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Pathological diagnostic tool based on the combination of different disciplines. Management of the preservation of cultural heritage. Application in the structural consolidation of rock structures

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ABSTRACT

The preservation of cultural heritage must encompass different disciplines for its management to be optimal. The behaviour of a historic building depends on many factors, which include its real geometry, the characteristics of the materials with which it was built, pathologies arising throughout its existence and the conditions of its surroundings. Different techniques are therefore required and these must be complemented in order to manage our cultural heritage comprehensively. Coria Cathedral (Cáceres) is an example of a singular building with secular pathologies. This study of the cathedral combined modern techniques of analysis and description. Geomatic techniques were used (differential levelling, terrestrial laser scanner, GNSS), geophysical prospecting methods (electrical tomography), geotechnical descriptive methods, three-dimensional modelling and verification of structural systems. The results obtained served as the basis to determine and locate the origin building's pathologies and to develop a project for the structural consolidation.

I. Introduction

The article presents the methodology used for the structural diagnosis of a secular building with star shaped groin vaults on pillars attached to load bearing walls. The geometry of the structure, properties of materials and surrounding conditions (foundations and orography) are analysed. The study centres on the cathedral of the city of Coria (Cáceres), a building that has suffered structural problems for centuries.

Coria Cathedral (Cathedral of Santa María de la Asunción) was built on the site occupied by the primitive visigoth cathedral, which was substituted by the Arabic mosque up until the old cathedral was built following the Christian reconquest and later military stabilization of the area. In the last years of the XVth century the cathedral's incumbents declared that “this, our church, is very dilapidated and old, and falling down, and also because it is so low and small that not even half the townspeople can fit into it”, and decided to proceed with the construction of what is known today as the 'New Cathedral'.

The site of the building is on the edge of a slope with a descent of around 40 m, the geology of which is made up of a deep stratum of clay overlain with a layer of loose clay based stones of thicknesses varying between 3 m and 6 m. At the foot of the slope lies the old bed of the nearby river Alagón, which altered its natural course towards the south by around 400 m following a flood, dated by some authors as occurring in the middle of the XVIIth century (Mogollón, 1999; Núñez and Molina, 2011; Travesí, 2013; Rodríguez, 2015).

The first 150 years of the history of this cathedral, the approximate time it took to build it, are ridden with hazards, incidents, structural failures, demolitions and reconstructions that gave many problems to the canonry and required the intervention of many master masons and architects (*e.g.* Martín de Solórzano, Bartolomé de Pelayos, Sebastián de Lasarte, Esteban de Lazcano, Pedro de Ybarra, Rodrigo Gil de Hontañón, Juan Bravo, Manuel de Larra y Churriguera, etc.) as well as considerable funding (Mogollón, 1999). A full description of the causes and solutions that these masters adduced and proposed cannot be undertaken here, though it can be said that during this period many and varied explanations were put forward, such as the weakness of the foundations or the excessive weight of the vaults (Travesí, 2013; Martínez, 1999). In addition to this trouble ridden history, the cathedral suffered serious damage on the morning of the 1st of November 1755 when the Lisbon earthquake (Rodríguez-Pascua *et al.,* 2011) struck, destroying part of the tower and caving in the main sanctuary and part of the vault of the main hall of the church (Mogollón, 1999).

To make a structural diagnosis of a building, its geometry, deformations and the loads it bears must be known. New metric surveying techniques can be applied to this task to construct complex 3D models using geometric information (Bitelli *et al.,* 2017). Terrestrial Laser Scanner (TLS) and photogrammetry based on structure for motion (SfM) are two techniques that have been used by several authors in the work of reconstructing and preserving heritage sites (Bitelli *et al.,* 2017). HBIM methods (Historical Building Information Modelling), used to analyse the damage suffered by a building as a result of an earthquake, are supported by 3D models of dense 3D point cloud obtained using TLS technology (Oreni *et al.,* 2017).

To gain the fullest knowledge of the development of possible deformations and movements of the building, periodic geometric monitoring of its structural elements and outer points was carried out. Thus, a reference system was created to distinguish between relative movements within the building itself and general movements of the surroundings. This work saw the application of Global Navigation Satellite System (GNSS) and high precision differential levelling, which gave millimetric or undercentimetric precision (Lovse *et al.,* 1995).

