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Implementation of a wireless structural monitoring system and reverse engineering for numerical analysis purposes of a 16th century church

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Abstract: The conservation of built heritage structures requires constant attention to the progression of existing damage and the assessment of their structural response to different phenomena or interventions. Quasi-real time structural monitoring allows the observation and measurement of the structure’s response over time, registering different kinds of metrics, which enable early detection of damage or changes. When combined with structural analysis it allows for a better contextualization of physical metrics and the possibility of global response assessment. This paper focuses on the implementation of a structural monitoring system in the Igreja Matriz de Freixo de Espada à Cinta, in the North of Portugal, and the process of reverse engineering the three-dimensional model built with data from a LiDAR survey. The monitoring system included the installation of wireless smart sensors in two areas of the church, where there is significant cracking. To measure the crack opening, the rotation of the walls, the vibration of the structure, and the effects of temperature and humidity, nine crackmeters, three tiltmeters, five accelerometers, and four temperature and humidity sensors were installed. A three-dimensional finite element model was built using the architectural modelling done with the point cloud information. Different conditions and scenarios are being studied, through preliminary linear and nonlinear phased analyses.

Keywords: LiDAR, monitoring, reverse engineering, 3D-modelling, heritage

1. Introduction

Management and maintenance of several heritage assets is a complex task that mobilizes a great number of resources, human and otherwise. Particularly in the case of heritage assets, early detection of damage is crucial to maintain the state of conservation and decrease the extent of interventions. Hence, the necessity to gather reliable data on the ongoing response of assets to natural and men-made hazards.

The project SIAP - Artificial Intelligence Warning and Alert System for Cultural Heritage was developed as a response to these challenges and therefore, proposes a shift from a reactive to a proactive management system. Machine Learning techniques will be applied to process the data acquired through several sources as shown in Figure 1: satellite SAR (InSAR), LiDAR, structural monitoring (Sensoring), seismic and climate data (Seismology and Meteorology), and historical documentation (Archival). This will enable effective heritage supervision and intervention optimisation. The implementation of an early-warning system will facilitate risk mitigation, increased safety, and significant reduction in maintenance costs.

The project is coordinated by Direção Regional de Cultura do Norte (DRCN) — the regional entity that manages the public heritage in the North of Portugal — and a series of partners that create interdisciplinary research and development in Architecture and geomatics, Civil Engineering, History and Heritage Sciences, Artificial Intelligence, Systems Engineering and Technology. Further information can be found at the project website [1].

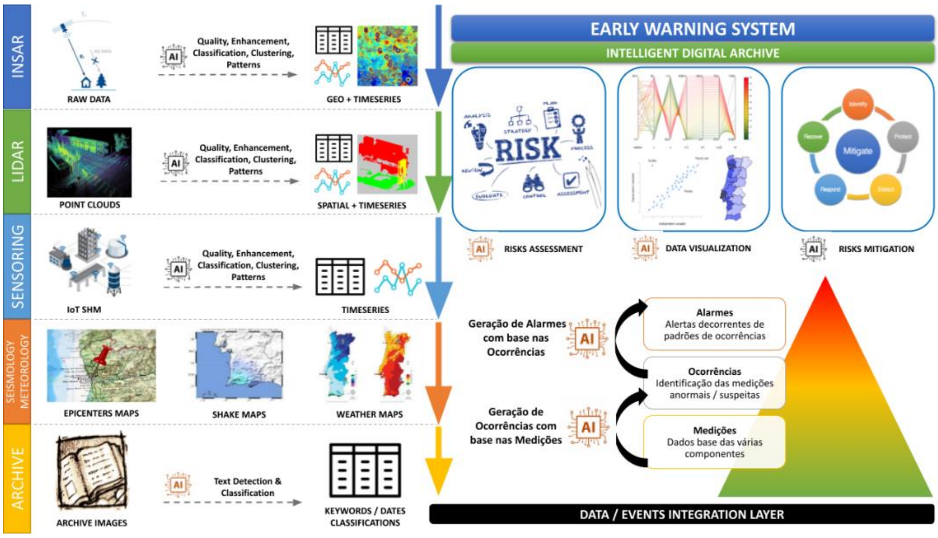


Figure 1. Summary of the approach implemented in the project SIAP [1].

The pilot project is constituted by three churches managed by the DRCN; however, this paper will focus solely on the Church of Freixo de Espada à Cinta, particularly on the works related with the implementation of the monitoring system and the preliminary structural analysis of the finite element model created from the LiDAR acquisition.

2. Case study: Church of Freixo de Espada à Cinta

The Church of Freixo de Espada à Cinta is located in the urban center of the town of Freixo de Espada à Cinta, in the northeast of Portugal but isolated from other buildings (see Figure 2a). It was ordered built by King Manuel in the 16th century. It is a hall church, with 2 aisles almost the same height to the nave, covered with ribbed vaults (Figure 2b), an apse, two apse chapels and a sacristy. The hall rectangular plan is marked by a set of exterior buttresses, and the volumes of the sacristy and the apses [2]. The choir loft is supported by granite regular masonry arches and the ceiling is composed by a set of eight-part ribbed vaults, in granite regular masonry. External walls and interior columns are assumed to be built with the same material and arrangement, although no material characterization was carried out. The roof structural system is formed by timber trusses that are supported by the external walls and interior wooden columns located in top of the vault structure.

