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The combination of geomatic approaches and operational modal analysis to improve calibration of finite element models: A case of study in Saint Torcato Church (Guimarães, Portugal)

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HIGHLIGHTS

- Numerical study applied to historical building with non-intrusive sensors.
- Structure from Motion, allows generating realistic and complete 3D models.
- The methodology presented transforms the data from geotechnologies into CAD models.
- Operational modal analysis for finite element model calibration.
- Modelled features from Structure from Motion can improve the dynamical response.

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ABSTRACT

This paper present a set of procedures based on laser scanning, photogrammetry (Structure from Motion) and operational modal analysis in order to obtain accurate numeric models which allows identifying architectural complications that arise in historical buildings. In addition, the method includes tools that facilitate building-damage monitoring tasks. All of these aimed to obtain robust basis for numerical analysis of the actual behavior and monitoring task.

This case study seeks to validate said methodologies, using as an example the case of Saint Torcato Church, located in Guimarães, Portugal.

1. Introduction

The conservation of historic buildings requires understanding their structural behavior, and consequently: (i) their boundary conditions, (ii) the characteristics of the constitutive materials (iii) the origin of the damage that the building suffers and (iv) their vulnerability [1]. Therefore the creation of accurate numerical models is imperative in order to obtain adequate restoration systems.

Masonry walls are very common in the vast majority of existing monuments. Cracked elements, associated with different events (settlements and/or excessive displacement loadings) are a common problem that reduces the service life of these structures [2]. The fracture phenomena (cracks) are caused by the masonry's high brittleness to tensile stresses. Furthermore, the structural behavior is highly dependent of the structural geometry. This is why four conditions are required to carried out proper analysis: (i) having a complete and accurate geometric characterization of the structure; (ii) knowing the material's mechanical properties (iii) characterizing all the loads acting in the structure; and (iv) providing

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Abbreviations: UAV, Unmanned Aerial Vehicle; SfM, Structure from Motion; PW, Photogrammetry Workbench; MAC, Modal Assurance Criterion; DR, Douglas–Reid Method; ICP, Iterative Closest Point; NURBS, Non-Uniform Rational B-Splines.

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numerical models that correctly simulate the characteristic behavior of the structure (non-linear material behavior, ground settlement, contact between bricks, etc.).

Modern restoration techniques for built heritage are characterized by minimal intervention, compatibility, durability and reversibility [3]. Identifying and to monitoring the pathological condition of the building plays a key role in understanding the current behavior of the structure and the choice of restoration methods to be accomplished [4].

Traditional measuring methods often had a significant dependence of the worker's skills and they normally have associated high time cost. These methods were replaced by direct interpretations done over the building plans (design models) [5–7]. The constant progress of the numeric method of finite elements and computer processing allows the generation of increasingly complex geometric models; that is why it is more and more imperative the necessity of relying on sensors capable to provide massive detailed data and features for the model. Is in this field where geomatic sensors like terrestrial laser scanner [8,9] or digital camera [10] have acquired important roles, due to the capacity of acquire accurate geometrical information needed by the numerical models.

In the present paper, the proposed methodology for data acquisition combines and enhances the laser scanning and digital camera system providing, beside the characteristics defined above, the versatility of adaptation to different infrastructures. All of this within a single application, a hybrid point-cloud, which greatly eases the preparation of geometrically precise numerical models that also serve as a basis for the monitoring of the structure through the analysis of, either the point-cloud or by the analysis of the obtained orthoimages.

The paper relies on the application of the proposed methodology on a case study, St. Torcato Church, close to the city of Guimarães, Portugal [1]. This historical construction has moderate to severe damage and needs to be strengthened. The methodology has been carried out to upgrade and calibrate the finite element model using a global dynamic identification, including crack and geometric improvement, in order to complement with the static and dynamic monitoring system and a future numerical analysis. All this will be made in order to obtain the current stress state of the building and asses the effectiveness of subsequent restoration mechanism that aims at stabilizing the damage.

Within this context, this article attempts to demonstrate a methodology for data acquisition and processing and it is organized in the following way: Section 1 is the introduction; Section 2 presents the instruments for data acquisition which are the laser scanner and the set formed by the UAV and digital camera; Section 3 wherein the methodology for obtaining the hybrid point-cloud and the calibration of the model is shown; Section 4 the data obtained by the laser scanner and the digital camera sensors is analyzed separately, for the presented case study and for the potential of the hybrid point-cloud (this applies not only to the numerical finite-element analysis but also to damage analysis monitoring); and finally in Section 5, the conclusions are drawn.

2. Materials and methods

As described in Section 1, the aim of this methodology is to generate precise finite-element numerical models for subsequent structural analysis. These must be precise, in terms of geometry accuracy and they must contain the necessary data to monitor and track the evolution of damages in the structure. All this within an accurate georeferenced framework and with non-intrusive sensors as the main source.

2.1. Laser scanner system: the terrestrial laser scanner

Currently the terrestrial laser scanning system has acquired great relevance by offering a wide range of advantages; one of the greatest one is the acquisition of non-contact three-dimensional geometry of the analyzed surface, preventing any disruption and allows to accurately capture geometry, providing a high density of data (millions of points) [11]. This feature includes that it does no dependency on specific lighting conditions [12]. It is therefore the combination of accuracy, speed and range of measures that has placed the system as the most powerful tool for three-dimensional modeling and reconstruction of monuments [13,14].

In order to establish a valid methodology to make more accurate finite element models, two different laser scanning systems have been analyzed based on different measurement principles (Table 1): (i) Riegl LMS-Z390i based on time of flight principle (ii) Faro Focus 3D based on the phase shift principle. For details on these measurement principles, refer to [15].

2.2. Imaging system: UAV and "Structure from Motion"

While the laser scanning system allows fast capture and processing of data, it has some drawbacks such as the difficulty for transport and the restriction of stationing in certain elevated places inside historic buildings, these places often are critical. Therefore, it is necessary to use additional platforms and sensors capable of providing accurate data from any position; for this the onboard digital camera on an Unmanned Aerial Vehicle (UAV) platform is used (Fig. 1).