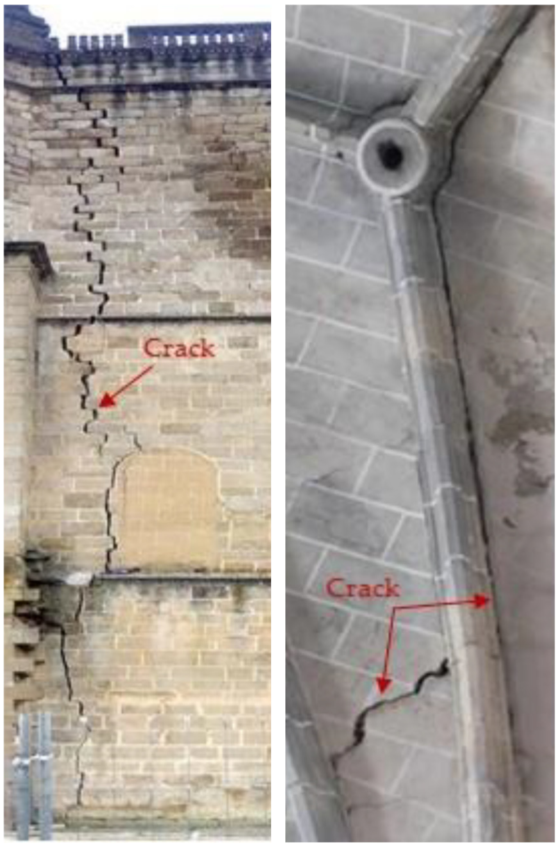
This work presents a pathological diagnostic tool based on the combination of different disciplines. From the data obtained by these techniques together with the geotechnical analysis and the analysis of the stability of the slope, a modelling was made of the ground and building as a whole in order to reveal the origin of its structural problems. This study establishes the basis for the necessary knowledge to be able to carry out the work needed to improve the structure and preserve the building (Jurado, 2014).

II. Research aim

This work is part of the study of the dynamics of a structure, transferred to a real case of analysis and prediction of deformations of a singular building of high historical heritage value in a precarious state of conservation. The aim of the research is to study the methodology to be followed for the diagnosis of the visible structural problems of a factory building. To this end, the study focuses on a building with serious structural pathologies and is analyzed based on multidisciplinary techniques that define the origin of structural problems. The behavior of the foundation and the terrain on which it is located and loads that the structure is supporting is analyzed. The repair work described in the study forms the basis for the definition and execution of the rehabilitation works in order to ensure the integrity of the building in a safe condition.

III. Materials and methods

Following the work of repairing the damage caused to the cathedral by the earthquake of Lisbon (1755), the existing documented data regarding the structural problems of the building disappeared. Even so, the cathedral has long been known for its glaring pathologies, particularly the cracks in the eastern façade (Figure 1a) and the vaults of the central nave (Figure 1b) (Mogollón, 1999; Martínez, 1999).



(a) (b)

Figure 1. The cathedral: a) Cracks in the wall of the eastern façade; b) Cracks in the vault of the central nave.

Using the most advanced technology and teams of multidisciplinary experts, uncovered the underlying problems causing the structural defects of the cathedral. These techniques included comprehensive geotechnical studies of the stability of the slope and foundations of the cathedral, implementation of modern monitoring systems and comprehensive modelling of the building using laser scanning technology, which, in addition to providing a three-dimensional model with sufficient geometric precision, formed the basis for a realistic analysis of the behaviour of the structure of the building. All of these studies culminated in the preparation of a constructive project aimed at the structural consolidation and restoration of the building.

Prior to the structural calculation, any movements in the foundations or structural elements (analysis of movements), the geometric configuration of the building (geometric analysis) and the carrying capacity and stability of the foundation grounds (geotechnical analysis) must be known. Also XIXth century terrestrial photogrammetry techniques were used for 3D architectural surveys of historic monuments. Other cases of preservation studies of buildings with high heritage value have used geomatics techniques of geometric assessment or to catalogue damage using 3D techniques (SfM and TLS), integrating the results into a HBIM system (Bitelli *et al.,* 2017).

TLS became available at the end of the XXth century and is used in a multitude of tasks. It is a tool for the collection of geometric information from a constructed element from which a 3D point cloud is created, or which serves as the basis for obtaining 3D models of the element scanned. Photogrammetry close range techniques from SfM technology offer a similar result, though this methodology requires greater effort in the data collection.