(a) (b)

Figure 2. Church of Freixo de Espada à Cinta: (a) Aerial view; (b) interior view facing the altar [source: authors].

3. Design and installation of the monitoring system

Previous inspections of the church indicated that most damage is concentrated near the main façade of the church (facing West), concerning cracking of the ribbed vault, its connection to the façade, and the façade wall itself, and cracking of the wall adjacent to the triumphal arch, on the North side. Therefore, the monitoring system was designed with the purpose of controlling the opening of existing cracks and the formation of new ones on the walls and vaults, as well as the inclination and vibration of the walls, on the aforementioned locations (see Figure 3 and Figure 4). Temperature and humidity sensors were also installed so that their influence on the movements of the structural elements can be considered when interpreting the results.

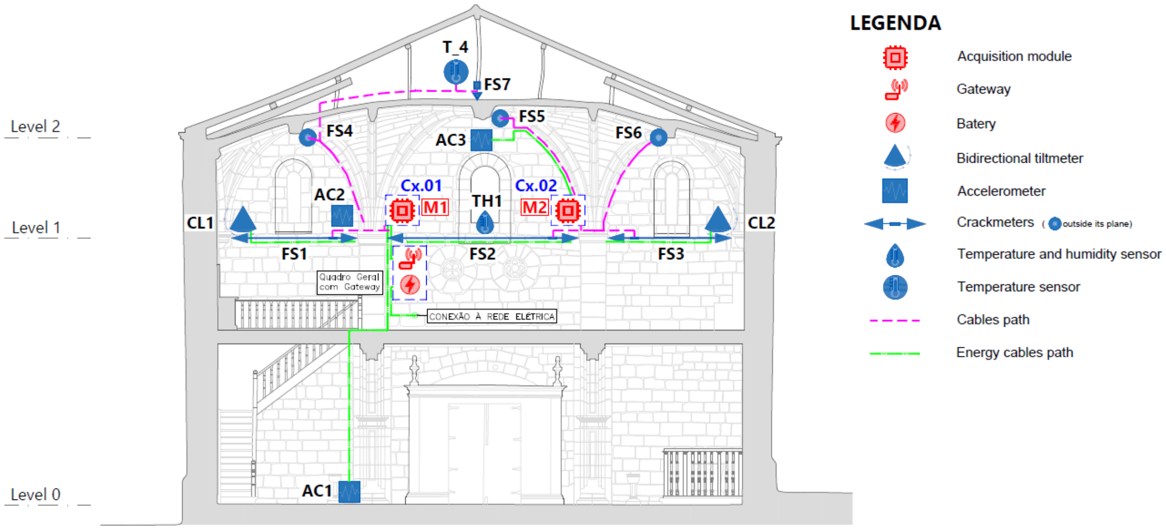


Figure 3. Monitoring system near the main façade (West) [source: authors].

The system comprises a total of twenty-one sensors among crackmeters (FS), biaxial tiltmeters (CL), triaxial accelerometers (AC), and temperature and humidity sensors (TH). The acronyms stand for the initials of the sensors in Portuguese. In Table 1, one can find the summary of sensors installed by type and level. The three levels were defined based on the height of installation relatively to the ground-floor level, as one can observe in Figure 3 and Figure 4. Besides the sensors, the system comprises three wireless acquisition modules (M1, M2, and M3) and one wireless gateway to control the external access to the network. Although, in both Figure 3 and Figure 4 are represented the paths of the cables, the system is based on wireless transmission between the nodes (sensors) of the network, which is composed by the wireless data acquisition modules (see Figure 5a) and the gateway (see Figure 5b), which were all placed at the main façade, facing West, with the exception of the module M3 placed on the wall adjacent to the triumphal arch.