The chosen photogrammetric platform was designed by Roca et al. [16]. It is made of aluminum and carbon fiber, and comprises a total of eight MK-3638 SLOW-FLY APC propeller motors controlled by a central 12 × 3.8 Brushless Control V2.0 that can manage separately the rotational speed of each of the motors. All of this provides the system with great stability and robustness against failure in flight.

In addition to this platform, a low-cost sensor, a Canon EOS 450D digital camera that had been previously geometrically calibrated (Table 2), and a Canon EF 20 mm wide-angle lens were assembled. The wide-angle lens is meant to minimize the amount of images taken.

In recent years photogrammetric data processing systems (SfM) have taken a great relevance; they are able to include into their structure the advantages of computer vision (automation and flexibility) and those of photogrammetry (accuracy and reliability) [17] in order to obtain dense three-dimensional models (point clouds) that can compete in accuracy with the laser scanner system [18]. Within this field highlights the Photogrammetry Workbench (PW) software, which implements the "Structure from Motion" system, ensuring automation (in the transformation of 2-D images to 3-D point clouds), flexibility (by allowing work with any type of camera, calibrated and non-calibrated) and quality (to ensure precision and quite acceptable resolutions).

3. Methodology

3.1. Generating the CAD model and its integration with finite elements

The early stage in the laser scanning and the Structure from Motion (SfM) data processing, have been omitted in this article, since our main interest is focused on establishing a robust methodology that serves as a template for subsequent restoration actions. This template will be based on the hybrid point cloud, which comes from the combination of data obtained from laser scanning, the SfM and the analysis of the products that are obtained from them. For more details about SfM flow see either [19].

Also is imperative to building an accurate CAD model which allows us to evaluate the actual behavior of the construction as a basis for the numerical analysis. However, at an early stage, the point cloud provided by the laser scanning and the SfM present superabundant information in different coordinate systems. As a result, this data is not suitable for CAD model building. Following a semi-automatic method that allows adapting the point cloud to an accurate and suitable CAD model for numerical analysis is presented (Fig. 2).

This methodology requires a multi-phase post-processing that involves three main steps: (i) data fusion at the same coordinate system through registration algorithms; (ii) point cloud resampling and (iii) point cloud simplification (removing certain architectural details without relevance) and parameterization for CAD model conversion.

3.1.1. Hybrid point cloud registration

A complete documentation of historical buildings requires the use of multiple point cloud data set. Is a requirement therefore to place all of these point clouds in the same coordinate system in order to be processed together.

Table 1
Comparison of technical specifications between laser scanner system Riegl LMS Z-390i and Faro Focus 3D.

	Riegl LMS Z-390i	Faro Focus 3D
Measurement principle	Time of flight	Phase shift
Wavelength	1550 nm	905 nm
Measurement range	1–400 m	0.6–120 m
Accuracy nominal value	6 mm a 50 m in specific lighting and reflectance conditions	2 mm a 25 m in specific lighting and reflectance conditions
Field of view	360° Horizontal 80° Vertical	360° Horizontal 305° Vertical
Capture rate	11,000 points/s	122,000/976,000 points/s
Beam divergence	0.3 m rad	0.19 m rad

Fig. 1. Image of the UAV platform and the digital camera (left). Image taken during the data collection of the point cloud SfM (right).

Table 2
Canon EOS 450D digital camera geometric calibration settings.

Parameter	Value
Sensor size	$W = 22.2425$ mm $H = 14.8336$ mm
Principal point	$X_p = 10.8716$ mm $Y_p = 7.4449$ mm
Focal length	$f = 20.4222$ mm
Radial distortion	$K_1 = 2.157\text{e}{-}004$ mm $K_2 = -4.189\text{e}{-}007$ mm $K_3 = 0$ mm
Tangential distortion	$P_1 = 4.321\text{e}{-}005$ mm $P_2 = -1.003\text{e}{-}005$ mm

The proposed methodology is based on a registration system coarse to fine. In an initial stage a point cloud pair-wise registration is carried out. This step takes as a base the ICP (Iterative Closest Point) algorithm [20], that minimize the difference between two points clouds, requiring a total of $n - 1$ alignments, where n is the number of point clouds.

Using pair-wise registration causes an error propagation along the registration of all the point cloud scans. In order to minimize this error accumulation a global registration, based on Generalized Procrustes Analysis [21], was used considering the pair-wise registration, previously made, as the rough registration needed.

3.1.2. Hybrid point cloud resampling and CAD conversion

Traditionally the step procedure from the raw point cloud to the CAD model could be made through three different approaches [22]: (i) orthogonal views; (ii) sections applied along directions and over the mesh and (iii) Non-Uniform Rational B-Splines (NURBS) generated from the mesh. The two first approaches require a high manual work made by the user, whereas the NURBS approach demands high computational cost.

In this article an alternative and semi-automatic approach is presented, which combines NURBS and parametric shapes approximations with the addition of a segmentation process described below, in order to build a suitable CAD model for structural applications. While NURBS-based method was used for complex shapes like (vault or domes), the parametric-based method was used for the rest of the structure.

Once the registration procedure has been completed, the resulting point cloud needs to be resampled (due to the high amount of data) in order to generate a suitable CAD model for the numerical analysis. In this case several methodologies could be applied based on [23]: (i) Principal Component Analysis; (ii) Quadric-Based Polygonal Surface Simplification; (iii) Clustering methodologies and (iv) Radial Based Function. For the proposed methodology a resampling based on curvature has been applied, in order to decimate flat surfaces without losing detail in features areas. This curvature based resampling follows the next steps: (i) creating a local neighborhood of the analysis point; (ii) local surface based on quadratic approximation and (iii) extraction of the normal and principal curvatures.

After that, the resulting point cloud is meshed, since the majority of segmentation procedures are also performed over meshes. The segmentation process is performed by Functionally Decomposed Surface Models [24]. Once the segmentation is done, the different surfaces created are approximate to NURBS and parametric shapes. As a result a manageable CAD model is generated and could be imported and used for a FEM package.

Additionally to the mentioned above, some relevant features like cracks, can be included into the CAD model that defines more realistically the building's behavior. It is sufficient to extract the area of interest from the point cloud, either SfM or laser, to mesh that area and to incorporate it into the CAD model (Fig. 3).

