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# DIGITAL TWIN FOR STRUCTURAL HEALTH MONITORING OF CULTURAL HERITAGE: THE BUILDCHAIN DEMO-PILOT, PALAZZO PONIATOWSKI-GUADAGNI IN FLORENCE

**P. CROCE*, F. LANDI * AND F. MELIGENI***

* Department of Civil and Industrial Engineering (DICI)
University of Pisa
Largo Lucio Lazzarino 2, 56122 Pisa, Italy
e-mail: pietro.croce@unipi.it, filippo.landi@ing.unipi.it

**Key Words:** FE models, Surrogate models, Uncertainty Quantification, Cultural Heritage, Masonry Structures, Structural Health Monitoring.

**Summary.** Preserving the historical and cultural value of the built environment complying with the recent EU directives addressing resilience, sustainability, and energy efficiency in the building sector, is a modern challenge for Europe, as historical urban centres are prone to earthquakes and climate extremes events. Masonry buildings are particularly relevant in this context and the proper definition of mechanical parameters can be a crucial issue since they can vary in a wide range significantly affecting the outcomes of the assessment and the intervention strategies. A robust treatment of material uncertainties would require a substantial number of material tests, which can be both costly and time-consuming, as well as not aligned with the requirements of preservation. For this reason, it is extremely useful to rely on Bayesian inverse methods for the calibration of structural models based on limited measurements of the structural response.

In the paper, the main steps towards the definition of digital twin for structural purposed of a heritage building are presented with reference to a significant case study, the Palazzo Poniatowski-Guadagni in Florence, a 18th century masonry building serving today as the headquarter of the local police. First, the development of Building Information Model (BIM) based on laser scanner survey data and the subsequent derivation of Finite Element (FE) model is shown. Then, a generalized Polynomial Chaos expansion (gPCE) surrogate model is introduced to reproduce the natural frequencies of the building. The surrogate model significantly decreases the computational time of the physics-based FE model, allowing the propagation of uncertainties in material properties, such as the elastic and Poisson's ratio of masonry, relevant for the building's dynamic response. Global sensitivity analyses are carried out using Sobol' indices to assess the impact of input variability on the eigenfrequencies, evaluating the need for experimental campaigns and the set-up of a structural health monitoring (SHM) system. Replacing the deterministic FE solver with a gPCE surrogate model will facilitate quasi-real-time SHM. Therefore, the outcome will be a digital twin that serves as a tool for early warning and damage detection, relying on the Bayesian inference approach. The developed digital twin will be part of the BUILDCHAIN system, including Digital Building Logbook (DBL) and BIM, contributing to demonstrate the benefits of implementing innovative DBLs for management and preservation of cultural heritage.

## 1 INTRODUCTION

The European building stock is distinctive and represents a fundamental aspect of European societal identity, which must be preserved while simultaneously undergoing renovation to enhance its energy efficiency and performance [1]. At the same time, it is characterised by a considerable age and a tendency to undergo minimal renovations over time. In fact, it is estimated that more than 220 million building units, representing approximately 85% of the total, were constructed prior to 2001. Furthermore, projections indicate that between 85% and 95% of the existing buildings will remain in use by 2050 [1].

An assessment of the resilience of cultural heritage (CH) sites and buildings is a fundamental component of developing a comprehensive and evidence-based preservation strategy. This assessment is particularly concerned with the structural integrity of these assets in the context of natural hazards, including climate-related factors such as snow and wind, and geohazards like earthquakes. Analysing the effects of such hazards on a building with the precision required means that reliable models of the building are needed.

Given that a significant proportion of Italy's historical building heritage is constituted by masonry buildings, it is evident that they play a pivotal role in the preservation and resilience of the built environment. In this context, the evaluation of mechanical parameters is of great importance, as they can vary significantly, affecting the outcomes of the assessment and the intervention strategies [2, 3]. A comprehensive analysis of material uncertainties would necessitate a significant number of material tests, which can be both costly and time-consuming, and may not align with the requirements of preservation.

