Building Techniques and Structural Damage of Historical Constructions Detected Through the Point Cloud Survey

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Abstract. The study of historical constructions belonging to the cultural and architectural heritage is often challenging as, in most cases, it is very complex to reach a full understanding and description of them, due to the long-lasting history and the numerous modifications throughout the centuries. Many instruments today available allow gathering information on the current state of these buildings and contemporarily can provide some evidence on their history and constructive techniques. As a matter of fact, data taken from the modern technique of laser scanning, applied to architectural heritage, can provide important information not only on the present deformed configuration of each building, but also on the construction techniques related to its components, their geometries and possible structural problems. By juxtaposing the slices taken from the point cloud survey, indeed, the correspondences or the differences of the profiles might prove either the regularities or the incongruences characterizing each building. The present study will prove the significance of such an investigation technique with reference to the case study provided by Santa Fosca church on Torcello Island. This is a Venetian-Byzantine church, dated back to the 11th century, very peculiar both from the structural and architectural point of view and subject to numerous interventions throughout the centuries.

Keywords: Laser scanning technique · Point cloud · Building techniques Deformed configuration · Historical constructions · Santa Fosca church

1 Introduction

The analysis of the structural health conditions of historical constructions is problematic as well as the knowledge of their complex history. The laser scanning technology, as known, applied to the architectural survey, allows to measure in the very detail all the parts of the building, even those less detectable, and to obtain a point cloud, which permits defining the 'skin' of the building [1].

In fact, in the case of the laser scanning survey, not only the irregularities in the building geometry are more easily detectable, but also the several out-of-plumbs and

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settlements of the structure might be identified and accurately measured. In this regard, the present work makes use of the emblematic medieval church of Santa Fosca on Torcello Island to provide a meaningful case study. The church peculiarities, indeed, give the opportunity to show the usefulness of the laser scanning technique from the point of view of both the constructive and structural analysis. This church presents an uncommon architectural scheme, where the covering of its Greek cross plan, consisting of a wood roof, has been the reason for a lively debate about the original configuration of the whole building. Through laser scanning, assumptions can be done on both the earlier existence of a dome and the church present conditions as well.

2 Methodology: Advantages and Criticalities of the Laser Scanning Technique

The 3D laser scanner is a survey device, which provides the spatial coordinates of the points belonging to a cloud, namely a set of points at close range among each other, disposed in a uniform manner, and describing the object under investigation. It can be carried out even without an adequate lightening system and its results are more accurate and precise than those provided by the traditional survey tools (e.g. tape measure, plumb line, toric veal…). More specifically, it offers a virtual 3D overview, whose resolution depends on the distance among the points of the resulting cloud. The resolution level can be defined considering the size and complexity of the element to be scanned, in relation also to the specific aim of the survey and considering that the higher are accuracy and dimension of the point cloud, the heavier is data processing. For this reason, surveys of small objects, statuettes for instance, can be carried out with high definition overviews, necessary especially if these objects are characterised by complex geometries, whereas surveys of buildings are generally less accurate. Their dimensions would require, indeed, to process a huge amount of data and the elaboration of the whole point cloud might result very heavy. Furthermore, while small objects sometimes need a full-scale representation, and therefore a very accurate geometrical survey, building plans and elevations do not need such level of detail. It is even worth stressing that, while other simpler investigation techniques, for instance the total station, need a previous selection and predetermination of the elements under investigation, the acquisition through the laser scanner is automatic. It provides, hence, a high range of data, which must be analysed at a later stage and further simplified from a 3D overview to a 2D image, more easily detectable.

Although this work aims at highlighting the importance of the laser scanning technique in the field of architectural heritage, it is even worth stressing that this 3D capturing system is recently finding more and more applications, even in the archaeological field. It allows, for instance, the analysis of pottery [2], it helps understanding the dimensions of tiers of seats in ancient buildings for spectacles [3] or can provide an exact representation of lithic artefacts [4]. Moreover, besides the detailed study of single archaeological remains, the laser scanning technique has been developed even for large-scale topographic studies, for mapping present and historic landscapes [5, 6] or monitoring modifications due, for instance, to flood modelling [7].

