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INTEGRATED APPROACH TO EVALUATE THE SEISMIC BEHAVIOR OF A FORMER CHURCH CONVERTED TO A MUSEUM: MARINO MARINI MUSEUM IN FLORENCE

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Abstract

This study explores the seismic behavior of the Marino Marini Museum in Florence (Italy) through an integrated approach. The research aims at realizing a finite element (FE) model that benefits from different sources of information, including advanced three-dimensional surveying techniques, historical documentation and thermography campaign. The Museum is located in the former San Pancrazio Church, a medieval building erected in the 10th century in the center of Florence, inside the UNESCO World Heritage area. Over the centuries, the structure has undergone many transformations, serving as an arcade during the Napoleonic period, a tobacco factory, and finally a museum in 1982. These modifications included the addition of new inner levels and other interventions in steel and reinforced concrete. The current museum is a complex architectural system, constituting the head building of an irregular aggregate made of different masonry units. To realize the FE model, a detailed laser scanner survey has been carried out and the geometrical information has been combined with the historical documentation on the past interventions. Various FE models have been realized to gain insights into the influence of past interventions on the structural behavior of the building, providing useful information for the seismic analysis. Nonlinear dynamic analyses were carried out to provide first insights on the dynamic response of the museum.

Keywords: Historical masonry buildings, Laser scanning, 3D FEM analysis, Seismic analyses.

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1 INTRODUCTION

A significant part of the world's cultural heritage consists of historical architectural structures, including churches, fortresses, palaces and castles, which are mainly made of masonry [1, 2]. It is well known that ancient masonry buildings are well suited to supporting vertical loads, whereas they often exhibit inadequate resistance to horizontal forces induced by dynamic events. Consequently, these structures are highly vulnerable to seismic loads, as evidenced by numerous instances of both global and local collapses during recent moderate-to-high magnitude earthquakes [3-6].

The assessment of the seismic vulnerability of such structures presents considerable challenges due to the intrinsic uncertainties affecting their geometry and both linear and nonlinear mechanical properties. The present configuration of every masonry building is the unique result of a long process of successive alterations, additions, demolitions and replacements of structural elements, often leading to significant structural heterogeneity.

Moreover, most historical centers have developed through the overlapping and juxtaposition of units originally conceived as independent structures, further complicating their overall stability and seismic performance. Therefore, a comprehensive structural analysis requires an in-depth understanding of their historical evolution, geometrical configurations, masonry construction techniques and existing damage patterns.

In the field of cultural heritage buildings, different approaches at various scales have been proposed, ranging from empirical simplified evaluations to detailed and probabilistic procedures [7, 8].

A broad spectrum of case studies available in the scientific literature, from experimental investigations [9, 10] to finite element analyses, both linear and nonlinear [11-13], relies on interdisciplinary methodologies to address the challenges posed by seismic hazards and structural vulnerabilities.

The present study focuses on the seismic behavior of the Marino Marini Museum in Florence, Italy, through an integrated approach. The research aims to develop a nonlinear finite element (FE) model that benefits from multiple data sources, including advanced 3D surveying techniques, historical documentation and thermography campaign.

The following section provides a detailed overview of the case study. After, a section is dedicated to the methodology, which integrates laser scanning survey and finite element modeling. The results of the numerical simulations are then presented and discussed in Section 4, followed by concluding remarks at the end of the paper.

2 CASE STUDY

The Marino Marini Museum is located in the historic center of Florence, a short distance from the Basilica of Santa Maria Novella and the Cathedral of Santa Maria del Fiore. Situated within a densely inhabited area of significant historical and architectural value, the museum is housed within the medieval Church of San Pancrazio, first documented in the early 9th century.

From the 14th century onwards, the church underwent significant renovations, culminating over a century later with the completion of the Rucellai Chapel in 1467.

