Diagnostic Use of Laser Scanning Data to Identify Current and Historical Deformations and Geometries: the case of the Modena Cathedral

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Abstract. The present research is focused on the deep analysis of laser scanning data to develop a semi-automatic methodology to identify structural deformations in cultural heritage applications. Particularly a new and innovative use of laser scanning technique is experienced to detect the geometric anomalies that might be the result of deformations occurred in the past. The methodology has been applied to the Modena cathedral, included within the UNESCO World Heritage List since 1997, in the context of the recent Restorations and Studies (2007-2014). The final purposes of this methodology are: 1) to investigate the structural behaviour of the monument; 2) to validate a new interpretation of the subsequent construction phases, based on the hypothesis that the elevation of the cathedral has been compromised by the structural failures, that caused the identified architectural anomalies present in the facades.

The geometry configuration has been properly described by investigating the different deflections of the elements from the horizontality and the verticality. The data obtained from the laser scanning have been integrated with the crack pattern and further information related to the history of the monument. Such a multidisciplinary approach allowed to proceed from the current geometry, to the historical ones, demonstrating the relation with construction phases and settlements, since the beginning of the elevation of the cathedral.

The laser scanning survey, indeed, allows to obtain a dense points cloud that constitutes a real ‘photograph’ of the actual geometric configuration of the structure, revealing the changing of the structure over time. The current geometric anomalies, indeed, are the manifesto of all processes that inevitably occurred in the past due to a complex series of construction phases, the interaction with the subsoil and external events, both natural and anthropic. All these contributions have potentially induced the stresses that were capable of generating displacements and consequently the current configuration.

The paper will briefly show the most interesting results such as the evidence of rotations and geometric anomalies, that are obtained thanks to this diagnostic approach.

Keywords. Laser scanning, structural analysis, geometric anomalies, crack pattern, cultural heritage.

1 Introduction

The laser scanning technique has become more and more popular for a wide range of applications because of its capability to acquire a lot of information with a high degree of detail and in relatively short time. Cultural heritage is surely one of the most promising field of application for the future development of laser scanning. This powerful methodology has been strongly used in cultural heritage applications where the documentation and the dissemination potentialities are well exploited. More details can be found in Guarnieri et al. (2004a and 2004b), Neubauer at al. (2005) and Bertacchini et al. (2010a). The ability to document artistic elements, to virtually reconstruct them by means of 3D modeling, in order to show how they would appear in the past, as well as to provide useful information for restoration schedules are just some examples of the traditional use of laser scanning in cultural heritage. A new philosophy, more concern to engineering issues, is growing up with the purpose to describe and analyze the geometric anomalies as well as the rotations, the displacements and the deformations affecting the structure and paying major attention to structural elements than to artistic ones. Further examples of this approach can be found in Castagnetti et al. (2012) and Capra et al. (2015).

Studying the critical aspects of a structure in terms of stability is of fundamental importance for the purpose of protection and preservation: the structural analysis is accomplished through the application of numerical simulation models (finite elements algorithm) that evaluate the response of the structure in relation to different types of stresses. In order to obtain reliable results, it is useful to have three-dimensional and geo-referenced models of structures that needs to be of considerable detail and with high degree of metric accuracy. A detailed and reliable description becomes more essential in case of ancient structures to determine the vulnerability in static terms, see Gordon at al. (2004), because those buildings are characterized by irregularities just during their construction that likely have been increased by changes occurred over time.

This paper discusses an innovative methodology, based on laser scanning datasets, able to extract information about structural features. It is based on manual measurements and semi-automatic analysis which are directly computed on the points cloud itself and it does not need to go through hard processing and modeling, which takes long time. The novelty of the approach, which is developed by Authors, lies in reading the same dataset by a different perspective: a structure-oriented point of view leads every analysis while no automatic software exists, no standard procedure were realized yet to this scope and no examples are present in literature. The approach is applied to a specific case study, the Modena cathedral, with the aim to combine laser scanning-based results with crack pattern evidences and improve the knowledge of the structure's history.

2 The Case Study

The multidisciplinary approach was tested on the cathedral of Modena (Modena, Italy) that is included within the UNESCO World Heritage List since 1997 (Figure 1). Being a monument of great historical and architectural assets, the cathedral, together with the nearby tower and the whole Piazza Grande, represents the symbol of Modena, and it is one of rare examples where two architectural styles, Romanesque and Gothic, coexist (Fig. 1).