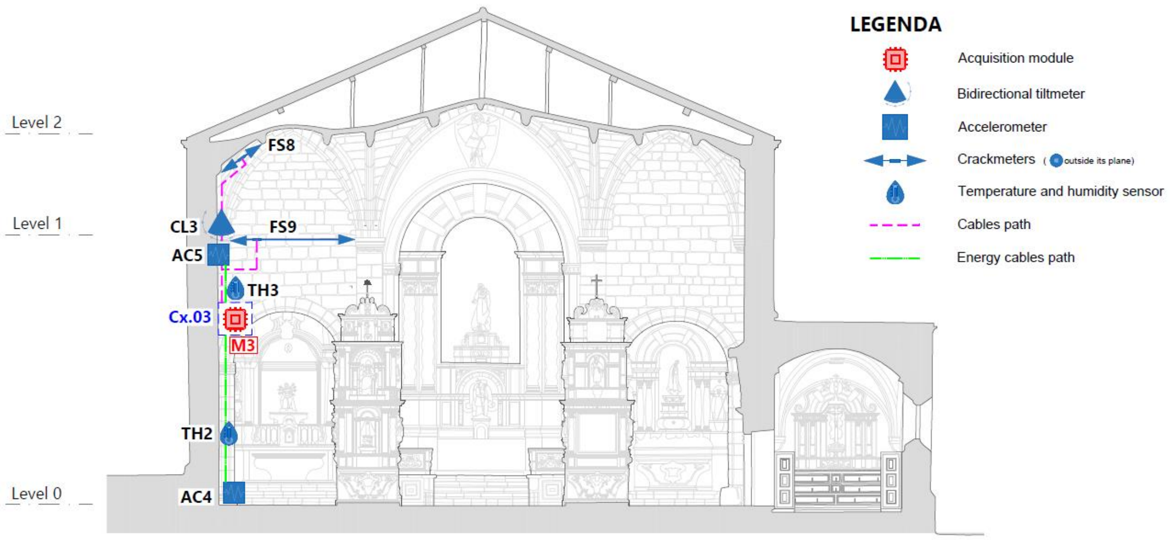


Figure 4. Monitoring system on the North side of the church, in the area adjacent to triumphal arch [source: authors].

Table 1. Summary of sensors installed

Level	Sensors			
	Crackmeters	Tiltmeters	Temperature and humidity sensors	Triaxial accelerometers
Level 2	FS4, FS5, FS6, FS7, FS8	-	T_4*	AC3
Level 1	FS1, FS2, FS3, FS9	CL1, CL2, CL3	TH1, TH3	AC2, AC5
Level 0 (Ground-floor)	-	-	TH2	AC1, AC4
Total	9	3(6*)	4	5
	21 (24**)			

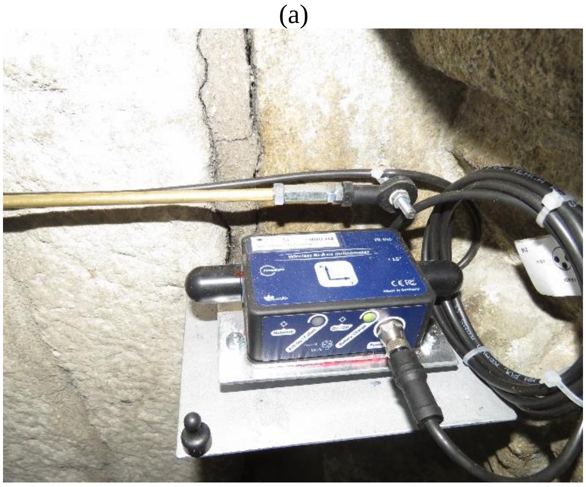
*Contrary to other temperature and humidity sensors, sensor T4 only measures temperature, therefore the acronym T.

** Each tiltmeter registers rotations in two directions A and B, therefore in practice, it generates two different sets of data.

The crackmeters installed are linear potentiometers with ball joints on the extremities, with a measurement range of 25 mm. To measure large distances, they are equipped with extension rods (see Figure 5c,d). Crackmeters FS1 to FS3, and FS8 and FS9 measure the in-plane deformation of walls, while crackmeters FS4 to FS6 measure the out-of-plane deformation, since they have one end positioned on the rib vault and the other end fixed to the façade. Additionally, crackmeter FS7 is measuring the out-of-plane deformation of the rib vault close to the façade (see Figure 5d). Their key performance indicator (KPI), meaning their control variable used for structural interpretation, is displacement (in mm), more precisely crack opening in respect to existing or new cracks.

(a)

(b)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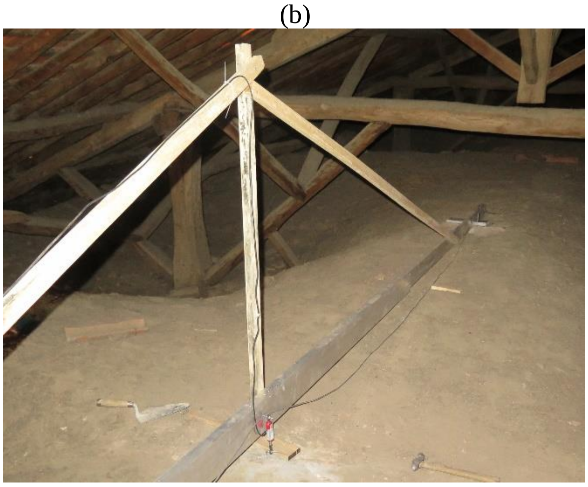
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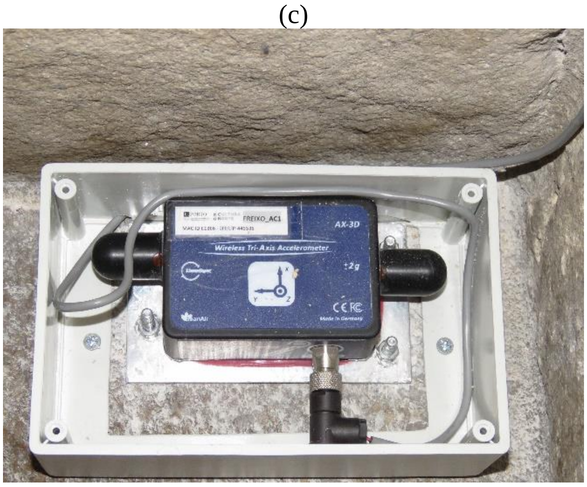