The point cloud allows also the development of the Historic Building Information Modelling (HBIM), by means of the 3D models elaborated through the laser scanning technology into parametric components [8, 9]. Such technique, if applied, provides a very accurate description of irregular geometries characterizing the constructive elements of historic buildings [10], through the detection and representation of complex profiles, such as arches, pendentives, niches, vaults [11].

It is worth stressing, however, that this kind of analysis should be used in connection with all the other available information sources. In the architectonic survey, for instance, this method does not provide information on the material consistency of the building, requiring, therefore, to be complemented with other types of analyses. Among the others, the visual inspection is of utmost importance for the detection of the materials, the decays, the preservation state, and is necessary for an overall comprehension of the problematic construction issues. In addition, a diagnostic campaign, where possible, could help characterizing materials in the wall internal layers or also the structural conditions. Actually, in relation to historical buildings – when made of bricks and mortar – the analysis of the masonry pattern, in case the plaster is not present, is a prerequisite to evaluate the construction techniques and possible structural problems. On the basis of the geometrical, material and crack pattern survey, hence, the most critical parts of the building can be identified and analysed through specific slices taken from the point cloud, which might clarify the reasons of the detected irregularities, either due to specific collapse mechanisms or, rather, to peculiar constructive processes. To this aim, it is worth stressing that the knowledge of the history of the detected architecture and of the local building techniques can be decisive to investigate the reasons of the irregularities: either some past interventions caused the present geometrical anomalies or the specific construction process brought the building to look like nowadays since the beginning. On the other hand, when the historical knowledge is scarce, the analysis through the laser scanning technique can be only partially conclusive, as it is shown in the frame of this work.

3 The Laser Scanning Technique Applied to a Medieval Building

The present study aims at stressing that both structural problems and construction techniques can be emphasised through specific slices taken from the point cloud, with reference to the above mentioned uncommon architecture of Santa Fosca on Torcello Island. The slices which were employed to interpret the church geometrical configuration are courtesy of the 3DEG Office from Treviso that acquired Santa Fosca point cloud on December 2012 (see Fig. 1). The surveys were carried out through the Leica ScanStation C10, a time-of-flight scanner, starting from the outside of the church. Some targets were used as landmarks, which subsequently were combined together. The data were finally elaborated through the CYCLONE software system.

Fig. 1. Santa Fosca point cloud: view from the main facade. Courtesy of the architecture Office 3DEG

3.1 Unsolved Historiographical and Conservation Issues

As above mentioned, the architectural scheme of Santa Fosca is very peculiar: it is characterized by a Greek cross plan where the apse is twice the length of the other three arms. At the intersection of the arms, furthermore, eight marble columns support four couples of hemispherical niches that allow the transition from the square organization of the ground plan to the circular shape of the masonry drum, located above the niches and covered by a conical wooden roof. No notices exist about the earlier presence of a dome in spite of the current conical roof; however, since the mid-1800s several assumptions have been formulated about the possible existence of a masonry dome at the time of the church erection (e.g. [12, 13]). Scholars further developed such a theory throughout the 1900s, some of them also added that the original dome might have collapsed after the seismic event of 1117, during which a huge number of architectures of North Italy was severely damaged (e.g. [14–16]). The lack of a masonry dome could be even related to ground settlement phenomena, very common in the Venetian Lagoon, which might have compromised the church structure, and, as a consequence, the dome stability. Analyzing the building structural problems, indeed, the church crack pattern suggests the real possibility that differential settlements are mining the church stability [17]. By means of laser scanning, additional considerations can be put forward about the drum in terms, on the one side, of the building technique and thus of the possible earlier existence of a masonry dome and, on the other, of the conservation issues concerning its structure.

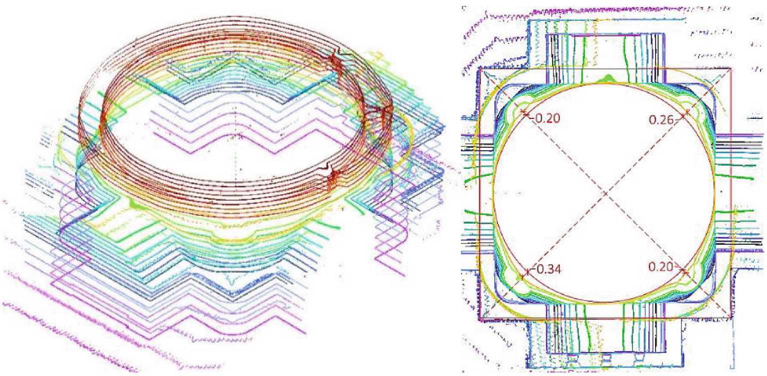
3.2 Focusing onto the Building Techniques