3.2. Crack recognition and characterization

Digital image analysis is a tool of great potential in the field of pathological characterization of buildings. Several authors demonstrate the feasibility of this analysis to characterize either from the terrestrial laser scanner [25,26] or from the image captured by a digital camera [27,28].

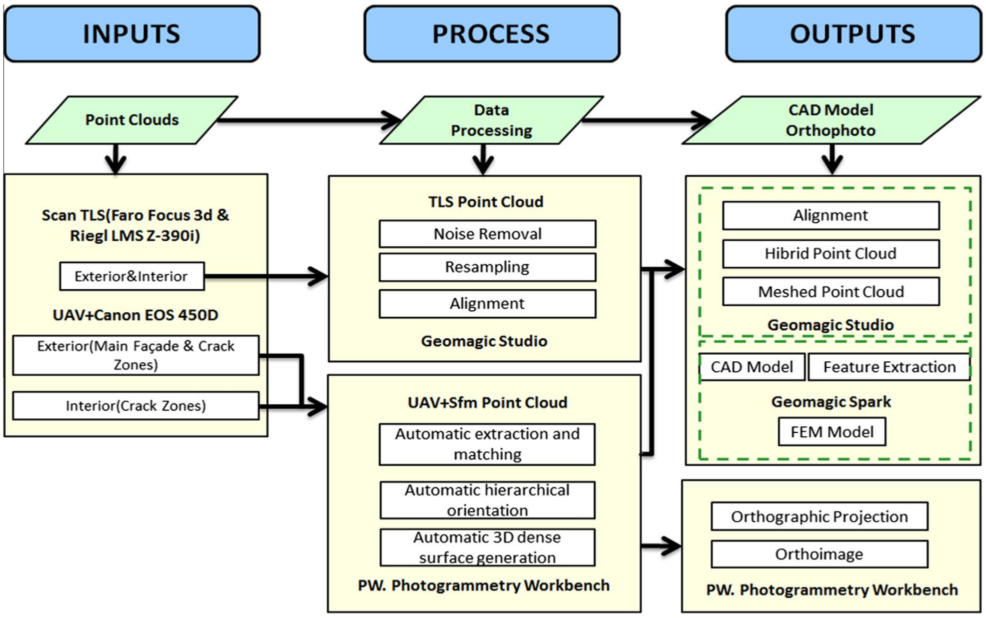

Fig. 2. Workflow for the proposed methodology.

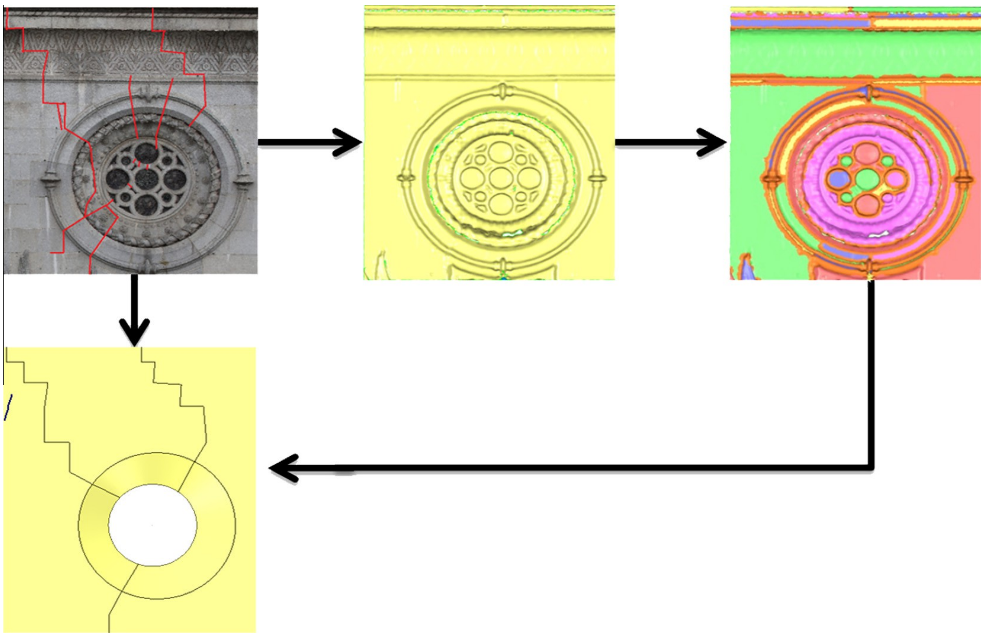

Fig. 3. Graphical description of the proposed methodology. From left to right: point cloud, mesh model, segmentation model, CAD model with major cracks.

Besides offering robust tools for generating three-dimensional models from two-dimensional data (digital image), PW can also obtain orthoimages on specific areas and specific levels, providing the user with precise documentation from anywhere in the building.

Given the high density of points gathered during the three-dimensional reconstruction, the production of orthoimages will require only two points to provide adequate scale, taken from the laser point cloud and a reference plane, in order to run an orthographic projection. The pixel size of this projection is calculated according to the density of the cloud of points, close to the resolution of the initial images [29].

Given the fact that the obtained orthoimage stands as a product without geometric distortions and in real scale, it is sufficient to directly measure on it and so obtaining crack characterization (length and opening).

3.3. Finite element numerical model

The geometric accuracy and high level of detail provided by the laser scanning systems and Structure from Motion, provide complex CAD models. In order to solve this geometric complexity, for the discretization elements it is required: (i) high flexibility to adapt themselves to the geometry and (ii) great compatibility with automatic meshing algorithms [7]. All this makes the tetrahedral discretization elements with an isoparametric formulation the most suitable for the meshing of complex CAD models.

3.4. Calibration of the finite element numerical model

The analytical results obtained from the calculation model are sensitive to material properties and boundary conditions [30] thus making necessary to gather experimental data to optimize the numerical model.

Among the different possibilities availables today for the implementation of in-situ tests on historic buildings, experimental modal identification is the most popular method [1]. This technique is a non-intrusive system with the capability to identify the global properties of the structure. It allows to obtain vibration frequencies, damping coefficients and mode shape of historic buildings, which may be related to various physical properties (Young modulus, density, stiffness of connections between parts, etc.) which makes possible to validate the analytical models [31].