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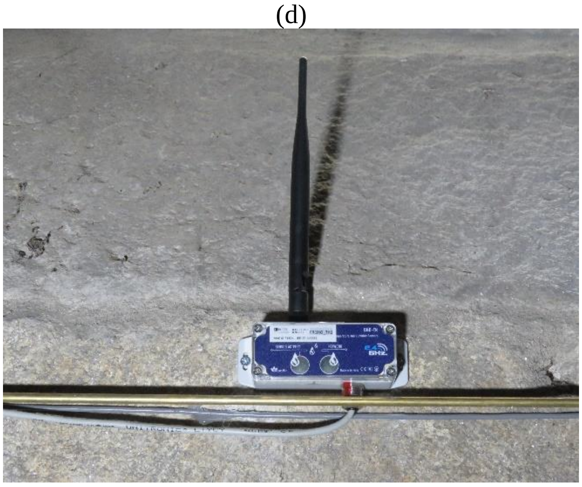

(f)

Figure 5. Monitoring system installed: (a) acquisition module M2; (b) gateway; (c) tiltmeter (CL2) and extremity of crackmeter FS3; (d) crackmeter FS7 installed on the extrados of the vault; (e) accelerometer (AC1); (f) temperature sensor TH1 and the extension rod of the crackmeter FS2 [source: authors].

For tiltmeters, were chosen wireless biaxial inclinometers, with a measurement range of ± 15°. The tiltmeters acquire measurements in two directions, described in the sensor as X and Y (see Figure 5c), corresponding respectively to the in-plane rotation and out-of-plane rotation of the wall. The KPI for tiltmeters is angle of rotation, measured in degrees (°) or mm/m. The accelerometers installed are triaxial wireless vibration sensors, suited for acceleration but also velocity monitoring, with built-in data loggers (see Figure 5e). Their measurement range is ± 2g. The KPI for the accelerometers are the resultant Peak Particle Velocity (PPV) and peak acceleration.

The temperature and humidity sensors are also wireless, with built-in data loggers, with a temperature range between -40°C and +85°C, and a relative humidity range of 0 to 100% (see Figure 5f). There are no KPIs associated with temperature and humidity measurements since they are being controlled to assess their influence on data from other sensors.

The monitoring plan contemplates continues acquisition of data for all sensors, except for the accelerometers, which will perform event-based measurements. A platform for data storage and visualization is under development, since for continues acquisition, dashboards are of crucial importance to better analyse the response of the structure. There are no available data since acquisition is still at an early stage.

4. LiDAR application and results

LiDAR is an acronym for Light Detection and Ranging and it is a system composed of active sensors that emit laser light at different wavelengths and then measure the time for the reflected light to return, which allows for the systematic calculation of coordinates of points on physical surfaces with accuracy and submillimetre precision. Its application on this project focuses on obtaining hight resolution three-dimensional (3D) data that will enable the development of 3D digital representations, interior and exterior, of the church as well as the study of stereotomy, deformations, etc. It also allows two-point cloud models from different campaigns to be compared and changes in location and therefore deformation and degradation to be identified.

Two data acquisition campaigns were carried out. The first one was a photogrammetric survey, from which resulted stereotomy and orthophotos of facades, plans and sections with surface attributes (see Figure 6), and other information regarding walls and the ribbed vaults such as of isolines maps for thickness and deformations, as well as the height of stone units used in the facades, interior and exterior faces (see Figure 7). This latter feature together with historical documentation can shed some light on the construction sequence of the church.

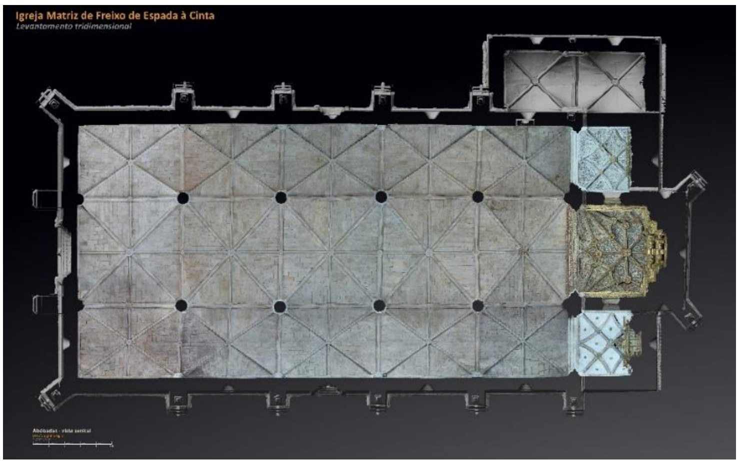


Figure 6. Orthophoto of the rib vault ceiling [source: HPires].

