An insight in the late Baroque architecture: An integrated approach for a unique Bibiena church

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In this paper a masonry baroque church by Antonio Galli Bibiena in Villa Pasquali is analyzed using a multidisciplinary approach. The importance of this monument is due to the prestige of its architect and to the peculiar system of masonry perforated vaults, which is an unicum in architectural history. Nevertheless, until now this church has not been studied, but historical data and significant crack patterns have pointed out its high vulnerability. The first step related to the knowledge of the building consists of the historical record of archival documents, which allow for the identification of the vulnerable elements. An accurate geometric survey is carried out with Terrestrial Laser Scanning in order to detect the complex three-dimensional geometry of the structure and crack patterns. Finally, a three-dimensional finite element model of the entire structure is developed and a comparison between the numerical results and the damage survey is performed.

Keywords:
Masonry
Vulnerability
Historical survey
Laser Scanner survey
Finite element modeling

1. Introduction and research aims

The conservation and restoration of ancient buildings belonging to the cultural heritage are important issues. Generally, national and international codes deal with new structures and specific recommendations for the safety of existing structures are difficult to find. In Italy, for example, the problem of the high vulnerability of ancient unreinforced masonry buildings has begun to emerge since the 1970s, after some notable earthquakes. In fact, as is well known, these structures are generally able to carry vertical loads, while they are quite vulnerable to horizontal actions [1–5]. In the current Italian Code [6] a specific section has been introduced to suggest how to assess the safety of structures belonging to the cultural heritage and to design the strengthening interventions. Further, other more recent and complete guidelines and recommendations [7,8] have been introduced. Since each ancient building is by definition unique, all the recommendations suggest that a thorough knowledge of these structures must be the starting point before any conservation and strengthening interventions. The knowledge of the building should involve a historical review, a geometrical survey and a diagnostic analysis of the structure. This information is essential in order to accurately understand the structural behavior of the building through analytical or numerical methods. An example of the importance of the historical analysis is reported for the case-study of *Palazzo della Loggia* in Brescia: the archival research was fundamental both to have a better understanding of the structural system and to address the diagnostic survey [9]. The importance of a precise geometrical survey for the detection of significant deformation patterns affecting the structural behavior can be seen, among others, in [10,11]. Several examples on the importance of the diagnostic survey can be reported [12–14]. A lot of analytical and numerical studies can be mentioned, aimed at simulating and understanding the seismic behavior of masonry structures [15–21], but also at assessing the effectiveness of some suggested retrofitting solutions [22].

This paper investigates the case study of *Sant'Antonio Abate* church in Villa Pasquali. This building was realized by Antonio Luigi Galli da Bibiena in the second half of the XVIII century.

The importance of this monument is related to the prestige of its architect as well as to its outstanding vaulted structures, for which

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this church can be properly considered an indisputable masterpiece of Baroque architecture.

The Bibiena family was one of the most thriving dynasties of architects, scenographers and painters active in many European courts between the XVII and XVIII centuries. For instance, Antonio Galli Bibiena was born in Parma in 1697 and then educated in Bologna; he came back to his country in 1751 with an international cultural background and renown acquired while working as second theater engineer in Vienna. The Bibiena's international fame is confirmed by the research of well-known art historians, such as [23,24], who studied and published about the artistic production of this family. The most innovative contribution of the Bibiena was in the use of both the space and the prospective. Their architectures (mainly theaters and sacred buildings) were conceived as scenic designs, which should be spectacular and must amaze and astonish the audience, as typical in the late Baroque style, through a clever use of light and *sfondato* technique. Surely, the majestic structures of the perforated vaults of *Sant'Antonio Abate* in Villa Pasquali fully express Bibiena's effort to create a blend of architecture and scenography. The theme of the perforated vaults is recurrent in Bibiena's works, both in scenographic framework (where through the decorations and paintings, the illusion of fake perforated domes was often recreated, see *Teatro Scientifico* in Mantua, by Antonio Galli) and in the architectonical one (see *Sant'Antonio Abate* church in Parma, by Ferdinando Galli and finished by Antonio Galli, and also *Santissimo Sacramento* chapel in Sabbioneta and Coffee House in *Palazzo Ducale* in Mantua). However, in *Sant'Antonio Abate* church in Villa Pasquali this theme is surely brought to its highest and most elegant expression. To the Authors knowledge, except from the perforated ribbed domes by Guarino Guarini in Turin (see e.i. *Santa Sindone* chapel and *San Lorenzo* church, as well as other his projects published in [25]) and by Bernardo Vittone (see Valinotto Santuary in Carignano, *San Bernardino* church in Chieri and *Santa Chiara* church in Bra), that are conceived in a very different and not comparable way, the example of the perforated vaults of *Sant'Antonio Abate* church in Villa Pasquali is an *unicum* in the international scene.

In spite of the unquestionable importance of this case study, before the present work the building has never been studied and the available documentation was poor and confused. An historical research performed with scientific accuracy did not exist; the geometrical survey was based on few handmade 2D drawings, carried out in the Eighties by means of a direct survey; the crack pattern was incomplete and no diagnostic test was performed. In addition, the church stability may be endangered by both the seismicity of the area and the high vulnerability of its particular structures. The earthquake that occurred in Northern Italy in 2012 surely pointed out this concern. In the present paper, a first step for the analysis of *Sant'Antonio Abate* church is presented.

2. Historical survey

For a long time, Ferdinando Galli Bibiena was believed to have been the architect of the Villa Pasquali parish church. This was mainly due to two reasons: (i) an inscription placed on the counter-façade of the church in the XIX century, according to which the foundations were laid in 1764 at the direction of the Bolognese architect; (ii) the similarity between the particular double vaulted system of *Sant'Antonio Abate* church in Villa Pasquali and the one used for *Sant'Antonio Abate* church in Parma, the latter certainly by Ferdinando [26–28]. Nevertheless, the latest studies have proved that the project is to be attributed to Antonio [29].

