in order to restore the original Romanesque features, cleaned of all the Baroque superstructures. In particular: the single windows in the apse and the main nave were restored and the main façade and the interior walls of the principal nave were stripped with the exposed brickwork re-establishment.

In the first decade of the XXI century, some interventions on the external churchyard and the restoration of the interior (mainly to the paving) have shown some ruins of the original Medieval structure.

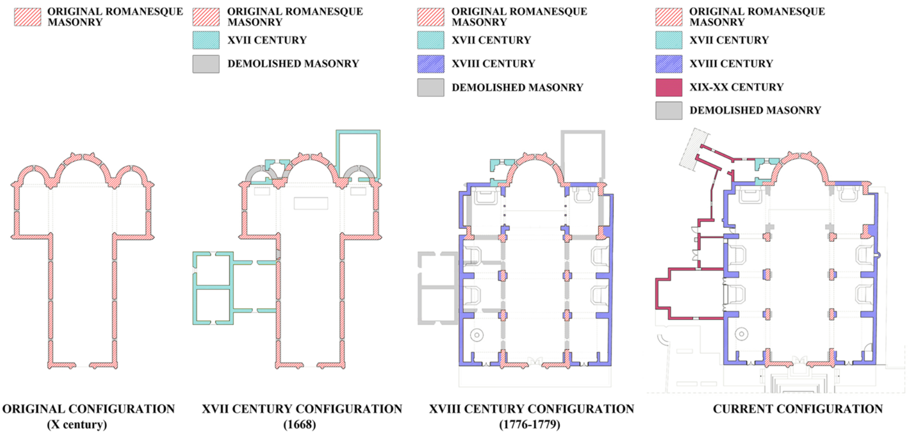
Figure 3 illustrates the construction phases of San Fiorentino Martire church.

2.3 Santa Maria Assunta church in Felonica

Santa Maria Assunta church is located in Felonica, a small town that lies in Po riverbank in the province of Mantua in Lombardia region, about 60 km south-east of Mantua.

The first historical reference of the existence of an ancient abbey in Felonica can be found in a notarial document dating back to 941. The monastery complex is mentioned in a successive document by Beatrice di Canossa, which dates back to 1053. In 1075 Matilde di Canossa rebuilt the church and made it part of the Benedictine monastery in Polirone. An inventory dating back to 1361 describes the Felonica abbey complex: it consisted of a cloister surrounded on one side by the church and on the other three sides by the chapter house, the refectory and the kitchen. Over the centuries, the Benedictine monks developed and preserved the church and the monastery. In 1797, during the Napoleonic suppression of the monastery of San Benedetto, all the goods of the monastery were given to the French army and it was the beginning of the monks dispersion.

According to some researchers, the original church was constituted by three naves (being the existing nave the ancient central nave) and the actual bell tower (dating back to the XV century) was located at the centre of the main façade. Nevertheless, this hypothesis seems to have no consistency and recent studies report that the church maintained over time its current configuration, characterized by a basilica plan. Surely, several interventions were carried out over the centuries on the church. In 1530, during the visit of Giulio



ORIGINAL CONFIGURATION (X century)

XVII CENTURY CONFIGURATION (1668)

XVIII CENTURY CONFIGURATION (1776-1779)

CURRENT CONFIGURATION

Fig. 3 San Fiorentino Martire church: the construction phases

Romano in Felonica, a document reports that the church needed restoration, even if it is unclear whether, at that time, it was completely destroyed or damaged. It is not easy to establish the entity of the interventions that occurred during the XVI century, even if surely the lateral bearing walls prove several interventions that occurred over time. Some minor works are documented between 1757 and 1769: they mainly concerned the repair of the roof, a new floor of the hall (it was documented that the original floor was 2 m below the current one) and some restoration works of the internal and external walls. The most recent major intervention was carried out between 1915 and 1920, when the church appeared in degraded conditions. The works were conducted by the Mantuan architect Aldo Andreani and mainly concerned the façade, which was completely adapted to a Gothic style in the lower part with the modification of the main entrance, and the two pointed windows at each side of the door. Inside, the architect rebuilt the atrium with the lateral chapels in a Romanesque style; with reference to Fig. 4a, the roof system was modified too. A new balustrade was inserted between the hall and the presbytery, with a clear reference to the middle eastern architecture. The last intervention was carried out after the Second World War with the aim of repairing the damage caused during the war. A greater stylistic coherence was given to the church, which currently maintains a clear Romanesque aspect enriched by gothic influences.

Figure 4 shows a comparison of the exterior of the church before and after the reconstruction works carried out by Aldo Andreani.

3 Geometrical survey and description of the churches under study

This section provides a brief description of the main geometrical features of the churches obtained through an integration between an accurate 3D TLS survey and a direct survey. The geometrical survey of the churches was performed after the 2012 Emilia earthquake.

3.1 San Benedetto Abate church in Gonzaga

The current church is oriented toward south-east and presents a Latin-cross plan characterized by three naves and a large transept with a little semi-circular apse in the northern

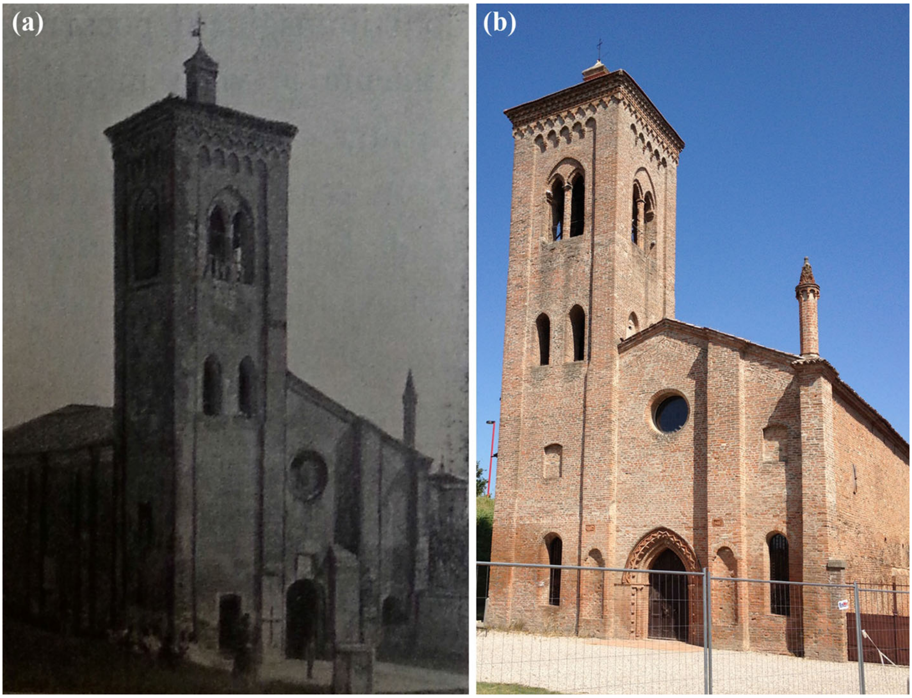


Fig. 4 Santa Maria Assunta church: the external view **a** before and **b** after the interventions performed between 1915 and 1920 by Aldo Andreani

arm. A rectangular presbytery and a semi-circular apse close the building. From the façade to the apse of the presbytery, the total length is about 46 m.

The hall is about 28.5 × 17 m and the transept is about 6.4 × 24 m. Cruciform columns supporting round arches separate the central nave from the aisles and the transept arms. The aisles are composed of five spans and small chapels with altars are present. Masonry cross vaults cover both the two arms of the transept and the spans of the aisles. The central nave has an *incannucciato* vault: such an old system consists of a non-structural false ceiling formed by reeds tied with wires, arranged along one or two directions, anchored to wooden structures and plastered at the intrados so that the reeds are bonded together. The wooden roof consists of trusses simply supported by perimeter load-bearing walls. The central nave has a height equal to 15.5 m at the ridge line and 13.3 m at the eave line. The presbytery with a masonry barrel vault is about 7.4 × 8.8 m; the apse presents a 3.7 m external radius and is covered by a masonry semi-dome.

The northern side of the church is flanked by several annexes. On the left side of the presbytery, an almost square cross-section (2.35 × 2.62 m) bell tower is attached only for one side to the building; it has a height of about 30 m and it is characterized by a belfry covered by a masonry cone-shaped roof. The sacristy is placed on the right side of the presbytery.

The exterior of the church is entirely in exposed brickwork. The tiered main façade reflects the internal space composition: the central part presents a height equal to 17.5 m at the ridge line and 14.8 m at the eave line; the lateral sides have a height equal to 10.5 m at the ridge line and 8.4 m at the eave line. The façade is characterized by a large rose window and two small openings in correspondence with the two aisles. In the bottom central part of the façade, the signs of the ancient prothyrum structure incorporated into the current building are clearly visible.

The structure is made up of brick masonry. The lateral walls of the presbytery and of the central apse, which represent the oldest part of the church, exhibit a thickness that ranges between 80 and 100 cm. The longitudinal walls of the central nave and the walls of the aisles, which date back to the XVI century, have a thickness ranging between 50 and 70 cm. The walls thickness of the bell tower and of the façade is around 70–90 and 120–130 cm, respectively. All the cross vaults present an *in foglio* arrangement.

Figure 5 illustrates the plan, the elevation views and the sections of the church; Fig. 6 shows the main façade and two inner views.

3.2 San Fiorentino Martire church in Nuvolato

The current church is oriented toward south-east and is composed of three naves, a transept and a semicircular apse. From the façade to the apse, the total length is about 27 m.

The hall is about 16.7 × 19.5 m and the transept is about 6.5 × 19.5 m. Round arches in the longitudinal walls connect the central nave with the aisles and the transept arms. The aisles are composed of three spans with small chapels with altars; other two altars and chapels are in each transept arm. Both the aisles spans and the transept arms are covered by cross vaults; the covering of the central nave roof is composed of a wooden structure with simple trusses directly in plain sight. The central nave has a height equal to 10.5 m at the ridge line and 8 m under the trusses bottom chord. The apse presents a 3.6 m external radius and is covered by a masonry semi-dome.

On the northern side of the apse, a square cross-section (side equal to 3.4 m) bell tower arises for a total height of 17.5 m. Other annexes are present along the northern side of the building.

The exterior of the church is partially in exposed brickwork (the central part of the main façade and the east façade with the apse) and plastered (the lateral façades and the lateral parts of the main façade). The central part of the tiered main façade has a height equal to 13.5 m at the ridge line and 11.6 m at the eave line; the lateral sides have a height equal to 8.3 m at the ridge line and 6.2 m at the eave line. The façade is characterized by a typical Romanesque decoration with three arches and masonry semi-columns, and a mullioned window is present in the middle of the façade.

The structure is made up of brick masonry. The thickness of the walls of the central nave and the apse, which are the oldest part of the church, ranges between 50 and 60 cm. The thickness of the walls of the aisles and the transept, which were rebuilt during the XVIII century, ranges between 40 and 75 cm. All the cross vaults are constituted by bricks arranged *in foglio*.

Figure 7 illustrates the plan, the elevation views and the sections of the church; Fig. 8 shows the main façade, an external view of the apse and bell tower, and an inner view.

3.3 Santa Maria Assunta church in Felonica

The current church is oriented toward south-east: it is composed of a long trapezoidal-shaped body, consisting of a single large hall that is preceded by a rectangular body serving as an atrium, closed by an almost square cross-section presbytery and a semi-circular apse. From the façade to the apse, the total length is about 37 m.

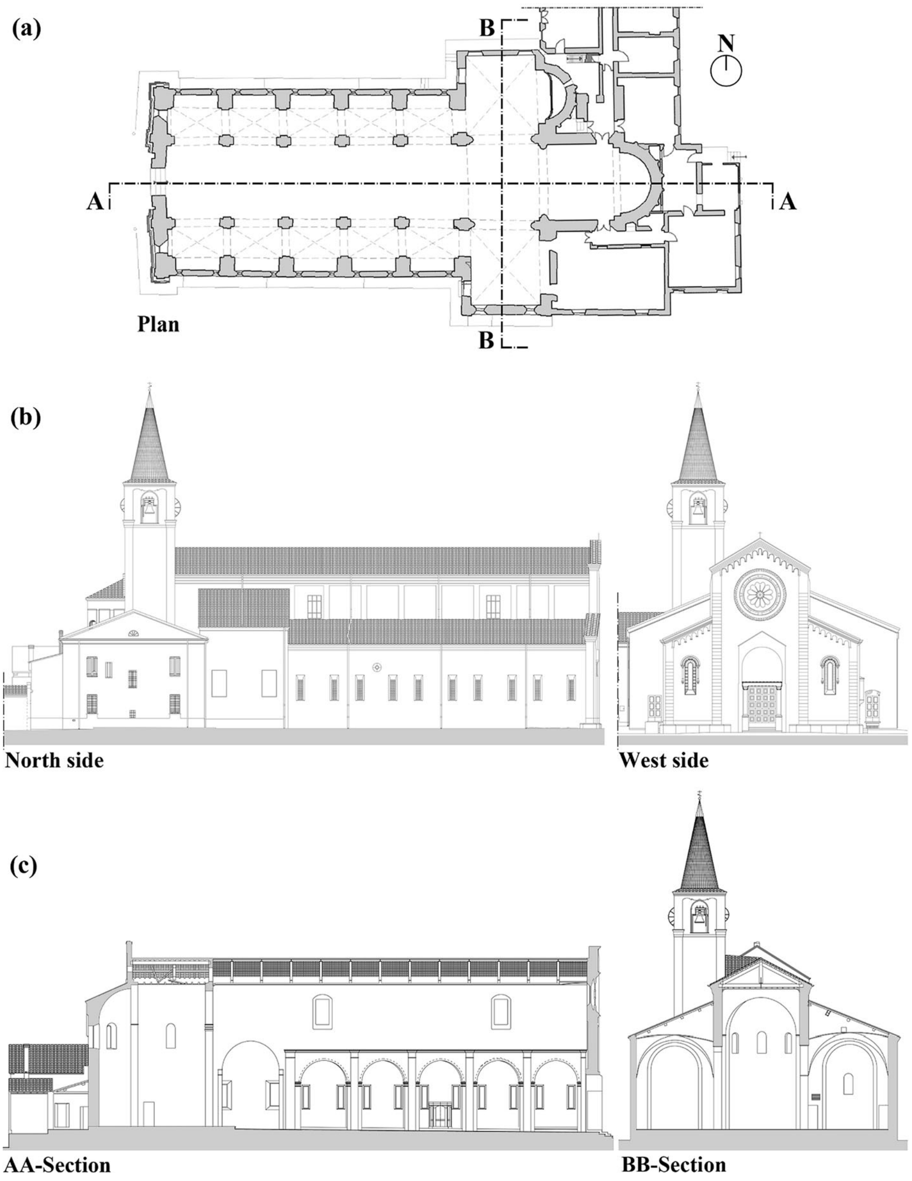


Fig. 5 San Benedetto Abate church: **a** plan, **b** elevation views, **c** sections

The atrium (4.1 × 12 m) is tripartite and arranged on two or more levels. On the ground level, the central space represents the access corridor to the church. The *Cappella Gemella* with the confessional is on the right side of the entrance; the *Cappella del Campanile* with the 23 m high bell tower is on the left side. Above the *Cappella Gemella* and the access corridor, there is the choir with the multi-mullioned window overlooking the hall divided by small pillars. Both the entrance and the choir are covered by a wooden structure, whereas the adjacent chapels are closed by masonry cross vaults. The hall is about 23 m

Fig. 6 San Benedetto Abate church: **a** main façade, **b** inner view of the central nave toward the entrance, **c** inner view of the church toward the apse

long and the width varies from 12 to 12.85 m. The roof consists of wooden trusses in plain sight, with a height equal to 11.1 m at the ridge line and 7.9 m under the trusses bottom chord. The presbytery has sides about 7.6 m long and is covered by a masonry cross vault, which hides the wooden structure of the roof. The apse presents a 2.5 m external radius and is covered by a masonry semi-dome, even if the roof is composed of a wooden structure.