During the Napoleonic era, the church was deconsecrated in 1808 and it was repurposed as the seat of the Imperial Lottery of France. The structure was altered in accordance with the neoclassical aesthetic of architect Giuseppe Cacialli, who introduced two central columns flanked by two lion sculptures on the façade.

After serving as a court, in 1883 the Church of San Pancrazio was converted into the Royal Tobacco Factory, undergoing a radical transformation: the central nave was partitioned into two levels through the installation of a metal mezzanine, whose riveted iron beams remain visible today. Between the 1960s and the 1970s, following its decommissioning by the military administration, the building began to be recovered. In the 1982 the restoration of the San Pancrazio complex was entrusted to architects Bruno Sacchi and Lorenzo Papi. Their project aimed to preserve and enhance the diverse historical layers into a unique museal path and the result is the current configuration of the museum (Figure 1).

The interventions by the two architects are characterized by a dynamic interplay of circulation paths, stairs and walkways clearly distinguished in form and colour from the ancient structures, and a deliberate contrast between the pre-existing masonry elements and the contemporary additions, which remain distinct in both materials and function.

The museum houses a vast collection of artworks displayed across all levels, comprising 183 pieces, including drawings, lithographs, paintings, and sculptures by the Pistoia-born artist Marino Marini, after whom the museum is named.

Figure 1: Current configuration of the museum.

3 INTEGRATED RESEARCH

3.1 Laser scanner survey

The available documentation concerning the structural configuration of the museum and its transformations over the centuries is limited, and the existing drawings contain significant qualitative and quantitative inaccuracies. To address this issue, a comprehensive survey campaign was conducted using terrestrial laser scanner (TLS) technology.

In the present study, TLS was used to acquire a complete point cloud of the entire museum building, including the Rucellai Chapel. To achieve a comprehensive survey with minimal data gaps and sufficient overlapping scans, a total of 296 scans was conducted with a resolution ranging between 3 mm and 6 mm.

The acquired point cloud data was processed using Autodesk ReCap Pro © software to generate 2D drawings for comparison with the existing design documentation. Specifically, horizontal sections at different elevations, from the ground floor to the fourth level of walkways, were extracted, along with vertical sections and internal elevations of the museum. The resulting graphic outputs were subsequently refined in a CAD environment. From the 2D drawings, a solid 3D model of the building was realized, constituting the geometrical basis for the numerical investigations.

3.2 FE model

The complexity and irregularity of the museum structure made the modelling step a very challenging task. The numerical modelling was conducted using the FE environment Abaqus CAE © [14]. The three-dimensional CAD model was imported into the "Part" module using the IGES format and subsequently meshed in Abaqus for numerical simulations.

Three-dimensional solid elements were employed to simulate masonry walls, slabs, columns, and beams. A homogeneous macro-modelling approach was adopted, representing masonry as a continuum material.

Two numerical models were developed to assess the influence of past structural modifications on the building's global behaviour. The first model represents the structure as it existed before the 18th-century renovations, while the second incorporates all subsequent interventions up to the 1970s. These include the insertion of reinforced concrete slabs and walkways at the different levels, which reduce the nave's original free height, as well the steel beams and columns added during the tobacco factory phase and the 20th-century interventions carried out by architects Sacchi and Papi.

The first FE model consists of 244351 nodes, 132740 quadratic tetrahedral elements (C3D10), the second model comprises 646871 nodes, 375028 quadratic tetrahedral elements (C3D10). In order to improve the reliability and the computational efficiency of finite element solutions, a mesh refinement around openings and vaults was made up to 0.3 and 0.15 m. Figure 2 provides a three-dimensional view of the two models and their meshed representations.