Villa Pasquali church was built on a site where, beginning with the first decades of the XVII century, there is information about the presence of two pre-existing older churches, oriented toward the East. The need to build a newer and bigger church was surely due to the significant demographic growth of the population. According to the most recent studies, the beginning of the construction of the new *Sant'Antonio Abate* church in Villa Pasquali, oriented toward the north, dates back to the spring of 1764 [29].

On the 19th of November 1766, while the church was still in its construction phase, the dome collapsed. The event was briefly described in a document kept at the Villa Pasquali Parish Archival and written by the parishioner Angelo Pescatori on the 19th November 1766, cited by [29–31]. The memory informs that the first church was constituted for the most of mortar (it was "*[. . .] costrutta [. . .] la maggior parte di malta*") and reused and non uniform clay bricks (the so-called "*pietre d'ogni sorta*") and it was "*senza ferri, et senza legatture*", without tie-rods or steel reinforcements. Certainly, the priest Pedrazzi donated some clay bricks and tiles, which had been recovered from a house located on a plot of land that the priest sold to the community in 1781 for the new cemetery. Perhaps, some of the materials derived from the demolition of an ancient church in the village were used; or perhaps some clay bricks were produced in makeshift rudimentary furnaces built in the surrounding countryside, in order to reduce the time and the construction cost. In addition, Pescatori indirectly provides information useful to put forward a hypothesis about the dynamics of the collapse. He reports cracking of the roof of Freschi's house ("*[. . .] colla semplice frattura del tetto in parte della casa Freschi [. . .]*"), which can be identified with the manor farm located near the western apse, according to the cadastral documents of the time. He adds that only the presbytery with the side chambers, which were generally built first in churches, did not collapse (*[. . .] essendo pur anche restato in piedi tutto il Presbitero, e Coro, e camere [. . .]*). No mention of the nave is made.

It is unclear whether the collapse was due to the fault of the architect (who considered the structure strong enough without any tie-rods) or to the client and the financiers (who omitted steel reinforcements in order to reduce construction costs) or to master builder ("*Crispino Milanese*"). Nevertheless, Bibiena's prestige was not undermined by the accident: in 1768 he was commissioned to design a similar (but smaller) dome in the *Santissimo Sacramento* chapel in *Santa Maria Assunta* church in Sabbioneta.

After the collapse of the dome, the community of Villa Pasquali started to reconstruct it. It is reported that in 1769 the priest of the nearby Martignana Po community, Pietro Carnevali, went to Villa Pasquali during the day devoted to Sant'Antonio Abate and admired the outstanding beauty of the new church [29–31]. Certainly, the reconstruction costs were high. The work finished in 1784, but the church was not completed, probably due to the high reconstruction costs. In particular, the bell tower on the left of the main façade was not built, the exterior remained as exposed brickwork and the interior decoration would have been completed only during the XIX century, Fig. 1. Mindful of the dome collapse, the new church was provided with appropriate reinforcing elements. A new tie-rod was inserted passing through the drum of the dome in the east-west direction, which was considered the most vulnerable one, as it was probably the one along which the collapse occurred. Under the wooden roof, this tie-rod was then connected to others anchored to the outer sides of the lateral apses, in correspondence with the pilasters, Fig. 2.

After construction, the stability of the church was jeopardized mainly by geological problems. Owing to the presence of an aquifer under the floor of the church, some foundations settlements and cracks are documented beginning with the third decade of the XX century. To address this, in the Thirties two tie-rods were inserted for containment of the arches and the double vault in the presbytery and apse [29,31,32]. Successively, in the Sixties, strengthening interventions of the foundation level were suggested, to solve

Fig. 1. (a) Main façade; (b) internal view of the church.

the particularly alarming situation of the north-east side of the church [29,31]. These interventions provided for the execution of a sub-foundation system based on the insertion of reinforced concrete prefabricated circular section piles (diameter equal to 25 cm), located under the existing foundations. This involved the demolition of a part of the existing foundations and the addition of reinforced concrete curbs. The effective accomplishment of the project was definitely ascertained thanks to some foundation inspections performed in 2015. After the intervention, the repair of the damaged walls was carried out.

Other structural interventions were performed during the XX century. In particular, several interventions involved the wooden roof with the complete replacement of the structure (documentations report interventions during the second, third, seventh, eighth, ninth decades of the last century) [29]. At last, other significant strengthening and restoration works involved: the replacement of the wooden roof of the dome (1902, 1986), some interventions at the windows of the main dome and the small domes of the four lateral chapels (1920, 1986), some works at the bell tower (1966), several interventions occurred over time in correspondence with all the openings and the strengthening of the perforated vaults of the pseudo-transept through a layer of gauged mortar at the extrados [29].

After the 2012 earthquake in *Lombardia* and *Emilia Romagna* regions, the crack pattern of the church was partially modified and new interventions for strengthening and restoration were required. In 2012, some interventions involved the strengthening of the windows of the east side, the repair of the damaged longitudinal walls and vaults of the nave by epoxy resin injections. In 2015, a new project for the apse and the presbytery strengthening was approved by the Soprintendenza.