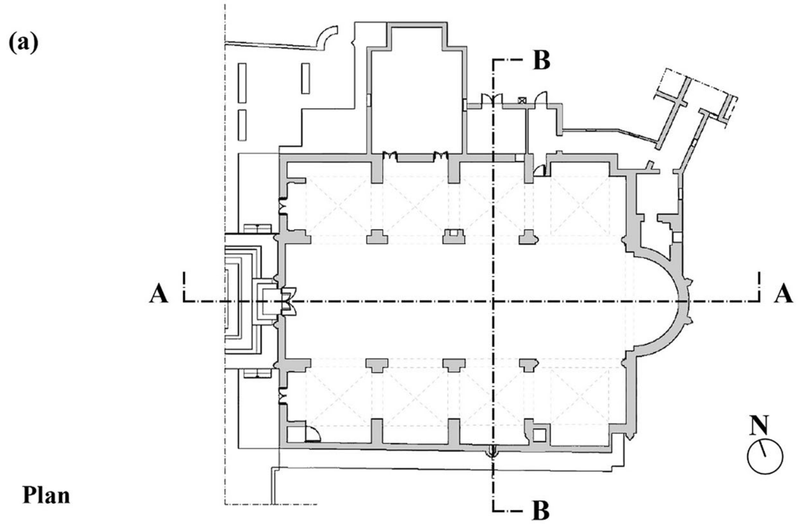
The exterior of the church is entirely in exposed brickwork. The gabled main façade is marked by thick pilasters that reflect the inner organization of the atrium, even if the presence of the bell tower on the left side breaks the symmetry of the composition. The height of the façade is equal to 11 and 8.7 m at the ridge and eave lines, respectively. It is characterized by a large rose window and a pointed arch entrance door; two tall and narrow lancet windows are in correspondence with the lateral *Cappelle*.

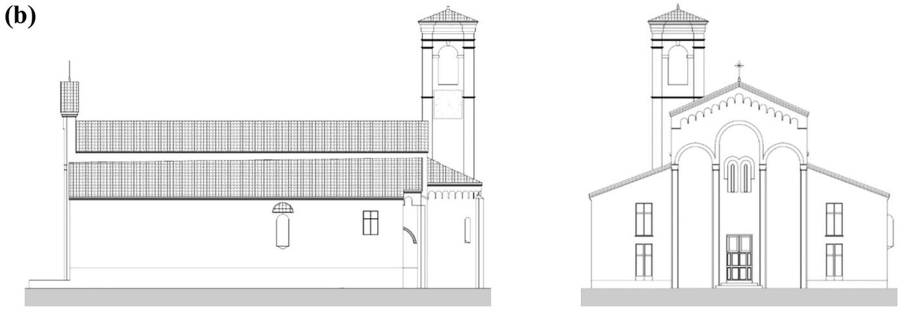
The structure is made up of brick masonry. The thickness of the walls is very variable and it ranges between 40 and 100 cm. All the cross vaults are constituted by bricks arranged *in foglio*.

Figure 9 illustrates the plan, the elevation views and the sections of the church; Fig. 10 shows the main façade and two inner views.

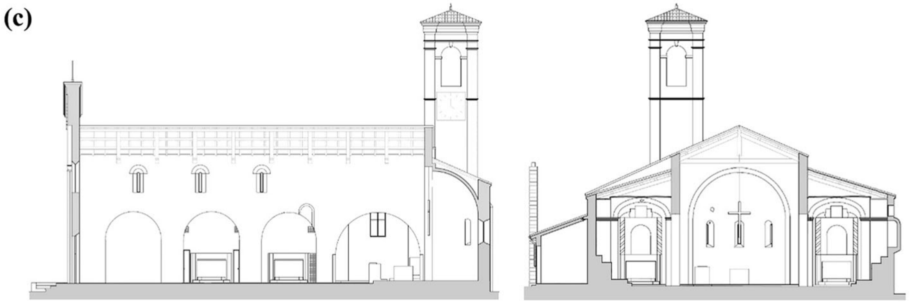
4 Materials and in situ tests

Experimental tests were carried out on materials and structures in order to identify the conservation state of the churches after the 2012 Emilia earthquake. Some results of qualitative and non-destructive tests carried out on San Benedetto Abate church are reported in this paper: video-endoscope and visual inspections, sonic tests with tomographic survey and termographic tests.





South side **West side**



AA-Section **BB-Section**

Fig. 7 San Fiorentino Martire church: **a** plan, **b** elevation views, **c** sections

4.1 Video-endoscope and visual inspections

Eighteen video-endoscope and visual inspections have been performed on different walls, columns, and arches—in order to detect masonry typologies, internal stratifications and

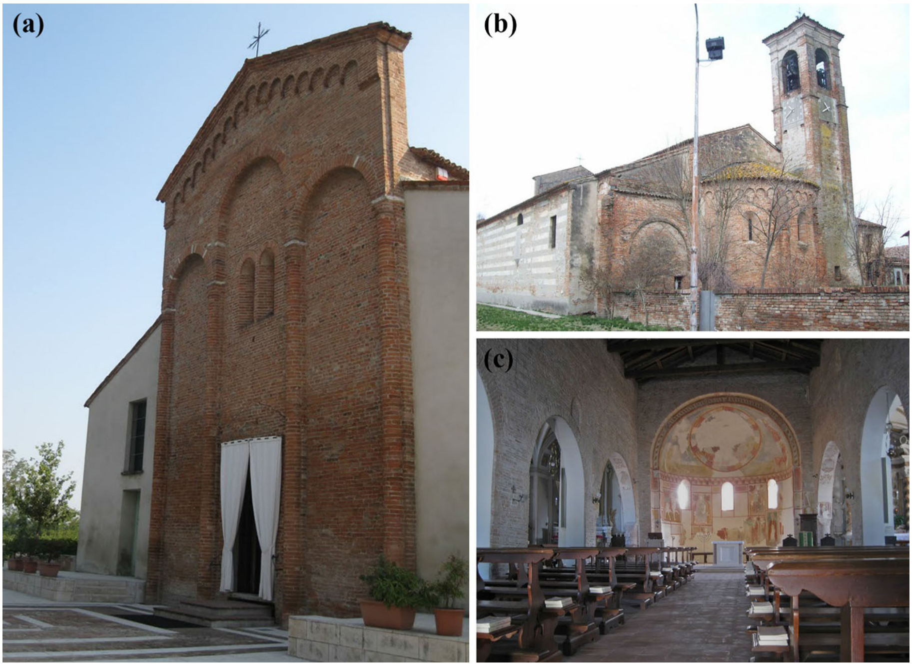


Fig. 8 San Fiorentino Martire church: **a** main façade, **b** apse and bell tower, **c** inner view of the church toward the apse

existence of empty and internal cavities—and in correspondence with the steel tie-rods—in order to evaluate the effectiveness of the anchorage into the wall. In addition, in some points, the results coming from the video-endoscope inspections were integrated with georadar and termographic surveys, which allow to better assess the masonry quality and the presence and location of elements that differ from the masonry components (e.g. residual of steel rods). It has to be noted that, due to relevant number of inspections and depending on the non-destructive nature of the test, the size of the holes (around 35 mm) is performed and calibrated to allow the penetration of the endoscopy only. The sampling of integer cores, which may be chemically and mechanically tested, is very difficult using such a diagnostic technique.

As a result of this qualitative survey, two different typologies of masonry were detected. The oldest Romanesque masonry of the transept and the façade—characterized by a greater thickness—proved to be a multi-wythe masonry made of two exposed faces with square and regular bricks and an inner core filled with irregular material bonded by quite compact mortar; the absence of voids was revealed. The XVI century masonry of the central nave and the aisles proved to be compact and consisting of solid bricks for the entire wall thickness; sporadic discontinuities were observed.

Figure 11 shows the locations and some images of the video-endoscope and visual inspections on a column of the central nave and on an arch of the aisles, in correspondence with a tie-rod.

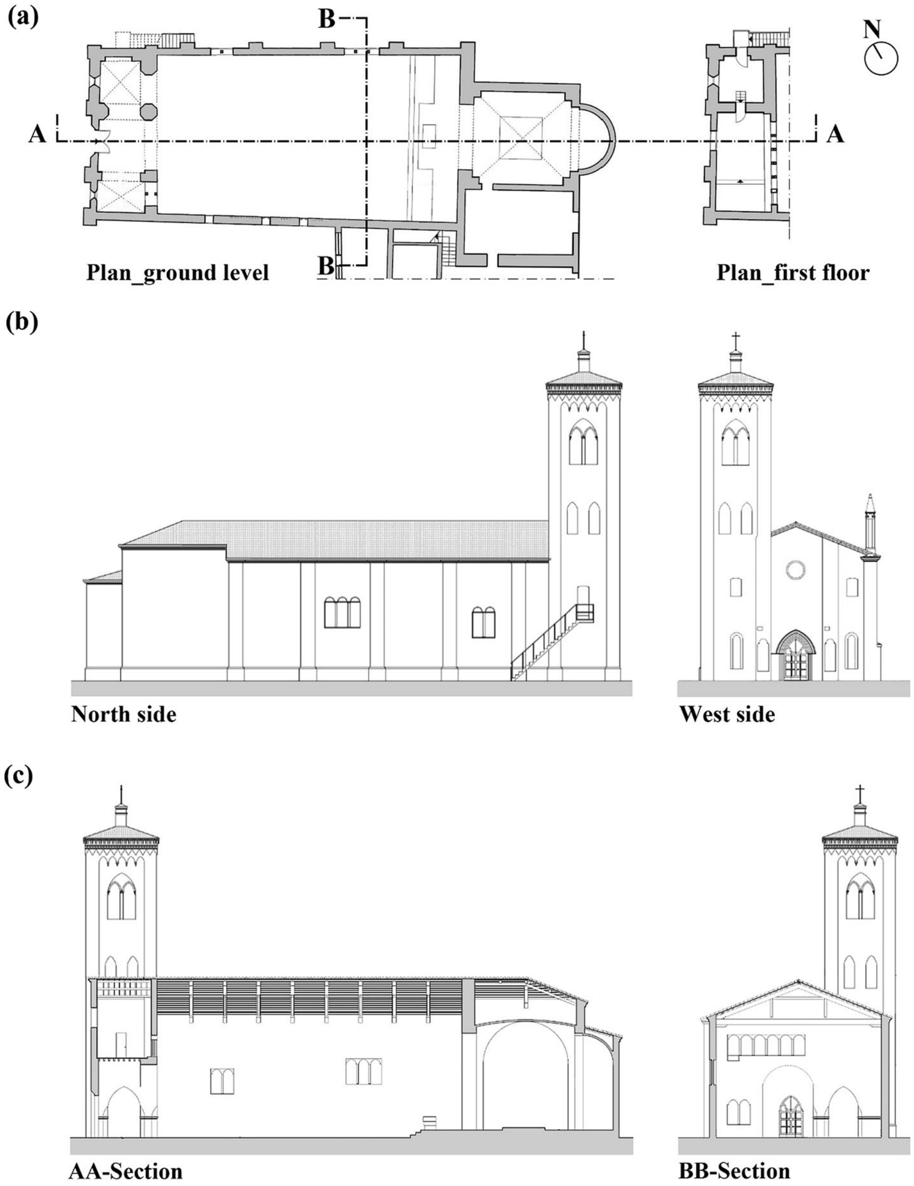


Fig. 9 Santa Maria Assunta church: **a** plan, **b** elevation views, **c** sections

4.2 Sonic tests with tomographic survey

Sonic and tomographic tests were carried out on four elements to verify the density and homogeneity of masonry by means of the sonic speed distribution. The locations of the tests and the results obtained for a column are shown in Fig. 12. Two columns of the central nave and two walls between the chapels of the aisles were selected, so that only the XVI century masonry was tested. The choice of these elements was performed on the basis

Fig. 10 Santa Maria Assunta church: **a** main façade, **b** inner view of the church toward the entrance, **c** inner view of the church toward the apse

of the level of accessibility and the possibility to perform the data acquisition for the tomographic elaboration around the entire elements.

From the data processing, it can be noted that the masonry sections investigated by sonic and tomographic tests are characterized by values of sonic speed mainly within 2000 and 2500 m/s. This result indicates a medium-compact masonry of fairly good execution. The absence of very low and heterogeneous speed values indicates that large masonry discontinuities are not present (i.e. internal holes or poor quality units). It has to be noted that, even if any sonic or tomographic test was performed on the Romanesque masonry, not too different findings may be expected on the basis of the outcomes obtained through the endoscopic inspections.

4.3 Termographic tests

Five termographic tests were carried out on some portions of the internal and external masonry, on the ceiling of the central nave and the presbytery and on the vault of the transept. Also in this case, the aim of the tests was to analyze the homogeneity of the masonry walls with the corresponding damage and degradation state, and to verify the configurations of the bearing structures, as regards the horizontal elements.