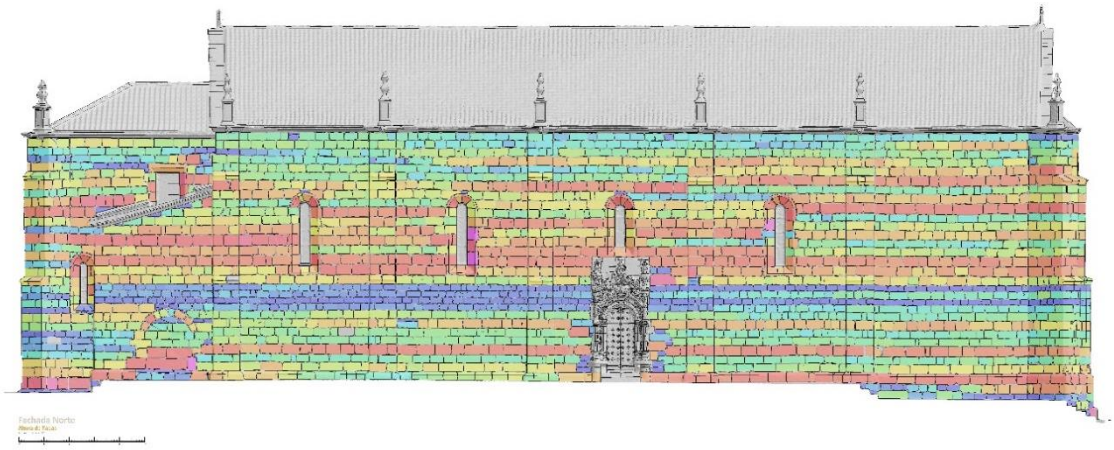


Figure 7. Colour map depicting the variation in stone units' height [source: HPires].

The second acquisition was a high-resolution survey with laser scanning, which allowed the following sequence of works: a) execution of a point cloud model; b) construction of a 3D model carried out in Rhinoceros 3D software, based on the point cloud model; c) simplified 3D model, which combines the point cloud data with simplified surface modelling for numerical simulation purposes (structural analysis). The laser scanning equipment uses laser light emitters to determine the distance between the transmitter and the object to be surveyed, recording simultaneously the angular direction of the emitted beam, allowing converting the position of measured points from a polar coordinate system in a rectangular one and referencing it to conventional geo-cartographic systems.

Hence, two types of models are being developed:

- Realistic model: very rigorous (the survey was done with 0.5 mm of precision) but computationally heavy. A model with all the information that will allow comparison with future acquisitions, enabling the detection of alterations or slight movements of the structures, for instance, deformations of the vaults (see Figure 8a).
- Simplified BIM model, which will be used for more functional applications, requiring less detail and therefore lighter memory use. It is a model compatible with various platforms, which can be accessed on any computer or mobile device. In Figure 8b. is presented the CAD (computer-aided design) model prepared for structural purposes.

(a) (b)

Figure 8. Models being developed: (a) realistic model [source: HPires]; (b) CAD model, geometry only [source: authors].

5. Preliminary numerical analyses

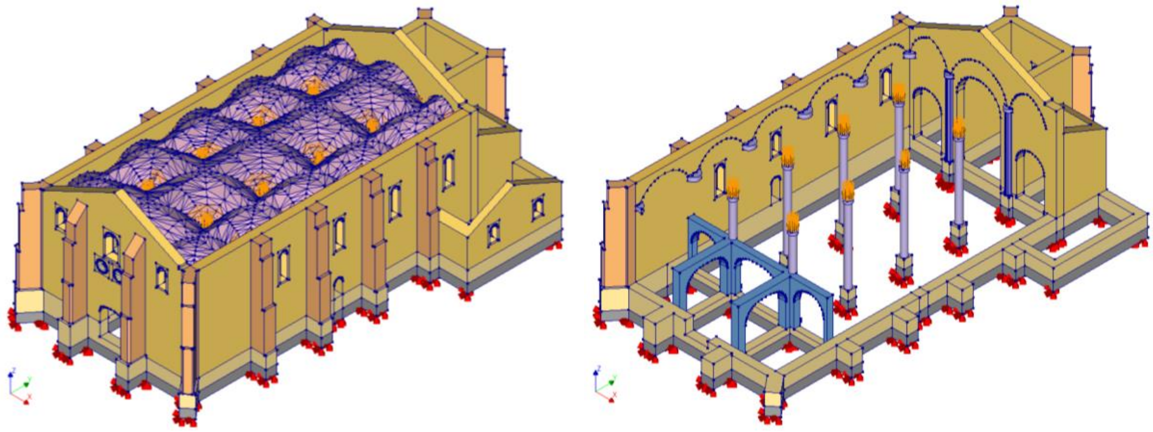
Through the process of reverse engineering, it was possible to obtain a three-dimensional model from the 3D point cloud data obtained with the LiDAR technology. In addition to the invaluable contribution in terms of architecture and historical record, the three-dimensional model can be the base of advanced numerical modelling. Through structural analysis, one can better understand what is causing the current state of conservation and assess the response to different kinds of hazards and the monitoring data.

