

# Remote sensing, archaeology and historical records: looking for 1624 earthquake traces in San Giorgio parish church of Argenta (Italy)

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## Abstract

The present work is part of a research program financed by INGV in order to look for traces of earthquakes occurred in the past on historical buildings. At that aim, a method based on remote sensing techniques was proposed and applied to San Giorgio parish church in Argenta (Ferrara, Italy). That church was chosen because of notable availability of historical and archaeological material, already catalogued in the past years, allowing the identification of structures belonging to periods before and after the 1624 earthquake. Data provided by terrestrial remote sensing techniques (digital photogrammetry supported by laser scanning) made possible the recognition of patterns that could be due to that strong seismic event or, in general, to one or more calamitous events. The results show that the proposed method can provide potentially useful data to help confirming or excluding historical hypotheses or helping to fill information gaps. However, it should be stressed that the proposed approach does not enable the identification of unknown seismic events, providing instead data that can be associated with already known events.

Keywords: Architectural Heritage; Earthquake-induced deformations; Morphological analysis; SfM; Laser Scanning; Geometric Modeling

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## 1. Introduction

The present work is part of the “Ricerca Libera Rescue Project” ([www.ingv.it/ricerca/progetti-e-convenzioni/progetti](http://www.ingv.it/ricerca/progetti-e-convenzioni/progetti)), aimed at carrying out a morphological study of some ancient parish churches to recognize possible effects of earthquakes occurred in the past. The idea was born from the extensive experience acquired after the 2012 Emilia-Romagna earthquake, when a large number of ancient buildings in this region was damaged. The morphological analysis of the leaning towers of Bologna, the apse of the Nonantola abbey, the bell tower of Mirandola and the parish church of Cantalovo [Pesci et al., 2012; Pesci et al., 2013; Bonali et al., 2014] and others showed how the application of modern remote sensing techniques enabled the identification of patterns due to deformations induced by strong seismic events.

It is important to underline that the remote sensing survey of a historical building, if carried out with right and rigorous criteria, enables the detailed reconstruction of digital metric models from which a lot of information can be extracted. Morphological maps are of particular relevance among the obtained data. The morphological map of a wall shows the differences between the model (or the 3D point cloud) of a wall and its corresponding primitive, which is a plane in the case of a planar wall [Pesci et al. 2013]. Sometimes, an iterative re-computation of primitives carried out excluding the areas highlighted by higher differences, leading to more reliable morphological maps in some areas, is necessary. Moreover, there may be cases in which the morphological maps are obtained by comparing the point cloud with a running cylinder or another mobile or variable primitive along a given direction, for example the vertical one in the case of a tower [Teza and Pesci, 2013]. Regardless of the method used, morphological maps enable the detection of everything that deviates from a condition of regularity. The method, together with its achievable precision and resolution, efficiency and adopted strategies, was presented in some papers [Pesci et al., 2013; Teza and Pesci, 2013; Bonali et al., 2014], demonstrating that the analysis of the identified patterns can provide information about the possible effects of earthquakes or other phenomena that acted on the studied structures. Furthermore, the morphological maps can be used to provide a detailed description of surface characteristics where differences with at least one third of the single point precision can be observed, i.e. a precision significantly better than the single point one can be achieved.

In this case study the morphological analysis is based on data provided by Structure-from-Motion digital photogrammetry (SfM), whereas terrestrial laser scanning (TLS) is a support for SfM surveys. The SfM data processing provides a 3D point cloud with RGB color information, starting from a large number of overlapped images taken moving around the object of interest. A truly usable point cloud (or a product obtained from the point cloud, e.g. a 3D model) must be metric and defined in a suitable reference frame. To obtain that, different approaches can be used: indirect georeferencing (IG), based on several ground control points (GCPs) acquired with topographical techniques [Eltner et al., 2016]; direct georeferencing (DG), typically used in drone-based SfM surveys, where position and altitude of the camera are acquired for each taken image [Zhang et al., 2019]; combination of IG and DG [Salas et al., 2022]. If the only need is to have a metric point cloud, the photogrammetric model can be scaled in post-processing stage by means of the polyline method [Pesci et al., 2019; Pesci et al., 2020; Pesci et al., 2024]. This method requires the availability of independent data about the length of some polylines connecting features recognizable in the SfM point cloud. To implement the polyline method, a reference TLS survey can be used.

As already stated, the morphological analysis was initially proposed to search for the effects of ongoing or recently concluded earthquake swarms on historical masonry buildings. This suggests the idea of applying the same analysis to identify traces of earthquakes (or other strong disasters capable of deforming the structure) occurred centuries ago, a kind of study which, besides being interesting for historical studies, could be also used to plan and implement adequate projects for the protection of architectural cultural heritage.

In order to test the idea, the San Giorgio parish church of Argenta (Ferrara Province, Northern Italy) was chosen because it is a very ancient building which, despite several reconstruction and renovation works, still contains many original parts and, therefore, seemed to be a good case study for the recognition of traces of strong seismic and climatic events over the centuries. The church was built in the sixth century and was extensively investigated in the past. A large amount of historical documentation, including the results of archeological excavations, is available and provides a lot of information describing the conditions of the church, its use, the phases of abandonment, the renovations, the changes and the deterioration problems along the centuries [Bertoldi, 1783; Brunetti, 1992; Gelichi, 1992]. The building was probably damaged by several natural events, including a 5.5 magnitude earthquake occurred in 1624. Most likely the destructive consequences of this earthquake had such a significant impact on the nearby city of Argenta as to divert attention from the parish church and, as a result, there is a sort of information gap on the conditions of this building. Although the church damages are not clearly and directly mentioned in historical reports, an earthquake of that magnitude is expected to cause significant damage or at least to left traces that could currently be detectable. In order to try to recognize this kind of traces, SfM was used to provide the 3D models, integrated with the results of a TLS survey to obtain the correct scale factor for the model registration into a metrical reference frame. Those models were inspected, analyzed and interpreted on the basis of historical sources with a methodological approach that can be applied to other ancient buildings.