3. Geometrical survey

From the archival research, the original design of *Sant'Antonio Abate* church by Bibiena was not found. The oldest recovered

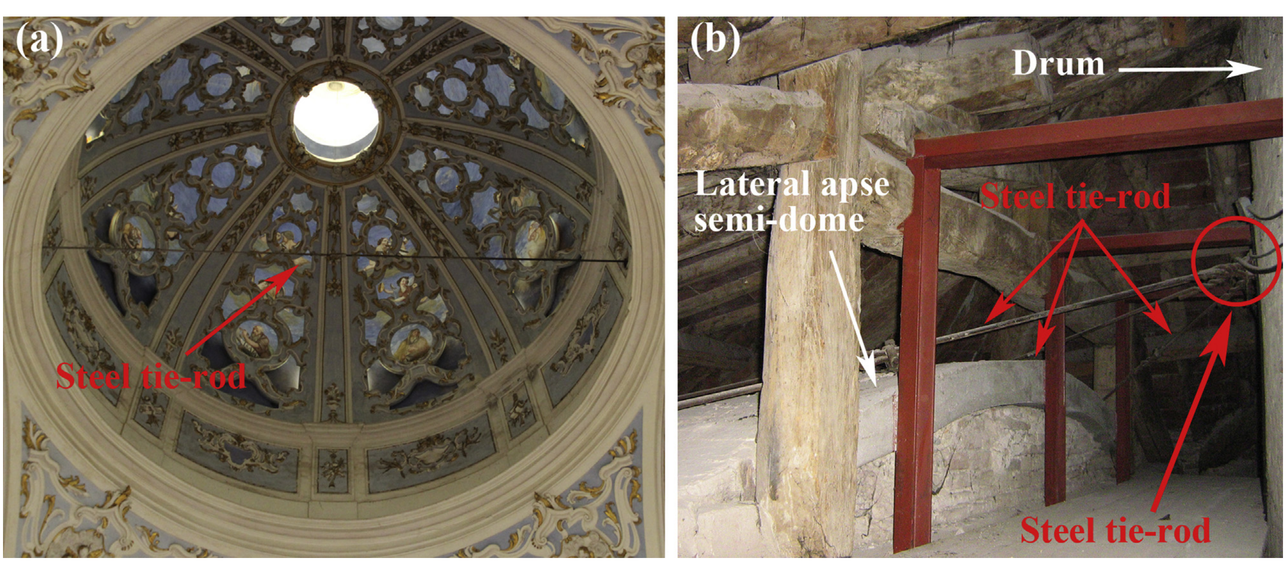

Fig. 2. Central dome and east–west direction tie-rod passing through the drum; (b) system of tie-rod in the lateral apses at the under-roof level.

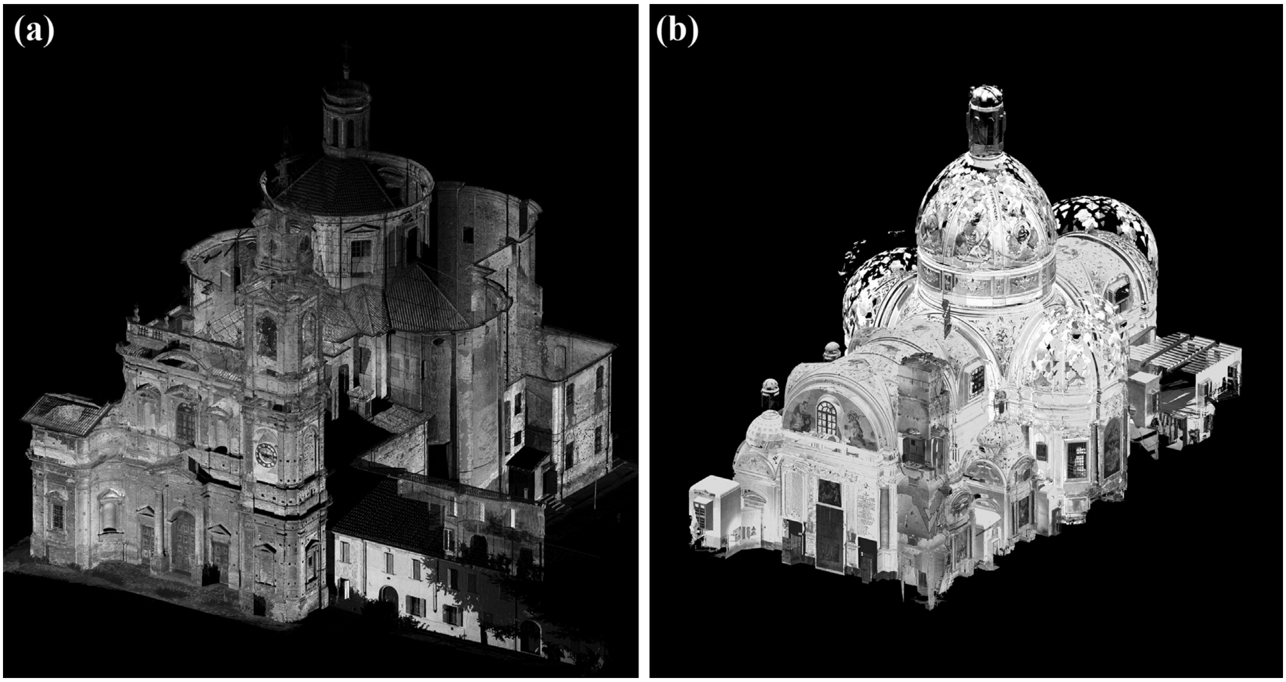

Fig. 3. (a) Union of the internal scan views; (b) union of the internal scan views.

geometrical survey drawings are related to strengthening interventions performed at the foundations and at the roof in the Sixties and Eighties. Obviously, they were based on a direct survey and illustrate the plan and some cross sections of the church, with some technical details of the intervention.

However, for the analyzed case study, a 2D geometrical survey is not sufficient in order to understand such a complex structure.

In July 2014, a complete 3D geometrical survey of the entire church was performed by means of HDS7000 scanner by Leica Geosystems. Laser database has been composed of 62 scans (49 internal, 13 external) oriented with a topographic network arranged by 14 topographical stations from which 40 ground control points (GCP) were acquired. The union of the internal (Fig. 3a) and the external (Fig. 3b) scan views is shown through the software Pointools. All the scan views were made in super high resolution, obtaining a points spacing equal to 3.1 mm at 10 m away. The overall average error obtained for scans orientation was about 0.01 m.