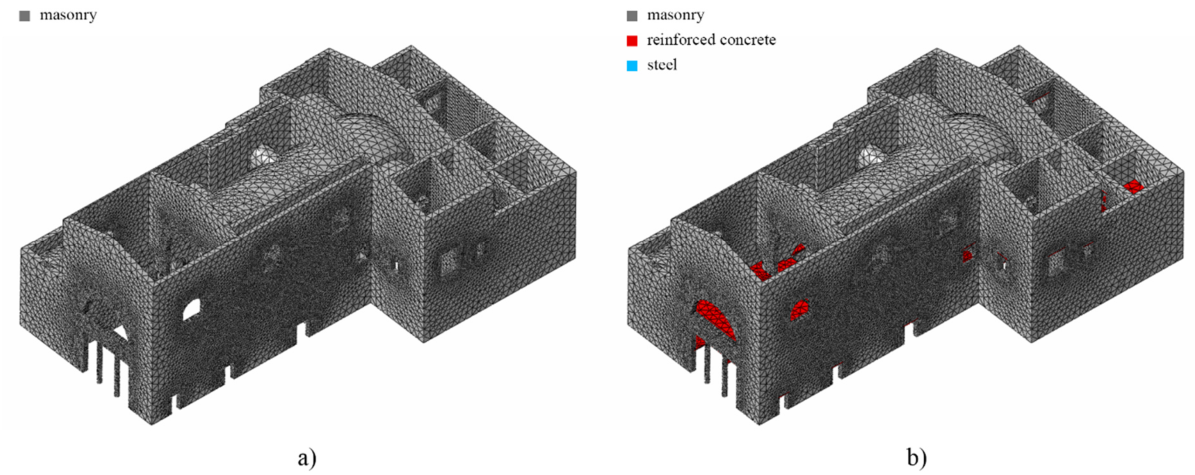


Figure 2: Mesh configuration of both numerical models: a) configuration before 18th- century interventions; b) current configuration of the museum.

Due to the heritage significance of the museum, destructive or semi-destructive material testing methods, were not permitted. A limited thermography campaign was conducted to check on the presence of concrete ring beams at the roof level of central nave, as to get insights on discontinuities hidden by the plaster layer.

The main mechanical properties adopted in this work are reported in Table 1. The nonlinear behaviour of the masonry is outlined in the 4.2 section.

	ρ [kg/m^3]	ν [-]	E [MPa]
Masonry	2000	0.15	1230
R.C.	2500	0.2	31500
Steel	7850	0.3	210000

Table 1: Mechanical parameters of the materials involved.

4 NUMERICAL ANALYSES

4.1 Modal analysis

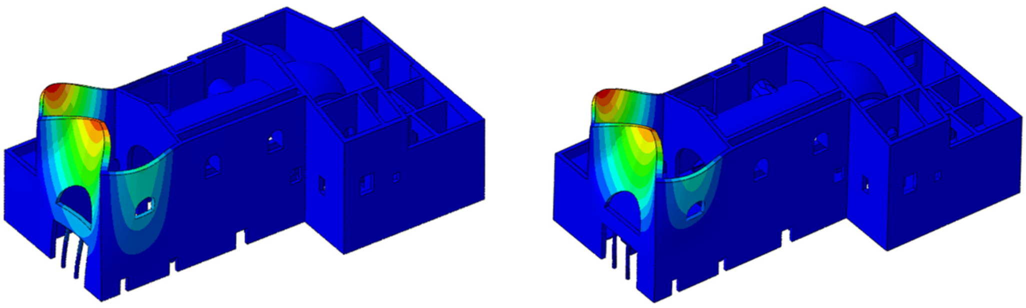
Modal analyses were conducted on both models to: i) identify the main frequencies and modal shapes of the investigated building; ii) understand the effects of historical interventions on the dynamic response of the museum; iii) get insights on the most-likely damage mechanism of the building.

In Table 2 the main frequencies for the two models are reported, assuming the mechanical parameters reported in the Table 1.

For both models, the first frequency of the building affects the main façade and its orthogonal walls towards an out-of-plane mode shape. Further modes are given by the inner addition of slabs, altering the dynamic response of the longitudinal walls of the central nave. These insertions lead to a lack of correspondence between the mode shapes of the two models. For the sake of brevity, in Figure 3, a comparison between the two models for the first mode shape only is presented.

