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THE "PIEVE DI SANTA MARIA" IN AREZZO (ITALY). FROM THE LASER SCANNER SURVEY TO THE KNOWLEDGE OF THE ARCHITECTURAL STRUCTURE

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Abstract. *The parish church of "Santa Maria" is considered one of the most important medieval buildings of Arezzo Although the church is attested from 11th century, it is between the 13th and 14th centuries that reached its current consistency, characterized by the particular façade with small columns on several levels and an imposing bell tower. Later, from the 16th to the 18th century, the church underwent profound transformations, that were almost completely erased by extensive restoration works in the second half of the 19th century.*

The architectural survey of the parish church of "Santa Maria" was carried out with a phase-shift laser scanner and a digital reflex camera (Z+F 5006h). 189 scans were performed for generating the 3D model of the church: 180 of them with high density and normal quality, lasting 5-6 minutes; the remaining ones with super high density and high quality, lasting 13-14 minutes. Vectorial drawings of plans and sections were then created from the 3D model.

Thanks to laser scanner survay of the chuch, it was possible to highlight the singularity of the structure of the basilical body and the transept. The tilt of walls and columns, the variations in the thickness of the walls, the considerable deformations of some arches, the cracks and textures of the wall facing were thus shown.

The information obtained attested an architectural structure created by complex construction events that over time have affected this building. The cnstructive singularities involve the medieval genesis of the building, the transformations during the following centuries and the following restoration works.

These composite features are specific and common to every ancient building. This peculiar epistemological condition eschews from simplifications and requires deep and complex studies closely linked to the problems of conservation of the structures.

1 INTRODUCTION

On the origin of the "Pieve" a fragmentary documentation is avaiable, such as the date of the foundation in 1009. Thus the dating of sculptural works in the church takes on particular relevance. The bas-relief of the Assumption in the central portal of the facade is dated to 1216; a further date 1221 is engraved in the lunette of the right portal. The extremely significant sculptures which represent the Months in the vault in front of the main entrance portal are dated to the thirties and forties of the XIIIth century[1]. It is believed that, except the bell tower and the presbytery completed around 1330[2], the construction of the church, including the entire external facade with the three levels of overlapping loggias, were completed around 1250.

The medieval structure, built through complex construction phases, is only a part of the history of the church, which was subsequently subject to further incisive changes. The structures today constitute a palimpsest very difficult to understand in its own varied formation.

In this article the understanding problem of the structural peculiarities is faced by integrating the historical sources with information obtained from laser scanner survey, using the 3D model to obtain useful plans and sections.

2 CHANGES TO THE BUILDING FROM XVITH CENTURY

From the XVIth century, significant transformations began with the aim of modernising the church. Among those that have had the greatest impact in the consistency of the structures, we can mention the opening of new windows and the expansion of others existing at that time. Furthermore the floor was raised, the crypt destroyed and new vaults were built[3]. Cristofano Conti's drawings, executed at the end of the XVIIIth century[4], document the naves of the Pieve covered by barrel vaults.

In the first half of the XVIIth century, a series of expert reports regarding the static instability of the Pieve began, and some interventions to the structures followed[5]. The engineer Francesco Nave in 1649 was first called. He removed the spandrel of the vaults and recommended the partial demolition of the drum to reduce the load on the arches of the crossing; he provided the crossing with a new roof and by ties made the structure reinforced. The work of Nave was not considered satisfactory, so in 1657 an opinion was asked to the engineer Francesco Valle, who carried out supports for the wall on via della Seteria and infilled the openings of three shops of the same side[6].

In the second half of XIXth century extensive restoration works of the church erased all the modifications deemed later of the medieval construction. It was a very common restoration methodologies at the time and persistent even in the following decades. In some cases it affected entire ancient towns[7]; in the Pieve extensive reconstruction of both wall facings and entire walls were involved; the crypt was built with a new design[8].

3 THE LASER SCANNER SURVEY OF THE PARISH CHURCH

Current survey methodologies of historical building heritage, exploiting massive geometric data captured by laser scanning or 3D Imaging techniques, rise many procedural questions about the treatment of these data in the various processing stages of the historical architecture knowledge[9].