This publication builds on the data obtained from the accelerometers configuration adopted in 2009. The campaign counted a total of 35 measuring points with 9 sets spread throughout the Church, for more details see [1] (Fig. 4).

The basic objective of these methods is to improve the correlation between the experimental data and those obtained from finite element model, through small changes in a group of model parameters [32]. The criterion often used to assess the correlation is the MAC (Modal Assurance Criterion), this being defined from the following formula (1) [33]:

$$\mathrm{MAC}_{u,d}=\frac{[(\varphi_i^u)^T(\varphi_i^d)]^2}{(\varphi_i^u)^T(\varphi_i^u)(\varphi_i^d)^T(\varphi_i^d)} \quad (1)$$

where φ_i^u y φ_i^d correspond to the mode shape vector on experimental and numerical model respectively for a vibration mode i.

As noted above, the goal is to minimize the existing differencies between the experimental behavior and numerical model, considering the experimental values as references. Used in 2007 for the calibration of the numerical model for the Monza Cathedral bell tower [34], the methodology proposed by Douglas–Reid [35] (DR) can be used for calibration of finite element numerical models. This method tries to minimize the difference between theoretical and experimental parameters through the natural frequencies, or another modal parameter, using the following approach:

$$R_i^{FE}(X_1,X_2,\dots,X_n)=\sum_{k=1}^{N}[A_{ik}X_k+B_{ik}X_k^2]+C_i \quad (2)$$

To solve these equations, a total of $2n+1$ values are required to be calculated, taking into account initial values, as well as lower and upper bounds for all updating parameters.

Using the methodology followed by [34], the next step consists of determing the modal frequencies and minimize their difference according to the following objective functions (3) and (4):

$$J=\sum_{i=1}^{m}w\varepsilon \quad (3)$$

$$\varepsilon=f_i^{EXP}-f_i^{FE}(X_1,X_2,\dots,X_n) \quad (4)$$

where J is the objective function to be minimized, w are the weights considered through engineering criterion and e represents the error function (difference between the frequency obtained by operational modal analysis f_i^{OMA} and numerical analysis f_i^{FE}).

The main drawback of this methodology lies in the consideration of a unique modal parameter; frequency. To obtain more

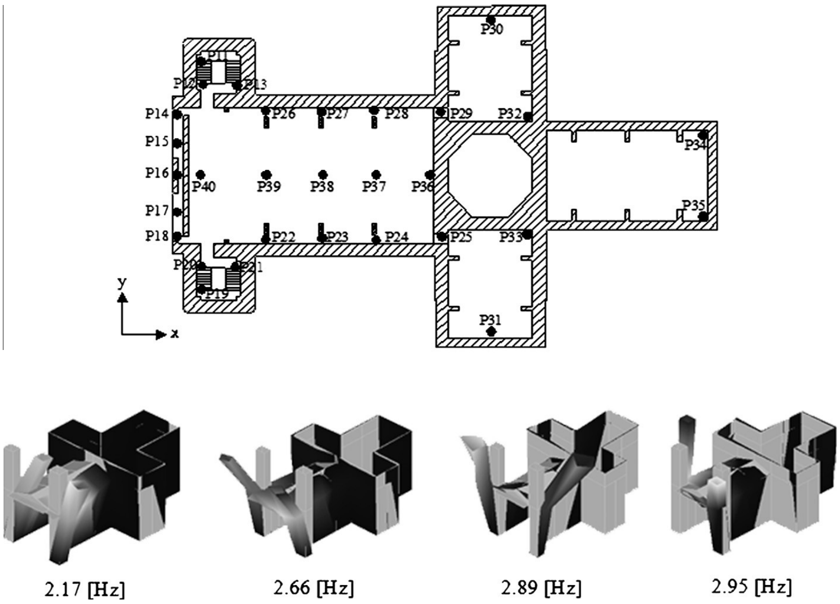

Fig. 4. Scheme of the arrangement of the 35 accelerometers on the Church (above). Mode shape obtained from operational modal analysis (bellow).

accurate results the objective function must be modified, including the MAC values (5):

$$J = 1/2\left[W_f\sum_{i=1}^{m}\left(\frac{f_{i,\mathrm{FEM}}^2 - f_{i,\mathrm{EXP}}^2}{f_{i,\mathrm{EXP}}^2}\right)^2 + W_m\sum_{i=1}^{m}(1-\mathrm{MAC}_{i,\mathrm{FEM}})^2\right] \tag{5}$$

where J is the objective function to be minimized, W_f and W_m are the weights considered for the frequency and vibration modes, f is the frequency and MAC the Modal Assurance Criterion values, both values corresponding to the vibration mode i.

4. Experimental result and discussion

Located in the village of St. Torcato, within the municipality of Guimarães (northern Portugal), the Church of St. Torcato is a clear example of historic building built in stone material, showing moderate-severe structural damage made evident mostly by cracks in its main façade. Starting at the entrance arch keystone, it extends through the rosette to the coronation, splitting this element in two macroblocks [1] (Fig. 5).

Such crack increases the width along its development up to the roof. The movement in opposite directions of the main façade towers due to the settlement suffered by the building is remarkable, as well as some "chrusing" type cracks caused by the compressive stress concentration resulting from eccentric loads originating in the towers.

Built in style "Neo-Manuelinio" the Church of Saint Torcato mix Classics, Gothic, Renaissance and Romanesque elements in its extension [6]. This gives it a special and complex aesthetic that along its length, with a height of about 50 m in the towers, prevents effective tridimensional data capture with laser scanner, topographic techniques or manual measurements [36]. The binomial Structure from Motion and laser scanning is the ideal solution allowing abundant and accurate three-dimensional data capture anywhere in the building.

The results obtained are hereby analyzed independently, according to the source sensor (laser scanner or digital camera) and the resulting numerical model of the combination of these and the calibration using operational modal analysis.

4.1. Terrestrial laser scanner

For the study we have considered the two most popular measuring systems for survey of buildings and civil infrastructures: the laser time of flight and phase difference [25].