The 3D geometrical survey of the church allows acquiring and precisely representing the geometry of the central dome and of the semi-domes of the apses. The central dome is composed of a sort of double shell system, even if the two shells are not connected and the lantern closes the outer one only. The inner dome is composed of eight masonry ribs with vertically laid bricks closed in a central ring and connected by thin masonry widely perforated sails with an *in foglio* arrangement of the bricks. The outer dome consists of a continuum masonry structure that rises over the bottom shell. Between the two shells, in correspondence with the ribs of the bottom one, eight windows opened onto the tiburio filter light in the interior space of the church through the perforated bottom dome. The described unique double shell system is adopted in the semi-domes of the main lateral chapels and apse, too. These are composed of inner semi-domes (with six ribs converging in a half-ring and five perforated panels) and of outer masonry semi-domes (which in correspondence of the lateral chapels are cut to leave a passage around the drum at the under-roof level). In the same way as the central dome, in the vault of the north apse the lightening is realized by four windows opened between the two shells and placed at the sides of the pilasters. Differently, in the vaults of the lateral chapels, the solution adopted for lightning is more refined and ingenious. At each side, eight strong splayed slits were opened in the outer wall, in correspondence with the spring of the bottom vault at the two sides of the external pilasters. The slits converge to the center of the pilasters and come together behind the ribs of the bottom shell, so that they are not visible from inside the church. In addition, always in the apses of the pseudo-transept, the upper half-domes have openings for filtering light from small portholes placed slightly below the eaves line. In Fig. 4, a scheme of the lightening system of the east apse semi-domes is reported. It is interesting to underline that, taking advantage of this very particular double shell system, it was possible to reference the points clouds acquired at the interior of the church and the ones acquired at the under-roof level, using some details of the decorations at the intrados of the outer shells as GCP. This allowed exactly detecting the thickness of all the masonry vaulted structures characterizing all the horizontal elements of the church.

Both 2D drawings and a 3D model were created. For what concerns the 2D drawings, TLS data were processed in Cyclone and Pointools to create orthogonal views of significant sections and of the façades; then they were re-elaborated in AutoCAD by CloudWorks application. 2D drawings were mainly aimed at describing the church in its structural and architectonical features and at checking the presence of possible significant deformations, in particular in the vaulted elements.

4. Damage survey

As reported in Section 2, the first historical information concerning the presence of cracks in the church was documented in the third decade of the XX century, although a precise description of these cracks with their position and extension is not reported. These cracks were ascribed to a foundation settlement involving the east side of the church and the northern apse.

After the 2012 earthquake, an extensive survey of the crack pattern was conducted. Based on both the TLS geometrical survey and