Figure 13a indicates the locations of the termographic tests. In Fig. 13b the results of the test on a portion of the apse wall are shown: the measures of different superficial temperatures highlight the presence of probable through-cracks that may create a discontinuity enabling the access of air. In Fig. 13c the results of the test on the ceiling of the central nave and of the presbytery are reported: different superficial temperatures evidence that the bearing structure is composed of wooden joists. The presence of some zones with

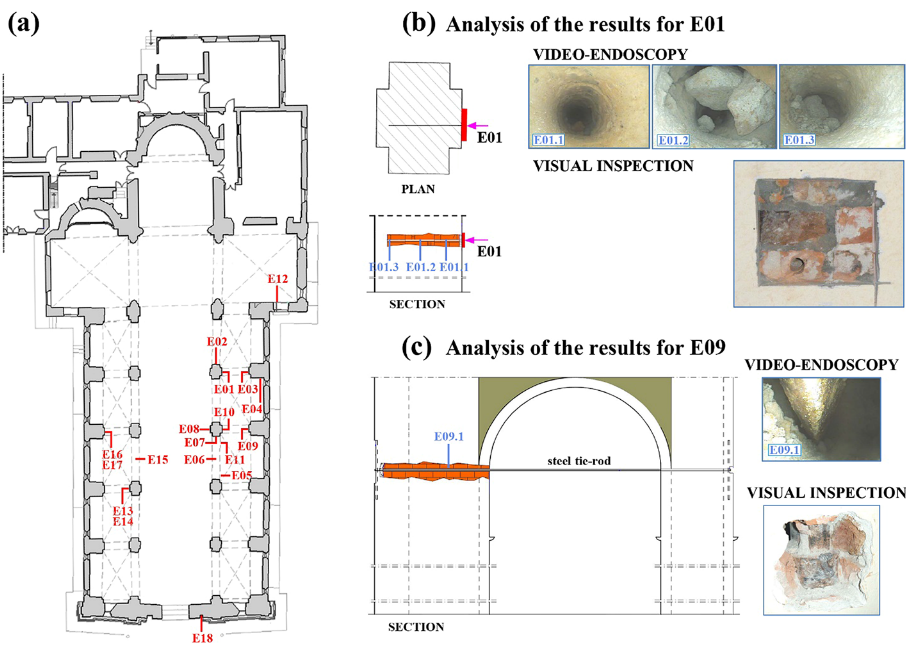


Fig. 11 **a** Locations of the video-endoscope inspections, **b** video-endoscope inspection on a column, **c** video-endoscope inspection in correspondence with a tie-rod

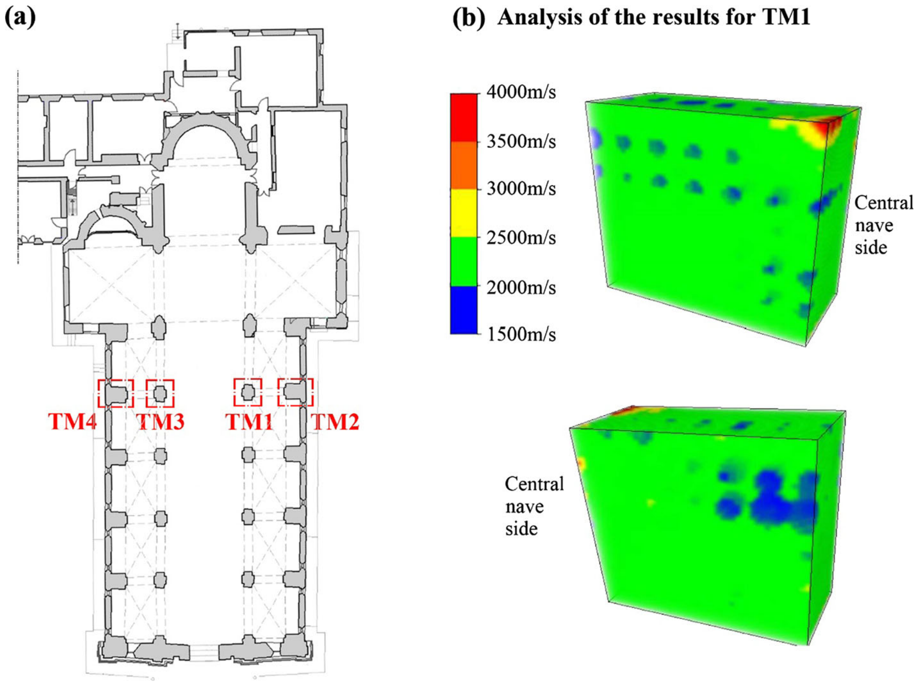


Fig. 12 **a** Locations of the sonic tests, **b** tomographic survey on a column

low emission temperatures is observed, highlighting problems of humidity related to water infiltrations from the covering.

4.4 General considerations

The diagnostic investigation performed on San Benedetto Abate church allowed to draw some general considerations on the masonry quality of the churches under study.

First of all, it has to be underlined that, because of the similarity of the three churches, it is reasonable to consider that they are characterized by a quite similar masonry. The three case studies were originally built in the same geographical area, in the same period and under the same patron: the builders and the resources available in the area and the construction practice were presumably the same. They are characterized by similar elements and by similar masonry thickness. Moreover, in accordance with the historical survey, the churches underwent the major interventions and reconstructions in the same periods (in the first half of the XVI century, in the XVIII century and during the XX century).

Masonry appears to be compact and homogeneous, characterized by a good quality and by the absence of voids. Masonry generally consists of solid clay bricks, even if masonry built during the X-XI centuries—and characterized by an important thickness, around 100 cm or more—may be a multi-wythe masonry characterized by two external regular faces made of bricks and an internal different core made of irregular material.

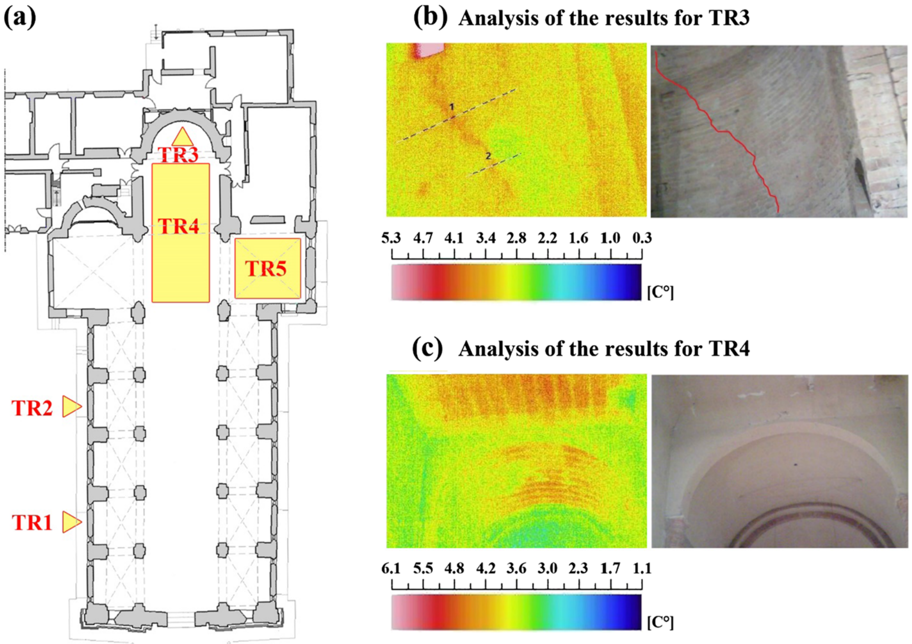


Fig. 13 **a** Locations of the termographic tests, **b** termographic test on the apse wall, **c** termographic test on the presbytery and central nave covering

5 Damage survey

A detailed damage survey of the three churches performed through Terrestrial Laser Scanning (TLS) and visual inspections has been carried out after the 2012 Emilia earthquake. Some drawings of crack patterns and a photographic documentation are reported in this paper.

5.1 San Benedetto Abate church in Gonzaga

San Benedetto Abate church in Gonzaga was very seriously damaged by the 2012 earthquake and it was classified among the “red code churches” by the Mantua Diocese (churches with very serious damage and estimated costs of intervention works between 1,500,000€ and 5,000,000€).

The main damage involves the following parts of the church:

- *Façade* The damage survey has revealed vertical cracks between the façade and the longitudinal walls of the hall, Fig. 15a (photos 01–02). Inside the building, the separation of the *incannucciato* ceiling from the façade has been detected, Fig. 15a (photo 03). The thrust of the seismic action in the longitudinal direction combined with the lack of efficient connections between the façade and the longitudinal walls may cause the detachment of these two elements with an out-of-plane overturning of the façade. Some cracks have been found also in correspondence with the moldings of the gable, Fig. 15a (photo 04).
- *Central nave* The damage survey has showed cracks located in the *incannucciato* ceiling, mainly along the longitudinal direction, Fig. 15b (photos 05–06). The thrust of the seismic action in the transversal direction may trigger an overturning mechanism of the longitudinal walls. Cracks have been detected along the longitudinal walls in correspondence with the keystone of the arches, the openings of the upper level and the pilasters edge (vertical and diagonal cracks), Fig. 15b (photos 07–08); sub-horizontal cracks have been surveyed on the pilasters, Fig. 15b (photo 08), and in correspondence with the horizontal molding above the pilasters. These cracks can be related to the presence of the aisles that represent a constraint only for the lower part of the longitudinal walls.
- *Presbytery* Vertical cracks near the openings and transversal cracks on the vault have been detected, Fig. 15c (photo 09). The presence of openings creates a discontinuity in the wall and the corners represent weakness points, where a stress concentration can cause the formation of cracks. The expected collapse mechanism involves the lateral walls of the presbytery. In addition, two cracks are located in correspondence with the arches between the presbytery and the apse, Fig. 15c (photo 09), and the presbytery and the central nave, Fig. 15c (photo 10). They indicate the detachment between the different structural elements.
- *Apse* The damage survey has showed a crack on the semi-dome, Fig. 15d (photo 11), and vertical and diagonal cracks on the wall starting from the openings, Fig. 15d (photo 12). The presence of the openings in the wall may be the cause of damage. The expected collapse mechanism is the apse overturning.
- *Transept* Cracks along the connection between the longitudinal walls and the cross vaults have been detected, Fig. 15e (photos 13–14). The damage was caused by the horizontal thrusts, both in the longitudinal and in the transversal directions, producing the detachment of the elements and the trigger of an overturning mechanism of the

transept lateral walls. In addition, externally, also in the upper connections between the central nave and the transept, vertical cracks have been observed, revealing a possible overturning mechanism of the entire structure of the transept, Fig. 15e (photos 15–16).
- *Aisles* Diagonal cracks in the *in foglio* vaults have been registered, Fig. 15f (photo 17). In the chapels of the aisles, the thrust action due to the earthquake generates a longitudinal response of the structure, causing high horizontal stresses in the light and thin vaults. Diagonal cracks are associated with different longitudinal relative displacements among the various elements. Some cracks can be observed also in correspondence with the keystone and the imposts of the arches that support the vaults and along the connection between the arches and the external longitudinal walls, Fig. 15f (photo 18). The damage was probably related to a different relative displacement between the edge bearing structures of the vaults.
- *External masonry walls* Cracks have been reported: in correspondence with the connection between two structural elements with different geometries, such as between the presbytery and the apse, Fig. 15g (photo 19); near the corners of the openings, Fig. 15g (photo 19); in the upper parts of the walls, Fig. 15g (photo 20). These cracks can be ascribed to problems related to the materials poor quality or to some masonry features—such as the lack of connection between the elements during the construction phase or the presence of discontinuities, such as openings even if later closed.
- *Bell tower* Vertical and diagonal cracks are localized near the connection between the bell tower and the wall of the church, Fig. 15h (photo 21), and along the tower body, mainly close to the openings corners, Fig. 15h (photo 22). These cracks may be caused by a significant difference in global stiffness between the body of the church and the slender bell tower and by the presence of discontinuities. A rotation of the bell tower was also registered toward the north-east direction.
- *Belfry* Cracking of the masonry pinnacle located on the bell tower has been detected, Fig. 15i (photo 23). In addition, horizontal cracks have been observed near the region of the belfry, Fig. 15i (photo 24). These cracks may be caused by the sliding of the pillars, due to the presence of heavy and thrusting covering. The horizontal thrusts caused by the earthquake, associated with the presence of significant mass, develop high shear stresses that lead to the cracking in critical regions, in correspondence with a reduction of the resistant cross-section.

Figures 14 and 15 summarize the crack patterns observed in San Benedetto Abate church.

5.2 San Fiorentino Martire church in Nuvolato

San Fiorentino Martire church in Nuvolato was strongly damaged by the 2012 earthquake and it was classified among the "yellow code churches" by the Mantua Diocese (churches with serious damage and estimated costs of intervention works less than 1,500,000€).

The main damage involves the following parts of the church:

- *Façade* Through vertical cracks along the connection region between the façade and the longitudinal walls of the central nave have been reported, Fig. 17a (photos 01–02). The damage survey has highlighted the lack of effective connections between the elements: such a deficiency could lead to a definitive separation of the façade from the lateral walls with an out-of-plane overturning of the façade.
- *Central nave* A lack of effective connections between the transversal wall delimiting the apse and the longitudinal walls has been observed and some cracks have been identified, Fig. 17b (photo 03). Such damage may cause the out-of-plane overturning of

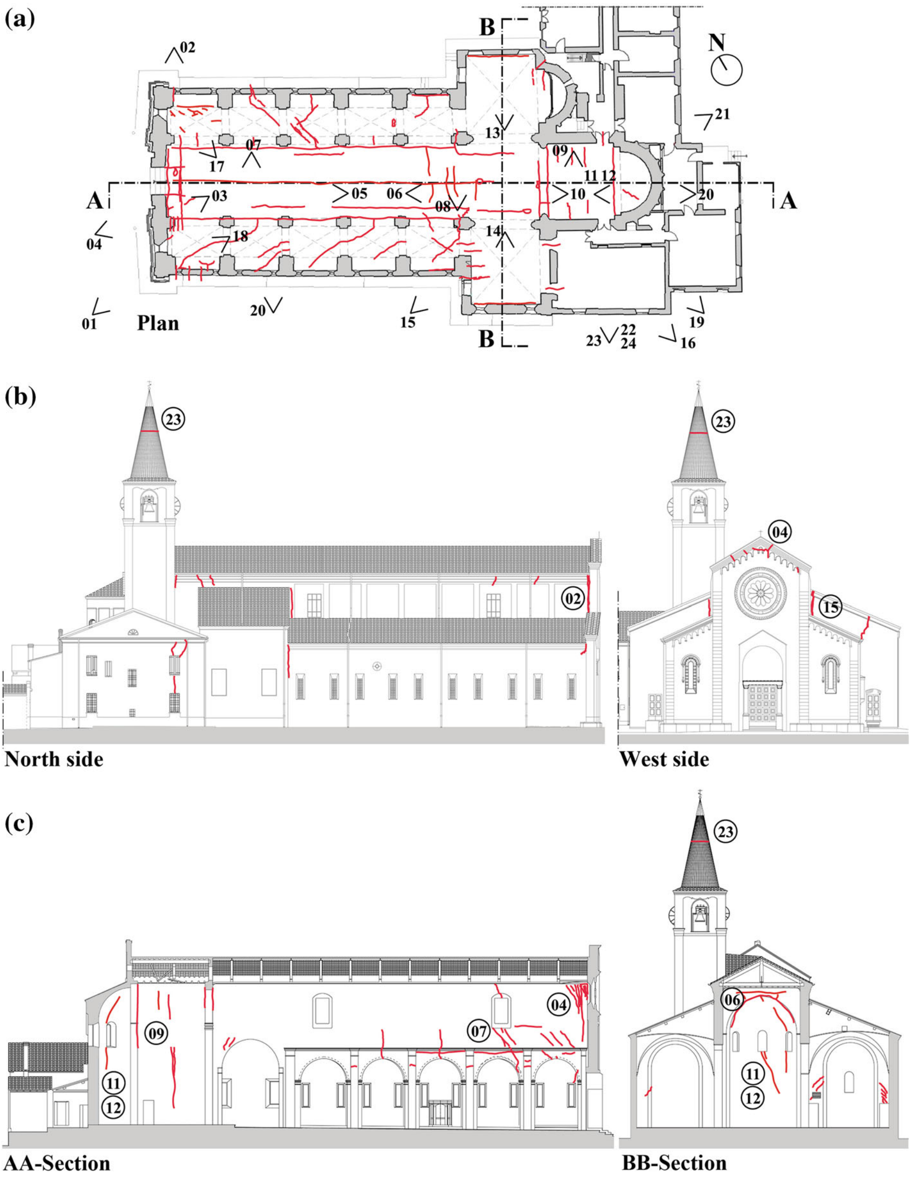
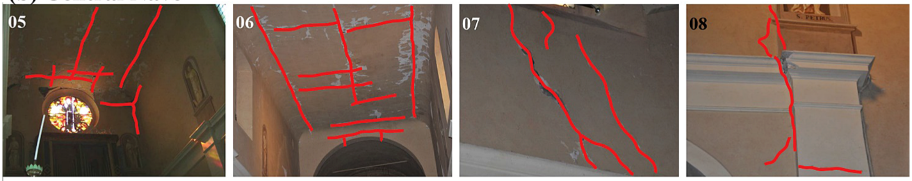


Fig. 14 San Benedetto Abate church damage survey: crack pattern

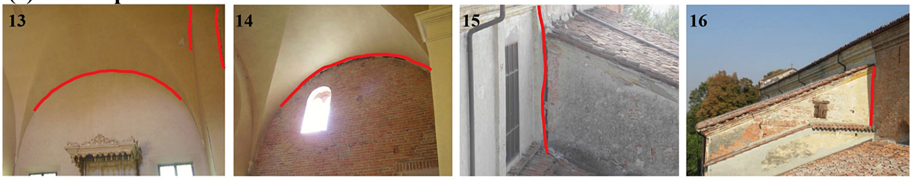
the apse. In addition, some cracks starting from the corners of the openings can be detected, Fig. 17b (photo 04).