Multiple tests have been carried out in the exterior as well as in the interior of the Church. Since the point-cloud is defined by density of points, the acquisition rate and range, the laser scanner LMS Z-390i Riegl (based on time of flight) is considered to be the most suitable for data capture in the exterior. Besides, it has a larger range compared to the Faro Focus 3D laser. Indoors, the data acquisition speed of the Faro Focus 3D scanner (122,000 points/s) compared to the speed of the Riegl LMS laser Z-390i (11,000 points/s), together with its portability proved to be the most important advantages for gathering the data in the interior of the Church.

While in both cases the laser system provides a sufficient and suitable density of points to accurately monitor deformations [37], the amount of data and distinctive features provided might be insufficient of the extraction and monitoring of cracks (for example, it does not record texture) (Fig. 6).

The final model had a total of 29 scans and 267,601,626 points: (i) 14 scans were done of the outside with the Riegl LMS laser Z-390i, (ii) 3 interior shots were taken with the Riegl LMS laser Z-390i and (iii) 12 interior scans were made with the Faro Focus 3D laser. However, the top of the towers and the rooftop of the Church could not be modelled because no suitable location was found for the laser to reach those areas. In addition, the data collection was hampered by additional conditions: the excessive laser beam skew angle on the ledge, top of the towers and the openings between the chapels preventing a complete and accurate characterization of the building and of the critical areas. Thus requiring a complementary technique capable of solving such weaknesses, UAV and SfM.

4.2. UAV and Structure from Motion

The point-clouds collected by laser scanning do not provide a sufficient amount of data for a full geometric characterization of the outer shell: either the distance from scanner to object the range is too large, the point of view is insufficient or the laser system cannot be placed in a certain location, such as in the upper region of the façade beyond the central cornice.

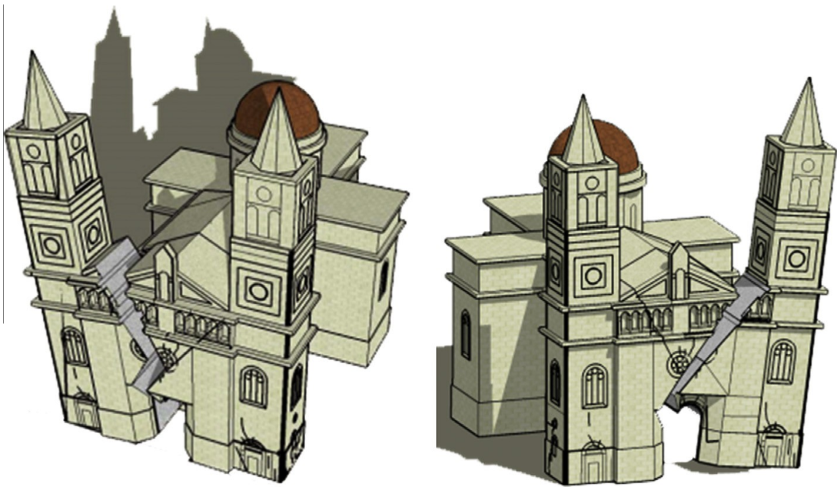

Fig. 5. Representation of the possible structural failure collapse mechanisms of the Church of Saint Torcato. It is possible to observe the formation of two macro-blocks.

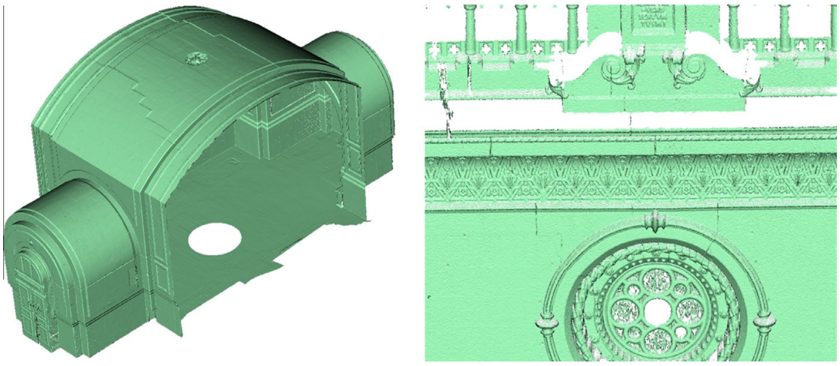

Fig. 6. Settlement of the entrance vault detail (left). Settlement of the entrance vault detail (right).

In addition to the aforementioned, the obliqueness phenomenon must be considered. As shown by authors such as [38,39], this phenomenon is highly correlated with the value of uncertainty in obtaining a point's spatial coordinates. This phenomenon is of great importance in obtaining accurate products and it is highlighted by this case study, where it is critical in certain areas, such as in the inclination of the towers or in the cracking of the central façade.

All this requires a supplementary technology to the laser scanning, this is UAV + SfM; a non-intrusive way of solving the problems described above through its great portability and ability to collect data. Besides, it gathers an extra supply of analyzable features, which makes it possible to get complete point-cloud models, which form the foundation for accurate and thorough CAD models. These models profit from the features obtained from the hybrid point-cloud, such as cracks (Fig. 7).

This model, generated through the described technique, is comprised of a total of 398 photographs taken by UAV platform: (i) 273 photos of the main façade dividen in 3 vertical strips (1 for each tower and one for the main façade) and (ii) 125 photos of the cracks on chapels, also divided in 3 vertical strips. Alongside these photographs, 117 additional shots were taken without UAV platform (terrestrial photogrammetry): (i) 85 photos of the arches of the chapels of the main nave and (ii) 32 photos at the level of the Church choir.

Both techniques, terrestrial laser scanner and SfM, complement to each other, and their combination is the ideal solution for restoring built heritage. While the laser scanner provides the system a set of precise, dense and fast capture data with which it is possible to monitor structural movement and generate a CAD model suitable for numerical analysis, the UAV + SfM system combines with it perfectly supplying the geometric data of the areas that were unreachable through the previous system. In addition, it characterizes completely the structure's pathological conditions by obtaining direct and georeferenced data.

Fig. 7. Front elevation of the point cloud obtained through SfM technique and PW software (left). Detailed comparison between the laser scanner point cloud and the one obtained in PW software (right).