In recent years, in fact, Geomatics have developed many measuring instruments characterized by high portability, ease of use, speed and precision in capturing. The outcome of an acquisition process carried out with these tools is represented by a point cloud, which provides a digital model of the building. It essentially consists of a dataset of geospatial coordinates, corresponding to as many points on the building surface, whose number depends on the acquisition density established in the instrumental setting phase. Then dedicated management software operate automated registration procedures of the various point clouds. The reliability of the obtained datasets is very high, in relation to the geometric accuracy generally required in the subsequent multidisciplinary analyzes to be carried out on the historic building.

However, the extraction of a "significant" geometry from massive data, useful for developing knowledge deepening phases, frequently proves to be a complex challenge. The outcome in uncertain, if not adequately oriented to the purposes[10].

In fact the vector mapping procedures require a huge activity of recognition of planes, surfaces, volumes, primitive or complex geometric shapes on the 3D point cloud; despite the recent automated procedures development, it is essentially based on manual editing. So the quality of the 2D/3D implementation depends not only on the appropriate choice of approximation algorithms, but also and not secondarily on the operator's ability to interpret the captured data. Every adopted simplification in the digital building implementation processes leads to a "modeling error"[11], which is always greater than the uncertainty owned by the raw data contained in the point cloud. The control of this deviation must be managed through a specific planning by preparing appropriate validation procedures of the modeled data.

This problem assumes considerable importance in the field of Building Information Modeling (BIM) techniques, because the digital model reliability does not lie exclusively in the degree of its geometric convergence with the physical artifact. The overall information content qualifies the "level of development" (LOD) of the BIM model[12] and the geometric accuracy is only one of the many parameters to be considered.

3.1 Data capture: the 3D model of the parish church of "Santa Maria"

The knowledge project of the parish church of "Santa Maria" in Arezzo intended to test a capture and implementation process of geometric data, divided into different study stages. It was aimed at interpreting the structural singularities of the basilica body, through the identification of a management workflow of geospatial datasets collected in geometric and informative outputs consistent with the research objectives.

In particular the point cloud has generated different exploration possibilities of the digital model, from which multiple 2D/3D implementations have been derived and focused on specific aspects of the building geometric configuration.

The use of digital scanning technology for three-dimensional surveying has had a significant development in the last decade. Taking advantage of the speed of light propagation and the reflective capacities of the materials, the laser scanner allows to capture in a very short time the spatial coordinates of millions of points[13].

Although the remote sensing technologies let us accomplish a large amount of measurements, the selection of points to be detected no longer takes place at the time of capturing, except the scanning grid; this is set more or less dense to be capable of grasping evident discontinuities and small deformations. The point cloud creates a sort of intermediate model between physical reality and graphic representation, in which building is broken down in spatial coordinates. Just later we can move selecting of the most significant points, discarding the redundant ones, and then define the 2D/3D geometric digital model. The undifferentiated set of captured points must undergo a processing procedure before extracting necessary information for the mathematical model implementation. The recognition of the primitive forms of the surveyed artifact represents one of the most critical but also interesting study phases; it is aimed to element classification, structural analysis and evolution in time of the building. In fact the point cloud conveniently processed makes available a massive data amount, which is useful to product graphics such as plants and elevations, but above all sections; these can have an accuracy and reliability much higher than those made through traditional techniques of survey.

However laser scanner technology has a series of inherent limitations, due to the way the geospatial point data are captured on the surface of the object. The laser ray must have a completely free rectilinear trajectory for reaching the point to be measured. Therefore any obstacle between the point and the laser source generates an information gap equivalent to the shadow projected by this obstacle on the object, the so called "occlusion space". The same morphological characteristics of the historic architecture (rich in details and irregular shapes) make the cited problem particularly complex in the data management phase. The need to carry out a high number of scans addressed to the same building area, for ensuring complete coverage, creates likewise a great redundancy of captured geospatial data.

A phase-shift laser scanner and a digital reflex camera were used to accomplish the survey project of the Parish Church of "Santa Maria", integrating where necessary with direct survey. The Z + F 5006h (Zoller+Fröhlich) laser scanner has a range of 79 m, a maximum speed of 1.000.000 points per second, a gripping angle of 360° horizontally and 310° vertically. The scanner is equipped with 5 acquisition presets, which correspond to as many levels of point cloud density: Preview, Middle, High, SuperHigh, UltraHigh.