## 2. Historical and archaeological data in geological framework

The San Giorgio parish church is located in Northern Italy, a few kilometers from Argenta, a small town in Emilia-Romagna, not far from the sea (Figure 1). The Emilia-Romagna plain, in which Argenta is located, is the result of the filling of the Padano Perisutural Basin, a vast depression delimited by the Apennine and Alpine reliefs, which occurred through a powerful accumulation of marine and alluvial deposits from the Pliocene and Quaternary ages [Pieri and Groppi, 1981; Livani et al., 2023]. The subsoil of the municipal territory of Argenta is made up of non-lithified alluvial and deltaic plain sediments with a thickness of several hundred meters. There is no clear contact between rigid rock units and the loose covering deposits. Subsurface units are characterized by a gradual, spatially non-uniform increase in stiffness due to non-deposition surfaces and stratigraphic unconformities. There is therefore no real solid bedrock. However, the transition between the Continental Quaternary and Marine Quaternary deposits corresponds to a surface below which the presence of seismic bedrock can be defined. As a consequence of these geological-geomorphological factors, the conformation of the territory is suitable for seismic wave amplification [Mascandola et al., 2021]. In particular, the local seismic amplification factor, expressed in terms of surface acceleration/seismic bedrock acceleration transfer function, can reach 1.7 in the territory of Argenta [Sgattoni and Brunaldi, 2011]. In addition, in case of earthquake, soil liquefaction is likely to occur because of an aquifer close to the ground and topsoil with prevalence of sand, as often happens in the Emilia-Romagna plain [Caputo and Papathanasiou, 2012; Caracciolo et al., 2012]. More specifically, the issue of liquefaction in the central region of the Po Valley, including an area near Ferrara, is discussed by Norini et al. [2021] who observed that, proceeding from West to East, and therefore approaching Argenta, the liquefaction susceptibility increases. On the other hand, it is well known that holocene fluvial deposits may suffer liquefaction due to seismic shaking generated by Apennine seismogenic faults and the seismic microzonation map of Argenta municipality shows that in the area near the San Giorgio parish church the Liquefaction Potential Index  $I_L$  can reach a value as large as 10 [Caleffi et al., 2021]. Thus, even earthquakes of relatively modest magnitude are expected to cause significant damage.

The interaction between the environment and human settlements in the area located east of Ferrara in Roman and subsequent times is discussed in Stefani and Zuppiroli [2010]. In particular, these authors highlighted that Argenta was founded in Early Medieval age on the northern levee of the new Po di Primaro channel, along the pathway towards Ravenna, at the same time of the abandonment of the majority of the Roman settlements, which were often buried by fluvial and marsh sediments.

This section summarizes the main results obtained by [Gelichi, 1992], who reported in detail the history of the parish church and the studies on the phases of use and change over the centuries, from construction to its state of



**Figure 1.** San Giorgio parish church location in Argenta (Ferrara, Italy) area.

abandonment. That study was carried out collecting and analyzing a large number of historical documents, as well as the results of archaeological campaigns and excavations carried out by himself, Bertoldi [1783] and Vandini (second half of the 1800s). A detailed description of the history of the San Giorgio church is provided in the Appendix.

Historical documents and archaeological excavations revealed a pre-existing paleo-Christian church which remains still partially exist beneath the north-eastern part of the current church. It had a single nave and a mosaic floor, and the collapse of its northern side was probably due to ground instability or other catastrophic events. The apse, which was the eastern part of the church in accordance with the liturgical orientation, had pentagonal plan. Over the centuries, the church has undergone phases of intense use, abandonment, major renovation and conservation works. In particular, in the 12<sup>th</sup> century it was deeply changed by the addition of two lateral aisles and the raising of the building. In the 16<sup>th</sup> century, the deterioration conditions became extreme: the naves were broken down and the church was restored to its original form (as at present).

The 1624 earthquake caused huge destruction in Argenta and in the neighboring areas as effect of seismic shaking and consequent internal tsunami and soil liquefaction phenomena [Caracciolo et al., 2012]. Although its magnitude derived from geophysical information and historical documents was not very large (estimated moment magnitude), the earthquake destroyed a large number of buildings, many houses became uninhabitable and the remaining ones were seriously damaged and unsafe. In 1699 the very bad conditions of the parish church were well known and almost one century later, in 1756, the church was flooded by swamp waters. In 1770 a fire destroyed the roof and the caretaker's house.

The main deductions of Gelichi [1992] are: (i) the discontinuity between the original mosaic floor of the central nave and the topsoil and lime mixture in the aisles-area ground; (ii) the floor slope, with a difference in height, from north to south, of almost 30 cm; (iii) the ancient level of the ground  $\sim 2.5$ -3 m lower; (iv) the remains of masonry structures, infill walls, steps and various anchorage elements suggesting the presence of ancient lodgings and houses set against the church; (v) the sequences of trampled and untrodden levels testifying a series of use and abandonment and the sand and clay layer thickness also suggest tidal and flood phenomena; and (vi) historical notes attest that the church was in use in 1624. Excavations data confirm information from historical documents.