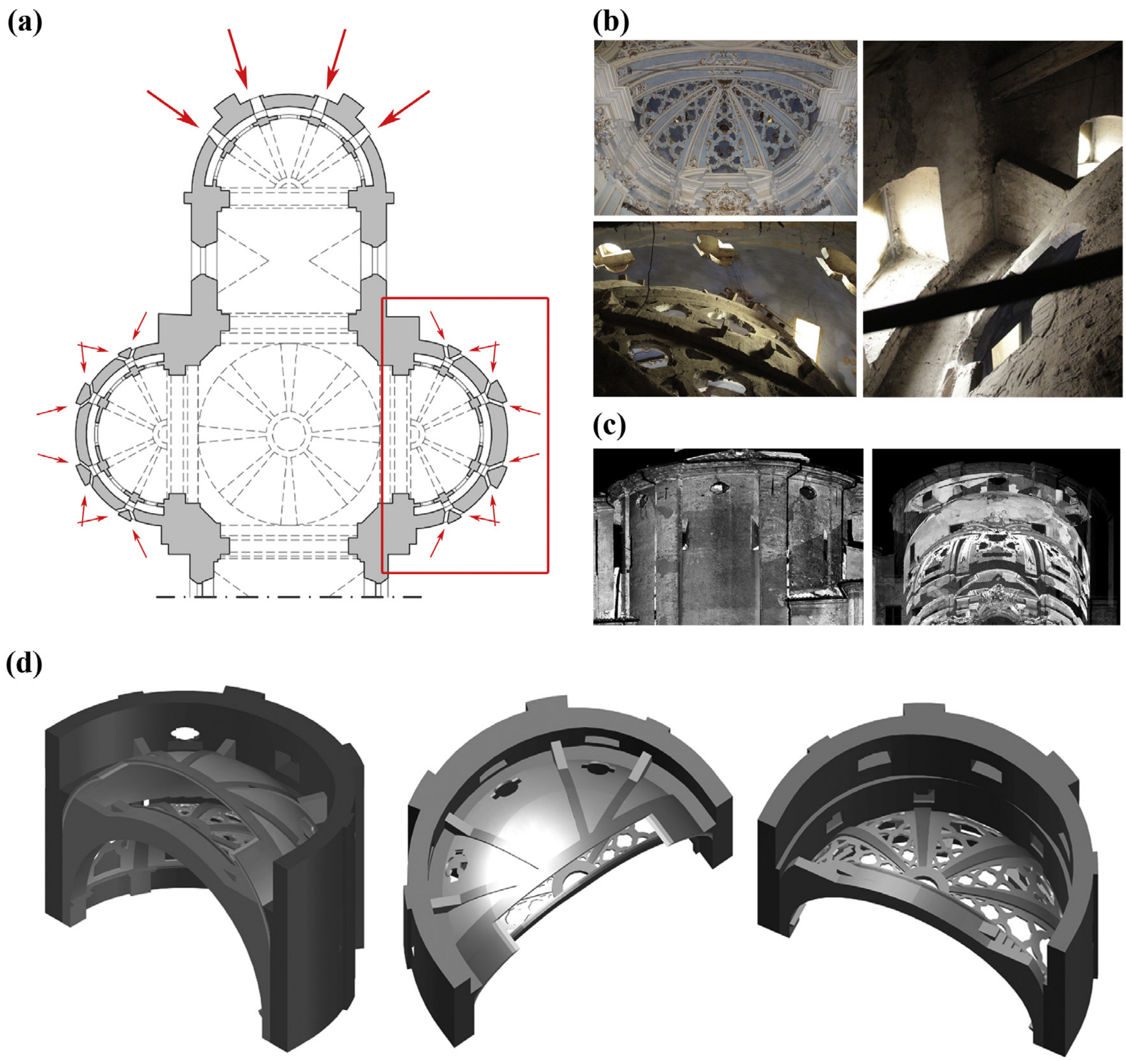

Fig. 4. East apse semi-domes. (a) Scheme of the lightening system; (b) visual inspection; (c) geometrical survey; (d) 3D model.

a visual inspection, the presence of some cracks was detected, in particular:

- *Cracks on the vaults and arches*. On the barrel vaults of the nave and the presbytery cross cracks between the vaults and the arches are evident. A large crack pattern was observed also at the haunches and crown of the vaults and, in particular, some diagonal cracks with a northeast–southwest direction were concentrated in the area closest to the bell tower. Some minor cracks were observed on the perforated vaults of the apse and on some small masonry domes of the lateral chapels. A significant crack pattern characterized by both vertical and diagonal cracks was detected on the continuum vaults of the apse and pseudo-transept. Moreover, despite the tie-rods, all the triumphal arches that support the main dome and the one between the apse and the presbytery are characterized by cracks in crown.
- *Cracks on the main dome*. A horizontal crack at the base of the drum was reported during a first survey after the 2012 earthquake. No significant cracks were observed on the bottom perforated vault and it was impossible to check the presence of cracks in the upper one.
- *Cracks on the walls of the pseudo-transept*. Vertical cracks (or sign of ancient repaired cracks) characterize all the four connections between the chapels of the pseudo-transept and the central space.
- *Cracks on the longitudinal walls of the nave, presbytery and apse*. Significant diagonal cracks are located in correspondence of the discontinuities, i.e. windows, choir and organ, mainly along the east side.

5. Structural analysis

A 3D model was used to assess the structural behavior of the building by means of the finite element (FE) program Abaqus, Fig. 5. The discretization was based on four nodes tetrahedral elements having an average size of 0.45 m, so that it was possible to have at least two elements in the perimeter walls. The total number of elements is equal to 377,103, for a total number of 91,637 nodes. Perfect connection was assumed between all the elements. The effect of the adjacent buildings (i.e. the rectory) was not considered because a careful examination showed that the rectory is not connected to the church and it does not represent a constraint; on the contrary, the volumes of the sacristy, on the east side of the presbytery, and of the chapel, on the west side, were modeled.

The masonry w and the modulus of elasticity E_m were assumed equal to 18 kN/m^3 and 1500 MPa, respectively. The steel tie-rods were modeled as linear springs having a negligible stiffness in compression and a stiffness in tension equal to $k = E_s A/L$, E_s and A being the modulus of elasticity and the sectional area, respectively, and L the length.

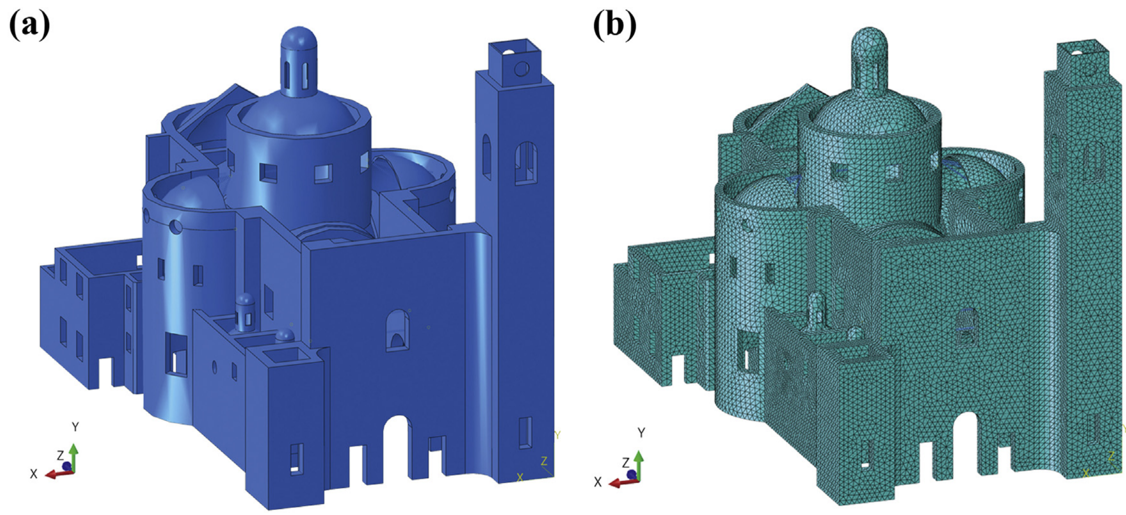

Fig. 5. Axonometric view of the (a) geometric model; (b) finite element discretization.

5.1. *Structural analysis under gravity loads*

A preliminary analysis of the church under gravity loads was performed. Fig. 6 shows some numerical results in terms of displacements for the entire church. The maximum horizontal displacements are registered for the bell tower and the maximum vertical displacements are observed in correspondence with the central dome and the drum, due to their considerable self-weight.