A. *Movement monitoring: Differential levelling and GNSS*

Visible structural damage to the walls and vaults of the cathedral (Figure 1) is a reflection of the differential movements the building has undergone. It must be determined whether these anomalous structural movements are the result of past problems or whether the structural movements still follow similar patterns today. Studies by Dierendonck *et al.* (1992); Lovse *et al.,* (1995); Caputo *et al.,* (2015) use geomatics techniques to monitor infrastructure movements, and the methodology methodology manages to determine movements of sub-centimetric order. Differential relative movements of the elements of the building and general movements of its surroundings were needed, and for this purpose two different techniques were implemented: a high precision differential levelling, for the study of movements at the base of walls, and GNSS for the analysis of roofs and surroundings.

Four sets of measurements were carried out between 2012 and 2015 to monitor movements so that any trend there may be in the structure could be analysed.

High precision differential levelling is a technique used as a basis or check in altimetry surveys (Caputo *et al.,* 2015; Calina *et al.,* 2015). A closed ring of levelling was followed containing readings of the GNSS bases of the proximity network and 17 points located in stone blocks, bases of walls of the cathedral structure and interior floor. An arbitrary high was established at one of the points in the first survey with the aim of obtaining a result that could be compared among surveys. The monitoring of this fixed point was maintained throughout the process.

For the analysis of movements using GNSS an external reference network was set up using stable points and this was connected to another network close to the cathedral building. Both networks were set up through the placement of permanent signalisations. The external network was located in cleared and stable areas for work using GNSS; the internal network was set up next to the cathedral, a building of significant height and surrounded by the buildings of the town centre. This latter network presented a challenge during processing, which was conditioned by the covered areas and possible reflections of the signal from satellites. The external network was adjusted by post-process using the data provided by the GNSS system of Extremadura (permanent antenna located in Coria).

All baselines are <1.3 km in length and have been observed for at least 3h post-processing (Heinrich-Wild-Strasse, 2008). These long observation periods ensure greater redundancy in ambiguity resolution and network adjustment. Likewise, these long post-process observations allow an exhaustive analysis to detect possible systematic and gross errors such as those caused by cycle slips or multipath. An initial adjustment of the network made in 2012 was established as a starting point on which to carry out the following checks. To minimize systematic errors, a GNSS observation protocol was established in which: the same sensor was always used at each point, the same anchor bolt and the same method of placement. The network close to the cathedral building was calculated from the data taken by the external network using a direct intersection in post-process with 5 base lines.

B. *Geometric analysis: TLS*

For the study of deformations in the cathedral structure requires the three-dimensional representation of the building, which in this case was performed using the terrestrial laser scanner technique (TLS), by which topographical and architectural surveys of structures can be carried out quickly and efficiently with great precision (less than a centimetre). The purpose of this method is to generate a 3D model that can identify cracks, twists, collapses, displacements, etc… Other non-invasive instruments (fissurometers, clinometers, micrometers…) provide data which, though they measure this kind of pathologies, offer specific values, whereas laser scanner facilitates knowledge of overall and all inclusive movement of the entire structure. Other highly useful information obtained using this methodology, thanks to the information stored in orthoprojected images, is any kind of section or view of the building, and this enables the generation of 2D views of the real geometry of the cathedral.

In this case a Leica C10 scanner was used, which provides precision ≤ 6 mm at under 100 m, a speed of measurement of up to 400,000 points per second and a field of vision capacity of 360º horizontally and 270º vertically. The resolution at which the work is carried out is 7 cm, which is the distance between the points on a mesh projected onto a wall face perpendicular to the scanner at a distance of 100 m. The configuration chosen is that of greater resolution in productive work times depending on the equipment available (18 minutes).

For the complete survey of Coria Cathedral ninety two measurements (11 on the exterior, 8 on the roof and 73 in the interior) were taken containing information on the point cloud, and six more of transition which, while not providing specific information, were necessary for putting the model together. To link together all the scans, 206 targets were used. Information processing was performed using the software Leica Cyclone.

The 3D model was placed in an overall system of coordinates, in this case the projected system of coordinates ETRS89 UTM H29, as this is the official system of coordinates in the region. In this way, taking the concept BIM, it is feasible and easy to integrate the cartography and the 3D model. Figure 2 shows the resulting 3D point cloud of the cathedral taken from the southwest.