One hundred and eighty nine scans were carried out over three days for generating a point cloud, which consisted of the whole geospatial data of the basilica body and the bell tower. The scans were recorded using Autodesk ReCap© software for assembling them together; they were used at least three targets located in the scene to shift and rotate the various point clouds, one on the other. Once the registration procedure was completed, the result was an only one point cloud with the complete 3D building model.

The file was saved in .rcp format to be imported for graphics production into the Autodesk Autocad© software, where it was possible to section the cloud with ideal plans at will and obtain screenshots. Then after setting the orthogonal UCS on the current section and the plan view, it was possible to outline the various profiles of interest of the building in wireframe and draw elevations, plans and sections.

The referred procedure allowed final drawings to reach the level of accuracy, decided upon the 1:50 scale at the start of the survey activities. The further detail required for representing moldings and architectural elements (1:20/10) was achieved by integrating the laser scanner survey with 3D Imaging techniques (digital photogrammetry and photo-modeling) with high resolution images from camera.

4 IDENTIFICATION OF DEFORMATIONS AND MODIFICATIONS OF THE STRUCTURES: AN APPROACH BASED ON THE 3D MODEL

The point cloud of the Pieve provides an almost unlimited possibility of extracting plans and sections. It is a very versatile tool both for studying structures and to obtain a rapid acquisition of information. In case of data processing does not require processing in autocad format, it is sufficient to perform sections by the 3D model.

The studied aspects of the church have concerned:

- the verticality and deformations of the pillars and walls;
- the conformation of the arches of the aisles;
- the configuration of the crossing structures.

4.1 The basilican body. Pillars, arches and walls

The inclination of the construction elements, walls and columns, has been verified by comparing plans carried out at different levels. The columns flanking the nave show diagonal displacements towards the outside, that have different magnitude in longitudinal and transversal directions (Figure 1).

On the side with three columns the inclinations towards the facade vary from 5 to 7 cm; starting from the facade, the external movement of the first two columns is small, 2/3 cm; it becomes about 10 in the column next to the cross, where the inclinations towards the outside have the greatest extent. The section across these columns shows a tilt under the thrust of the arches of the crossing, where not by chance the pillar is inclined about 6 cm towards them. In the opposite side of the crossing, the conspicuous wall of the facade, being an effective buttressing, has maintained the plumb position of the pillar.

It is noted that the greatest deformation have occurred in the two central arches. In the current construction, the crossing thrusts on a system of diaphragm arches that rests on the massive facade wall, and such deformation seems little justifiable.

This deformation could not even be attributed to the thrust of the barrel vaults which were added in the basilican body after the medieval period and then demolished by the restoration works. It could be hypothesised that the peculiar static conditions occuring in the construction works phases could have contributed to determine it; in many cases the static condition during and after the construction works are infact very different.