Despite the large amount of available data, there is an information gap concerning the impact of the 1624 earthquake and its direct and indirect effects on the church. The gap is due to the lack of historical documents which have likely been badly preserved and as a consequence lost during the centuries. However, it is worthwhile to note that the church is not mentioned at all between 1624 and 1699, year in which historical documents show that it was be unusable. On the other hand, it is important to underline that for all the periods in which the church was in use there is some written document that directly or indirectly alludes to its actual use. Trying to fill this lack of information, SfM and, as a support technique, TLS were used to study the building walls and their main elements by means of the morphological analysis described in [Pesci et al., 2013]. In particular, finding a deformation pattern likely to be due to the earthquake would imply that the documented bad conditions of the church in 1699 might have arisen from a period of abandon and inactivity of the church as a consequence of the seismic event. However, it must be stressed that a period of non-use does not necessarily imply major structural failures, but could be due to a damage that would compromise its use and, moreover, it is reasonable to assume the lacking of a collapse because, if that were the case, the church would probably have been demolished.

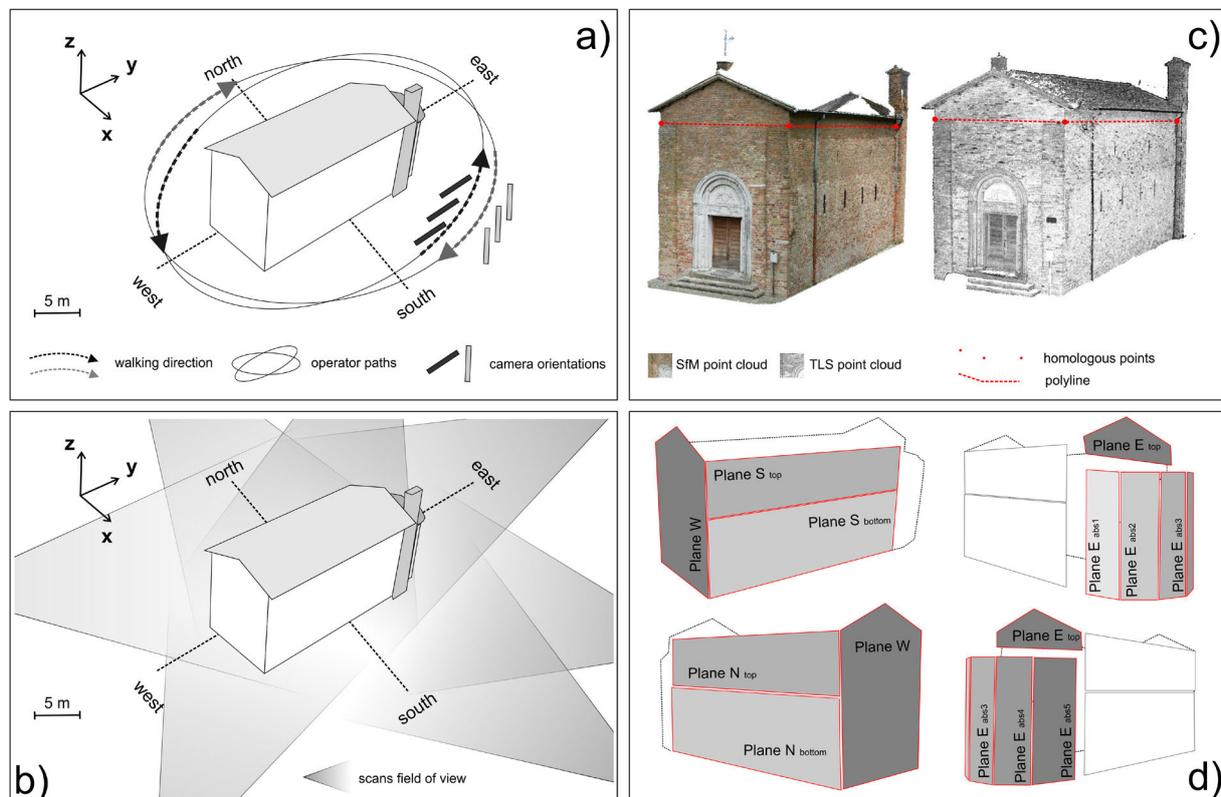
### 3. Remote Sensing Surveys

A survey was carried out by means of SfM, which is a remote sensing technique characterized by highly automated modeling thanks to very efficient algorithms for image registration and iterative bundle adjustment [Granshaw and Fraser, 2015, Remondino et al., 2014]. SfM is currently used in both geological/geomorphological and architectural surveying [Brunier et al., 2016, Mistretta et al., 2019]. Precision and resolution achievable in geometrical modeling of buildings also enables to perform accurate morphological analysis of planar, circular or other shaped building walls [Teza et al., 2016]. The results of SfM data processing was a 3D point cloud with RGB color information. A TLS survey was also carried out in order to verify, integrate and provide the metric to the SfM-based model by means of the polyline method described in Pesci et al. [2019].

The main technical data of the used equipment (a Nikon D3300 prosumer camera and an Optech ILRIS-3D TLS instrument) are summarized in Table 1. Figure 2 describes surveys and procedure. About 170 images were taken walking twice around the church perimeter and, for each walk, the incidence angle of the main camera's pointing

direction with respect to the observed surface was kept a little tilted to optimize rendering in image processing. The photogrammetric modeling was carried out by means of Agisoft Metashape package (<https://www.agisoft.com/>). The chosen image alignment option was “high accuracy”, i.e. full-size and no subsampled images were used. The chosen option for the dense point cloud generation was “high”, meaning that also in this case full-size images were used. It should be noted that lighting conditions (in particular, their quasi-invariance during the survey), exposure times, camera sensor, number of images (in particular, image overlap), acquisition distances and directions are determining factors in generating a good point cloud.

The TLS scans were acquired from 7 stationing points around the church with highly overlapped zones and were aligned providing a single oversampled 3D point cloud. It should be stressed that although the TLS instrument is quite dated, its calibration certificate is still valid and its precision and resolution are comparable to the ones of more recent instruments. Its only weakness relates to the sampling speed. Table 2 summarizes the main settings of the survey.