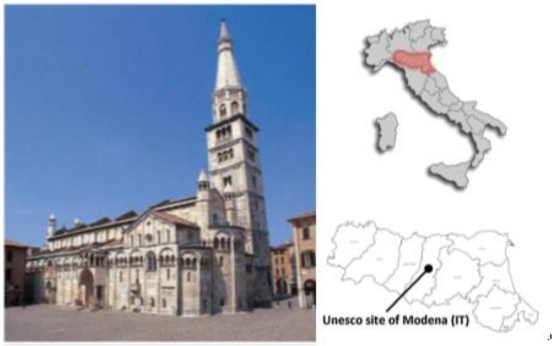

Fig. 1 The cathedral of Modena, belonging to the Unesco site of Modena, Italy. A picture of the Unesco site, with the cathedral and the civic tower (left); the location map (right) (Castagnetti et al., 2016).

The cathedral of Modena has a long and complicated construction story even because of the interaction with the contemporary construction of the nearby civic tower, the Ghirlandina Tower, and because of the interaction with the soil that caused deformations and instabilities since the initial construction. The beginning was supposedly started in 1099, together with the adjacent tower, designed by the architect Lanfranco and its coworkers while in 1220 the Maestri Campionesi phase took place with the construction of elevation parts; for more details, see Peroni (1999). The assumptions relating to the subsequent stages of construction are multiple and sometimes conflicting, but all experts recognize that the cathedral, as it appears to our eyes today, is primarily the result of the following corrections that were made during the various stages of realization because of phenomena of instability, which occurred over time with the effect, so far averted, of undermining the stability of the whole structure. Moreover, a recent study provided by Silvestri (2013) supposes a new interpretation of the history of the cathedral, suggesting that the construction phases were compromised and determined by the structural failures caused by the influence of the near tower and the subsidence of the soil during the elevation. The multidisciplinary approach as described in this paper, by providing scientific basis thanks to real datasets, can validate and demonstrate the new hypothesis.

The current geometry together with the existence of differential components leads to the strong need of monitoring the structure in order to achieve protection and conservation. The cathedral, indeed, has been extensively studied over the years by technicians and by a Scientific Committee to understand its vulnerability and its history; joint analyses showed that the current geometry is surely due to the different steps of construction that have historically taken place and also to the phenomenon of subsidence in Modena. More details about these topics can be found in Bertacchini et al. (2010b), Silvestri (2013) and Castagnetti at al. (2016).

3 Methods

3.1 Terrestrial Laser Scanning Survey

A terrestrial laser scanning survey of the whole cathedral was carried out by means of a time-of-flight instrument, model *ScanStation 2 by Leica Geosystems*. Details on the survey in Castagnetti at al. (2012). Figure 2 shows the equipment during the survey and the locations of scanning positions. Retroreflective targets were applied on the structure for a proper alignment of the various point clouds by means of homologous point identification. The survey was carried out both indoor and outdoor with a resolution of 8 mm with respect to the operating distance between the surface and the instrument. An additional survey by means of a robotic total station, model *TCR1201+ by Leica Geosystems*, was also performed in order to account for an accurate alignment between the indoor and outdoor point clouds.

Fig. 2 The laser scanning survey of the cathedral of Modena: location map of the scanning positions (left) and a picture of the equipment, terrestrial laser scanner model *Scan Station 2 by Leica Geosystems*, during survey operations (right) (Castagnetti at al., 2012).

The overall accuracy of the final alignment, which was also refined by means of the ICP (Iterative Closest Point) algorithm on the basis of the surface matching, was 10 cm. Details on the ICP algorithm in Besl and McKay (1992), Chen and Medioni (1992) and Zhang (1994). The final point cloud of the structure is obtained with two more refinement steps: noise filtering and data cleaning, aiming at removing every points which is not related to the structure. The software, that has been used to process and to manage the laser scanning dataset, is *Cyclone by Leica Geosystems*.

3.2 Point Cloud Analysis

Once the point cloud 3D model is obtained, the methodology of data analysis and geometric features extraction was developed considering the complexity and the characteristics of the cathedral. In fact, there are no standard procedures to be adopted as the elements to be investigated vary depending on the type of structure that needs to be studied. Moreover, no software exist that allow the whole automatic extraction of this information, precisely in consideration of the fact that there is no standardized list of analysis to be conducted. By the way, the cathedral of Modena provided to be a great case study to develop and suggest a methodology for the use of laser scanning datasets with diagnostic purposes.