In Fig. 7, a qualitative correlation between the observed damage and the numerical results in terms of maximum principal stresses is shown. In particular:

- From a top view of the numerical model, Fig. 7a, a tensile stress concentration on the barrel vault of the nave and the presbytery is related to tensile stresses in longitudinal direction: this reveals that the cross cracks are due to a disconnection between the elements of the vaults and the arches, probably associated with an opening mechanism of the main nave. From a frontal view of the model, a tensile stress concentration is located in the corner between the façade and the bell tower, due to tensile stresses in the transversal direction: the cracks, which are mainly located in the first portion of the barrel vaults, seem to be due to both the asymmetric configuration of the main façade and the presence of only one bell tower that, in the upper part, is subjected to a transversal displacement in the south-east direction.
- In Fig. 7b, the tensile maximum stresses in the cross sections appear in correspondence with the main dome. The numerical analysis indicates the presence of a critical point at the base of the drum, probably related to the significant weight of the dome and the drum on the arches defining the central space. However, the numerical analysis does not justify the four vertical cracks in the lateral chapels.
- The two longitudinal sections of the numerical model, Fig. 7c, reveal a tensile stress concentration in correspondence with the upper windows, but the map does not correspond with the damage survey. This seems to demonstrate that the crack pattern is not probably due to gravity loads, but to seismic actions.

5.2. *Non-linear dynamic analysis*

In order to obtain a preliminary insight into the seismic response of the church, non-linear dynamic analyses were performed on the 3D FE model. Artificial accelerograms generated by means of the Simqke software [33] were used in order to match the response spectrum of the Italian NTC Code (soil type C) for the site under consideration. A damage plasticity material model, exhibiting softening in both tension and compression and available in Abaqus as Concrete Damage Plasticity (CDP) model, is used for masonry [34]. The stress–strain relationship in tension adopted for the non-linear dynamic analyses consists of a linear-elastic branch up to the peak stress $\sigma_{to} = 0.04$ MPa followed by a softening branch. In compression, the response is linear up to the yield stress $\sigma_{co} = 1.9$ MPa: then, a linear hardening is assumed up to the crushing stress $\sigma_{cu} = 2.4$ MPa, followed by a simplified softening branch.

The results obtained through a non-linear dynamic analysis under peak ground acceleration PGA = 0.08 g are reported in this paper. Contour plots of damage parameters (especially in tension, considering the low masonry strength) are used to identify the critical regions of the church. Fig. 8 shows the tensile damage distribution at the end of the numerical simulation: red color is associated to full (1) damage and blue color to zero (0) damage.

The non-linear dynamic analysis shows the following aspects:

- The nave and presbytery vaults suffered a significant damage, already shown by the gravity loads analysis and compatible with the cracks detected in situ. Damage is localized along the diagonal ribs of the cross vaults. In particular, a significant damage can be noted in the connection region between the façade and the nave vault.
- A clear damage is registered at the base of the lantern placed at the top of the central dome, however not visible in the real crack pattern.
- The transversal sections in correspondence with the pseudo-transept indicate a considerable damage at the base of the central dome, along the pendentives and in the semi-domes of the transept: this damage is confirmed by in situ survey and already highlighted by the numerical simulations under gravity loads. Moreover, a severe damage is registered near the openings of the transept: these cracks are observed in the surveyed damage and did not emerge clearly from the previous analyses.
- The façade shows a visible damage close to the central window. Moreover, a vertical damage is detected in the connection regions between the bell tower and the façade (as already indicated also