5.1 Preparation of the numerical model

The architectural model obtained from the cloud point, by itself, is not yet ready for structural analysis. As an intermediate step, there is the need to identify the structural system and define which elements will be included in the numerical model, and how they will be represented. These decisions are based on structural significance, feasibility, and computational cost vs. analysis objectives. Hence, the geometrical model for structural purposes is already an approximation of the architectural model.

In this case, the structural system of the church is composed by the perimetral granite masonry walls and interior columns that carry the loads transferred by the granite masonry eight-part ribbed vaults that cover all the volumes of the church; it also has a set of three granite masonry arches that support the choir loft, granite masonry buttresses against the perimetral walls, and timber trusses to sustain the roof. The latter unload on the perimetral walls and interior columns. These elements were represented in the model, except for the rib vaults over the two apse chapels and the sacristy, as well as the timber structure of the roof, which was included solely as load. The foundations were considered as continuations of the walls, buttresses, arches, and columns' base, with one metre depth, since a previous report of 2014 regarding archaeological excavations [3] verified that at least the columns of the arches were directly supporting on a rock outcrop at a shallow depth. These elements were modelled as solids, while the ribbed vault was modelled as a shell. Geometric simplifications focused mainly on the walls, being assumed a constant thickness throughout their height for each block, but their relative position was respected, meaning that the north and south wall are slightly oblique, not being parallel to each other. Regarding the ribbed vault, each part was approximated with triangular shells to ensure continuity between faces, walls, and columns. Hence, one attempted to inflict minimum changes in the geometry obtained from the cloud point (see Figure 9). The 3D finite element model was developed and analysed in the software Diana FEA.

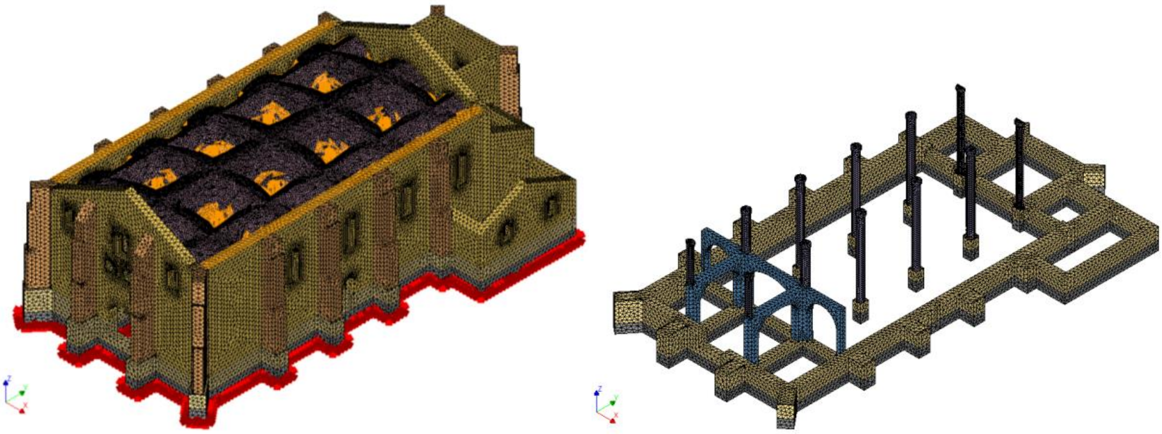
The model calculates the self-weight of the modelled elements, based on the density of the materials assigned to each element. Additional loads, referring to the timber structure of the roof and the infill of the rib vault were applied to the model. For the timber structure, it was assumed a distributed weight (horizontal projection) of 1.40 kN/m^2, which were then calculated and applied as distributed forces on the top of the columns and north and south walls. The infill was considered to have a specific weight of 12 kN/m^3 [4] and it was applied as a normal surface pressure to the elements of the rib vault, up to mid-height of their development. For the boundary conditions at the base, it was assumed that the nodes would be pinned, which with solid elements translates also for restricted rotations (see Figure 9).



(a) (b)

Figure 9. Geometry, loads and boundary conditions of the numerical model: (a) complete view; (b) view of the interior [source: authors].

Then, the mesh element type defined for the foundations, walls, buttresses, columns, and arches was the four-node, three-side isoparametric solid tetrahedron element (TE12L) and for the rib vault was the three-node triangular isoparametric curved shell element. Due to computational cost, only elements with more detailed geometry were discretized with a desired mesh dimension of 0.20 m, such as the rib vault, the columns, the arches, and the wall openings. The remaining of the model has a desired mesh dimension of 0.40 m (see Figure 10).



(a) (b)

Figure 10. Mesh of the numerical model: (a) complete view; (b) view of the interior [source: authors].