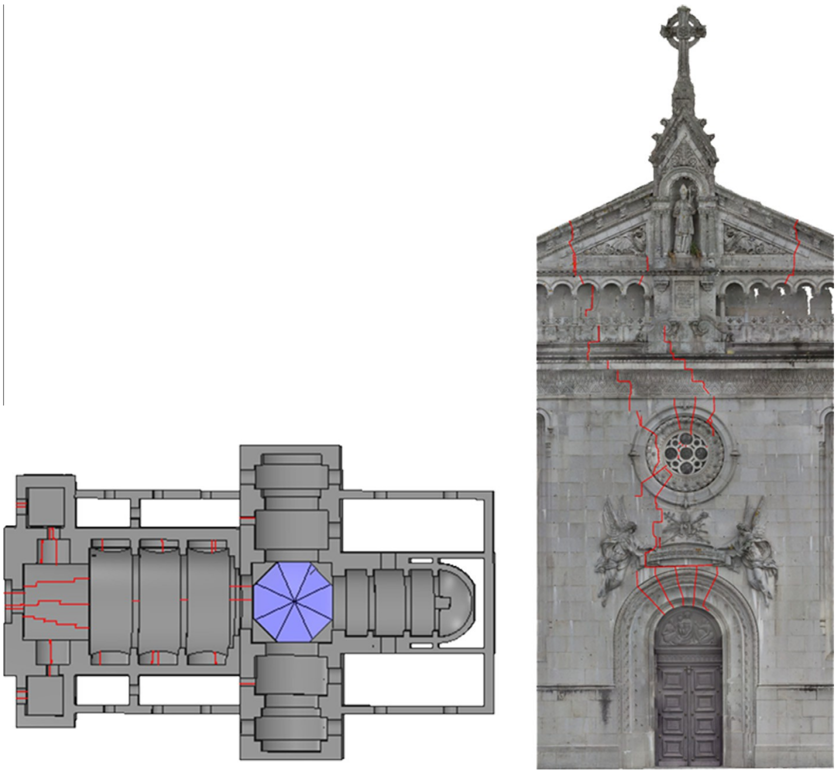

Fig. 8. Results of the inspection for damages: plan view at ground level (left). Main façade orthoimage inspection for damages (central part) (right).

However, the resulting data of both sensor show different coordinate system but the high redundancy allows the creation of a single model applying the methodology explained in Section 3, that finally is converted into a valid CAD model of the building for the subsequent analysis. An average value of 0.0125 with a standard deviation of 0.0065 was found in the coarse registration process. Later, in the fine registration process this values down to 0.0035 with a standard deviation of 0.0011. The final hybrid point cloud had a total of 40,359,060 points (that represents a 10% of the original set).

4.3. Characterization of structural pathologies

The characterization of cracks plays a fundamental role in structure monitoring in terms of stability and safety. Traditionally such monitoring was conducted with graduated cards, mechanical or electronic gauges, or LVDT (linear variable differential transformer). However, this equipment has significant drawbacks [27]: (i) firstly, there is a need for permanent plates, that may become damaged or can be lost, (ii) they provide data only from certain points and certain directions, (iii) the cracking is not directly measured; it is assumed that its activity is correctly defined by the variation of the reference points. In addition to this, some of these methods strongly rely on temperature (this is the case of electronic gauges).

Thanks to the combined use of the shown spatial-data capture techniques, it is possible not only to obtain high density point-clouds and photorealistic textures (this is the case of UAV + SfM system) but also high quality orthoimages in any position and on determined surfaces, thus solving the problems described above. All supplemented with direct product georeferencing, which makes perfectly viable to monitor the movement of the structure and the evolution of damage that may arise.

The aforementioned methods combined with an accurate numerical model will comprise all the necessary tools for sizing and evaluating the restoration system of the building.

The first damage inspection of the monument [6] was carried out in 1998. The inspection indicated that the façade suffered structural damages, made evident by cracks running from its bottom, in the keystone to the coronation. In addition, patologies are observed in the entrance dome keystone under the choir, in the arcs are that make up different bays of the main nave and in cracks on the side of the building.

It is on the main facade where the building shows a greater amount of these pathological conditions, spread along as cracking and displacement on elements of arches and vaults (Fig. 8). Fig. 8 results of the inspection for damages: plan view at ground level (left). Main façade orthoimage inspection for damages (right).

4.4. Geometrical CAD model

Made by the proposed methodology, the Saint Torcato CAD model has greater geometric complexity than the one exposed by Lourenço and Ramos [6]. Within this geometric improvement is remarkable a better characterization of the main façade and towers, including architectural details over the balcony and along the towers.

Since most of the façade shows structural pathological conditions, it is therefore expected that the dynamic response of the structure will be influenced in part by such cracking. The high correlation between the CAD model and the actual photogrammetric point cloud allows to incorporate these characteristics into the