The finite element (FE) models of civil engineering systems inevitably encompass certain inaccuracies stemming from the idealisation, simplification and discretisation inherent to their construction, in addition to the inherent uncertainties associated with the geometry, materials, boundary conditions and connection details between the various elements of the system. Accordingly, the integration of a probabilistic methodology into the model updating process, based on the Bayesian inversion, enables the incorporation of these errors and uncertainties [4,5].

The present study investigates the possibility to develop digital twin of heritage structures for structural purposes, focusing on the Palazzo Poniatowski-Guadagni in Florence, a 18th century masonry building serving today as the headquarter of the local police. A high-resolution 3D model, derived from Building Information Model (BIM), was initially used to investigate how variations in the natural frequencies of the structure are influenced by uncertainties in material properties, such as the elastic modulus and Poisson’s ratio of masonry. To efficiently assess the impact of these uncertainties, we employed the generalized Polynomial Chaos Expansion (gPCE) technique to surrogate the Finite Element (FE) model specifically for the first natural frequencies [6]. This approach facilitated the calculation of the Sobol Indices (SIs), which provided a quantitative measure of how much each uncertainty in the input masonry properties contributed to variations in each frequency [7, 8].

These techniques allowed us to determine not only the degree to which uncertainties influence the structure's eigenfrequencies but also to pinpoint which frequencies were most affected by the respective material properties. This comprehensive understanding was further enhanced by generating response surfaces for the natural frequencies, a tool for accurately replicating the dynamic behaviour of the structure and decrease the computational time of the physics-based FE model.

This represents a crucial initial step in the development of a digital twin (DT), which will serve as the foundation for a quasi-real-time structural health monitoring and early warning system for the Palace [9]. Such a system is essential for continuously assessing the structural integrity of the building, enabling the timely detection of potential issues and the implementation of preventative measures. This effort is a key objective of the EU-funded BUILDCHAIN project (Grant Agreement #101092052, website: https://buildchain-project.eu/), which is coordinated by the University of Pisa and aims to demonstrate the potential of DBLs to achieve a smart and sustainable EU built environment, thereby creating a knowledge base that can track all events associated with the built environment [10].

## 2 MATERIAL AND METHODS

### 2.1 Case study

The Palazzo Poniatowski-Guadagni is located in the city center of Florence, close to "Porta al Prato." Its architectural form is somewhat irregular (see Figure 1), resulting from the integration of multiple construction phases. The initial phase, completed after the second half of the 18th century, exhibits a more uniform and geometrical shape, while the subsequent phase, undertaken during the 19th century, displays a more irregular profile, aligning with the emerging urban grid.

The Palace is a three-story masonry building, with a total height of 18m. Its load-bearing structure is composed of masonry walls, which are primarily constructed from stones. The building exhibits a highly articulated and complex structural configuration, with seven different types of floors exhibiting disparate heights and basements that are not interconnected. The dimensions of each floor are approximately 857 $m^2$, except for the first mezzanine, which measures 313 $m^2$, and the attic, which is 206 $m^2$.

The Palace is distinguished by its valuable architectural features, which were designed during the restoration of the entire complex in 1864. These include curvilinear plan geometries and curved ceilings. The structure incorporates four principal staircases that facilitate vertical connectivity between levels. The primary staircase is a semi-circular structure situated near the entrance and made of "*pietra serena*".

**Fig.1.** Main facade of the Palazzo Poniatowski-Guadagni in Florence.

The sloping roof is characterized by an irregular shape, the form being influenced by both the underlying structure and the presence of protruding elements on the surface, including skylights, a turret and the attic.

To accurately recreate the irregular and complex structure of the Palace, a comprehensive digital survey was conducted using advanced laser scanning technology. This meticulous survey process involved the execution of 485 individual scans, resulting in the collection of 5 billion data points. Each point was captured with a sampling precision finer than 5mm, ensuring a high level of detail in the resulting model. The data collected from this extensive survey was then processed and used to create a comprehensive point cloud, which served as the foundational data set for the development of the Heritage BIM (H-BIM) model.

### 2.2 From H-BIM to FE model

The process of deriving a Building Information Model (BIM) from the results of a laser scanning survey is not straightforward, particularly when dealing with historic buildings. Indeed, the data capture facilitated by heritage laser scanning technology is much faster than the post-processing in the BIM environment. The two main challenges have been the accurate representation of irregular elements and the enrichment of the model with relevant properties.