In the nave, most structural elements evidence an external face of regular arranged granite blocks with mortar joints, although, at the roof level, is visible that at least the tympanums were built with smaller stones arranged in a more irregular form. Thus far, no material characterization was carried out, therefore two types of materials properties were adopted, as shown in Table 2. The walls, tympanums, buttresses, arches, and foundations (thicker elements) were assigned a set of properties similar to the ones of regular granite masonry, while for the columns and rib vault (slender elements) were adopted finer properties, corresponding to ashlar granite, as found in literature [5], [6].

In this exploratory phase of the model, different conditions and scenarios are being studied, through preliminary linear and nonlinear phased analysis. The base model (M0) corresponds to the one described so far, being the connections between perimetral walls and rib vault and the latter and the columns assumed continuous. A second model (M1) was developed to explore the influence of the connections between the rib vault and the perimetral west and east walls (adjacent to the triumphal arch), since there is damage concentration on these areas. Modal and linear static analyses were carried out with these models to understand the influence of the connections. The connections between shells were modelled as 3D line interfaces, following a Coulomb friction model, with normal stiffness, k_n, of 0.003 MPa/mm and shear stiffness, k_s, of 0.004, cohesion of 0.03 N/mm^2, friction angle of 30º, dilatancy angle of 2º, and a tension cut-off of 0.3 N/mm^2 [6], [7].

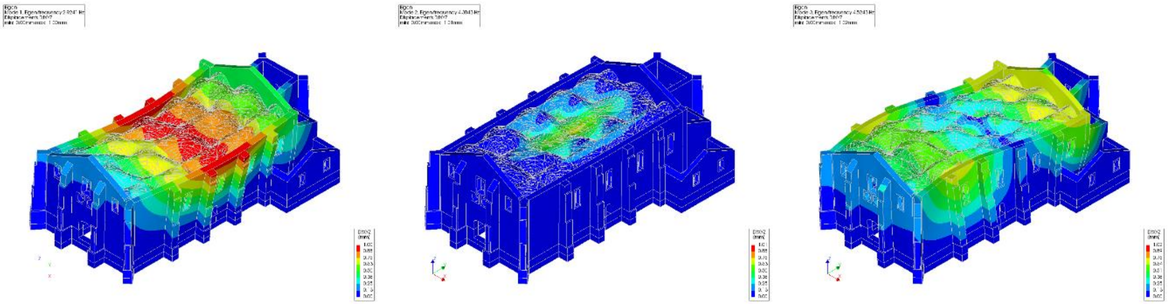
Table 2. Summary of materials used in the model

Material	Element	Density (kg/m^3)	E (GPa)	ν	f_c (MPa)	f_t (MPa)	G_f (N/mm)	G_c (N/mm)
Regular granite masonry	Walls, buttresses, foundations, arches	2000	1.50	0.20	2.60	0.26	0.05	4.16
Granite ashlar masonry	Columns and rib vault	2200	2.40	0.20	5.80	0.58	0.05	9.28

A phased analysis, with nonlinear static analyses, was carried out, considering two constructive moments of the church. The first one (Phase 1) being the present configuration plus the existence of two annexes built in continuity with the west façade (main façade), and the second one (Phase 2) corresponding solely to the present configuration (without the annexes). These annexes were demolished around 1950, as part of conservations works. The phased analysis allows the assessment of the impact of the architectural alteration, and if further studies need to include this simulation or not.

5.2 Results

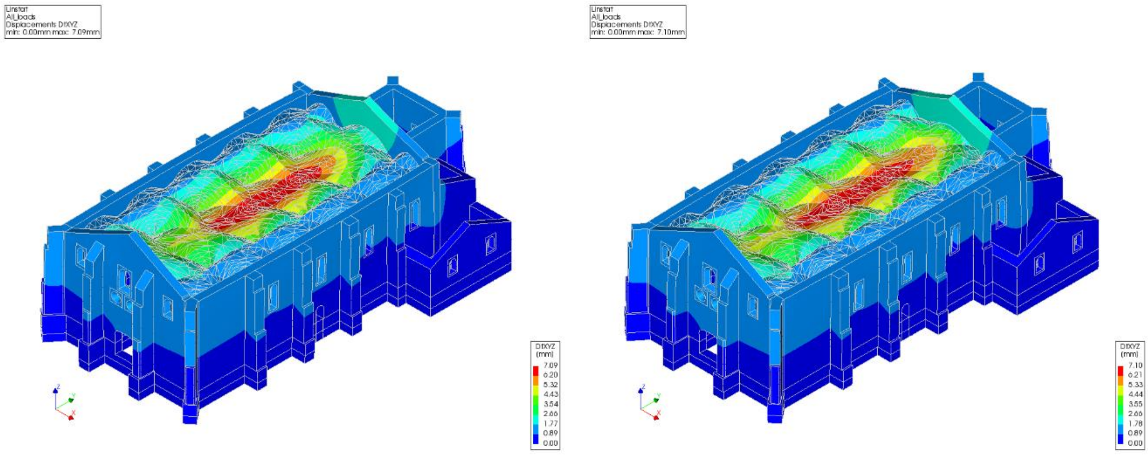
A summary of the preliminary findings is presented next. Figure 11 shows the first frequencies and modal shapes obtained for the base model M0. The first mode (Mode 1) corresponds with a predominant translational movement of the walls of the nave in the y direction, with a modal frequency of 2.92 Hz. The second mode (Mode 2) describes a local mode of the out-of-plane movement of the vault and interior columns, with a frequency of 4.38 Hz. The third mode (Mode 3) concerns again the longitudinal walls of the nave but it is anti-symmetric.