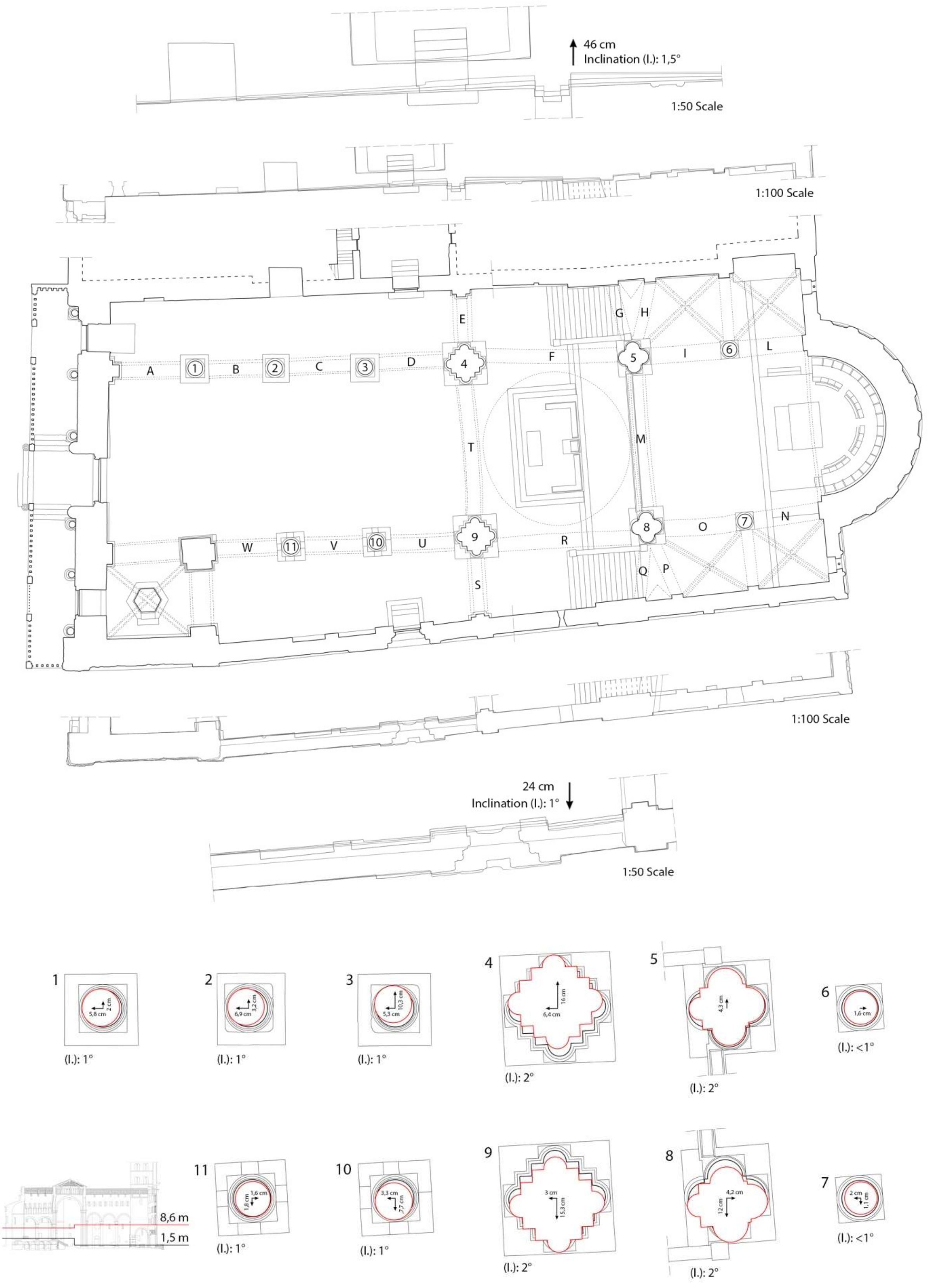

Figure 1: Plan of the church; we can see the maximun inclinations of the pillars and walls.