The H-BIM model was constructed in Autodesk Revit after importing the test space point cloud (see Figure 2). A comprehensive account of the employed workflows can be found in [11]. The main reference plans were defined with the primary objective of identifying elements that could be realized with existing families, such as floors and masonry. In these cases, the profiles of the masonry sections were defined, and the existing components were inserted, modifying the properties of the existing Revit family types.

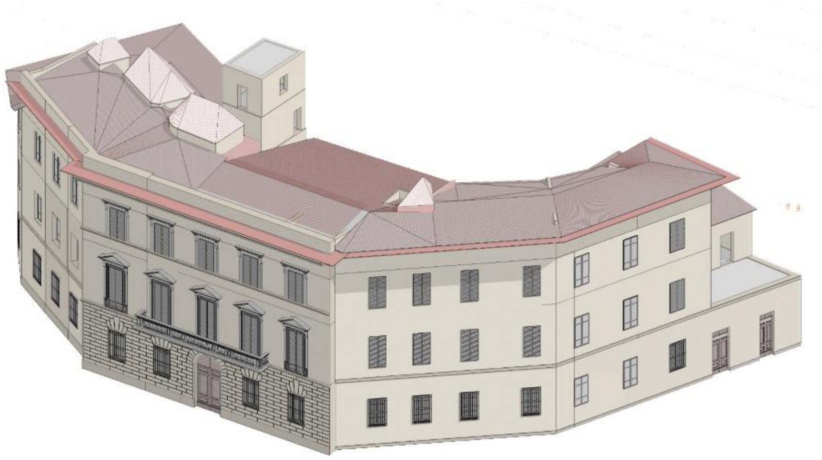

**Fig.2.** The H-BI model of the palace.

From the outset, it was imperative to undertake a comprehensive mechanical characterization of the materials employed in the Palace. To achieve this, the mechanical parameters for the various masonry types were subjected to careful assessment and subsequently incorporated into the BIM model. The values for these parameters were derived from a combination of sources. In the first instance, the average values recommended by the Guidelines for the Application of the Italian Building Code [12] were employed as a foundational reference point.

These standardized values were selected based on engineering judgement, informed by historical documentation and records pertaining to past restoration and consolidation efforts. These records not only provided crucial insights into the materials' type, as they had been observed and recorded, but also information related to floor characterization, such as the stratigraphy of the element, the direction of the span and the category of use, according to the intended purpose.

The construction of an accurate FE model was made possible by the utilization of the BI model. The model encompasses all the main structural features, including external and internal walls, internal columns, different types of floors, staircases and roof structures. However, all decorative elements were excluded from the model.

The interoperability between Revit and finite element software facilitated the conversion of the "wall" elements, which had been previously created in the architectural model and distinguished between structural and non-structural walls, as well as floors, roofs, and stairs. These elements were converted into "shells," while internal columns were transformed into frame elements.

The computational mesh of the structure is composed of approximately 220,000 shell elements, with minimum and maximum edge lengths of 0.10 m and 0.20 m, respectively.

The displacements of the base node of the palace were constrained in three directions, while those of the surface of the floors were constrained along the axis orthogonal to the surface itself. To conduct this preliminary analysis, all seven types of flooring were transformed into analogous shell elements with identical mass but different stiffness.