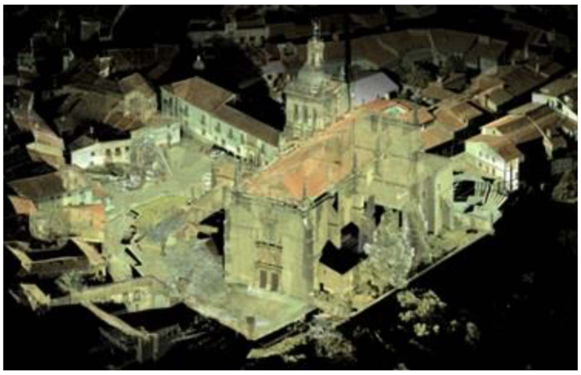


Figure 2. Full point cloud from the southwest view of Coria Cathedral.

Metric quality and photographic detail were obtained in the point cloud orthoimages, making them highly useful in the preparation of a qualitative assessment that distinguishes colours, materials, imperfections, etc. Twenty eight orthoimages were generated. The GSD (Ground Sample Distance) used was of one centimetre, though in most of the orthophotographs it was below this limit.

C. *Geotechnical studies*

The history and antecedents of Coria Cathedral and the stated aims of searching for the ultimate causes of its pathologies necessarily lead to a deep study of the geotechnical characteristics of the ground on which the cathedral stands. Previous studies have been limited to providing results of tests on samples obtained either from pitches or from surveys. It was necessary to go deeper in the sense that a geotechnical study is not an end in itself, but rather one step in a broader process of calculating the behaviour of the building-foundations-slope as a whole. It is strange that in the most recent studies (the end of the XXth century and beginning of the XXIst) the possible harmful effects of the cathedral's location next to a 40 m high slope were overlooked, more so we consider that old cathedral experts had warned of the problem and even designed solutions for the contention of the slope, such as Juan del Ribero Rada in his proposal in 1597 (Mogollón, 1999; Núñez and Molina, 2011).

Geometric definition is inconsistent if the model is not given robust mechanical content, so a model of calculation is required that takes geometry and geotechnics into consideration. Previous studies are complemented by tests to determine the geotechnical properties of the foundation grounds and slope. On one hand, the heritage value of the working area does not allow the use of destructive techniques (sampling), and on the other the size of the cathedral and slope require high yielding methods. Geotechnical characterization is used as a prospection technique that applies several electrical tomography profiles (Figure 3), determining the real electrical resistance which, together with augers in which the diameter of rotation is 86 mm with a perpetually recovered drill hole samples, permits geological levels to be established depending on their depth.

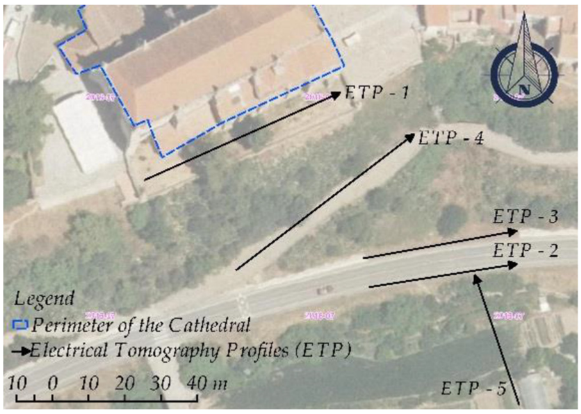


Figure 3. Floor plan of electrical tomography profiles. Source: Canonry Cathedral Coria-Cáceres (geotechnical study by LACOEX and GA-MA GEOFÍSICA).

Using the 3D geometric models and geotechnical description the stability of the slope building as a whole was estimated for different hypotheses. Elaborations were made using the program Geo-Studio, which estimates safety factors according to the Morgenstern & Price method (Cuenca, 2001; Kamanbedast and Delvari, 2012), a method that has been more widely used and which is more precise than the methods of Bishop and Jambu (Cuenca, 2001), following Mohr-Coulomb constitutive tension models (Bishop and Morgenstern, 1960; Bishop, 2008), in which the different geological materials of the undersoil are considered, as well as the fabric of the cathedral building and the loads borne (Figure 4).