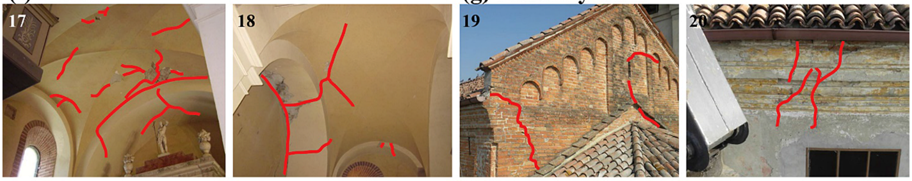
- *Apse* Vertical cracks near the openings of the apse have been reported, Fig. 17c (photos 05–06). The presence of the openings in the wall and the thrusting vaults may be the causes of the damage. Such cracks also can trigger an overturning mechanism of the apse wall.
- *Transept* Vertical cracks in the corners between the longitudinal and transversal walls and cracks along the connection between the longitudinal walls and the cross vaults


(a) Facade


(b) Central Nave


(c) Presbytery
(d) Apse


(e) Transept


(f) Aisles
(g) Masonry walls

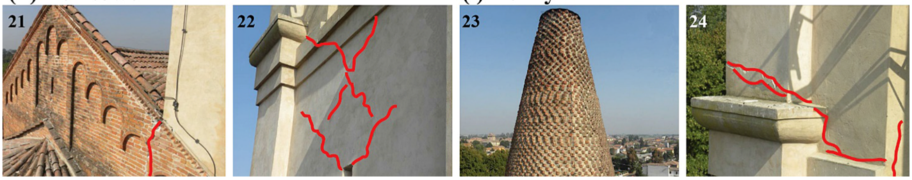

(h) Bell tower
(i) Belfry

Fig. 15 San Benedetto Abate church damage survey: photographic documentation

have been detected, Fig. 17d (photo 07). The damage was due to the horizontal thrust actions, both in the longitudinal and in the transversal directions, producing the detachment of the elements and the trigger of an overturning mechanism of the transept lateral wall. Some cracks were also detected at the keystone and imposts of the arches that separate the transept from the aisles, Fig. 17d (photo 08).

- *Aisles* The damage of the aisles concerns:
  - vaults: the damage of the cross vaults consists of: (i) the complete collapse of the vaults of the first two chapels in the left side, Fig. 17e (photo 09); (ii) the partial collapse and a diffused crack pattern in the other vaults, with cracks oriented both along the diagonal ribs and along the edge structures, Fig. 17e (photo 10). The damage was probably due to the excessive vibrations of the edge bearing structures with a different relative displacement between the elements. This caused a detachment between the vaults and the load-bearing masonry walls and, in some cases, the collapse of the structures. It has to be considered that the detachment may be also ascribed to the different periods in which the elements were built and to the consequent impossibility to carry out an effective connection between the aisles and the central nave;
  - arches: survey of cracks at the keystone and impost locations with the possible collapse of the arches supporting the vaults, Fig. 17f (photos 11–12);
  - walls: diffused vertical cracks on the walls.
- *External masonry walls* Cracks have been reported near the corners of the openings, Fig. 17g (photos 13–14). These cracks can be ascribed to problems related to the materials poor quality or to some masonry features—such as the lack of connection between the elements during the construction phase or the presence of discontinuities, such as openings even if later closed.
- *Bell tower* The bell tower presents widespread damage on the walls, with cracks mainly localized near the connection with the church roof and close to the load-bearing elements of the belfry, Fig. 17h (photos 15–16). In detail, cracks have been observed in the arches and at the edges of the slender pillars of the belfry. The interaction between elements with different behavior can generate cracks due to hammering between the different parts.

Figures 16 and 17 summarize the crack patterns observed in San Fiorentino Martire church.

5.3 Santa Maria Assunta church in Felonica

Santa Maria Assunta church in Felonica was partially damaged by the 2012 earthquake and it was classified among the “blue code churches” by the Mantua Diocese (churches with moderate damage and estimated costs of intervention works less than 500,000€).

The main damage involves the following parts of the church:

- *Façade* Vertical cracks in correspondence with the entrance door extended up to the rose window have been reported on the internal side of the church, Fig. 19a (photo 01). In addition, vertical cracks extend from the wooden rafters of the roof, Fig. 19a (photo 02). These cracks can be related to the presence of openings and concentrated loads, and they are due to the seismic action longitudinal component.
- *Atrium* Vertical cracks have been observed in the longitudinal walls of the atrium: at the ground floor in correspondence with the keystone of the arches of the lateral adjacent chapels, Fig. 19b (photo 03), and at the first floor in correspondence with some openings, Fig. 19b (photo 04). The latter cracks are due to the presence of discontinuities and to the seismic action longitudinal component.

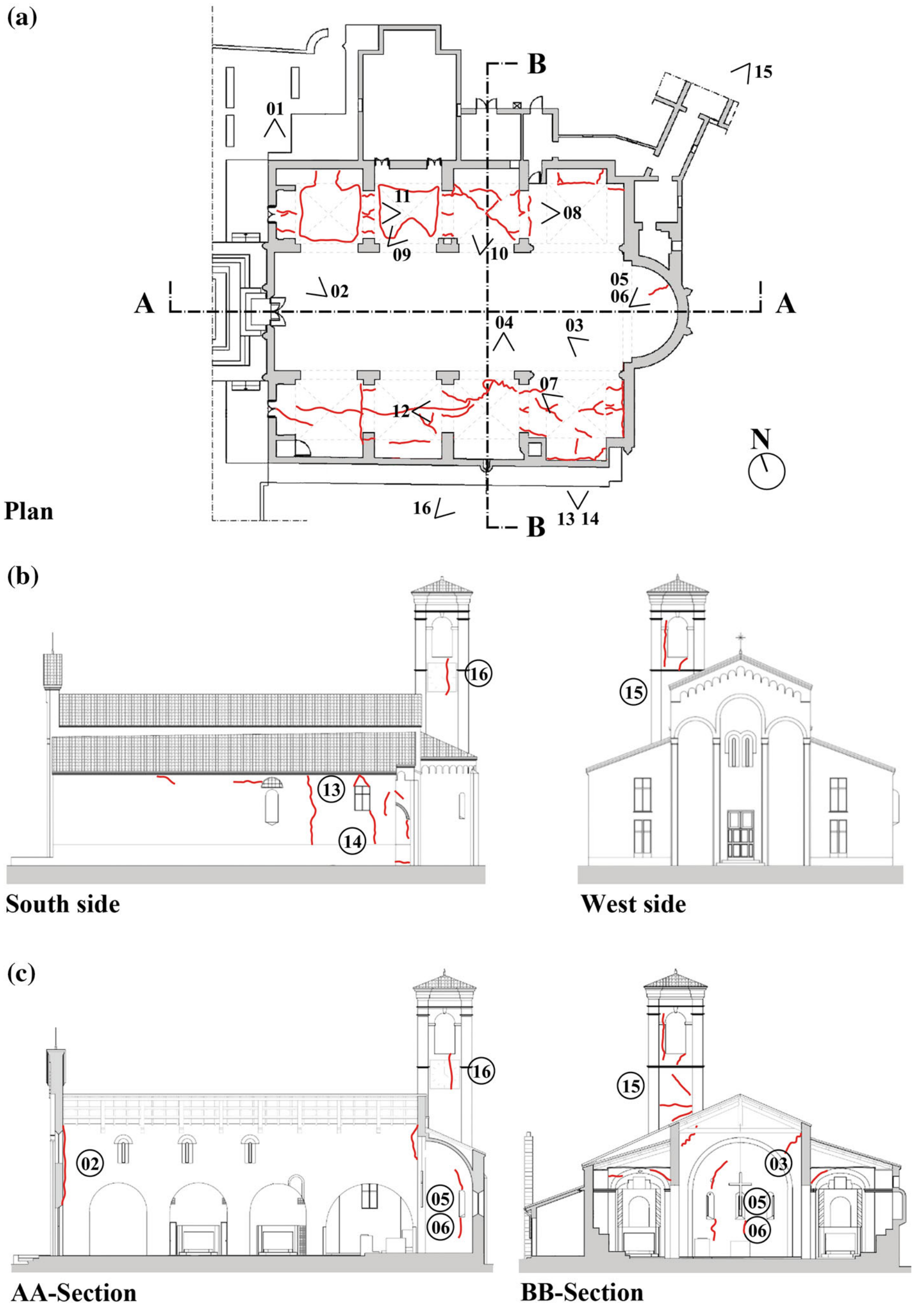
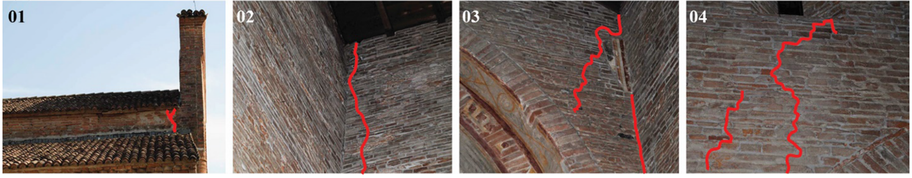


Fig. 16 San Fiorentino Martire church damage survey: crack pattern

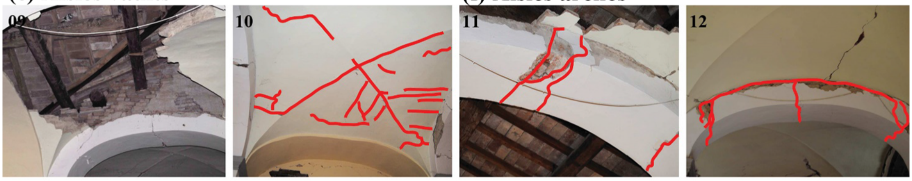
- *Atrium chapels* The damage survey showed vertical cracks starting from the openings of the façade, Fig. 19c (photo 05), along the connection region between the vaults and the walls, Fig. 19c (photo 05) and in the cross vaults, Fig. 19c (photo 06). These cracks

(a) Facade (b) Central nave



(c) Apse (d) Transept

(e) Aisles vaults (f) Aisles arches



(g) Masonry walls (h) Bell tower

Fig. 17 San Fiorentino Martire church damage survey: photographic documentation

are due to the presence of openings and to an excessive oscillation of the walls that are not restrained by the thin and light vaults system.

- *Presbytery* Some cracks have been found on the cross vault and along the connection between the vaults and the walls, Fig. 19d (photos 07–08).
- *Hall* Vertical cracks in south-west corner have been reported, Fig. 19e (photo 09). These cracks are due to the probable lack or ineffectiveness of the connections between the longitudinal and transversal walls. Vertical cracks on the southern wall, in correspondence with the connection with the annexes, have been detected, Fig. 19e (photo 10). These cracks are due to the geometrical difference between the two structures. Other vertical cracks have been observed along the longitudinal wall in correspondence with some supports of the wooden roof, Fig. 19e (photo 11), that causes the presence of concentrated actions. At last, vertical cracks, starting from the mullioned windows and extending up to the joints of the roof, can be observed on the western wall of the atrium, Fig. 19e (photo 12). These cracks are promoted by the presence of concentrated actions (supports of the joists) and by discontinuities in the wall (mullioned windows).
- *Bell tower* Through vertical cracks between the bell tower and the body of the church (the nave wall and the façade) have been observed, Fig. 19f (photos 13–16). The cracks

are due to the great difference in stiffness and dimension between the bell tower and the church, and to the probable lack of effective connections between the different elements.

Figures 18 and 19 summarize the crack patterns observed in Santa Maria Assunta church.

6 Numerical models

Detailed three-dimensional FE models of the churches under study were created using the data obtained through the geometrical survey. Figure 20 shows the geometrical and FE models of the three churches. The numerical models were developed considering the vertical bearing walls and the masonry vaults of the aisles, when they are present. It is worth mentioning that for all the analyzed churches, light wooden roofs are present, in accordance with the building traditional technology of such a typology of structures in the region considered. Their membrane stiffness is safely assumed negligible for horizontal loads, as well as the box behavior induced by their presence in the FE models. For this reason, only vertical loads transferred by the roof to the top of perimeter walls are introduced in the models.

The discretization of San Benedetto Abate church consists of about 120,000 four nodes tetrahedral elements having a size ranging between 50 and 70 cm. The roof of the bell tower and the masonry pinnacle are introduced in the model considering an equivalent pressure distribution. A system of steel tie-rods, arranged transversally to the longitudinal axis of the church, is inserted in the model. In detail, two steel tie-rods restrain the wall of the presbytery and a series of steel tie-rods is arranged in the arches between the chapels of the aisles, Fig. 21.

The discretization of San Fiorentino Martire church consists of about 98,000 elements and presents an average size of the four nodes tetrahedral elements ranging between 50 and 70 cm. The FE model of Santa Maria Assunta church consists of 62,000 elements and the size of the four nodes tetrahedral elements ranges between 50 and 80 cm.

It is worth mentioning that the choice of the dimensions of the mesh elements may play a certain role in non-linear dynamic analyses. In order to have an insight into such an issue for the cases under study, comprehensive sensitivity analyses have been carried out for a reliable investigation of the structural behavior of the churches in the non-linear dynamic range. The mesh was defined as a good compromise to perform sufficiently reliable analyses with a reduced computational effort.