	(a)	(b)
Mode #	f [Hz]	f [Hz]
1	1.418	1.486
2	1.679	1.786
3	1.845	2.147
4	2.362	2.650
5	2.419	2.739
6	2.551	2.891
7	2.629	3.087
8	2.728	3.220
9	2.770	3.298
10	3.032	3.499

Table 2: Natural frequencies of both numerical models.



a) b)

Figure 3: First modal shape of both numerical models: a) configuration before 18th- century interventions; b) current configuration of the museum.

4.2 Nonlinear dynamic analysis

Nonlinear time-history analysis was executed on the FE model representing the current configuration of the museum. To this aim, a nonlinear behavior was defined to characterize the masonry elements through the Concrete Damage Plasticity Model (CDP) [15]. Although originally defined to describe the behavior of concrete elements, the latter has been widely used to investigate masonry structures [16, 17]. CDP is based on a plasticity-damage relation through two distinct tensile and compressive curves. The maximum compressive value was assumed equal to 2 MPa, according to the values available in MIT2019 [18] for the considered masonry typology (Rough block masonry with non-homogeneous thickness of the external faces). For the tensile strength, the value was considered equal to 1/10 of the compressive one. The nonlinear curves describing the two constitutive laws were defined according to [19]. In Table 3 the mechanical parameters adopted in the CDP model.

Dilation angle	Eccentricity	f_{b0}/f_{c0}	Kc	Viscosity parameter
37°	0.1	1.16	0.667	0.001

Table 3: Mechanical properties of the CDP model used in the numerical procedure.

For the seismic analysis, a return period of 712 years was assumed, corresponding to the 10% of probability of occurring within a reference life of 75 years (life safety limit state). Considering the area where the Museum is located, a soil class B was assumed, leading to an acceleration at the building foundation equal to 0.18 g. The seismic input was selected through the REXEL-web tool [20] matching the demand spectrum for the city of Florence. In this work, a single accelerogram was adopted (SM.103.00.HN.IS-2000-0048) and the analysis was limited to the most energetic part of the record. The load was given along the Y direction of the model (parallel to the main façade) applying the 30% of its amplitude along the X direction.

Prior to the application of the seismic action, gravity loads were applied by a nonlinear incremental procedure. During the analysis, different control points of the building were considered.