D. *Structural analysis*

One of the aims was to elaborate a three-dimensional model that permits the structural analysis of its behaviour based on its real geometry, the product of its constructive evolution and the accumulation of movements, and not on the original projected dimensions that may have undergone considerable variations. Using the 3D model and the description of the materials of the structural elements of the cathedral by means of the extraction of drill hole samples in wall faces and resistence tests, the structural system of the building was modelled using bars and thick sheet fine elements. The analysis of movements and tenso deformational states of the different structural elements was performed with the software Sap2000 v.14.

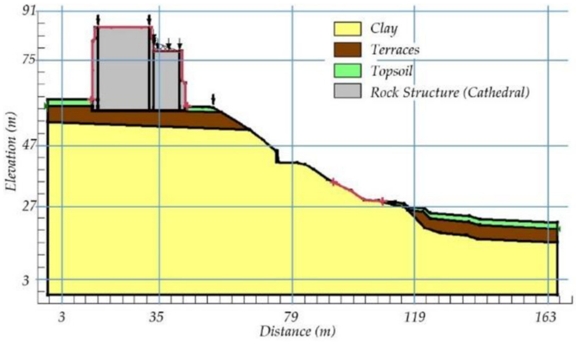


Figure 4. Geotechnical modelling of a topographic profile of the slope cathedral complex.

Using the estimation model, which considers the real dimensions of walls, arches and vaults as well as the resistant characteristics of materials, tensional behaviour under different hypothetical loads is studied. The model reproduced the pathologies present in the cathedral locating the main cracks and deformations.

IV. Results

From the analysis of the cathedral it was deduced that, during development of the works, it does not suffer movements tending towards any imbalance in its structure.

A. *Obtaining the orthoimages*

The orthoimages of the floors elevations and sections were obtained from the projection of a plane to infinity, that is, with an orthographic view, such that its content and parallel to the plane their real measurements were retained. The floors were generated from the section of the point cloud by a plane of a certain level, Z, and the planimetry obtained is expressed in an overall system of coordinates.

From these orthoimages the wall faces and elements of interest (Figure 5) were digitalized using CAD software.

B. *Topographic calculations and geometry*

The comparison of results according to the precision achieved reflects the absence of movement of the structure and of the foundation ground. High precision levelling throughout the surveys and of the points read presented maximum drops of 2 mm. The work carried out by high precision levelling reflects measurement tolerances of 0.1 mm. Of the 24 points studied, 20 remained materialized from 2012 until 2015.

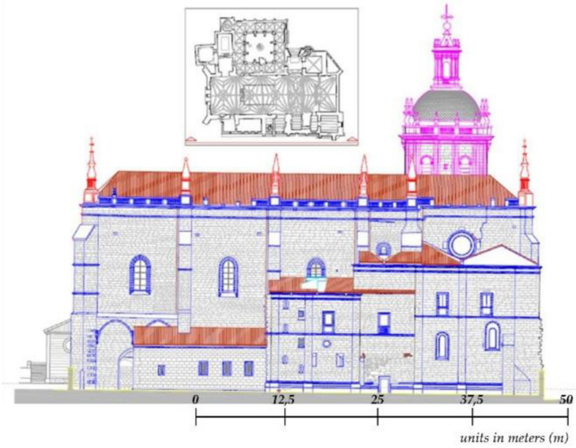


Figure 5. Delineated plane in CAD, seen from the eastern façade of the Coria Cathedral.

Regarding the measurements with GNSS in the different surveys, the fit of the external network presented maximum differences of 3 mm in planimetry and 5 mm in altimetry. The proximity network, processed from the data of the external network and for the coordinates obtained in the first processing, presented maximum variations of 7 mm in planimetry and altimetry. The differences found were of less than 10 mm, which is the precision of the measuring system, reflecting the absence of greater movements of this range in the foundation platform of the cathedral. The proximity network posed some difficulty in data collection and processing: problems in the location of the bases (accessibility, stability and robustness of the signals over time); errors due to occlusion or obstruction of satellites; errors due to the poor rebound of the multichannel signal; errors due to jumps in the cycle in the resolution of ambiguities.

The problem that arises in data collection resides in the location where the GNSS reading points are located. As they are situated in the interior of the streets of the town, shadows and reflections in satellite readings are inevitable. Moreover, during the measuring process the sensors used are exposed to passersby and vehicles, which increase the effects of shadows and reflections. The methodology was difficult to implement, above all that of the proximity network, to a great extent owing to the characteristics of the area of measurement within the urban centre surrounded by so many buildings of significant height.