The non-linear behavior of masonry is modeled through the Concrete Damage Plasticity (CDP) model presented by Lubliner et al. (1989) and then modified by Lee and Fenves (1998). The model formulated by Lubliner et al. (1989) was conceived to describe the non-linear behavior of concrete, but its capacity to simulate the non-linear behavior of other brittle/quasi-brittle materials—such as masonry—was proved too. The modified formulation given by (Lee and Fenves 1998) makes the model particularly appropriate for the analysis of structures subjected to cyclic and dynamics loads, since it allows taking into account the stiffness recovery that occurs when the load changes sign. In particular, the CDP has been already used to describe the seismic behavior of ancient masonry structures, see, among the others, (Barbieri et al. 2013; Milani and Valente 2015b).

The CDP model implemented in Abaqus (Abaqus 2014) assumes a linear and isotropic behavior in the elastic range and a plastic and damaging behavior in the post-elastic

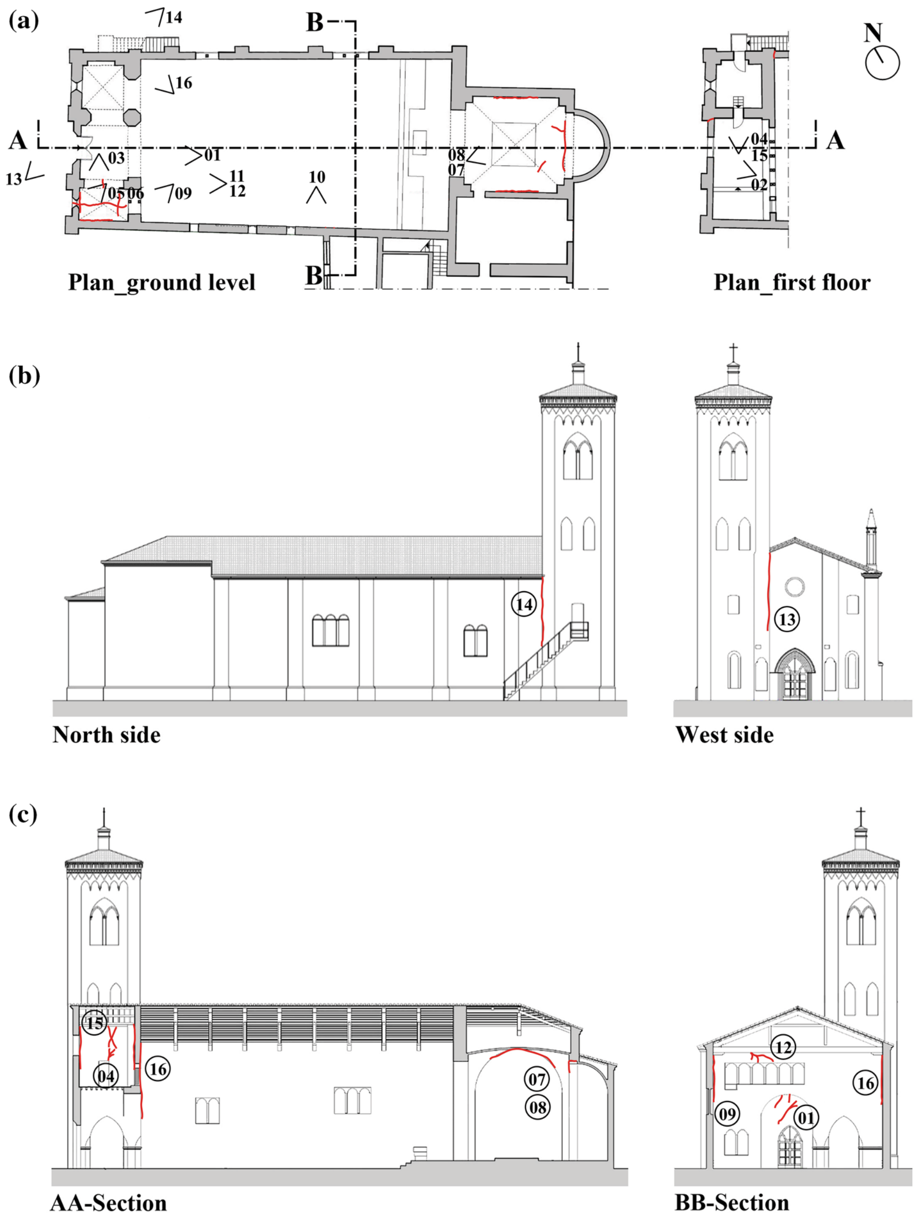


Fig. 18 Santa Maria Assunta church damage survey: crack pattern

regime, which allows taking into account the differences (in strengths and global behavior) in compression and tension. The model assumes that two different failure mechanisms (tensile cracking and compressive crushing) may occur. In the case of a brittle/quasi brittle material, the post-elastic phase in uniaxial tension (after the failure stress σ_{t0}) is represented by a softening branch; on the other hand, the post-elastic phase in uniaxial compression (after the yield stress σ_{c0}) is first described by an hardening curve up to an

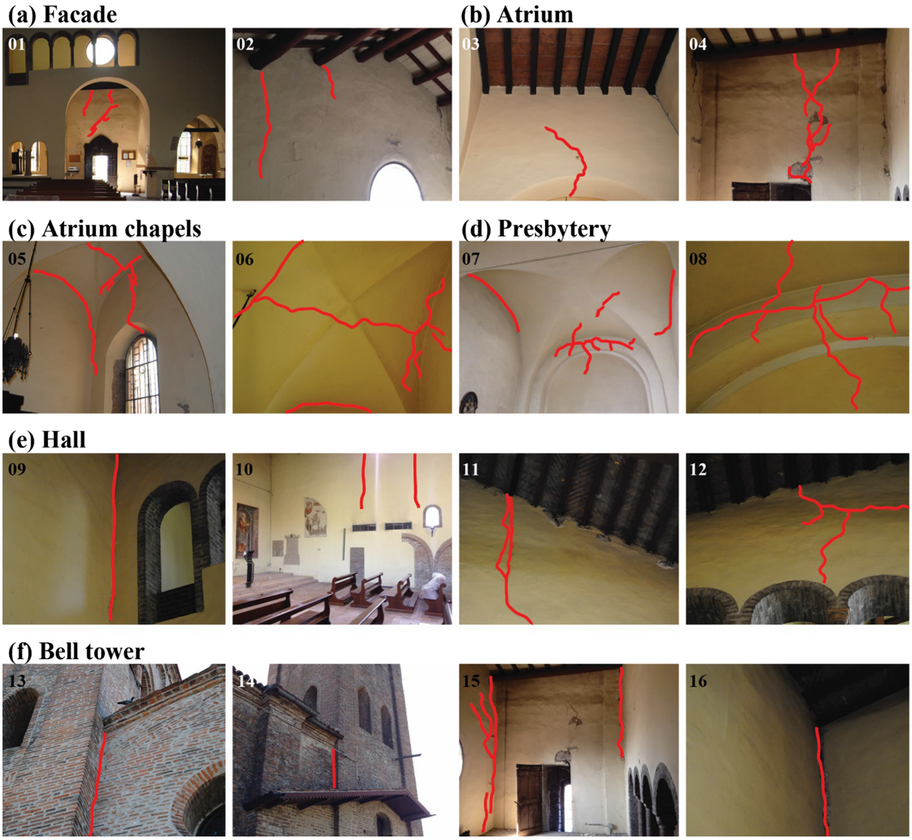


Fig. 19 Santa Maria Assunta church damage survey: photographic documentation

ultimate stress σ_{cu}, and then by a softening branch. The response of the material that is unloaded at any point of the post-elastic branch may be described by a degraded elastic stiffness defined as follows:

$$E = (1 - d)E_0 \tag{1}$$

being E_0 the initial undamaged stiffness and d the degradation. The degradation is governed by two distinct scalar damage variables (d_t for tension damage and d_c for compression damage), the values of which can range from zero, representing the undamaged material, to one, representing the total loss of strength. Under cyclic loading conditions, quite complex degradation mechanisms are activated, due to the opening and closing of the micro-cracks. As the load changes from tension to compression, some recovery of the compressive stiffness seems to occur, since tensile cracks close. On the other hand, the tensile stiffness is not recovered as the load changes from compression to tension once crushing micro-cracks have developed.

In uniaxial stress conditions the loss of elastic stiffness is computed as follows:

$$(1 - d) = (1 - s_t d_c)(1 - s_c d_t) \tag{2}$$

where s_t and s_c are functions of the stress state and are introduced to model stiffness recovery effects due to stress reversal. They are computed using Eq. 3:

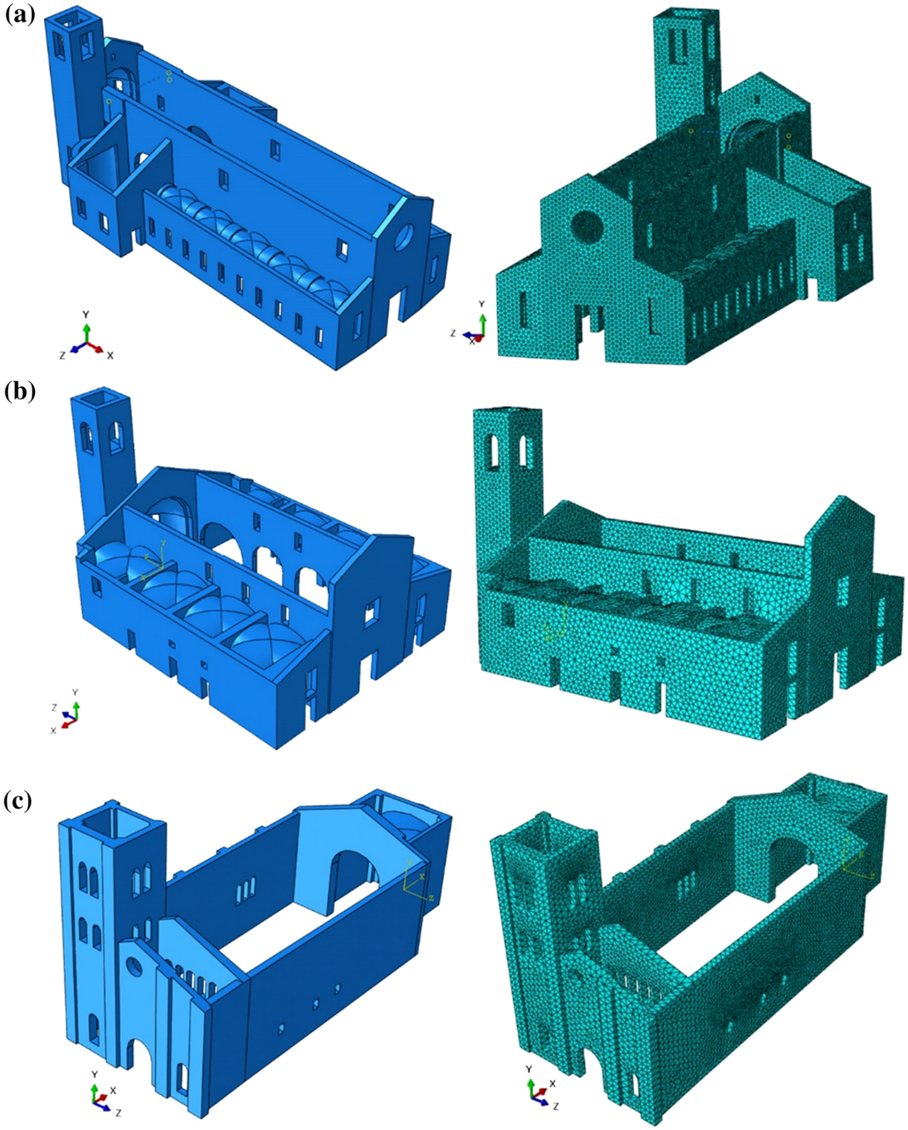


Fig. 20 Geometric and FE models of the three churches. **a** San Benedetto Abate church, **b** San Fiorentino Martire church, **c** Santa Maria Assunta church

$$\begin{cases} s_t = 1 - w_t H(\sigma_{11}) \\ s_c = 1 - w_c(1 - H(\sigma_{11})) \end{cases} \tag{3}$$

where w_t and w_c are the weight factors (assumed as material properties) that control the recovery of tensile and compressive stiffness upon load reversal: they can range from zero, which represents no stiffness recovery, to one, which represents a total stiffness recovery. $H(\sigma_{11})$ is the Heaviside function that is assumed equal to 1 if $\sigma_{11} > 0$ and equal to 0 if $\sigma_{11} < 0$.

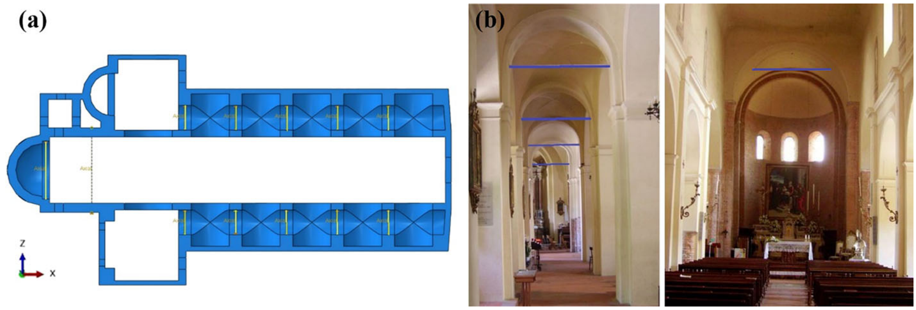


Fig. 21 Numerical model of San Benedetto Abate church: **a** location of the steel tie-rods, **b** internal view of the lateral nave and of the central nave with the steel tie-rods

In Fig. 22 the uniaxial load cycle is reported.

In this study, the same masonry material is assumed for all the models of the churches. This assumption could be adopted since, as previously discussed, the churches under study are reasonably made of a very similar masonry typology. Due to the lack of precise experimental data, the main mechanical properties were assumed referring to the indications provided in the Italian recommendations for existing buildings and built heritage (NTC 2008; Circolare 2009; DPCM 2011). According to Table 8.2.1 in (Circolare 2009) and adopting, for safety reasons, the lowest knowledge level LC1 (NTC 2008), the following assumptions have been taken into account for a masonry made of solid bricks and lime mortar: (1) the density and the elastic modulus are equal to $\rho = 1800$ kg/m^3 and $E = 1500$ MPa, respectively; (2) the compressive strength is equal to $\sigma_{cu} = 2.4$ MPa. The tensile strength is assumed equal to $\sigma_{to} = 0.1$ MPa, obtaining a ratio between the tensile and compressive strength equal to about 0.04. The damage variable in tension d_t is defined to be equal to 0.95 in correspondence with a plastic strain of 0.005.

The values reported for the masonry mechanical properties seem to be reasonable considering the results of experimental investigations performed on the components of similar masonry by the same authors (Valente et al. 2016).