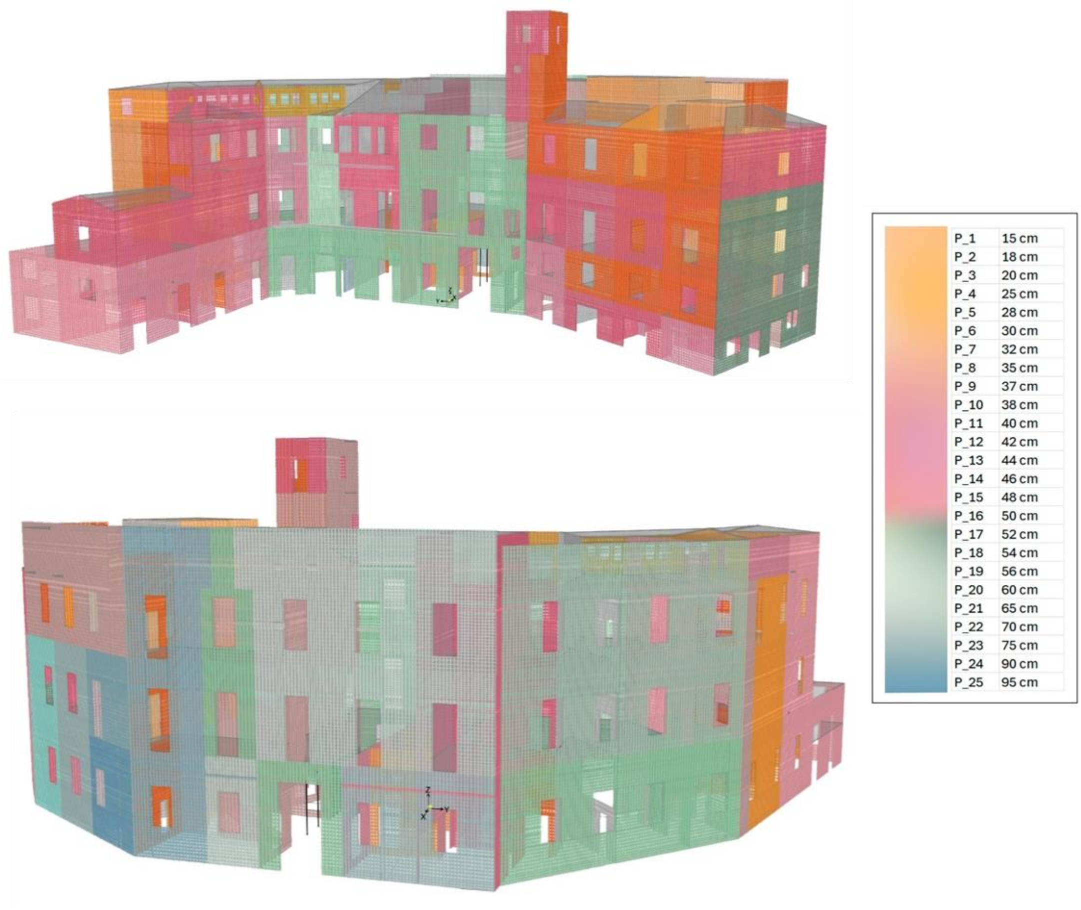

**Fig.3.** The FE model of the palace.

The classification of construction materials is detailed in Table 1 according to [12], where different types of masonry are categorized based on their composition and construction method. The first category, "*Muratura in pietra a spacco con buona tessitura"* (Stone masonry), includes 25 distinct types, which are labeled P1 through P25. The second category, "M*uratura in mattoni pieni e malta di calce*" (Brick masonry), consists of 8 types, labeled L1 through L8. These classifications are essential in understanding the structural model illustrated in Figure 3, which accurately represents the real thickness of each wall in the construction. This model is designed to replicate the actual conditions of the structure, considering the variations in material types and their corresponding thicknesses.

**Table.1** Classification of construction materials included in BIM model.

| | **f [N/mm$^2$]** | **$\tau_0$ [N/mm$^2$]** | **$f_{V0}$ [N/mm$^2$]** | **E [N/mm$^2$]** | **G [N/mm$^2$]** | **w [kN/m$^3$]** |
|---|---|---|---|---|---|---|
| | min-max | min-max | | min-max | min-max | |
| **Stone Masonry** | 2,6-3,8 | 0,056-0,074 | - | 1500-1980 | 500-660 | 21 |
| **Brick Masonry** | 2,6-4,3 | 0,05-0,13 | 0,13-0,27 | 1200-1800 | 400-600 | 18 |

In Table 2, the statistical data describing the Young's modulus and Poisson's ratio of walls made of stone masonry are provided. The distribution of elastic modulus is derived according to the results of a large experimental campaign carried out by the authors for existing masonry buildings in Florence and described in [13] while for the Poisson ratio reference values from literature are considered [3].