**Figure 2.** SfM and TLS surveys: (a) SfM survey scheme: operator paths around the church and camera-target observation angles; (b) TLS survey scheme: seven stationing points and corresponding field of view; (c) SfM and TLS point clouds scaling: the red line is a polyline obtained connecting 3 homologous points and its length (20.45 m) is used to provide the metric for the SfM point cloud; (d) scheme of primitive selection.

Photogrammetry	
Camera	Nikon D3300
Focal length	18-35 mm
Crop Factor	1.5
Sensor n.pixel	6000 × 4000
Senzor Size	23.5 × 15.6 mm
Pixel Size	0.0039 mm
Aperture	f/8
Sensibility	400 ISO
Laser Scanning	
Instrument	Optech ILRIS 3D
Wavelength	1535 nm
Laser class	1M
Sampling frequency	2.5 kHz
Field of view	40° × 40°
Operational range	5 – 1500 m
Rangefinder accuracy	7 mm (100 m range)
Spot size	20.5 mm (100 m range)
Spot spacing	2 mm (100 m range)

Table 1. Instrument parameters.

SfM surveying	
N°. images	168
Focal	30 mm
Exposition	1/320 s
Mean GSD	2 mm
Mean distance	8 m
Tie points	62250
Mean overlapping	> 80%
Covered area	154 m <sup>2</sup>
TLS surveying	
N° scans	7
Mean points/scan	1.5 M
Mean distance	20 m
Mean resolution	4 mm
Mean overlapping	> 70%
Alignment error	1 mm

Table 2. Surveying main settings.

## 4. Data Analysis

The point clouds obtained by SfM and TLS were analyzed according to a procedure based on reference primitives. For each main element of the church, i.e. façade, sides and apse, one or two reference planes (for the apse, which has pentagonal-like shape, five reference planes) were generated by data fitting on the specific area. The reference plane (or primitive) is a mathematical representation, at least at local level, of each building element; this primitive is assumed to represent the element in its unperturbed form. Since an ancient building is affected, over the time, by alterations of different types and origins, the current shapes of its façade, walls and apse are highly affected by deterioration, deformation and alteration and could have been heavily remodeled. Possible surface irregularities and patterns in the local arrangement of the point cloud due to anthropic activities, deformation and/or deterioration can be easily recognized in the morphological map, i.e. the map of differences between the local point cloud and the corresponding primitive. That approach was proved to be very useful in the study of structures deformed by an earthquake [Pesci et al., 2013]. Obviously, in case of a cylindrical apse or, more in general, of a structure with a circular section, the primitive must be chosen accordingly and a moving/changing primitive approach could be necessary [Teza et al., 2013].

The morphological maps are shown in Figure 3, whereas the corresponding main data about the reference planes are summarized in Table 3, where the plane positions are expressed in terms of normal angles in the reference frame defined in accordance with the cardinal directions depicted in Figure 2. Figure 3 also shows examples of typical rupture schemes due to seismic shaking. It should be noted that the corresponding expected features generally concern large portions of walls or entire architectural elements. The primitive related to the façade, West (W) side, was obtained interpolating all the points with the exception of pilasters, portal and steps. The North (N) side wall was described by means of two reference planes; the first representing the lower part and the second the upper one. The East (E) side, i.e. the pentagonal apse, was approximated by five different reference planes. The South (S) side, like the N one, was described by two planes.

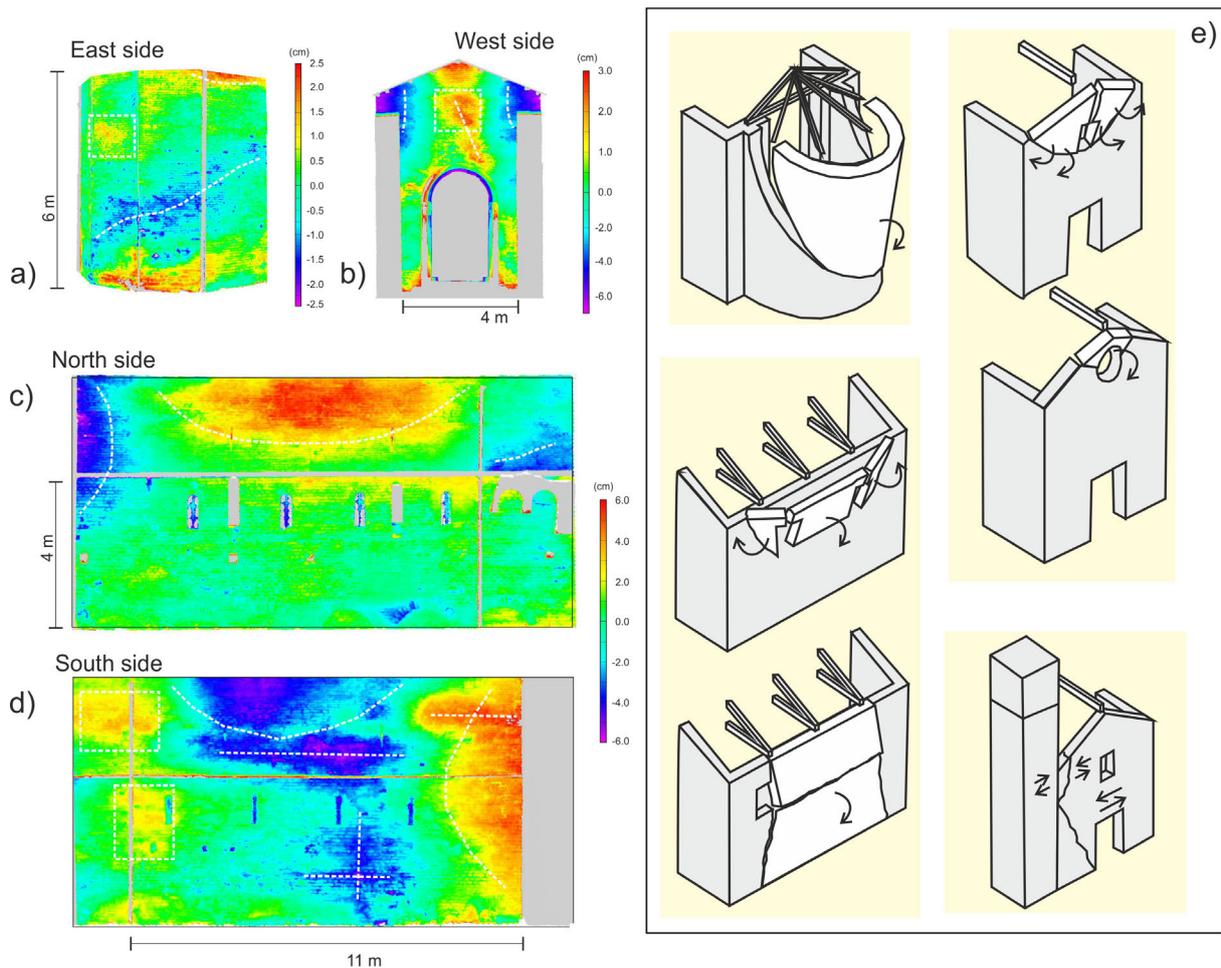
An inspection of the morphological maps reveals several interesting evidences listed below in a clockwise order, going from W to S side:

- 1) The building façade (W side) shows a fairly regular arrangement with negative residues in the upper part (on top of the pilasters) and positive ones in the central part (from the portal top to the roof). The differences range is  $[-7 \text{ cm}, +3 \text{ cm}]$ , where negative values imply inwards displacement, and positive outwards;

Primitives	Points (K-number)	Fit RMS (mm)	Normal angles ( $\alpha_x, \alpha_y, \alpha_z$ )
Plane N (bottom)	828	7	179.6° 90.3° 90.4°
Plane N (top)	537	24	179.6° 89.8° 90.4°
Plane S (bottom)	941	19	0.9° 90.6° 89.4°
Plane S (top)	663	26	0.7° 90.7° 90.2°
Plane W (façade)	295	12	90.2° 178.6° 91.4°
Five planes E (apse)	203	14	15.0° 75.0° 89.5°
	240	5	52.8° 37.2° 89.9°
	156	9	88.4° 1.6° 89.8°
	219	8	126.3° 36.3° 89.8°
	228	6	162.4° 72.4° 89.9°

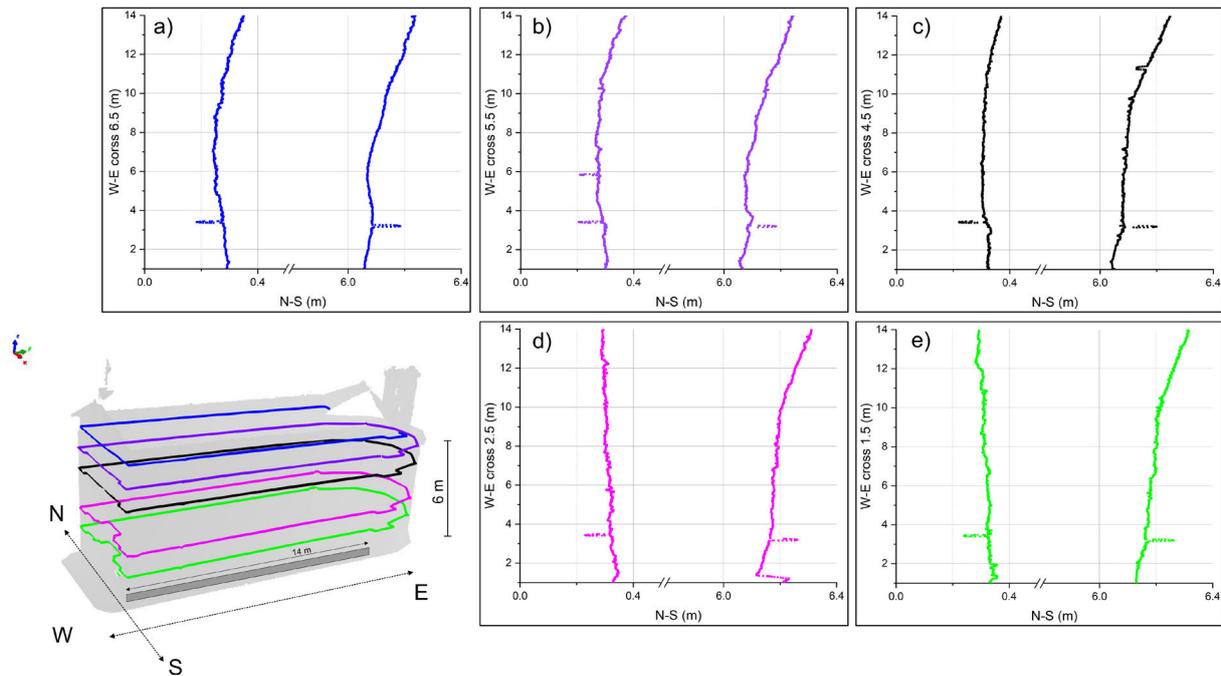
**Table 3.** Primitive and fit description.