With TLS, an exhaustive knowledge of the structural configuration of the cathedral was obtained with 2,987 million of points. This information facilitated a reliable structural calculation of the building in its real state, eliminating assumptions or simplifications of parameters and provided the real thicknesses of walls, the deviation of vault ribs and their thicknesses, the height of the backfill of de vault, all leading to the correct estimation of the loads that the structure is bearing.

An equally exhaustive study was made of existing pathologies. Figure 6 and Table 1 reflect the study of cracks in the eastern façade. In order to obtain the geometry of the cracks (Table 1) two procedures were used. Firstly, direct measurement on the point cloud at 60 different locations. Table 1 shows the highest value obtained. In order to check it is measured once more in CAD from the orthophotographs of elevations generated with a resolution of 0.5 centimetres. The difference in the results of the two methods is below the resolution limit.

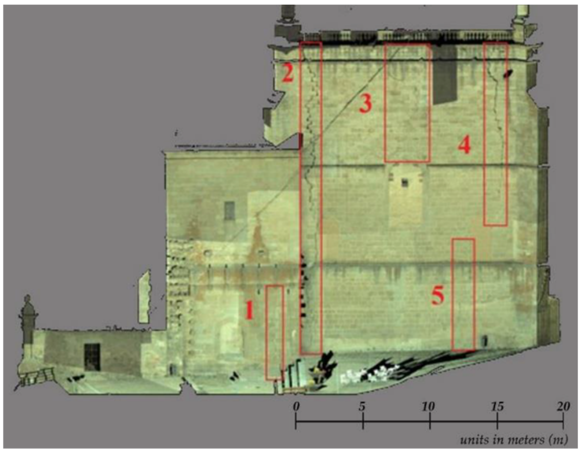
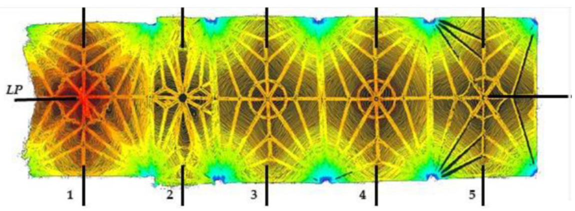


Figure 6. Analysis of the cracks in the eastern façade.

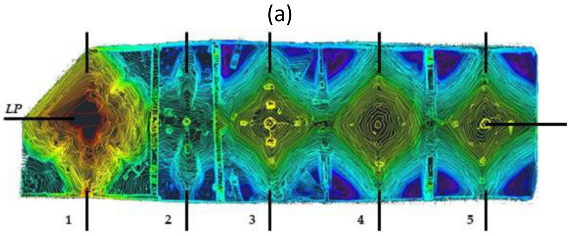
Table 1. Results of the geometric analysis of cracks in the eastern façade

Crack number	Lenght [m]	Maximum width [cm]
1	6.467	8.2
2	24.322	10.1
3	8.066	4.8
4	14.235	8.8
5	9.219	6.2

Vaults 2 and 5 (in the central nave) are those that have the best preserved symmetry (Figure 7a) (Figure 7b). Vaults 1 and 4, particularly the latter, are those with the greatest deformations with respect to their theoretical model. Vault 4 presents a marked deformation in the upper left part, both in the intrados (Figure 7a) and in the extrados (Figure 7b).



(a)



(b)

Figure 7. Topography of the vaults obtained from the 3D point cloud: a) Bottom of vaults; b) Top of vaults

C. *Structural stability*

The cathedral rests on a granular upper layer, a few meters thick, of siliceous gravel with a clay silt matrix from the Quaternary, draining, with medium compactness and sufficient capacity to bear the load. Under the granular substrate there is another of clay silt, of great depth, cohesive, non-expansive and with low plasticity.

The foundations of the cathedral are direct, in which the load bearing walls, hardly increasing its section, are supported by both the described substrates. The estimated tensions transmitted to the foundation grounds reach maximum values of around 7 kp/cm^2 which is higher than that required for this kind of material in a new construction.

From the studies carried out on the stability of the slope we can conclude that the slope on which the cathedral sits, specifically the east-south area, presents tension and deformation states close to a limit situation, and local phenomena of instability may arise in conditions of ground saturation within the foundations or of moderately intense seismic waves.