**Table.2** Statistical data of stone uncertain parameters.

| **Parameter** | **Distribution** | **Statistical Data** |
|---|---|---|
| **E [N/mm$^2$]** | LogNormal | μ=1816 MPa<br>σ=708 MPa |
| **ν** | Uniform | 0.15-0.25 |

## 2.3 gPCE-based surrogation of the dynamic properties

A surrogate model of the modal frequencies of the Palace, i.e. an analytical formulation able to reproduce the FE model outputs, is developed to significantly speed up the computations. The surrogate model is obtained through a general Polynomial Chaos Expansion (gPCE) of the FE model response [14]. Without going into mathematical details, we consider $M$ as the numerical model producing the uncertain output $Y$ based on the vector of uncertain parameters $\boldsymbol{X}$. A gPCE form of the model response can be found as a linear combination of orthonormal polynomials $\boldsymbol{P}_i(\boldsymbol{X})$, and it becomes an approximation when we consider only polynomials up to a given degree $n$.

The polynomials belong to specific families whose choice depends on the statistical description of the input parameters, i.e. Hermite for Normal distribution and Legendre for uniform distribution. Unknown combination coefficients $\boldsymbol{\alpha}_i$ are obtained from a set of known input-output pairs, which knowledge requires running the original model a very limited number of times compared to Monte Carlo methods. After evaluating the difference between the numerical solutions and the surrogate models, a degree $n$ equal to 4 was chosen leading to a set of 25 samples obtained from a full-tensor grid representation.

To assess sensitivity, the gPCE-based surrogation allows to directly evaluate Sobol' indices (SIs) [7], which belong to the field of variance-based sensitivity measures. In this way, it is possible to assess the effect of variability in uncertain inputs upon the variability of the output. The first seven natural frequencies of the model of the Palace are considered here as the monitored output. The calculation of Sobol' Indices is based on a decomposition of the variance associated with a given output $Y$ of the model, Var($Y$), into contributions associated with each input parameter. For an input $X$, the associated $SI_X$ is therefore the ratio between the decomposed variance and the total variance of output $Y$. Sobol' Indices vary between 0 and 1, with higher values indicating a higher influence of the input variability on the variability of the output.

## 3 RESULTS AND DISCUSSION

The modal behavior of the numerical model of the Palace is shown in Fig. 4 which shows the mode shapes of the first three natural frequencies.

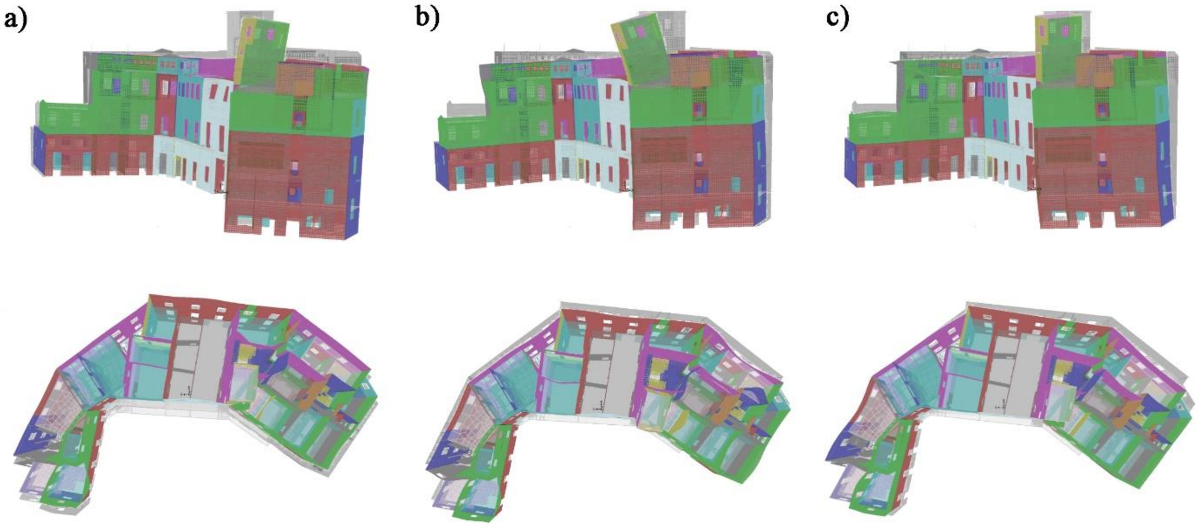

**Fig. 4**. Mode shapes of the numerical model of the Palace: a) 1st mode–bending; b) 2nd mode– bending (N-S); c) 3rd mode – torsional.