(a) (b) (c)

Figure 11. Modal shapes of the base model M0: (a) Mode 1- mostly transversal shape; (b) Mode 2 – local mode of the out-of-plane deformation of the vault and columns; (c) Mode 3 – anti-symmetrical transversal shape [source: authors].

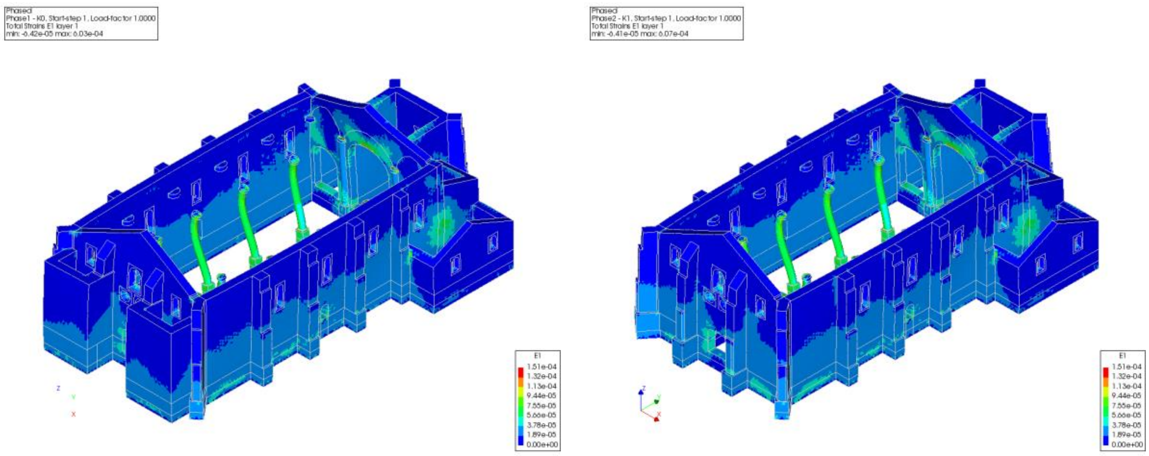
Figure 12 presents the total deformations of the base model M0 and model M1, which in general do not portray significant differences, being maximum deformation located at the vault, with the values 7.09 mm and 7.10 mm. The most visible difference is the spreading out of the larger deformations towards the perimetral walls, which could have an influence on the assessment of current visible damage.



(a) (b)

Figure 12. Total deformations: (a) base model M0; (b) model with interfaces M1 [source: authors].

The nonlinear phased analysis was carried out for a load factor of 1, considering all the permanent loads and interfaces described previously. No significant cracking was observed, except for the top of the columns, which were already cracked during Phase 1. Figure 13 shows the distribution of the principal strain in tension (ε_1), for Phases 1 and 2, which varies from -6.42E-05 to 6.03e-04, and -6.41E-05 to 6.07e-04, respectively. For better, understanding of the distribution, the vault was removed. There is no significant increment or change on the distribution of strains from one phase to the other.



(a) (b)

Figure 13 : Distribution of the principal strain in tension (a) Phase 1; (b) Phase 2 [source: authors].

6. Conclusions

Through the case study presented, it was possible to demonstrate the feasibility of the SIAP project, which is ongoing and will contribute directly to the optimization of resources dedicated to heritage assets maintenance.

The wireless monitoring system is fully operational and will enable a better control over the evolution of the existing damage. Data can be later integrated in the numerical model.

Transitioning from a cloud point model to a finite element model requires several steps, being the main output the CAD model that describes a simplified structural geometry. As expected, this transition revealed to be time consuming, with great computational cost and highly dependent on manual control, which can be a setback when aiming at a large-scale application. Future implementation will benefit from semi-automated construction of CAD models from point clouds, and from a smoother transition and integration between CAD/BIM models and SIM models.

The development of the numerical model enables the analysis of different scenarios, regarding possible hazards affecting the structure and impact of constructive alterations. Preliminary results, point out that modelling the connections might be a necessity and a sensitivity analysis considering different properties for the interfaces is advisable. Regarding the phased analysis, it was possible to conclude that the removal of the annexes probably had low impact on the structural performance of the church. A seismic analysis must be carried out to better clarify this matter.

Future developments should include material characterization through non-destructive testing and ambient vibration tests to calibrate the model material properties and levels of connectivity between elements.

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