- 2) The N wall shows an evident bulge-like rounded shape in the highest part which affects about half of the surface analyzed and, on the vertical edges, especially near to the E one, there is a significant indentation which extends for more than half of the wall side length. In both cases differences are large, amounting to +6 cm and -6 cm respectively;
- 3) The apse (E side) shows an interesting pattern characterized by negative differences that seems to cut the entire element diagonally. As a whole, the differences in the apse range from -2 cm to +3 cm;
- 4) The S side shows a concave arrangement in its highest part involving almost the entire surface. Moreover, in the eastward part of the wall there is a protrusion pattern extending along the whole height. Differences in this side are in the range  $\pm 6$  cm.



**Figure 3.** Morphological maps: (a) apse (E side); (b) façade (W side); (c) and (d) walls (N and S sides, note the different primitive planes for lower and upper part of each wall); (e) examples of typical rupture schemes due to seismic shaking. White dash lines indicate discontinuities areas.

The horizontal cross sections taken at some heights (from 1.5 m to 6.5 m above the current ground level) provide additional interesting information. In particular, Figure 4 shows that the cross sections of the N and S walls highlight a very irregular shape. Interestingly, that confirms the evidences from the analysis of the morphological maps. However, it should be underlined that the morphological maps derive from the comparison of the point cloud with the local primitives, describing a relatively setting (deformation), while the cross sections are relative to the entire point cloud. The obtained results are therefore consistent with each other.



**Figure 4.** Cross sections at different heights from the ground: (a) 6.5 m; (b) 5.5 m; (c) 4.5 m; (d) 2.5 m; (e) 1.5 m. The  $x$  and  $y$  scales are intentionally not proportional in order to highlight the side shapes into a common reference frame.

## 5. Data interpretation and discussion

Before discussing the data interpretation, it is appropriate to briefly summarize the known historical and geological information. First, the earthquake occurred on March 19<sup>th</sup>, 1624 ( $M_w = 5.5$ ) destroyed many buildings in Argenta, including medieval walls and seismic swarms affected the area since October 1623, as foreshocks for the main event which epicenter was immediately north of the town. Second, in ancient times, up to the 17<sup>th</sup> century, a large marshy area, called Valle Padusa and characterized by ponds and islets of various dimensions, was extended from the Po Delta to Argenta and beyond. Third, the geological-geomorphological conformation of the territory is suitable for seismic wave amplification and soil liquefaction because of the existence of an aquifer close to the ground and topsoil with prevalence of sand.

These factors make San Giorgio of Argenta church particularly well-suited for the application of morphological analysis, which was developed in order to evaluate seismic-induced surface deformations of architectural structures in emergency conditions [Pesci et al., 2013], to identify patterns due to past earthquakes that shook historical buildings. The strength of morphological analysis is the capability of recognizing patterns in structures due to anthropic and/or natural stress. Archaeological excavations rarely enable identification of seismic and/or coseismic effects, but together with historical documentation can provide useful information about the life stages of a building along the time, including type of use, restoration works changes to the structure, and so on.

Both morphological maps (Figure 3) and cross sections (Figure 4) show that a large part of the church walls is affected by distortions of natural and anthropic nature, making possible to observe/isolate a seismic effect, if existing, on the basis of the expected rupture scheme.

Considering the available historical/archaeological information and the evidence of the sloping original floor, the following statements can be derived:

- The N and S sides show large irregularities; in particular, a bulge on the N side and a depression on the opposite side are clearly visible and have similar values. Those patterns, for shape and extension, resemble the ones which are typical of structures reacting to seismic solicitations. Dashes in Figure 3 underline the main discontinuities from positive to negative values on the building walls. Even assuming that restoration works might have been well made, the obtained evidences agree, or at least do not disagree, with the typical rupture schemes;
- The asymmetry between the N outward bulge and the recessing on the S one, together with the large size of the deformed areas, suggest that the current cumulative deformation of the building has an arched shape with

respect to the upper parts and an altered conformation, if compared to the original ancient one. The cross sections confirm this evidence (Figure 4);

- The apse shows a clear linear deformation of about 6 m length that cuts it obliquely. No fractures are visible in the external walls and no restoration materials can be seen. The deformation might be related to the typical rupture mechanism described in [Doglioni, 2000] and was also observed in the Cantalovo church, which was damaged by the 2012 Emilia-Romagna earthquake [Bonali et al., 2014].