The laws of effort the structural elements withstand have been calculated and the main pathologies exhibited by the cathedral are reproduced. The results of vertical descent movements, horizontal deformation, movements according to different directions, maximum and minimum tensions, Von Mises tensions, for both vaults and walls, are obtained for different hypotheses of calculation. The model finds the existing cracks. From the geometric information of the building, the laws regarding efforts and deformations of the model bar elements, as complete arches of vault, have also been calculated, locating which areas of the arches are working a traction effort.

V. Discussion

Coria Cathedral is a special case of a large building which has suffered a long history of damage. The incorporation of modern geomatic techniques in which structural and geotechnical analyses have been used to support the work have helped to deepen the research into the secular causes of the building's ills. These have been narrowed down and identified.

The three-dimensional model of the whole building and its most immediate surroundings were essential for the development of the remaining activities, such as the geometric analysis of the elements making up the building, the study of the pathologies according to the cathedral's distribution and real dimensions, the elaboration of a structural model that fits the reality and the geometric basis for the drawing up of a constructive project.

The preparation of valid graphic documentation for the preparation of the project and the construction of models requires a manual process using CAD for the transformation of the point cloud and orthoimages to vectorial geometric entities that define floors, elevations and sections. This manual work requires the development by qualified personnel with knowledge not only of geometry, but also of architecture and engineering.

The TLS data collection work was efficiently, the problem really arose in the upper parts outside the building (roofs), because of inaccessible areas or those difficult to access and the possible dangers the work may involve on steeply sloping surfaces at height. Nevertheless, despite these difficulties, practically the entire building was surveyed with the exception of individual points that are not of the utmost importance to the studies carried out, such as, for example, the upper part of the lantern that crowns the tower vault, which is inaccessible.

No movements were detected in the cathedral surroundings during the surveys. The three-dimensional geometric model is a suitable basis for the elaboration of the corresponding analysis model and structural calculation used. Its validity would only be in doubt as a result of possible differential movements or displacements of sufficient size as to invalidate the model, which would certainly be reflected in the increase in the size of the existing cracks in the building, the appearance of new ones or variations in the verticality of the walls, among other phenomena. None of these were detected during the work. The results of the structural and geotechnical calculations have shown the behavior of the building and its surroundings.

VI. Conclusions

The studies and works carried out on the cathedral of Coria are an example of how an interdisciplinary approach must be applied in the comprehensive conservation of buildings of historic heritage.

The validity of the application of geomatic techniques with terrestrial sensors in the management of the preservation of cultural heritage is clear. Through the technique of TLS exhaustive knowledge of the geometry of an individual building is achieved permitting the later development of exact studies of geometric, structural and even geotechnical analyses. They are, therefore, techniques that can be used within a much broader spectrum of uses than simply data collection itself.

The combination of these Terrestrial Laser Scanner (TLS) and Global Navigation Satellite System (GNSS) establishes reliable bases of graphic and exact information which clears the way to creating models of structural and geotechnique analysis, that can lead to the design of projects whose aim is the preservation and stabilization of buildings of heritage value. The case of the work performed on Coria Cathedral is the paradigm of the use and interrelationship of different techniques leading to the definition and execution of restoration works and structural consolidation in which geomatic techniques are placed, if not as the starting point, at least as the fundamental basis that opens the way to other disciplines.

The techniques and methodologies used offer results of real and exact geometry associated with the date the data are collected. The monitoring of movements in this kind of buildings with secular pathological problems must involve the analysis of the evolution of movements of structural elements or those that constitute the building itself.

Traditionally, analysis has been made using fixed apparatus auscultation of relative movements in local elements. These are high precision sensors with relatively short runs, which can measure the opening of cracks and fissures (fissurometers), twists in wall faces (clinometer), relative movements between wall faces (convergence cells) etc. These sensors have the advantage that they offer readings with cadence to be defined by the user by means of suitable software, though they have the drawback of their location at one point and the need to keep the auscultation system itself in place for a long time. It would be interesting to explore the possibility of a system that coordinates both techniques, one of high precision auscultation sensors and of periodic data collection by complete geomatic techniques of singular or sensitive elements on an initial model of the entire building.

The works and studies described in this article have been of great importance to the development of technical projects of consolidation and restoration of Coria Cathedral.

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