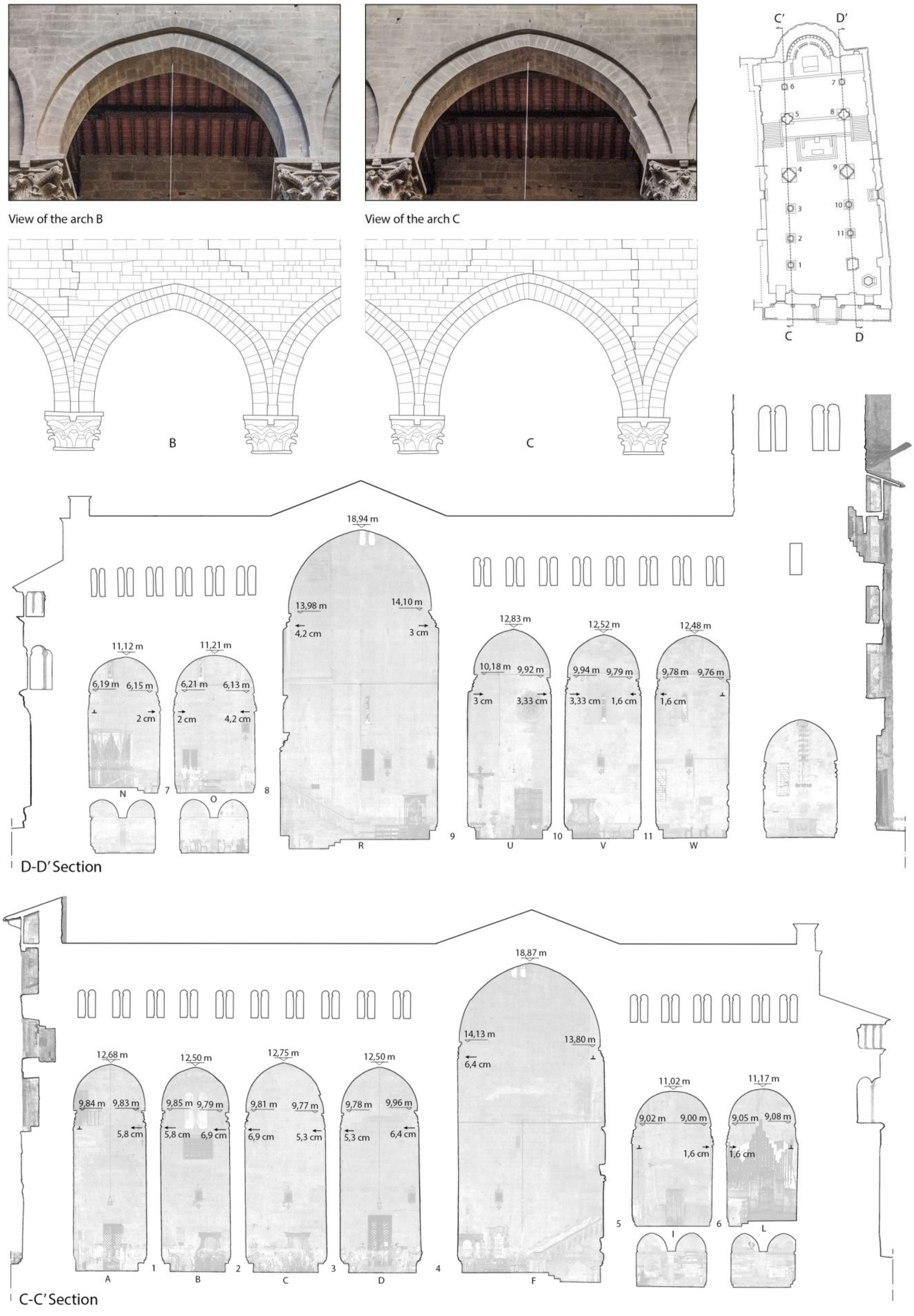

Figure 2: Longitudinal sections corresponding to the pillars which highlight the deformations of the structure.

The XIXth century restorations contributed to make the interpretation of the elements under consideration particularly complex. The barrel vaults of the naves, for example, should have necessarily left relics of the springer, of which today there is no trace in the facing wall. This is substantially homogeneous except for small vertical discontinuities.

The third arch (starting from the facade) is equally singular for the offsets on the intrados (Figure 2). It is unknown if consider them construction phases evidence, or corrections of curvature of the arches made during the restoration works.

On the opposite side of the nave the arches are three due to the presence of the bell tower; here the inclination of the columns is few accentuated, except for the one close to the crossing that has a tilt by about 8 cm on the outside.

The sides of the church have the greatest deformations where the transverse arches are aligned with the largest pillars of the crossing. Each of the pillars has an inclination of 2° towards the outside; the corresponding sides of the church have outwards tilts of 1° on via della Seteria, 1.5° on the opposite side.

However, the wall on via della Seteria has a particularity which needs to be explained. The part that flanks the aile is inclined, while the remaining stretch that extends to the presbytery area is perfectly vertical. The part between the out plomb wall to the vertical one takes place in correspondence of the pilaster aligned with the largest pillars of the crossing.

This peculiar structure makes clear that the vertical wall was definitely rebuilt and this had to be carried out during the restoration works in the years 1873-1874[14].