After a first evaluation of the results with average values of masonry parameters, the probabilistic framework described in the previous Section has been applied to propagate uncertainties in input parameters and evaluate sensitivities on the estimation of natural frequencies via the developed FE model.

The resulting average natural frequencies and their coefficient of variation (V) are summarized in Table 3.

**Table.3** Mean value (μ) and coefficient of variation (V) of the first eight frequencies of the FEM of the Palace.

| Parameter | $f_1$ | $f_2$ | $f_3$ | f4 | f5 | f6 | f7 |
|---|---|---|---|---|---|---|---|
| **μ** | 2.74 | 2.96 | 3.06 | 3.13 | 3.21 | 3.74 | 4.77 |
| **V** | 0.17 | 0.17 | 0.17 | 0.17 | 0.18 | 0.18 | 0.17 |

The sensitivity analysis that was carried out according to the procedure illustrated above reveals the absolute dependence of the natural frequencies on the elastic modulus with SI almost equal to 1.

A more significant outcome of the gPCE surrogation is the availability of analytical response surfaces that can provide a direct computation of frequencies without further onerous runs of the refined FE model. These could be very useful for model updating procedures considering the planned installation of a monitoring system in the Palace. As an example, in Fig. 5, the response surface of the first natural frequency of the FE model is shown.

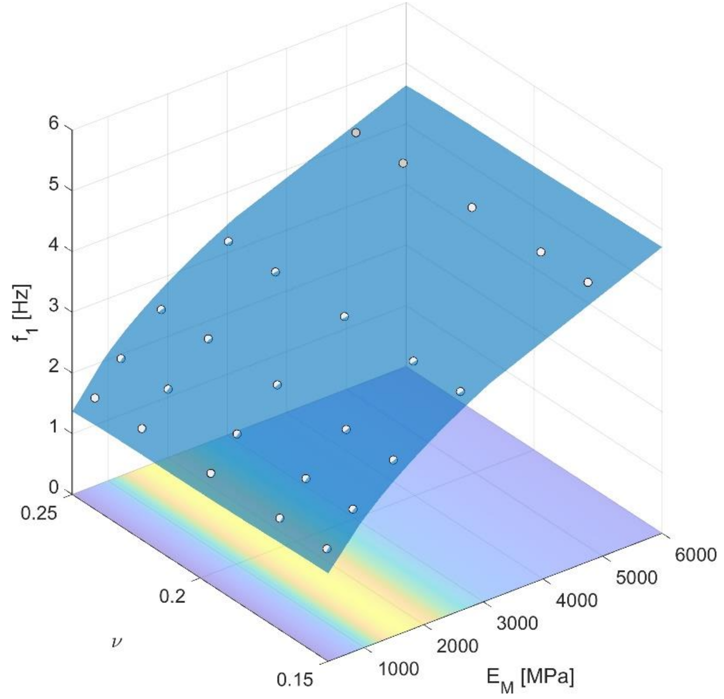

**Fig.5.** Response surface of the first natural frequency of the FE model.

## 4 CONCLUSIONS

This study presents a first step towards the development of a digital twin for the structural health monitoring of a heritage and strategic building in Florence, the Palazzo Poniatowski-Guadagni. A refined FE element model of the building is derived from the Building Information Model to investigate its dynamic behaviour, and a gPCE-base surrogation is proposed as a tool to speed up computations, propagate uncertainties and monitor possible changes detected by means of the sensors that will be installed in the building.

Future activities of the project will focus on the acquisition of ambient vibration data, the identification of experimental natural frequencies and the subsequent calibration of the developed DT.

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