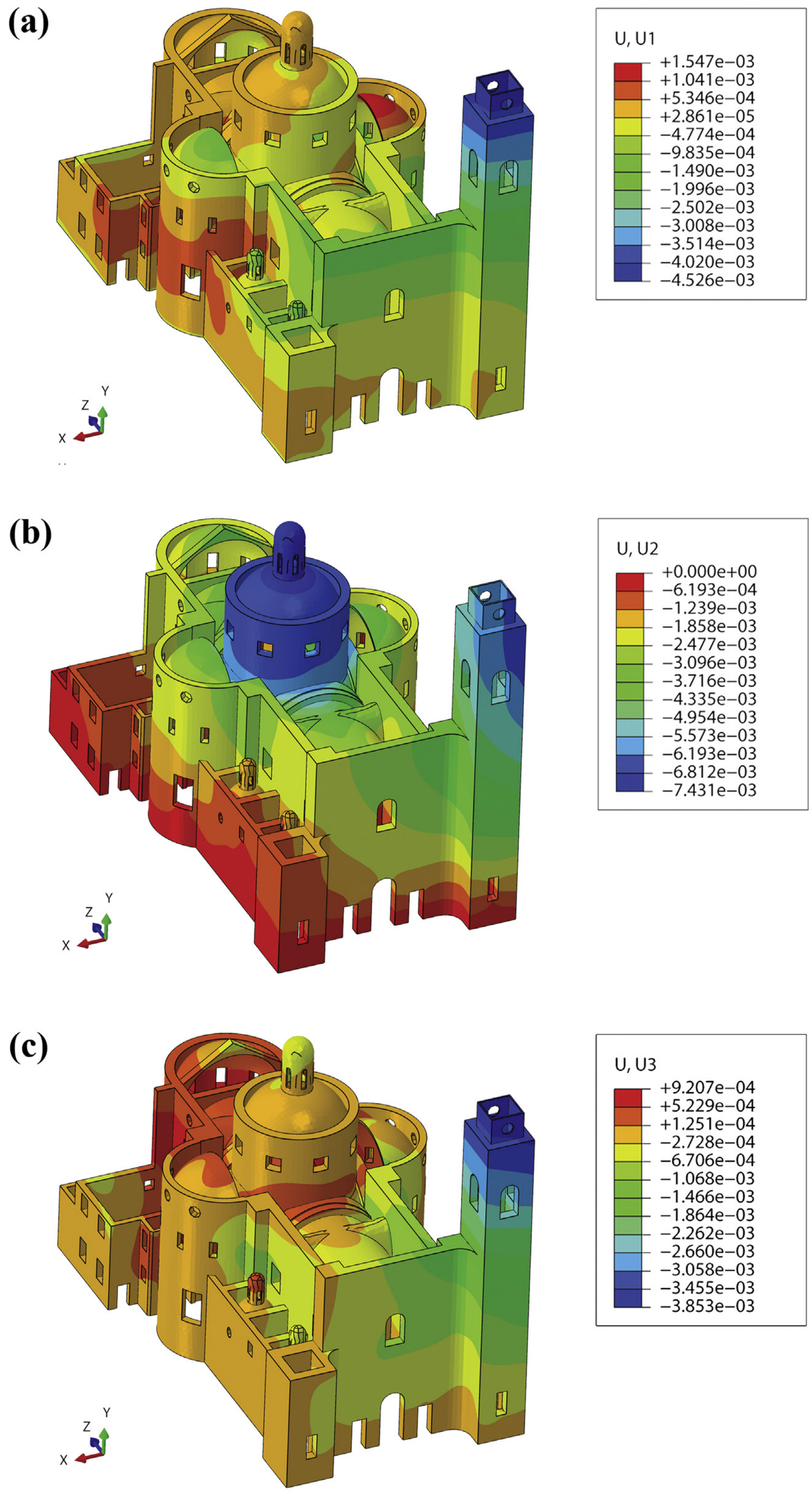

Fig. 6. Map of displacements (expressed in m) in (a) longitudinal direction; (b) transversal direction; (c) vertical direction.

in the gravity load analysis) and between the bell tower and the perimeter wall. There is a widespread damage near the openings of the belfry, not visible in the real crack pattern.

- The lateral side of the model shows a slight damage that is consistent with cracks observed near the openings of the nave, the lateral chapels and transept walls.

The results of the non-linear dynamic analysis show the high vulnerability of the church under horizontal loads and prove that the FE model may be a useful tool to identify the parts of the church subjected to major damage.

A comprehensive description of the diagnostic research aimed at assessing the main material properties along with the results of

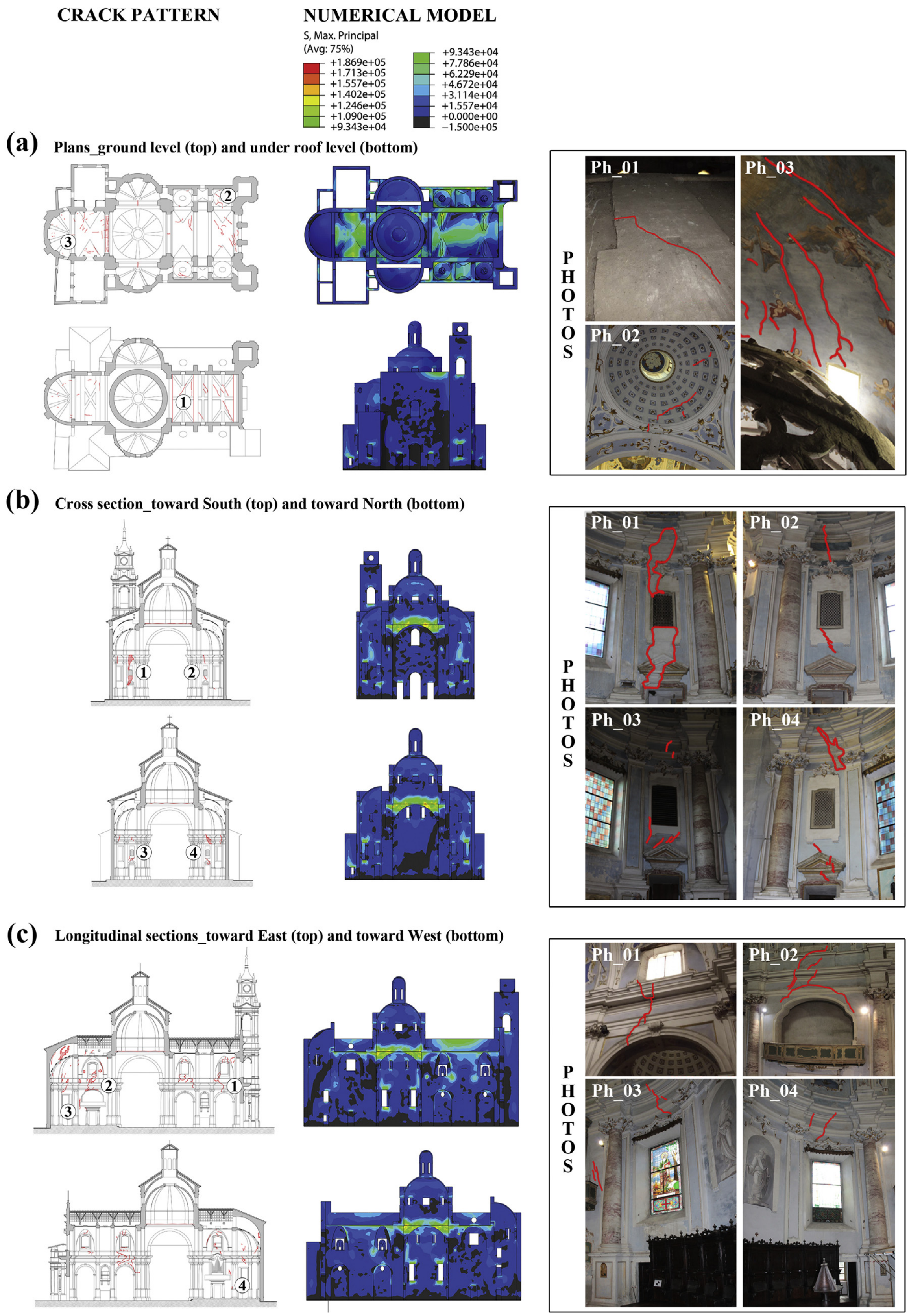

Fig. 7. Maximum principal stresses (expressed in N/m^2). (a) Cracks on the vaults; (b) cracks on the cross sections along the pseudo-transept; (c) cracks on the longitudinal sections.