The characteristics of these walls have a further relevant aspect to consider. The entirely rebuilt wall should be considered homogeneous, while the out plomb one is made up of stone facing rebuilt in adherence to an original nucleus. In this case, the problem of the effectiveness of the connection between facing wall and inner core arises. In fact, for the earthquakes impact, detachment sometimes occurs between reconstructed facing and original masonry. That is due to the difficulty of creating a strong connection between these two differents parts.

This happened for example in the basilica of San Francesco in Assisi, where the earthquake of 1997 caused the collapse of a recontructed portion of masonry in the southern tympanum of the transept[15].

4.2 The crossing

The four pillars of the crossing have a first singular aspect concerning the difference, not only in features but also on resistant section, between the two adjacent to the naves and the other towards the apse. These last compared to the first ones have a reduced section by 30%. Today the pillars support a drum covered by a wooden covering, which might seem an unfinished work.

Moving on the examination of structural deformations, the pillars of the crossing show an inclination of 2° to the outside, except for the north-east one inclined by 1°; while they are on a modest tilt towards the naves.

It should be underlined that between the pillars of the crossing there are also differences in the structural connections with the sides of the church. The largest ones are connected with a diaphragm arch, the smaller ones with two diaphragm arches that diverged into a V starting from the pillars themselves, thus distributing the thrusts on a wider area of the sides.