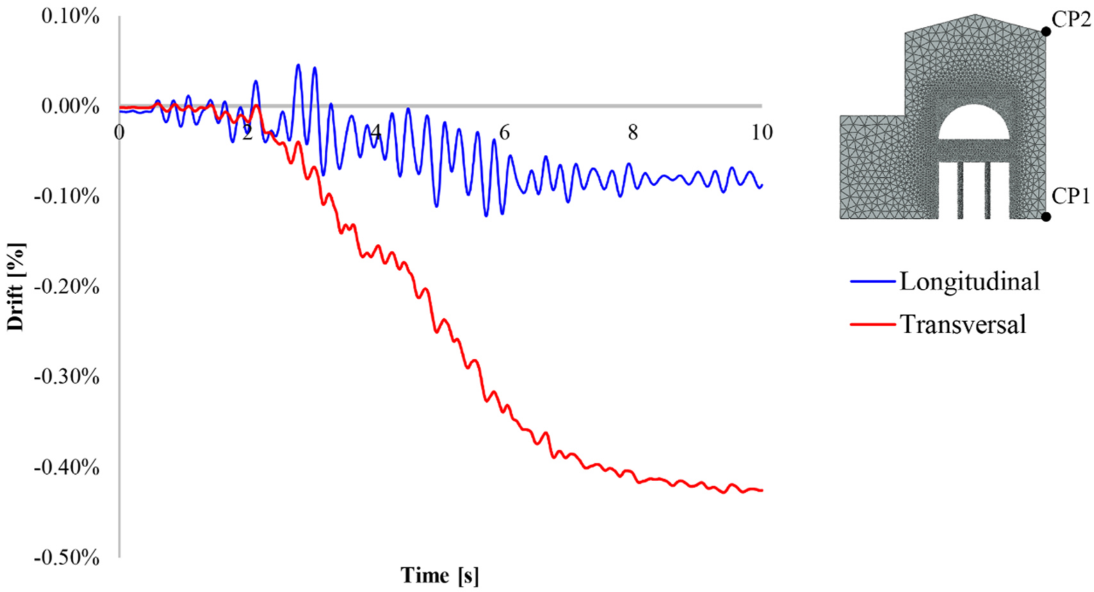


Figure 4: Inter-story drifts.

The outcomes of the dynamic analysis highlight a relevant damage suffered by the building, not included for sake of brevity in this text. Although the main seismic input was given along the longitudinal direction (Y axis), the building exhibited a out-of-plane failure of the façade. This outcome is coherent with the insights provided by modal analysis, and in line with the multiplier activating the mechanism calculated according to kinematic analysis. As a matter of fact, Figure 4 shows the results of the nonlinear dynamic simulation in terms of non-dimensional drift, considering both the out-of-plane direction (X) and the in-plane (Y) directions of the building façade. The paper reports the results with reference to the two control points, CP1 and CP2, located at the base and the top of the main façade of the museum, respectively. The drift in the X direction (transversal) is significantly higher than the one in the Y direction (longitudinal). The maximum drift recorded in the transversal direction is 0.43%, whereas in the longitudinal direction it reaches a peak value of 0.12%.

5 CONCLUDING REMARKS

This study investigates the seismic response of the Marino Marini Museum through an integrated methodology that combines advanced 3D surveying techniques, historical documentation, and thermography to develop a refined FE model.

The conducted research, through the analysis of two distinct configurations, has permitted gaining insights into the influence of past interventions on the building, in terms of frequencies and mode shapes. The modal analysis performed on the two models showed how the introduction of reinforced concrete and steel elements altered the dynamic behavior of the structure.

The outcomes of nonlinear dynamic analysis, for the considered seismic input, showed relevant damage in the building, providing the first insights into the museum’s structural response. These preliminary results indicate the need for further in-depth investigations and refined analyses. Future research will focus on considering additional seismic inputs as well as conducting in-situ dynamic identification of the construction. This in-depth research is oriented toward a reliable seismic assessment of this complex building, based on model updating procedures to calibrate the FE models and reduce uncertainty.

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REFERENCES

[1] P.B. Lourenco, P. Roca, C. Modena, D.V. Oliveira, Reducing the seismic vulnerability of cultural heritage buildings. In *Proceedings of the 7th European Conference on Safeguarded Cultural Heritage: Understanding & Viability for the Enlarged Europe (SAUVEUR), Prague, Czech Republic*, 31 May-3 June 2007.

[2] V. Despotaki, V. Silva, S. Lagomarsino, I. Pavlova, J. Torres, Evaluation of Seismic Risk on UNESCO Cultural Heritage sites in Europe. *International Journal of Architectural Heritage*, **12**, 1231-1244, 2018.

[3] N. Augenti, F. Parisi, Learning from construction failures due to the 2009 L'Aquila, Italy, earthquake, *Journal of Performance of Constructed Facilities*, **24**(6), 536-555, 2010.

[4] A. Penna, P. Morandi, M. Rota, C.F. Manzini, F. Da Porto, G. Magenes, Performance of masonry buildings during the Emilia 2012 earthquake, *Bull Earthquake Eng*, **12**, 2255-2273, 2014.

[5] M. Acito, M. Bocciarelli, C. Chesi, G. Milani, Collapse of the clock tower in finale Emilia after the May 2012 Emilia Romagna earthquake sequence: Numerical insight, *Engineering Structures*, **72**, 70-91, 2014.