The procedure fully exploits the informative content of the point cloud by focusing on the verticality and the horizontality of structural elements. The basic hypothesis is that, in the initial original condition, the structure was characterized by a perfect verticality and horizontality. The modifications suffered over the time may have generated rotations that occur today in a not perfect horizontality or verticality of these structural elements. To identify the mentioned geometric anomalies, a semi-automatic procedure has been developed: first of all, a manual inspection allows the operator to identify the significant structural elements and to extract the geometric features by the point cloud within the same software used for managing laser scanning data. Once this information is exported by the software, it is processed automatically by specific routines, especially implemented in *Matlab* language by the Authors, in order to create detailed graphs and products that combine information from multiple structural components. This combination allows to provide a comprehensive overview and facilitates the next phase of interpretation. This step has been automated to speed up the procedure as a whole; the approach do not only consists in the creation of detailed combined plots but also in the verification of the correctness and of the reliability of final products that need to be consistent, homogeneous and comparable.

The correctness of the performed analysis is ensured by the fundamental steps of the procedure, being the definition of a conventional reference system, the control of coincidence between the *z*-axis and the vertical axis, the definition of cutting planes, the definition of significant vertexes describing the elements and the visualization of detailed and combined graphics.

4 Results

4.1 Verticality

The verticality analysis focuses on structural elements with main vertical attitude, such as columns, semi-columns, best-fitting plane of walls and so on. In this case, the longitudinal path is investigated by extracting the *z*-component of a significant number of points belonging both to the element and to the same cutting plane. By comparing the element path with the vertical axis, it is possible to analyze the anomaly. Figure 3 shows the summary map of such study that was carried out on the semi-columns belonging to the outer perimeter of the cathedral. The map clearly highlights that different portions of the cathedral are subject to differential mechanisms.

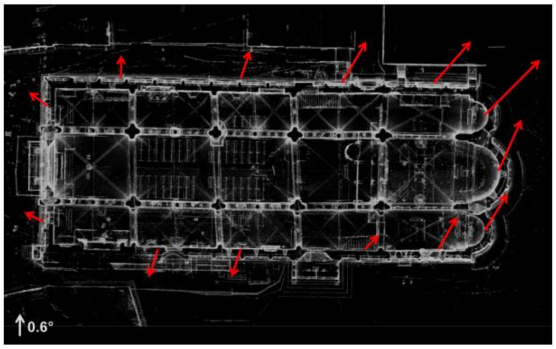

Fig. 3 Example of verticality analysis: summary map showing direction and magnitude of the identified inclines. The analyzes were carried out on semi-columns of the outer perimeter of the cathedral (the length of vectors is representative of the incline magnitude) (Castagnetti at al., 2012).

The major tendencies occur in the Northeast, the area adjacent to the Ghirlandina Tower, and affect all the apse area including the one belonging to the South side. In the rest of the cathedral there is a tendency to open to the outside, manifested from positive tilt vectors in a direction orthogonal to the walls for all the facades. In the plane of the wall, instead, the tendency is manifested by differential rotations, having the opposite direction along the longitudinal axis of the cathedral.

4.2 Horizontality

The horizontality analysis focuses on structural elements with main horizontal attitude, such as the basement, the sequence of arches at the base of the upper loggias, the eaves of the roofs and so on. In this case, the longitudinal path is investigated by separately extracting the *x*-component and *y*-component of a significant number of points belonging both to the element and to the same cutting plane. By carefully looking at the plot of these components, it is possible to identify the anomaly. Figure 4 shows a detailed analysis of the difference in elevation between the North side and the South side calculated from the comparison between the profiles of the two upper loggias bases.

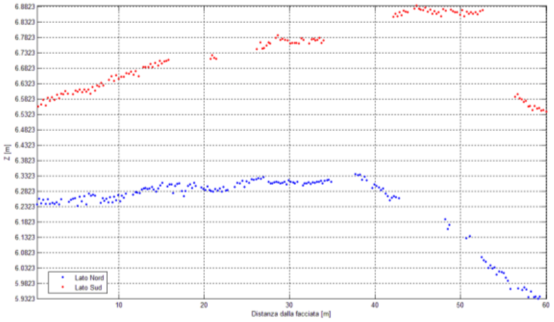

Fig. 4 Example of horizontality analysis: comparison between the elevations of North façade (blue colored points) and South façade (red colored points) of the cathedral of Modena. The analysis is performed on the sequence of arches at the base of the upper loggias.