The values of the main parameters adopted for the CDP model (Abaqus) in the non-linear dynamic simulations are the following: (1) the dilation angle ψ is equal to 10° in agreement with experimental data available in the literature, (Van Der Pluijm 1993); (2) the strength ratio σ_{b0}/σ_{c0}, which expresses the ratio between the biaxial and uniaxial compression strength, is equal to 1.16 in agreement with experimental results reported in (Page 1981); (3) the K_C parameter, which governs the shape of the yield surface in the deviatoric plane, is set equal to 0.666 in order to define an approximate Mohr–Coulomb strength domain; (4) the correction parameter of the eccentricity ε is assumed equal to the default value 0.1, which implies that the material has almost the same dilation angle over a wide range of confining pressure stress values, (Abaqus); (5) the viscosity parameter λ, which is introduced in the model in order to obtain a visco-plastic regularization of the constitutive equations and allows to overcome convergence difficulties, is assumed equal to 0.002 (small values help to improve the rate of convergence in the softening branch without compromising the results).

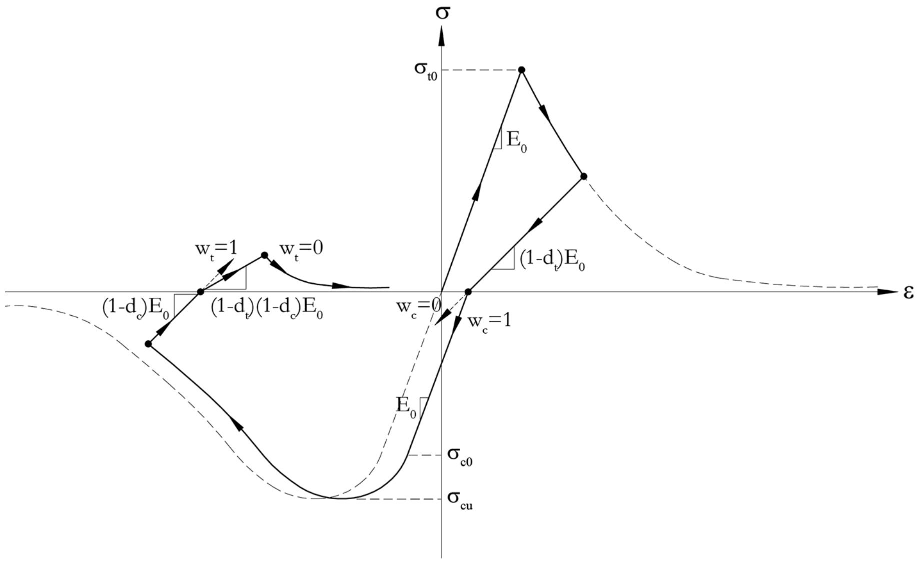


Fig. 22 Uniaxial load cycle tension–compression–tension

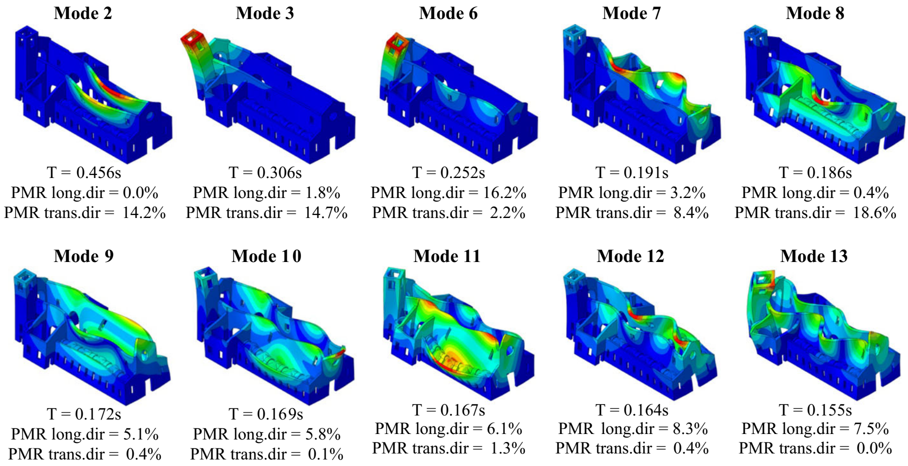
7 Modal analysis

A modal analysis was conducted on the 3D FE models in order to obtain a preliminary insight into the dynamic behavior of the churches under study, identifying the main vibration modes, the corresponding periods (T) and the participating mass ratios (PMR). The modal deformed shapes associated with the main vibration modes characterized by participating mass ratios larger than 5% and the corresponding periods are illustrated in Figs. 23, 24 and 25 for the three churches.

7.1 San Benedetto Abate church in Gonzaga

The first ($T = 0.459$ s) and second ($T = 0.456$ s) modes involve the upper part of the walls of the central nave, even if only the second mode presents a relevant PMR (14%) in the transversal direction. The third ($T = 0.306$ s) and sixth ($T = 0.252$ s) modes mainly concern the bell tower and the adjacent walls: the third mode presents a relevant PMR (15%) in the transversal direction and a small component (2%) in the longitudinal one, the opposite for the sixth mode (2 and 16%, respectively). The seventh ($T = 0.191$ s) and eighth ($T = 0.186$ s) modes involve the right and left sides of the church – the upper part of the longitudinal walls and the vaults of the aisles—as well as the façade with a relevant PMR (8% and 19%, respectively) in the transversal direction. The seventh mode has a not negligible component (3%) in the longitudinal direction too. Modes 9–13 involve a significant PMR (in the range 5–8%) of the whole structure—the walls of the central nave and of the aisles, the vaults, the transept, the façade, the bell tower—in the longitudinal direction.

As it is possible to observe, the upper part of the walls of the central nave, the bell tower, the vaults of the aisles and the façade may be the most critical elements of the church.



Mode 2
T = 0.456s
PMR long.dir = 0.0%
PMR trans.dir = 14.2%

Mode 3
T = 0.306s
PMR long.dir = 1.8%
PMR trans.dir = 14.7%

Mode 6
T = 0.252s
PMR long.dir = 16.2%
PMR trans.dir = 2.2%

Mode 7
T = 0.191s
PMR long.dir = 3.2%
PMR trans.dir = 8.4%

Mode 8
T = 0.186s
PMR long.dir = 0.4%
PMR trans.dir = 18.6%

Mode 9
T = 0.172s
PMR long.dir = 5.1%
PMR trans.dir = 0.4%

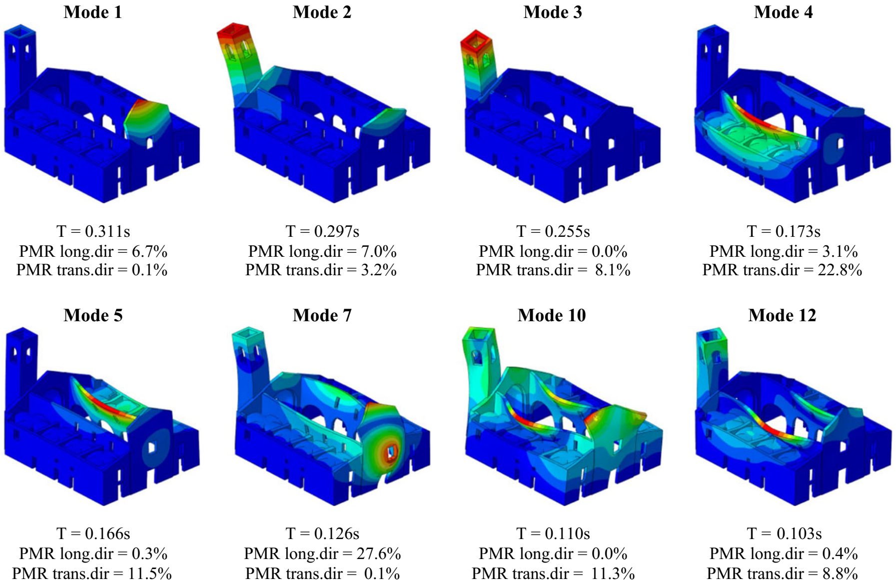
Mode 10
T = 0.169s
PMR long.dir = 5.8%
PMR trans.dir = 0.1%

Mode 11
T = 0.167s
PMR long.dir = 6.1%
PMR trans.dir = 1.3%

Mode 12
T = 0.164s
PMR long.dir = 8.3%
PMR trans.dir = 0.4%

Mode 13
T = 0.155s
PMR long.dir = 7.5%
PMR trans.dir = 0.0%

Fig. 23 San Benedetto Abate church: deformed shapes of the main vibration modes, corresponding periods and participating mass ratio in the longitudinal and transversal directions



Mode 1
T = 0.311s
PMR long.dir = 6.7%
PMR trans.dir = 0.1%

Mode 2
T = 0.297s
PMR long.dir = 7.0%
PMR trans.dir = 3.2%

Mode 3
T = 0.255s
PMR long.dir = 0.0%
PMR trans.dir = 8.1%

Mode 4
T = 0.173s
PMR long.dir = 3.1%
PMR trans.dir = 22.8%

Mode 5
T = 0.166s
PMR long.dir = 0.3%
PMR trans.dir = 11.5%

Mode 7
T = 0.126s
PMR long.dir = 27.6%
PMR trans.dir = 0.1%

Mode 10
T = 0.110s
PMR long.dir = 0.0%
PMR trans.dir = 11.3%

Mode 12
T = 0.103s
PMR long.dir = 0.4%
PMR trans.dir = 8.8%

Fig. 24 San Fiorentino Martire church: deformed shapes of the main vibration modes, corresponding periods and participating mass ratio in the longitudinal and transversal directions

The first two hundred modes correspond to a total participating mass ratio of 87% in the longitudinal direction and 90% in the transversal direction.

7.2 San Fiorentino Martire church in Nuvolato

The first mode (T = 0.311 s) involves the tympanum of the façade with a significant PMR (7%) in the longitudinal direction. The second mode (T = 0.297 s) concerns the bell tower

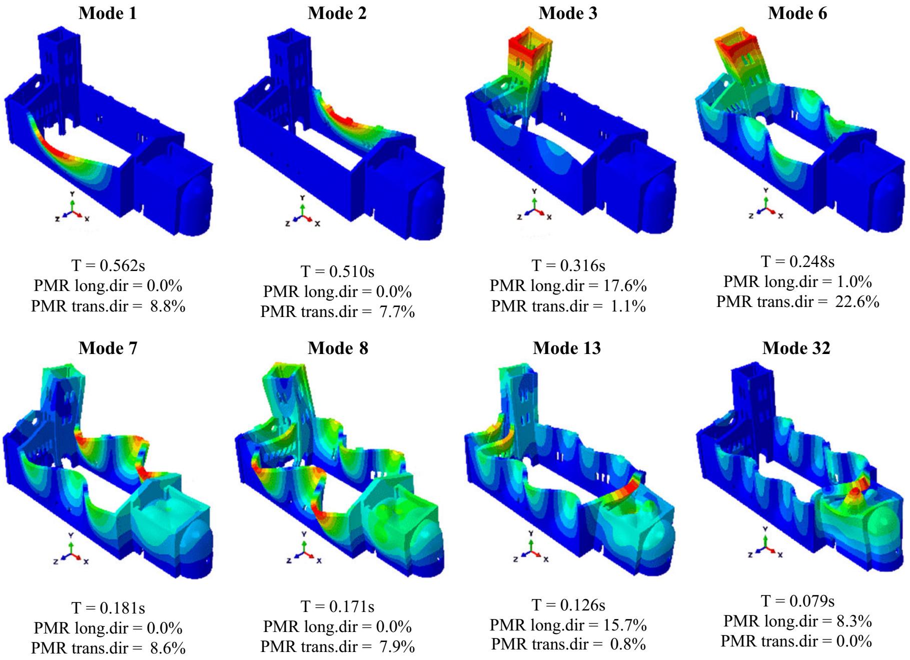


Fig. 25 Santa Maria Assunta church: deformed shapes of the main vibration modes, corresponding periods and participating mass ratio in the longitudinal and transversal directions

and the tympanum with a considerable PMR (7%) in the longitudinal direction and a not negligible component (3%) in the transversal one. The third mode (T = 0.255 s) involves the bell tower with a significant PMR (8%) in the transversal direction. The fourth (T = 0.173 s) and fifth (T = 0.166 s) modes concern the upper part of the longitudinal walls of the nave and the aisles (with their vaults) at the left and right sides of the church, respectively, with a very considerable PMR (23% and 12%, respectively) in the transversal direction. The other relevant modes involve the walls of the nave, the façade and the bell tower with a significant PMR in the longitudinal (Mode 7 T = 0.126 s, PMR = 28%) and transversal (Modes 10 T = 0.110 s, PMR = 11% and Mode 12 T = 0.103 s, PMR = 9%) directions.

It can be noted that the tympanum of the façade, the bell tower, the upper part of the longitudinal walls and the vaults of the aisles may be the most vulnerable elements of the church.

The first two hundred modes correspond to a total participating mass ratio of 89% in both transversal and longitudinal directions.

Moreover, it is interesting to note some differences with San Benedetto Abate church, though the configuration of the two churches is similar. The first mode of San Fiorentino Martire church involves the façade in the longitudinal direction; on the contrary, the first two modes of San Antonio Abate church involves the upper part of the walls of the central nave in the transversal direction. This result can be explained mainly by the different geometry of the macro-elements of the two churches. The tympanum of San Fiorentino Martire church presents a larger height and smaller thickness than that of San Antonio

Abate church; the walls of the central nave of San Antonio Abate church exhibit a larger height from the top of the aisles than that of San Fiorentino Martire church.

7.3 Santa Maria Assunta church in Felonica

The first (T = 0.562 s) and second (T = 0.510 s) modes involve the right and the left walls of the nave, respectively, with a significant PMR (9% and 8%, respectively) in the transversal direction. In the third mode (T = 0.316 s), the bell tower and a part of the façade are involved with a considerable PMR (18%) in the longitudinal direction and a small component (1%) in the transversal one. The sixth mode (T = 0.248 s) concerns the bell tower, the façade and the walls of the nave with a very high PMR (23%) in the transversal direction and a small component (1%) in the longitudinal one. The seventh (T = 0.181 s) and eighth (0.171 s) modes concern the walls of the nave, the presbytery, the apse, the bell tower and the façade with a significant PMR (9 and 8%, respectively) in the transversal direction. The thirteenth mode (T = 0.126 s) presents the same elements involved with a relevant PMR (16%) in the longitudinal direction. The thirty-second mode (T = 0.079 s) presents a significant PMR (8%) in the longitudinal direction, involving the walls of the nave, the presbytery and the apse.

From a careful analysis of these preliminary results, the lateral walls and the bell tower can be identified as the most vulnerable parts of the church. It is evident that in this case the absence of the aisles weakens the lateral walls in the transversal direction.

The first two hundred modes correspond to a total participating mass ratio of 88% in the longitudinal direction and 91% in the transversal direction.