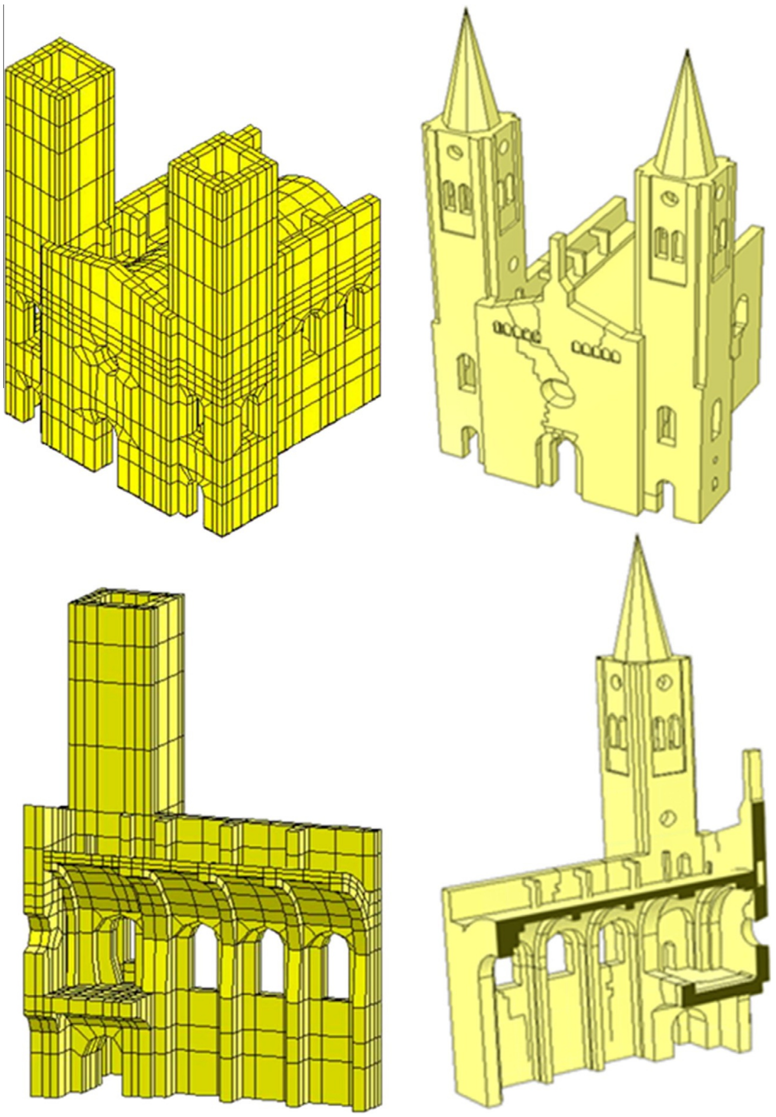

Fig. 9. Isometrics views of the initial geometric model (left) and the one generated by the proposed methodology (right).

CAD model directly, only requiring the meshing of the area under study. Also this model, presents different wall thickness, increasing the model realism (Fig. 9).

4.5. Definition of the numerical calculation model

While the geometric aspect has been completely improved by the methodology presented, the material characterization (homogeneous and isotropic), since at the time no experimental test were carried out, the input loads and boundary conditions remain the same than the initial one. For the loads have been consider: (i) gravitational loads; (ii) truss self-weight and (iii) roof self-weight.

Complementary to this loads conditions, it is necessary to correctly simulate the elastic behavior (Winkler model) of the ground in which the structure stands and also a proper simulation of the behavior of the transcept. Such behavior has been emulated through CONTACT173/TARGET170 elements [40].

The discretization of the model has been carried out considering a 4-node isoparametric tetrahedral element (SOLID65) with a maximum size of 0.60 m. In order to increase the robustness of the tetrahedral mesh, element softening has been carried out using Laplace algorithm [40].

All this results in a total of 218,244 discrete elements into the numerical model (212537 SOLID65, 5707 CONTACT173/TARGET170) (Fig. 10).

4.6. Modal analysis, calibration of the numerical model

The next step required to obtain an accurate finite element model is to calibrate their elastic parameters and thus adapt the dynamic behavior of the numerical model to the real one. In order to accurately calibrate the numerical model it is necessary to follow a three-step procedure: (i) initial hypothesis, (ii) manual calibration and (iii) robust calibration. The initial hypothesis considered were: the elastic properties of masonry, the major

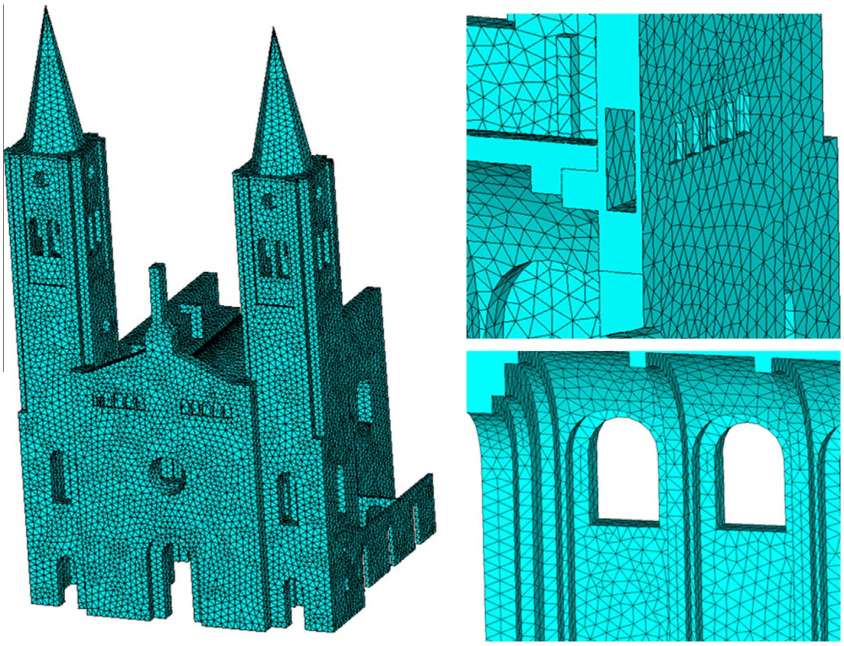

Fig. 10. Isometric view of the mesh model (left). Mesh detail of the balcony and chapels (right).

Table 3
Summary of the adopted values for the calibration of the numerical model.

	Initial values	Lower bound	Upper bound	Updated value
$E_{MASONRY}$ (GPa)	10	5	15	9.19
$\delta_{MASONRY}$ (kg/m^3)	2500	2400	2700	2600
$K_{NFAÇADE}$ (GPa/m)	0.0001	0.00005	0.01	0.0004
$K_{TFAÇADE}$ (GPa/m)	0.1	0.05	1	0.53
$K_{NFIRSTCAP}$ (GPa/m)	1	0.05	5	0.40
K_{NSOIL} (GPa/m)	0.585	0.0585	5.85	0.627
$K_{NTRANSCEPT}$ (GPa/m)	0.1	0.005	1	0.29
$K_{TRANSCEPT}$ (GPa/m)	0.0001	0.00001	0.01	0.00002