The slices taken from the point cloud can give an effective outline of the current complex geometry of the building, and, in particular, of the drum. It has been already underlined that such a survey must be integrated with other possible analyses. First, it is worth observing that the masonry pattern of the church is visible from the inside, whereas the external walls are plastered. In relation to the drum materials and geometry, it can be noted that different typologies of bricks characterise this upper part of the church (see Fig. 2): masonry patterns of reused bricks alternate with surfaces composed of the so-called *altinelle*, i.e. bricks belonging to the Venetian civil construction tradition until the early 14th century [18].

Fig. 2. Detail of the drum masonry pattern

Unfortunately, due to the presence of re-pointed mortar all over the inside masonry walls, and, in particular, on the drum, it is not possible to understand the stratigraphic sequence of this element. In any case, a clear difference can be observed between the masonry pattern of the drum and those belonging to the underneath arches and pendentives: at a first glance, focusing only on the visual inspection, it can be stated that the drum and the couples of niches do not belong to the same construction phase.

The analysis of the slices taken from the church point cloud can further deepen the observations coming from the visual inspection. To this aim, Fig. 3(a) shows the horizontal slices of the upper part of the church: the first six slices from the bottom (identified with the violet and blue colours) are taken every 50 cm and correspond to the profile of the lower niches. The others (from the pendentives to the upper part of the drum) are taken every 20 cm: the light-blue and green slices correspond to the upper niches whereas the orange and red slices show the drum profile.



(a) (b)

Fig. 3. Horizontal slices of the upper part of Santa Fosca church: (a) assonometric view; (b) plan view

As it can be seen in Fig. 3(b), the drum shows a vertical development in the proximity of the middle sides of the square, where the horizontal slices from its bottom to its top always match. This overlapping does not occur above the couples of niches, through which the transition from the octagon to the circle is not completely achieved: the circle at the top of the drum is finally obtained through the drum itself that shows a slant development next to the diagonal direction. Hence, as shown in Fig. 4, in order to reach the perfect circle, the drum fills the gap of about 20 cm and even more, by corbelling courses for about 1,9 m.

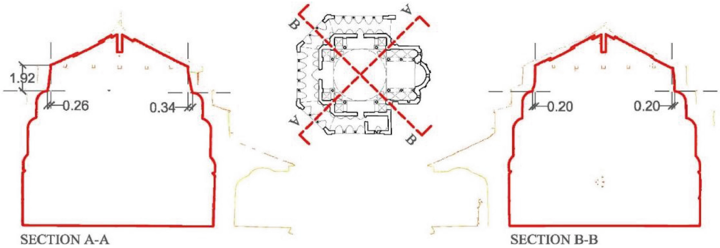


Fig. 4. Juxtaposition of the slices taken in the middle of the aisles

The drum irregularity is emphasised by juxtaposing the vertical profiles of the four main corners of the building. In fact, while the profiles corresponding to the pilaster strips, the pendentives and the couples of niches are similar to each other, the development of the drum results particularly lopsided (see Fig. 5).

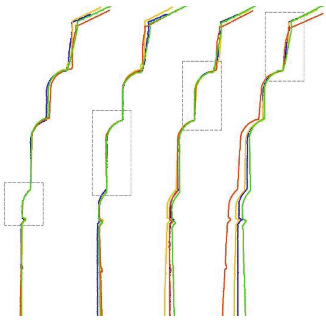


Fig. 5. Different criteria to overlap of the corner slice profiles: overlapping of pendentives (a), lower niches (b), upper niches (c), drum (d). The only constructive element showing an irregular development is the drum.

Hence, the irregularity shown by the visual inspection is further highlighted by the analysis of the slices taken from the point cloud for these specific portions of the church. It is worth noting that this irregularity is more or less the same all over the perimeter walls of the drum. While the evidence coming from the visual inspection leads to believe that this element partially collapsed and was irregularly rebuilt above the pre-existing niches, the analysis of the slices suggests even that the peculiar architectural scheme might have brought the builders to adopt this constructive technique by corbelling bricks with the available materials since the beginning of the construction.