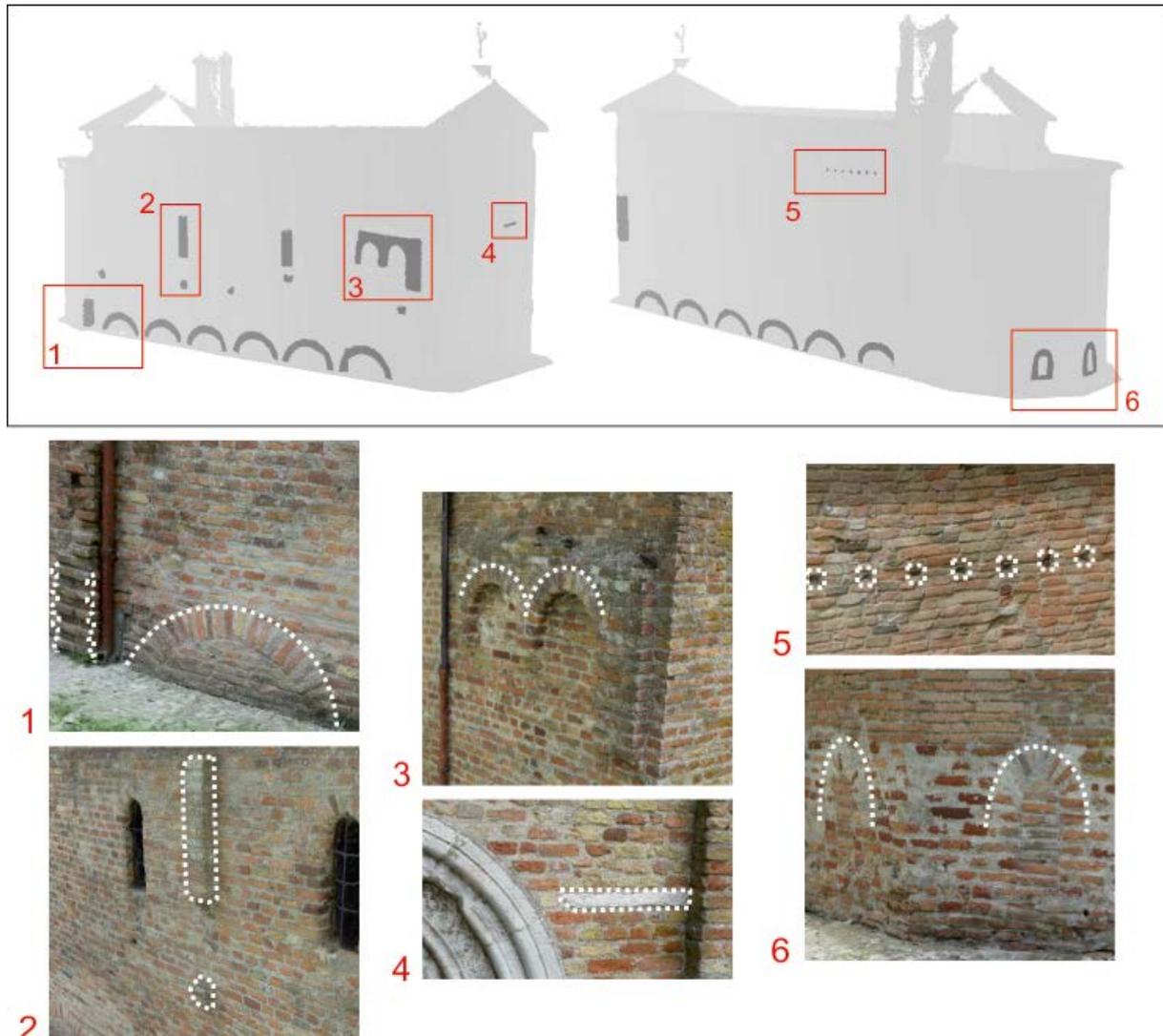
The above listed deformation patterns might have resulted from an earthquake which is likely to have been the one occurred in 1624. The statement is in contrast with the commonly belief based on historical knowledge indicating the 5.5 magnitude earthquake of November 1570 (with epicenter in Ferrara) as a huge disaster. However, although the 1570 event destroyed half Ferrara city and permanently damaged a large part of its buildings, historical documents report that in Argenta it did not cause significant damage, so that the corresponding estimated Mercalli-Conconi-Sieberg (MCS) intensity is V-VI (Strong Earthquake Catalogue, <https://storing.ingv.it/cfti/cfti5>).

The church was also affected by other natural disaster. Effects of floods and inundations were detected as archeological excavations were carried out, even if it is very difficult to date them. The subsoil shows layers of clay and sand evidently due to these phenomena. Some layers seem to be compacted by trampling and this was interpreted by archaeologists as an indication of the use of the church after the phenomena. Other layers seem to have remained untouched, which could indicate that the above-mentioned phenomena precluded the access to the church. However, the main consideration supporting the hypothesis that morphological maps very likely show earthquake effects, is the extension of the observed alterations which take entire walls, the entire apse, and other large architectural elements (see e.g. Figure 3e). Clearly, this cannot be affirmed with certainty, even if a the hypothesis can be considered well founded.

Besides the described deformation patterns, other interesting features, mainly due to rebuilding and renovation stages, can be seen in Figure 3. Arches, infill walls, holes for the coverings of the naves, pilasters, remnants of ancient windows, discontinuities for reconstructed areas, and wall textures are clearly visible and by means of photographic images, colored point clouds and texturized models can be resolved to about 2 mm. The macro elements that have been recognized from both geometrical patterns and RGB information of the point cloud (Figure 5) are listed below:

- N side. In the lower part, up to the height of 1 m, ancient filled arches are present (element 1 in Figure 5); at about 2 m height some support elements (possibly for the roof beams of the naves) are evident (element 2); at 4 m height, a macro discontinuity separates the main wall from the raised one; in the apical part, throughout the horizontal band, the discontinuity due to a second rise below the roof can be observed; the decorative arches extend towards the W edge (element 3);
- Façade (W side). On top of the portal there is a central part resulting from a mixture of bricks belonging to various periods and arranged in filling patches; a horizontal marble element, positioned on the right of the portal, indicates a discontinuity remnant, probably related to the previous height of the church (element 4). The morphological map highlights that it corresponds to an oblique arrangement of the portal marble decoration on the façade;
- S side. Some areas showing out-of-scale values and regular geometric aspect suggest either a past presence of windows or doors, or possible residues of removed items. The row of holes (element 5), for example, might have been the supports of covering elements;
- Apse (E side). Ancient windows (elements 6) can be identified in the lower part together with some positive anomalies just below the roof (see Figure 3).