This analysis has been done to validate the new hypothesis that the façade has been the last side to be built, as stated in Silvestri (2013), supposed by the observation of the anomalous difference of 30 cm existing in the center of the front façade between the level of the North side and of the South side upper loggias. That difference has been attributed to the lowering and slight rotation of the apses towards North during the first construction phase. The detailed analysis of the configuration of the loggia along its perimeter in the point cloud model could prove this new theory, confirming that the construction did not proceed in parallel from the two sides, namely the main façade and the apses, like supposed until now by the majority of the researchers, from Porter (1917) until Peroni (1999).

4.3 Crack Pattern

The point cloud analysis could provide numerical data to be integrated with the crack pattern survey and with the study of the historical structural damages in a multidisciplinary approach. The surveying and the analysis of the cracking pattern, joined to the study of historical damages, due to subsidence and earthquakes, show two areas of the cathedral to be particularly vulnerable: the fourth span from West, at the limit between the naves and the presbytery, and the second span from West, along a line parallel to the front façade. In particular, the cracks at the limit of presbytery are related to the lowering and slight rotation of the apses towards Northeast, that started with the construction of the cathedral but still goes on increasing. That area coincides, according to the new interpretation, with a later construction phase, called *'C'* phase, that was necessary in order to repair some damages due to early soil settlements manifested during the first two phases. Further descriptions in Silvestri (2013).

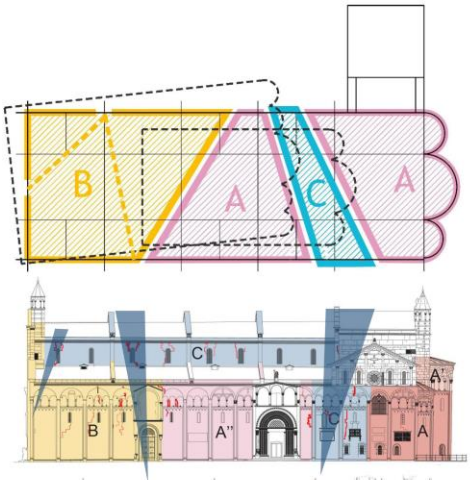

Fig. 5 Relation between the construction phases and the crack pattern of the cathedral of Modena (Silvestri, 2013).

5 Conclusions

In this research, a novel approach has been developed about the treatment of laser scanner datasets for cultural heritage purposes. 3D point clouds are traditionally used for spectacular 3D representations of monuments or for documentation by means of classic 2D products. The research deals with an innovative methodology that uses laser scanning datasets in a diagnostic way for engineering applications and focuses on structural elements in order to document the current geometric state of the monument. The analyzes allow the identification of interesting geometric anomalies and are carried out in close cooperation with experts of the construction history, architects as well as experts of the soil behavior and foundations. Such an interdisciplinary approach allows to define a multidisciplinary methodology able to retroactively date the structural failures suffered by the cathedral by starting from the current geometry of the monument, as given by laser scanner dataset. The methodology allow to manually identify and compute geometry features and to display them in semi-automatic mode. Results prove that the 3D point cloud plays a key role in improving the knowledge of the monument and in validating the hypothesis at the basis of the new theory about the construction history of the monument.

In fact, the initial failures that were suffered in the past by the structure play an important role in the interpretation of the phenomena that have occurred over time because they are responsible for the current geometric appearance of the monument. Following this mindset, the analysis performed on the point cloud are essential to describe the geometry state in 2014, thus the identified geometric anomalies may be considered traces of the changes undergone by the structure over time. The past studies, indeed, gave clear indications that most of the current vulnerability of the cathedral follows the original vulnerability, which occurred in the first years of life. This statement is confirmed by the survey of crack patterns and by the study of historical failures shown in Silvestri (2013) and also by the movements due to subsidence over the last twenty years shown in Castagnetti et al. (2016). These results follow the same trend observed in the past during the early phases of construction.

The implemented interdisciplinary methodology, based on the joint interpretation of the crack patterns and the geometric anomalies, leads to a strong improvement on the knowledge of the monument and its structural history, thus contributing to highlight the role of 3D point clouds in this application field.

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