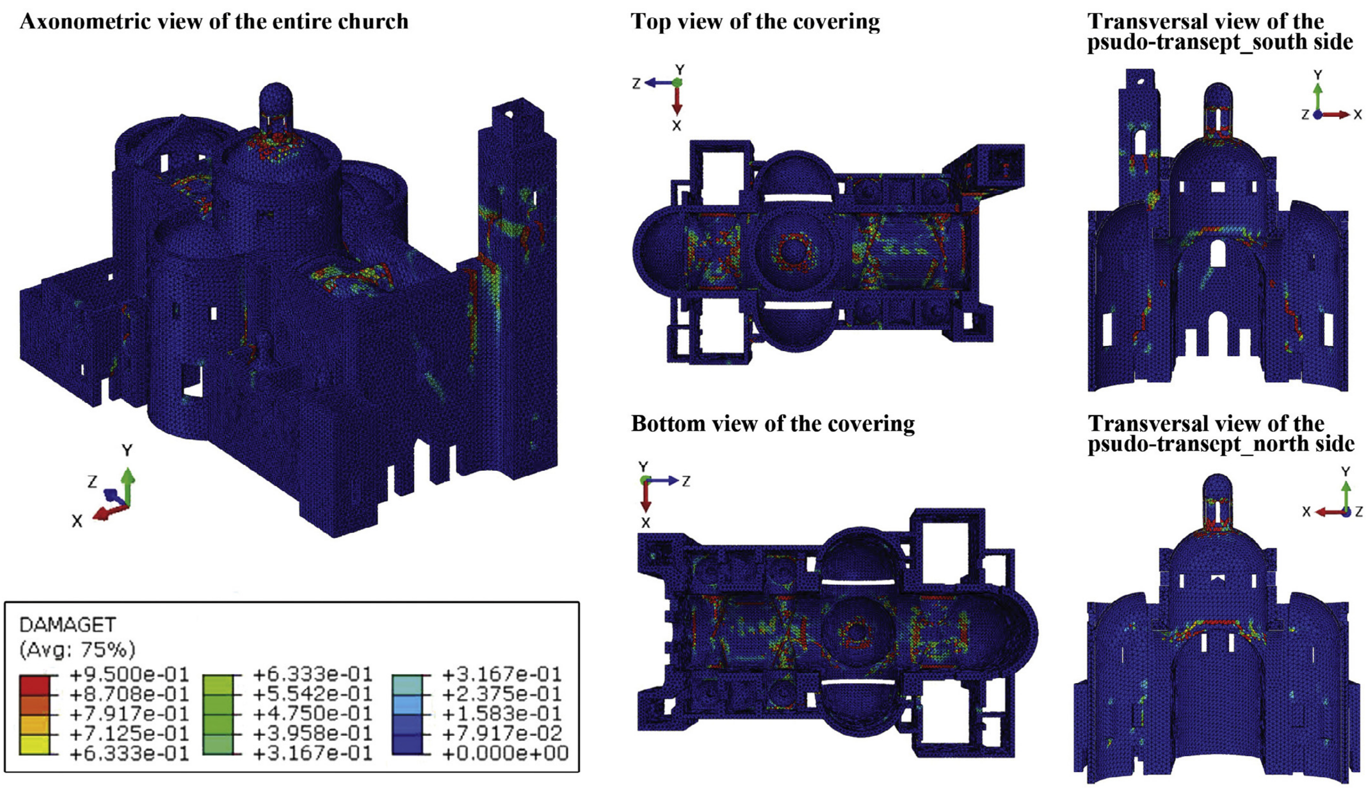

Fig. 8. Tensile damage contour plots obtained at the end of the non-linear dynamic analysis.

seismic analyses will be presented in a second part of the present work.

6. Conclusion

In this paper a multidisciplinary approach is used to obtain an accurate knowledge of a Baroque church designed by Antonio Luigi Galli da Bibiena in Villa Pasquali. Although this historical monument is not well-known, it can be considered, to the Authors knowledge, as an *unicum* in the international scene due to its complex system of perforated masonry vaults.

An historical survey was extremely useful for a better understanding of both the techniques used to build the church and the previous problems that involved the building. An important archival document, containing the description of the collapse of the central dome during the construction phase, gave important information on the quality of the materials used and on the aims of the complex system of tie-rods. A geometrical survey with TLS laser scanner allowed for a thorough knowledge of the geometry of the entire building and of the complex vaults system. The survey of the crack pattern revealed the presence of different types of cracks, pointing out the vulnerability of the church.

A detailed FE model of the church was developed and a preliminary classification and explanation of the crack pattern were provided by a gravity load analysis. Then, a non-linear dynamic analysis allowed a better understanding of the damage distribution detected in the church: some cracks observed in situ could be justified and the vulnerable parts of the structure were highlighted, confirming some intuitions derived from the results of the preliminary gravity load analysis.

Some future developments of the current work can be related to the following items: (i) a diagnostic investigation of the materials and techniques in order to better assess the masonry properties; (ii) a study on the possible causes related to the collapse of the dome during the construction phase; (iii) a more detailed and comprehensive numerical investigation for the seismic assessment of the church in its current state; (iv) a study of the possible strengthening interventions that can be carried out to increase the seismic safety of the church.

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