[6] F. Clementi, G. Milani, A. Ferrante, M. Valente, S. Lenci, Crumbling of Amatrice clock tower during 2016 central Italy seismic sequence: Advanced numerical insights, *Frattura ed Integrità Strutturale,* **14(51)**, 313-335, 2020.

[7] S. Lagomarsino, On the vulnerability assessment of monumental buildings, *Bull Earthquake Eng,* **4**, 445-463, 2006.

[8] S. Lagomarsino, S. Cattari, PERPETUATE guidelines for seismic performance-based assessment of cultural heritage masonry structures, *Bull Earthquake Eng*, **13**, 13-47, 2015

[9] M. Pieraccini, D. Dei, M. Betti, G. Bartoli, G. Tucci, N. Guardini, Dynamic identification of historic masonry towers through an expeditious and no-contact approach: Application to the "Torre del Mangia" in Siena (Italy), *Journal of Cultural Heritage*, **15(3)**, 275-282, 2014.

[10] G. Bartoli, M. Betti, S. Giordano, In situ static and dynamic investigations on the "Torre Grossa" masonry tower, *Engineering Structures*, **52**, 718-733, 2013.

[11] P. Spinelli, L. Salvatori, R. Lancellotta, M. Betti, Preliminary Assessment of The Seismic Behaviour of Giotto's Bell Tower in Florence. *International Journal of Architectural Heritage*, **17(1)**, 23-45, 2022.

[12] M. Tanganelli, F. Trovatelli, T. Rotunno, Evaluation of the Seismic Vulnerability of Giotto's Bell Tower: Comparison of Different Methodologies, *International Journal of Architectural Heritage*, 1-25, 2022.

[13] A. D'Ambrisi, V. Mariani, M. Mezzi, Seismic assessment of a historical masonry tower with nonlinear static and dynamic analyses tuned on ambient vibration tests, *Engineering Structures,* **36**, 210-219, 2012.

[14] ABAQUS, *Theory and user's manuals 2018*, Pawtucket (RI, USA): Hibbit, Karlson and Sorensen, 2018.

[15] J. Lubliner, J. Oliver, S. Oller, E. Oñate, A plastic-damage model for concrete, *Int J Solids Struct*, 1989. doi:10.1016/0020-7683(89)90050-4.

[16] S. Degli Abbati, A.M. D'altri, D. Ottonelli, G. Castellazzi, S. Cattari, S. De Miranda, S. Lagomarsino, Seismic assessment of interacting structural units in complex historic masonry constructions by nonlinear static analyses, *Computers & Structures*, 2018. S0045794918306916–. doi:10.1016/j.compstruc.2018.12.001

[17] M. Valente, G. Milani, Seismic assessment of historical masonry towers by means of simplified approaches and standard FEM, *Construction and Building Materials*, **108**, 74-104, 2016.

[18] MIT2019: Circolare 21 gennaio 2019, n.7 Istruzioni per l'applicazione dell'<<Aggiornamento delle "Norme tecniche per le costruzioni">> di cui al decreto ministeriale 17 gennaio 2018. G.U. n. 47 del 26/02/2009, Supplemento Ordinario n. 27, Rome, (in italian) (2019)

[19] V. Alecci, M. De Stefano, R. Luciano, A.M. Marra, G. Stipo, Numerical Investigation on the Use of Flat-Jack Test for Detecting Masonry Deformability, *Journal of Testing and Evaluation*, **49(1)**, 2021.

[20] S. Sgobba, R. Puglia, F. Pacor, L. Luzi, E. Russo, C. Felicetta, G. Lanzano, M. D Amico, R. Baraschino, G. Baltzopoulos, I. Iervolino. REXELweb: a tool for selection of ground-motion records from the Engineering Strong Motion database (ESM) 7th International Conference on Earthquake Geotechnical Engineering (ICEGE) 17 - 20 June 2019, Rome, Italy.