Figure 26 shows the distribution of the participating mass ratios of the first one hundred modes in the longitudinal and transversal directions as a function of the corresponding vibration periods for the three churches. It can be noted that low values of participating mass ratios are associated with the first main modes, highlighting that the dynamic response of the churches is characterized by the local behavior of the different macro-elements. In particular, San Benedetto Abate church presents values of participating mass ratio smaller than 20% for all the modes. Moreover, the main vibration modes involving high percentages of participating mass ratio exhibit period values in the following ranges 0.15–0.45 s for San Benedetto Abate church, 0.1–0.31 s for San Fiorentino Martire church and 0.07–0.56 s for Santa Maria Assunta church. Considering such a distribution of vibration modes associated with the code pseudo-acceleration response spectra, it is clear that such structures may experience high amplifications of the peak ground acceleration. These features may provide a preliminary explanation of the damage suffered by the churches during the seismic sequence.

8 Non-linear dynamic analysis

The seismic response of the three churches was studied through non-linear dynamic bi-directional analyses using artificial accelerograms generated by means of the Simqke software (SIMQKE 1976) in order to match the Eurocode 8 response spectrum (soil type B). The same accelerograms, presenting equal intensity in the two orthogonal directions, were used for the numerical simulations of all the churches. Figure 27 shows the acceleration time histories with PGA = 0.08 g applied in the longitudinal and transversal directions and the corresponding acceleration response spectra. The duration of the accelerograms was assumed equal to 10 s because of the high computational demand

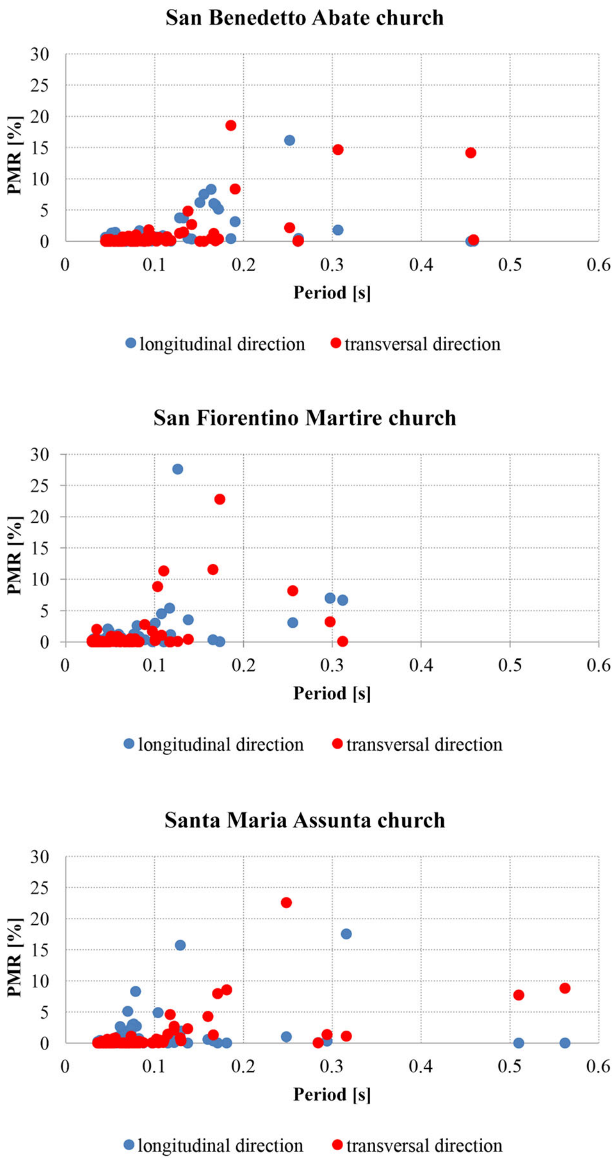


Fig. 26 Distribution of the first one hundred modes in the longitudinal and transversal directions for the three churches: modal participating mass ratios as a function of the corresponding vibration periods

required by the analyses. The tensile damage contour plots, obtained at the end of the numerical simulations with three different peak ground accelerations ranging between PGA = 0.08 g and PGA = 0.17 g, are reported for the three churches under study in Figs. 28, 29 and 30. The highest values of the PGA used in the non-linear dynamic analyses were similar to the ones registered in that region during the 2012 Emilia earthquake. The main aims of the numerical simulations are: (1) to identify the most vulnerable elements of the churches and compare the results with field observations; (2) to assess the evolution of damage for different levels of seismic action.

8.1 San Benedetto Abate church in Gonzaga

The non-linear dynamic analysis under PGA = 0.08 g shows that damage is diffused in the cross vaults and arches of the lateral chapels: it develops mainly in the connection region between the vaults and the walls of the central nave. Such damage is consistent with what was observed in situ, (Fig. 15f, photos 17–18). A vertical damage is registered in the connection regions between the transept walls and the perimeter walls of the hall, as emerged also in the real case, (Fig. 15e, photos15–16), and between the façade and the longitudinal walls, as reported also by the in situ survey, (Fig. 15a, photos 01–02). In addition, a widespread damage may be noted in the façade, close to the rose window. The apse walls exhibit an onset of damage near the corners of the openings, as can be shown by the in situ survey, (Fig. 15d, photos 11–12). The bell tower presents a slight damage extended both in the belfry, (as emerged by Fig. 15i, photo 24 and Fig. 15h, photo 22), and in the connection region between the bell tower and the perimeter wall of the church, (as emerged by Fig. 15h, photo 21).

The non-linear dynamic analyses under higher values of PGA highlight a widespread damage in the aisles chapels: it is consistent with the cracks observed in the vaults *in foglio* of the aisles from in situ surveys. A vertical damage is evident in the connection region between the façade and the longitudinal walls: a possible overturning mechanism of the façade can be expected considering the poor connection between the walls. The façade exhibits a widespread damage that clearly increases with the peak ground acceleration. The connection region between the bell tower and the perimeter walls shows a damage concentration due to the different stiffness and geometry of the elements. Moreover, a considerable damage spreading from the corners of the openings is registered in the belfry: it is consistent with the crack pattern observed after the field survey. Vertical damage starting from the top is recognizable in the walls of the central nave. Additional damage can be found near the openings in the walls, starting from the corners: it is compatible with the cracks observed from the in situ survey.

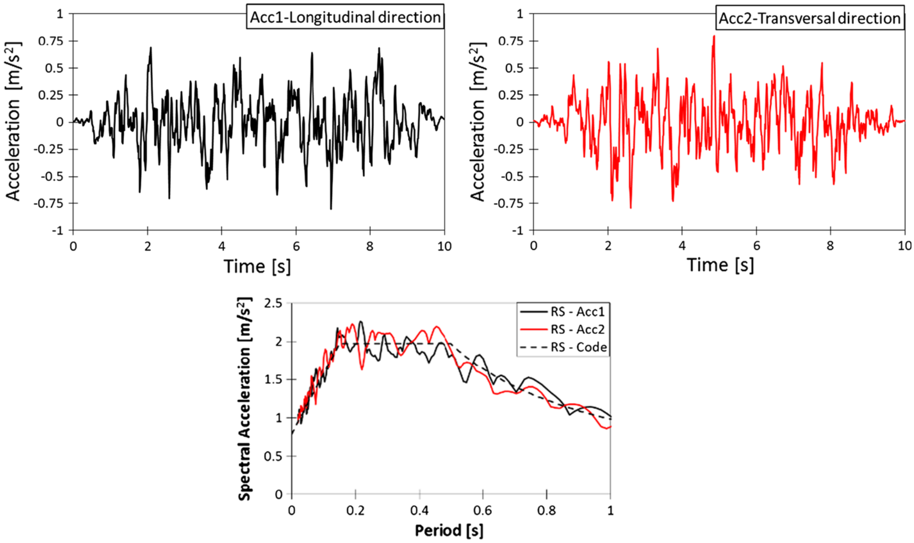


Fig. 27 Accelerograms used in the non-linear dynamic analyses and corresponding response spectra

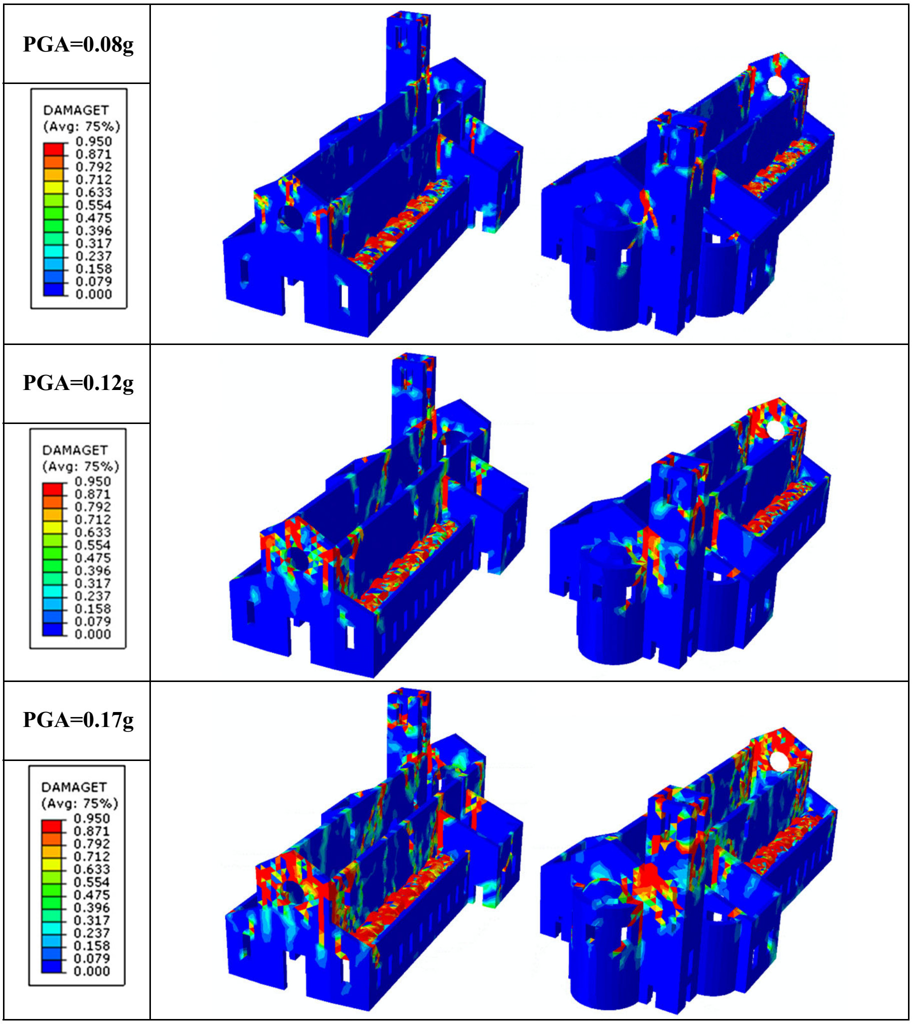


Fig. 28 San Benedetto Abate church: tensile damage contour plots at the end of the non-linear dynamic analyses for different peak ground accelerations

A specific evidence has not been found for the damage reported in the presbytery, (Fig. 15c, photos 09–10), and along the connection region between the transept vaults and the external walls, (Fig. 15e, photos 13–14). In order to explain such a discrepancy of results, it can be noted that the presbytery dates back to the Romanesque period and it could be composed of an internal nucleus that weakens the element, as emerged from the historical and diagnostical surveys.

Figure 28 shows the evolution of the tensile damage in San Benedetto Abate church for different values of peak ground accelerations.

The non-linear dynamic analyses show that the maximum normalized displacement (horizontal displacement/height) is registered for the tympanum in the longitudinal direction and for the wall of the central nave and the bell tower in the transversal direction.

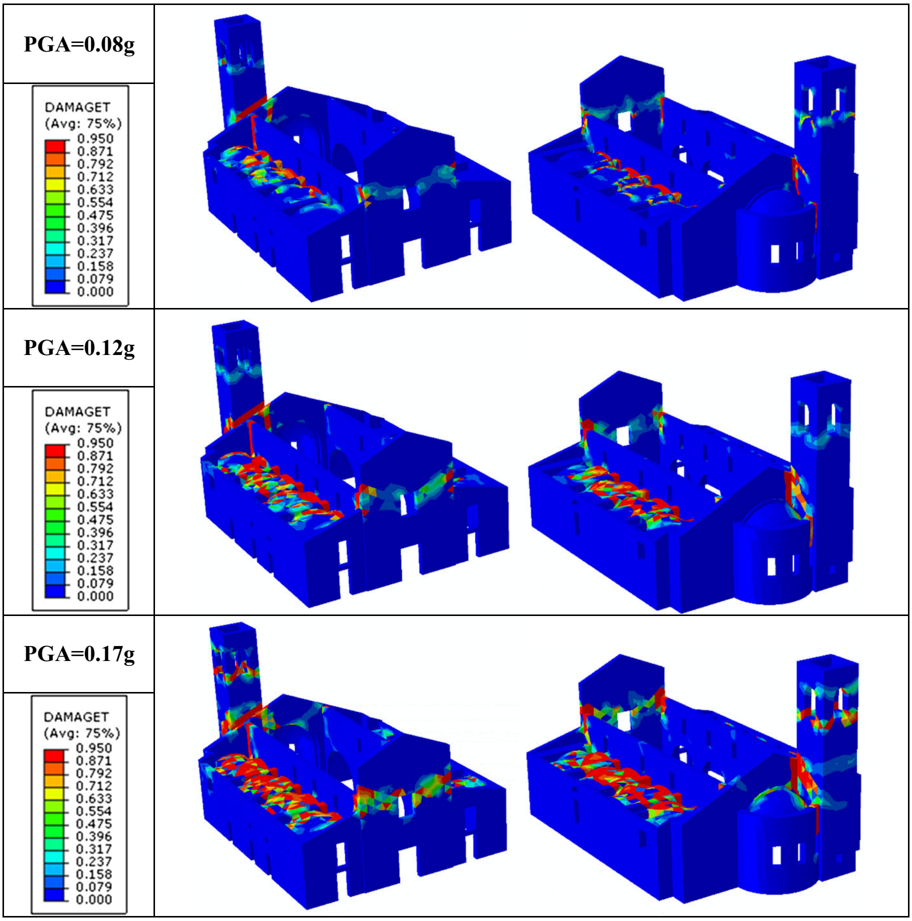


Fig. 29 San Fiorentino Martire church: tensile damage contour plots at the end of the non-linear dynamic analyses for different peak ground accelerations

8.2 San Fiorentino Martire church in Nuvolato

The non-linear dynamic analysis under PGA = 0.08 g shows a significant damage in the vaults of the aisles chapels, localized mainly in the connection region with the walls of the central nave and along the arches connecting the different chapels: such damage is consistent with what observed in situ, (Fig. 17e, photos 09–10; Fig. 17f, photos 11–12). A slight damage starting from the central opening is visible on the façade. A vertical damage is registered between the façade and the longitudinal walls of the central nave, as observed during the damage survey, (Fig. 17a, photos 01–02). A localized damage is observed between the bell tower and the hall wall and between the bell tower and the apse wall, as documented by the damage survey, (Fig. 17h, photos 14–15). The bell tower presents a slight damage near the openings of the belfry, as reported by the in situ survey, (Fig. 17h, photos 14–15).