3.3 Detection of the Structural Problems

By analysing the drum more in depth, it is also possible to observe that its geometry is mined by some structural problems that involve the whole building: Fig. 3 shows an out-of-plumb of about 34 cm near the South-West side. This anomaly is emphasised in Fig. 6 where the vertical profiles of the four corners are compared. The South-West corner (the green profile) is in a rearward position with respect to the others: its out-of-plumb measures around 10 cm at a height of about 3,5 m from the ground level.

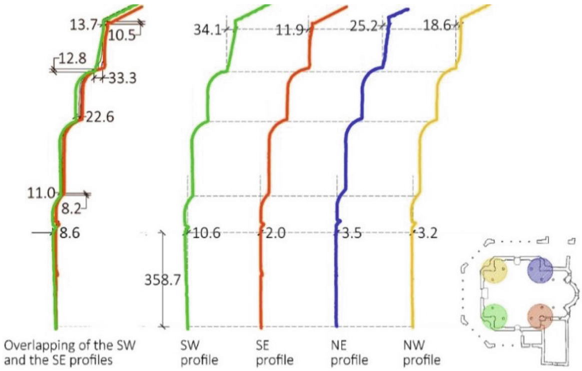


Fig. 6. Comparison among the profiles obtained from the diagonal sections

This significant out-of-plumb is coherent with the inside relevant cracking analyzed in [17]. In particular (see Fig. 7), the Northern elevation shows the highest out-of-plumb in the Western direction, while the Western elevation shows that the out-of-plumbs of the Southern wall and of the columns are coherent with the vertical cracks present on the upper part.

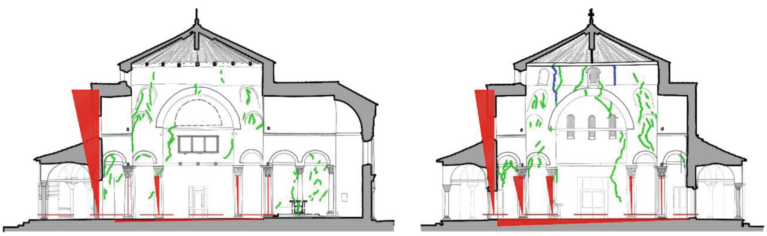


Fig. 7. Superposition of the crack pattern and the deformations detected through the point cloud survey: Northern (on the left) and Western (on the right) internal elevations

The crack pattern, together with the analysis of the deformed situation, suggests that the South-West corner is subject to a differential ground settlement. This assumption is further sustained by looking at the crack on the ground floor, dividing the South-West corner from the rest of the church and consistent with the displacements of the ground floor observed on the Western and Southern sides. Unfortunately, up to now it has not been possible to know the details about Santa Fosca foundation system, since only punctual excavations were made in the past.

4 Concluding Remarks

This contribution has shown how the laser scanning technique may be helpful for a deeper understanding of the construction processes and pathologies of a very complex medieval building. In the specific case of Santa Fosca church, the issue of the existence of a dome remains unsolved; however, it has been highlighted that the drum irregularities might be due to a particular construction technique, where the brick rows are corbelled, in order to reach the perfect circle at the top of the drum. This effort might justify the original intention to build a dome above this constructive element. Suitable slices taken from the point cloud have also underlined that the church is subject to a remarkable out-of-plumb: the South-West corner is moving, probably due to a differential ground displacement between this part and the rest of the church. Ground settlements might also justify the current absence of a masonry dome at the top of the drum. The assumption that it collapsed due to a progressive ground movement is unlikely, since the dome could progressively adapt to slow movements; however, it might be assumed that, during the erection of the upper part of the building, the builders noticed the church settlement and avoided to add a heavy and stiff masonry dome, adopting the solution of a wood roof.

In the frame of this work, hence, the discussion of the case study highlights that the laser scanning technique plays a fundamental role in the analysis of the architectural heritage, whose results must be complemented with other forms of knowledge, related to the history and the study of the specific construction materials and discontinuities, which, only partially, can be detected through the laser scanner. In fact, only simultaneous analyses from different perspectives will contribute to both a wider awareness of the building present conditions, and a broader understanding about its past as well.

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