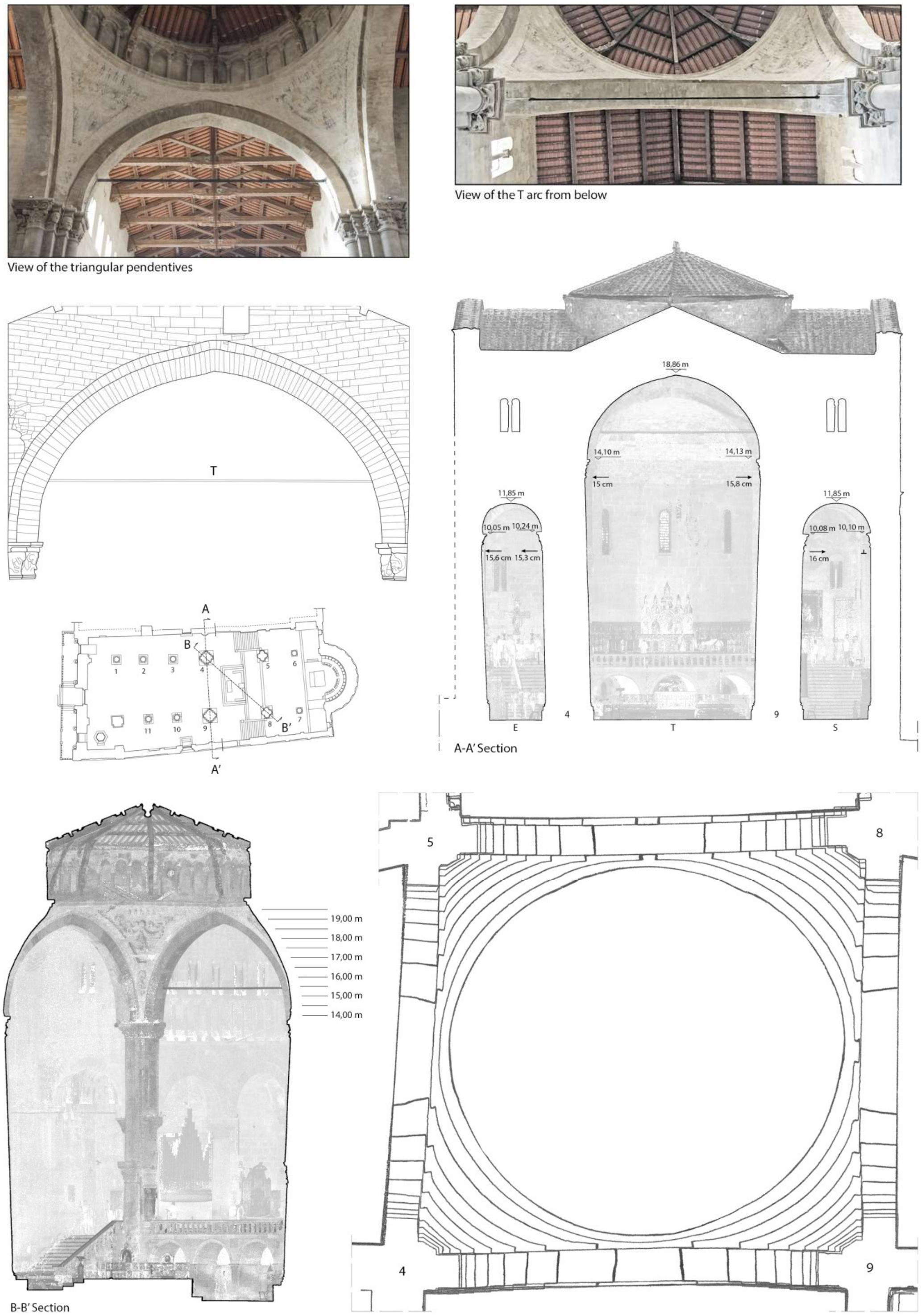

Figure 3: Crossing surveys: plan of the pendentives with horizontal level lines, the arch in front of the nave, cross and diagonal sections.

The arch of the crossing in front of the nave has a number of unique features (Figure 3). Its horizontal projection is not as straight as one would expect, but is visibly curved towards the crossing. In addition, the arch has the intrados with a marked vertical displacement in the central part; it is a deformation that must be related to the fact that, at the height of the capitals, the underlying pillars are inclined outside by a total of about 31 cm.

The structural alteration of the pillar-arch system has been confirmed by the stone facing above the arch. It shows rows with a rotation, towards the center of the arch, which varies between 7° and 9°; so the maximum vertical displacement of the rows is about 50 cm.

The pendentives of the crossing, analysed with plans at different levels, look similarly curved. The diagonal sections highlight pendentives with similar and slightly curved profiles.

We have no specific information on the facing wall of the pendetives. However, as far as visible from their facing, it can be assumed they were made by rows of progressive overhanging ashlars and they are probably part of a wall extended in depth until reaching the extrados of the adjacent arches. The pendetives are probably a type of massive masonry block which extends as far as inserting itself into the haunches of the arches. At the same time, the pendentives made stiffened the haunches and created a cantilever supporting the drum. In fact, in the arch in front of the nave, the center is the most subjected part to deformation over the level of the haunches.

The construction context of the crossing has a larger transversal vulnerability, resulting by displacements. Longitudinally, diaphragm arches stand on the massive walls of the facade and of the apse, which act as buttressing. The diaphragm arches, transversely, rest on the sides of the aisles, built up of rather thin walls.

However, it is questionable whether the displacements were produced by loads due to both the current modest drum and the wooden roof of the crossing; otherwise it should be assumed at least the beginning of the construction of a dome, which collapsed following the displacement of the underlying structures.

The investigations on the crossing and the data obtained pose therefore new questions concerning the construction phases and the interpretation of the structures. In this regard, the structural modeling of the church could be useful, to deepen the relationship between displacements and loads, such as an in-depth study of the blind loggia placed on the inner side of the drum.

5 CONCLUSIONS

The analysis of the structures of the “Pieve” highlighted the importance of understanding the history of the constructions varied over time, by relating different fields of studies, archival documents, architectural diagnostics and structural modeling.

In the current situation the building shows architectural features and types of structural alterations that reflect conditions changed over time. The time dating back to the organization of the medieval construction sites, the time of subsequent modifications, the time of the restoration works that deeply contributed to built the architecture and consequently the structure of the “Pieve di Santa Maria”.

Starting from the outcomes illustrated in this work, a new research line based on Scan-to-BIM processes, was also identified for the implementation of parametric models aimed at the information management of the historical building heritage (H-BIM). Some investigation developments are already underway regarding the following areas of study: 4D modeling of the evolution phases of the monument; structural analysis and simulations; integration of heterogeneous datasets (archive data, photographs, drawings and geospatial datasets); integration of intangible information (cultural meanings and values) associated with specific components or spaces; interoperability for data sharing and their reuse by the property manager; testing of interfaces with different information management systems, such as GIS, CAFM and other databases.

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