The non-linear dynamic analyses under higher values of PGA show a considerable enlargement of damage, involving the entire vaults system. In particular, it is possible to

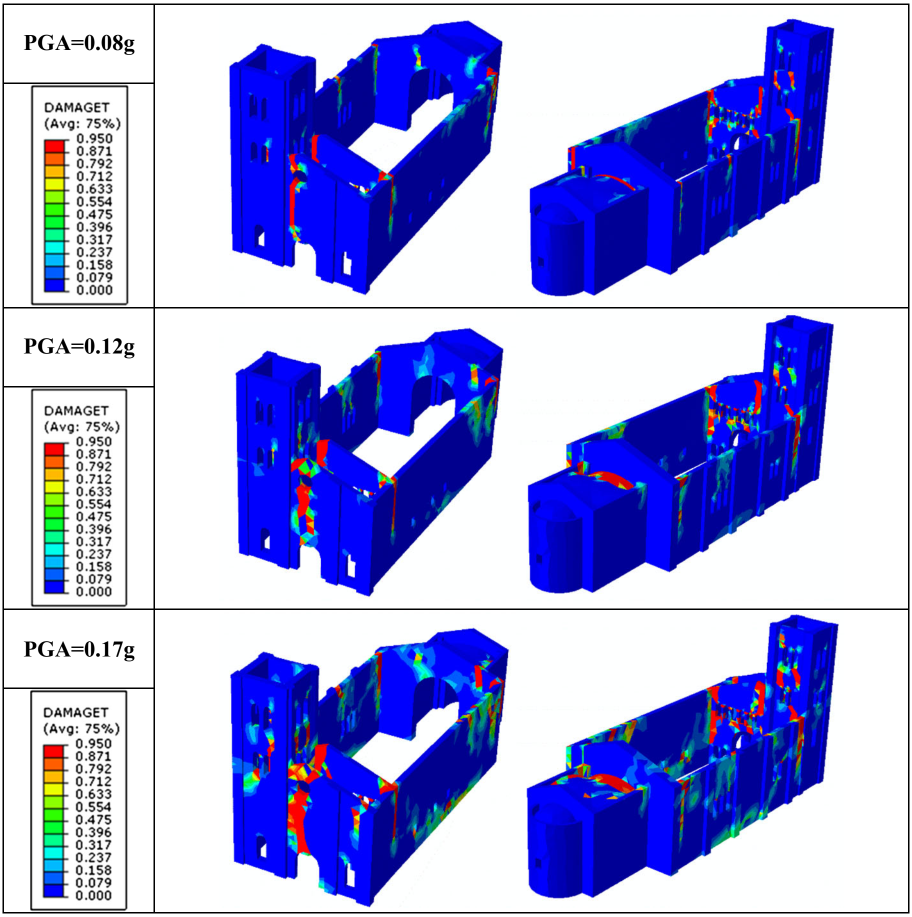


Fig. 30 Santa Maria Assunta church: tensile damage contour plots at the end of the non-linear dynamic analyses for different peak ground accelerations

observe a widespread damage along the ribs of the vaults of the side chapels, a possible detachment of the aisles vaults from the walls of the central nave and a significant damage in the arches of the masonry vaults. A localized damage can be noted in the contact region between the bell tower and the walls of the church. Furthermore, a clear damage is registered near the connection region between the façade and the walls. The façade presents a significant horizontal damage near the central opening and an extensive damage with sub-horizontal distribution is visible in the belfry, above all in the analysis under PGA = 0.17 g. The apse does not present damage in the external wall, but a severe damage can be noted along the contact region between the apse wall and the bell tower, visible also in the analysis under PGA = 0.08 g.

A specific evidence has not been found for the damage reported in the walls of the central nave, (Fig. 17b, photos 03–04; Fig. 17g, photos 13–14), of the apse, (Fig. 17c, photos 05–06), and of the transept, (Fig. 17d, photos 07–08). It is worth mentioning that the damage observed in the wall of the central nave from the in situ survey may be related to the Romanesque origin of the macro-element (which may consist of a multi-wythe masonry) and to the several interventions performed on this macro-element over time (e.g. the opening of arches to connect the central ancient nave to the adjacent aisles).

Figure 29 shows the evolution of the tensile damage in Santa Maria Assunta church for different values of peak ground accelerations.

The peak values of the maximum normalized displacement are registered for the tympanum in the longitudinal direction and for the wall of the central nave and the bell tower in the transversal direction.

8.3 Santa Maria Assunta church in Felonica

The non-linear dynamic analysis under PGA = 0.08 g shows that damage is mainly concentrated in the regions where the bell tower interacts with the walls of the church, involving the main façade and the transversal and longitudinal walls of the nave: such damage may be explained considering the different geometrical and dynamic features of the adjacent elements. A vertical damage is detected in the connection regions between the bell tower and the façade and between the bell tower and the perimeter wall: it is consistent with what was observed in situ, (Fig. 19f, photos 13–16). Moreover, a significant vertical damage is recognizable in the corner between the southern longitudinal wall and the transversal one: it was partially observed in situ, (Fig. 19e, photo 09). A visible damage along the connection between the vaults of the atrium and the supporting walls emerges and it reflects the real damage, (Fig. 19c, photo 05). A clear damage is visible along the arch connecting the presbytery and the hall: it does not represent exactly what was detected in situ, (Fig. 19d, photos 07–08). A localized damage is concentrated in correspondence with some openings along the longitudinal and transversal walls of the hall, the bell tower and the atrium: it was partially observed in situ, (Fig. 19b, photo 04; Fig. 19e, photos 11–12).

The non-linear dynamic analyses under higher values of PGA show an enlargement of damage in the façade and in the connection region between the bell tower and the perimeter wall. The perimeter walls exhibit a clear vertical damage that increases with increasing levels of PGA: such damage is compatible with in situ survey, even though it is less marked. The analysis under PGA = 0.17 g reveals a localized damage near the openings of the belfry, not visible in the real crack pattern. The damage maps clearly show a considerable damage in the masonry vault of the presbytery, which may indicate an incipient detachment between the vault system and the wall, not registered during the in situ survey. An extension of damage is also observed: (1) in the counter-façade, with damage that develops mainly close to the openings, as observed in situ, (Fig. 19a, photos 01–02); (2) in the chapels walls, with damage generally close to the arches, as observed in situ, (Fig. 19a, photo 03); (3) in the longitudinal and transversal walls, with vertical damage spreading from the top of the walls; (4) in the connection regions between the masonry vault of the *Cappella Gemella* and the longitudinal wall, with clear evidence of the detachment of the vault from the wall.

Figure 30 shows the evolution of the tensile damage in Santa Maria Assunta church for different values of peak ground accelerations.

The non-linear dynamic analyses show that the maximum normalized displacement is registered for the lateral wall in the transversal direction and for the bell tower in the longitudinal direction.

9 Conclusion

This paper has investigated the seismic behavior of three Matildic churches that are all located in the Mantuan Oltrepò region and were damaged during the 2012 Emilia earthquake. The churches analyzed in this study are representative of a large number of churches belonging to the province of Mantua and could be used as a first step for a seismic vulnerability assessment analysis at provincial scale.

- The work proves the importance of an integrated approach for the damage assessment of historical masonry churches after seismic events. The knowledge of the history, an accurate geometrical survey and the evaluation of the actual state of the structure and materials are essential steps to define suitable numerical models and should be considered as integral to the seismic vulnerability assessment of any historical structure.
- The damage survey performed through Terrestrial Laser Scanning (TLS) and visual inspections has provided useful preliminary results for the seismic vulnerability assessment of the churches. The most vulnerable elements and the main damage mechanisms have been identified with reference to different macro-elements composing the churches. The outcomes of the post-earthquake inspections on the masonry churches have evidenced, in the majority of the cases, a poor seismic performance with the occurrence of significant damage in different macro-elements. The collection of damage data in each single architectural element of the churches allows to evaluate the need for provisional interventions.
- The field observations and the results of the numerical analyses have highlighted the high vulnerability of this typology of structures to seismic actions. The main weaknesses of the churches investigated in this study are correlated to the out-of-plane mechanisms of both the façade and the lateral walls as well as the vaults system of the naves and the bell tower.
- The results provided by the standard eigen-frequency analysis have shown that low values of participating mass ratio are associated with the first main vibration modes, highlighting that the dynamic response of the churches is characterized by the local behavior of the different macro-elements. The periods of the main vibration modes involving a significant percentage of participating mass ratio exhibit low values ranging between about 0.07 s and 0.55 s for the three churches. As a consequence, such structures experienced the highest amplifications of PGAs. These features can partially justify the damage caused by the seismic sequence to the churches. Moreover, a preliminary assessment of the most vulnerable macro-elements has been roughly provided.
- The non-linear dynamic analyses performed through refined FE models have allowed to study the evolution of the tensile damage for different peak ground accelerations, identifying the main parts of the churches characterized by severe damage. The numerical simulations have provided a valuable picture of possible damage, with damage localization generally in a good agreement with the results of the survey carried out in situ after the seismic events.
- In view of the design of efficient strengthening interventions, sophisticated non-linear dynamic analyses may be useful tools to address the retrofitting actions and to assess their effectiveness in order to reduce the seismic vulnerability of the churches (e.g. the introduction of new tie rods, simulation of the application of FRP materials).

Acknowledgements The Authors express their thanks to the Technical Office of the Mantova Bishop, SGM S.r.l—Ingegneria Sperimentale and to Architect Gabriele Vittorio Ruffi (for San Benedetto Abate church), to Architect Giorgio Gabrieli (for San Fiorentino Martire church and Santa Maria Assunta church) and to Engineer Alberto Mani (for Santa Maria Assunta church) for having contributed to this work by making available all the information and data at their disposal. GB gratefully acknowledges the Unesco Chair of the Politecnico di Milano—Mantova Campus for providing support for her graduate studies.

References

ABAQUS (2014) Theory manual, version 6.14

Andreini M, De Falco A, Giresini L, Sassu M (2014) Structural damage in the cities of Reggiolo and Carpi after the earthquake on May 2012 in Emilia Romagna. Bull Earthq Eng 12:2445–2480

Barbieri G, Biolzi L, Bocciarelli M, Fregonese L, Frigeri A (2013) Assessing the seismic vulnerability of a historical building. Eng Struct 57:523–535

Barbieri G, Valente M, Biolzi L, Togliani C, Fregonese L, Stanga G (2016) An insight in the late Baroque architecture: an integrated approach for a unique Bibiena church. J Cult Herit. doi:10.1016/j.culher.2016.07.006

Betti M, Vignoli A (2008) Modelling and analysis of a Romanesque church under earthquake loading: assessment of seismic resistance. Eng Struct 30:352–367

Cattari S, Degli Abbati S, Ferretti S, Lagomarsino S, Ottonelli D, Rossi M, Tralli A (2012) The seismic behaviour of ancient masonry buildings after the earthquake in Emilia (Italy) on may 20th and 29th, 2012. Ingegneria Sismica 23:87–111

Circolare (2009) Circolare n. 617 del 2 febbraio 2009 Istruzioni per l'Applicazione Nuove Norme Tecniche Costruzioni di cui al Decreto Ministeriale 14 gennaio 2008 (**in Italian**)

DPCM 09/02/2011 (2011) Valutazione e riduzione del rischio sismico del patrimonio culturale con riferimento alle Norme tecniche per le costruzioni di cui al DM 14/01/2008 (**in Italian**)

Foraboschi P (2013) Church of San Giuliano di Puglia: seismic repair and upgrading. Eng Fail Anal 33:281–314

Foraboschi P (2014) Resisting system and failure modes of masonry domes. Eng Fail Anal 44:315–337

Foraboschi P (2016) The central role played by structural design in enabling the construction of buildings that advanced and revolutionized architecture. Constr Build Mater 114:956–976

Golinelli P (2004) Matilde e i Canossa, Mursia, Milano (**in Italian**)

Lagomarsino S (2012) Damage assessment of churches after L'Aquila earthquake (2009). Bull Erthq Eng 10:73–92

Lagomarsino S, Cattari S (2015) Seismic performance of historical masonry structures through pushover and nonlinear dynamic analyses. Geotech Geol Earthq Eng 39:262–292

Lee J, Fenves GL (1998) Plastic-damage model for cyclic loading of concrete structures. J Eng Mech 124:892–900

Lualdi M, Lombardi F (2014a) Significance of GPR polarisation for improving target detection and characterization. Nondestruct Test Evalu 29(4):345–356

Lualdi M, Lombardi F (2014b) Combining orthogonal polarization for elongated target detection with GPR. J Geophys Eng 11(5):8

Lubliner J, Oliver J, Oller S, Oñate E (1989) A plastic-damage model for concrete. Int J Solids Struct 25:299–326

Milani G, Valente M (2015a) Comparative pushover and limit analyses on seven masonry churches damaged by the 2012 Emilia-Romagna (Italy) seismic events: possibilities of non-linear finite elements compared with pre-assigned failure mechanisms. Eng Fail Anal 47:129–161

Milani G, Valente M (2015b) Failure analysis of seven masonry churches severely damaged during the 2012 Emilia-Romagna (Italy) earthquake: non-linear dynamic analyses vs conventional static approaches. Eng Fail Anal 54:13–56

NTC (2008) Nuove Norme Tecniche per le Costruzioni. Ministero delle Infrastrutture (GU n.29 04/02/2008), Rome, Italy; 14/01/2008 (**in Italian**)

Page A (1981) The biaxial compressive strength of brick masonry. In: Proceedings of the Institute of Civil Engineering, pp 871–893

Parisi F, Augenti N (2013) Earthquake damages to cultural heritage constructions and simplified assessment of artworks. Eng Fail Anal 34:735–760

Penna A, Morandi P, Rota M, Manzini CF, Da Porto F, Magenes G (2014) Performance of masonry building during the Emilia 2012 earthquake. Bull Earthq Eng 12:2255–2273

Preciado A, Bartoli G, Budelmann H (2015) Fundamental aspects on the seismic vulnerability of ancient masonry towers and retrofitting techniques. Earthq Struct 9:339–352

SIMQKE (1976) A program for artificial motion generation: user's manual and documentation. MIT Department of Civil Engineering, Cambridge

Sorrentino L, Liberatore L, Decanini LD, Liberatore D (2013) The performance of churches in the 2012 Emilia earthquakes. Bull Earthq Eng 12:2299–2331

Valente M, Milani G (2016a) Non-linear dynamic and static analyses on eight historical masonry towers in the North-East of Italy. Eng Struct 114:241–270

Valente M, Milani G (2016b) Seismic assessment of historical masonry towers by means of simplified approaches and standard FEM. Constr Build Mater 108:74–104

Valente M, Barbieri G, Biolzi L (2016) Seismic assessment of two masonry Baroque churches damaged by the 2012 Emilia earthquake (Submitted and under review)

Van Der Pluijm R (1993) Shear Behaviour of bed joints. In: Proceedings of 6th North American masonry conference, Philadelphia, pp 125–136