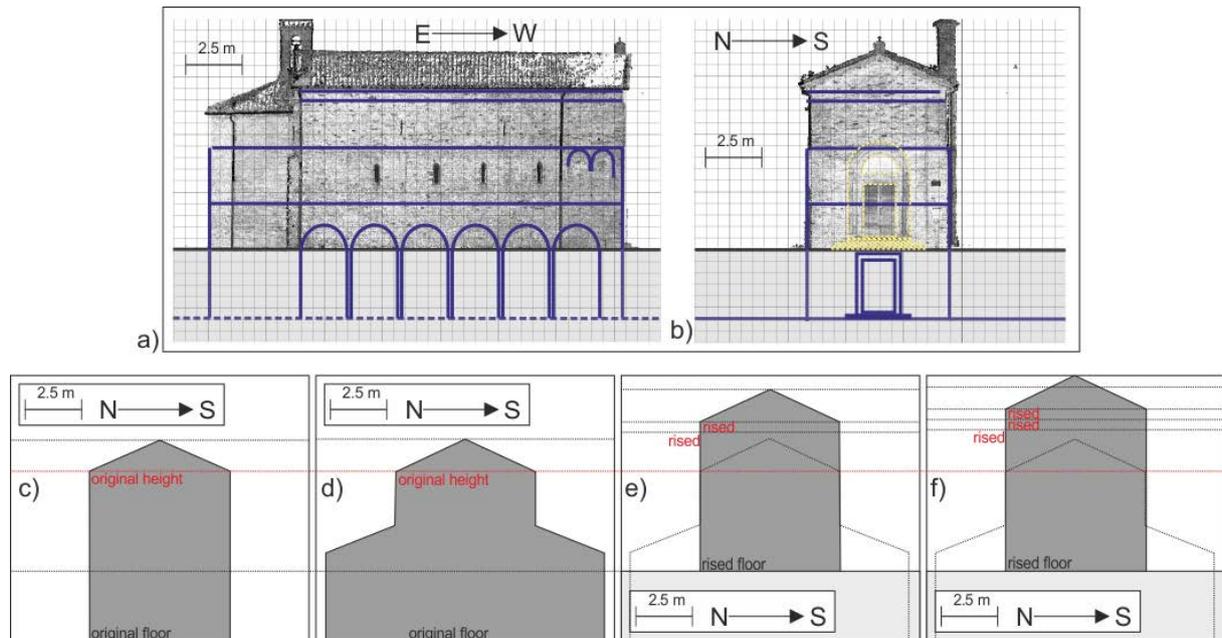
The present study, based on morphological analysis and evaluation of the macro elements in a common reference frame carried out on remote sensing data, historical information on the restoration works, direct observations of the church and archaeological data on buried remains, enables formulation of a hypothesis about the main changes which led to the present shape of the church (Figure 6). The height of the ancient arches (4 m at the arch top, now 1 m from the ground) provides a strong constraint on floor location and the height of the previous church is inferred by architectural elements and pattern discontinuities. In particular, the changes in ground levels, described by the stratigraphic analysis, reveal the occurrence of flood events, with consequent material deposition in thick layers, because of which the church had to be raised up.



**Figure 5.** Some details from pictures and digital models selected from point clouds: 1) arches and connecting elements; 2) remains of columns and support elements; 3) double decorative arches typical of the apical areas of the walls; 4) element of discontinuity at the same height as the double arch on the façade, witnessing the height of the previous church; 5) holes for the possible insertion of covering elements, such as the roof of a rectory; 6) ancient arches/windows in the apse area.

However, it must be stressed that although being reasonable and probable, the hypothesis remains a hypothesis, which needs to be confirmed. The present work has shown that the remote sensing techniques can be fruitfully applied to the classical cultural heritage studies to fill the unavoidable gaps due to the poorness of historical and archaeological information on long periods of time.

The study presented here focuses on the morphological analysis, the recognition and interpretation of the features and the stratigraphy of the walls of the examined church, a kind of approach reminding the techniques now in use in the archeology of standing buildings [see e.g. Fiorini, 2016]. Recent developments of 2D building archeology analysis move towards Historic Building Information Modeling (HBIM) environment, which has an intrinsically 3D nature [Stanga, 2023]. A 3D digital model can also be textured with the information inherent to the morphological analysis and, furthermore, any recognized features (e.g. fractures, traces of removed or modified architectural elements, etc) can be added to it. Therefore, in perspective the obtained results could be included in the HBIM workflow to provide a complete model of a historical building.



**Figure 6.** Hypothesis on phases of the past church life: (a) and (b) N side and façade point clouds on which the scheme of ancient states is overlapped. Schematic representation of the main changes in a common scale from a WE sight direction: (c) original shape (6<sup>th</sup> century); (d) enlargement with naves (16<sup>th</sup> century); (e) naves demolition and rising (17<sup>th</sup> century); (f) present day setting. The thick blue curves and lines outline the boundaries of the church in the various eras, while the yellow dashes indicate the nowadays elements to better observe the changes. The areas filled in light grey represent the subsoil once occupied by the parish church and filled up over the centuries.

## 6. Conclusions

The San Giorgio church in Argenta was studied in the frame of a research project aimed at searching for earthquake-related deformation patterns on ancient buildings. The church appeared to be suitable for an accurate analysis due to its small size, good location in an area free from obstacles and availability of historical/archaeological data. The morphological maps and cross sections revealed interesting patterns which are compatible with typical seismic-induced ruptures due to a relatively strong earthquake, likely to be the 1624 one for two reasons: it was the strongest seismic event in the Argenta area and historical documents refer about the church activity up to that time, followed by a long period of abandonment. However, it is important to underline that the proposed interpretation of morphological maps, although reasonable in the cases of deformations extending to entire walls, does not offer certainties, but possible scenarios.

The proposed method can be applied to buildings which may have been hit by earthquakes that occurred in past centuries. In this way, provided that there is adequate information regarding the geology of the area, SfM can be a useful support for classical cultural heritage studies, both helping filling historical and archaeological gaps, and giving strength to the available ones on the basis of a quantitative analysis.

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