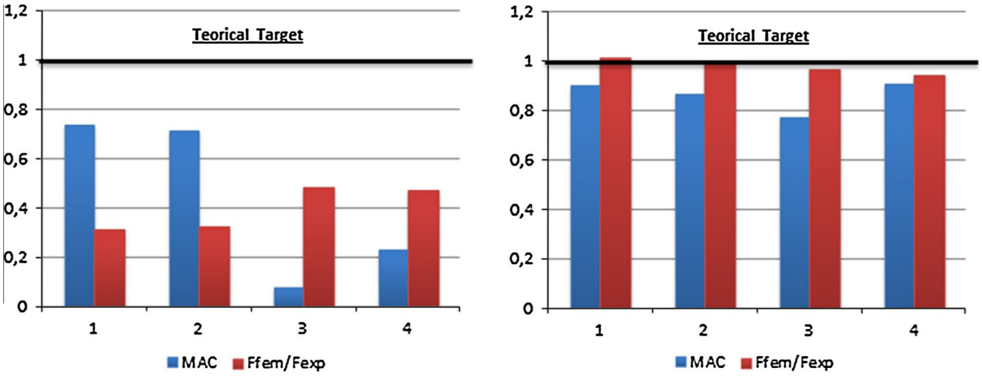

Fig. 11. Comparison between representative values of dynamic response (frequencies and MAC): value ratio of the initial model proposed by Lourenço (left). Ratios obtained with the hereby proposed methodology (right).

cracks on the main façade and the main nave, the elastic behavior of the soil, and the simulation of the connection between the nave and the transcept.

Within the manual calibration stage, numerous tests have been required, evaluating separately each of the considered elastic variables and rejecting those that did not bring improvements to the numerical model. Finally, have been chosen a total of eight parameters, namely: Young modulu's of the masonry ($E_{MASONRY}$) and its density ($\delta_{MASONRY}$), the normal ($K_{NFAÇADE}$) and shear ($K_{TFAÇADE}$) stiffness of the major cracks on the main façade, the normal ($K_{NFIRSTCAP}$)

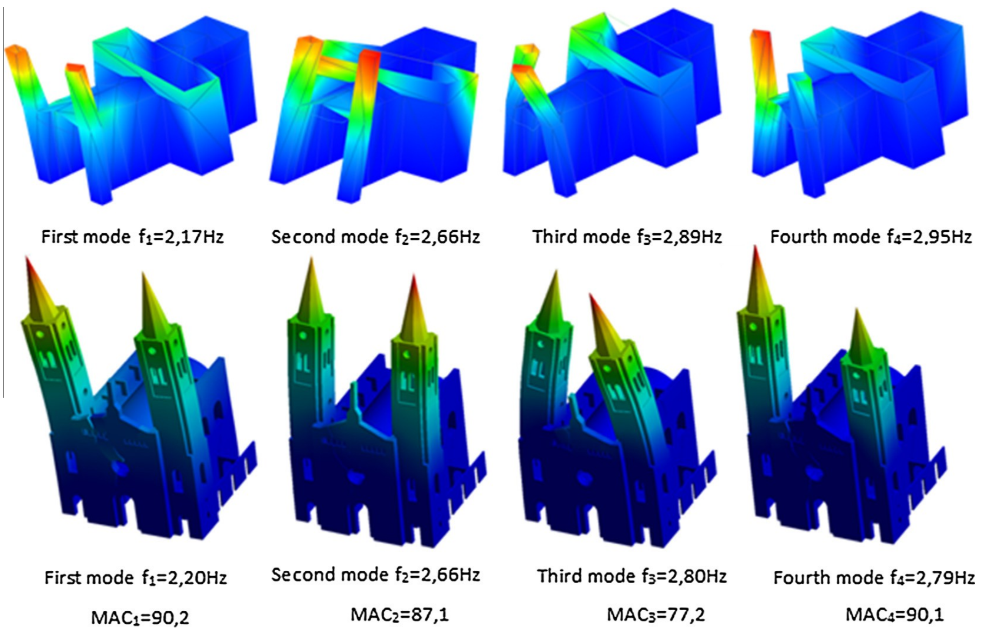

Fig. 12. Comparison between the vibrational model form the OMA and those from the hereby presented finite element numerical model.

stiffness of the major cracks on the main nave, the soil's normal stiffness (K_{NSOIL}), as well as the simulation of the connection between the main nave and the transcept through a normal stiffness ($K_{NTRANSCEPT}$) and a shear one ($K_{TTRANSCEPT}$). During the last step, the accurate calibration of the previously discretized parameters through DR methodology (described above) was required, providing the results presented below (Table 3).

The now calibrated elastic properties of the masonry show a globally damaged material. The high elasticity obtained in the simulation of the transept confirmed that the building, as it progressed, suffered settlements and cracking. However, the rise in rigidity of the elastic properties in comparison to the initially calculated in [6], denote soil compaction. As shown in (Fig. 11) (Fig. 12), the relative ratios between the experimental and numerical frequencies, with a value close to one for the standard MAC indexes denote a high correlation between the experimental dynamic behavior of the building and the numerical one. Through the simulation of the cracks, it was possible to correctly simulate the dynamic behavior and the high existing elasticity in the central area of the building.

5. Conclusions

The methodology presented aims to compile the information from different sensors in order to establish a complete geometric characterization of historic buildings. The combined method for data acquisition solves most common problems encountered today like the preparation of accurate CAD models and the analysis of structure characteristics (displacements and cracking).

Using the laser scanner alone would not solve some of the problems that arise today, i.e. the lack of data in areas that are not accessible to the system or the difficulty of cracking identification. That is why it is essential to incorporate a complementary data capture system able to meet solving problems. The perfect complement for an accurate, quick and complete data capture is the Image Structure from Motion System on UAV platform. Other advantages provided by this second capture system, lies in the potential that digital image analysis gives to the graphical product. This digital image analysis makes possible to completely characterize cracking (length and opening).

The binomial SfM-laser scanner is a reliable foundation from which to analyze appropriate restoration actions, following the procedure: (i) analysis of the causes through the numerical model (ii) displacement and stress state along the structure (iii) analysis of the effectiveness of the system (analysis of the numerical model including restoration activities, analysis of cracks and collapses systems).

The methodology presented can be applied to other infrastructures, such as tunnels or bridges, given the high versatility of the sensors described and the wide range of possibilities that they offer. All this is complemented by a global dynamic analysis of the structure that allows a reliable calibration of the numerical model through the elastic system variables.

The Saint Torcato Church (Guimarães, Portugal) represents an ideal case study for evaluating the potential of the method developed. Based on the geometric characterization performed through the presented methodology, several research works are taking place, in order to improve the characterization of the different materials by Ground Penetration Radar and Boroscopic Camera, for further FEM analysis.

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