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Assessing Interactions Between the Structural Units of a Rubble Stone Monumental Aggregate using Equivalent Frame Models

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ABSTRACT

Rubble stone monuments, common in Mediterranean countries, are particularly vulnerable to seismic activity due to their construction techniques and materials. These structures typically consist of irregular, uncut stones, loosely bound with weak mortar, resulting in low tensile strength and poor cohesion. In addition, these historical structures are usually built as irregular aggregates, contributing to their earthquake vulnerability. Due to their cultural importance, in addition to safety and economic reasons, it is of utmost importance to perform accurate seismic assessments of historical masonry structures to preserve them. Most of the time, however, it is not easy for engineers to consider the interactions between different structural units in the aggregate, especially when it is difficult to define these units themselves.

The National Palace of Sintra, located in Sintra, Portugal, is a representative example of irregular, large-scale rubble stone monuments built in aggregate without previous planning. This paper presents an overview of the study conducted on the Palace, including the historical research and experimental campaign carried out to perform its seismic assessment. The equivalent frame numerical modeling of such a complex case study is also discussed, focusing on the interaction between the structural units. This modeling strategy was chosen due to the limited number of parameters required, which makes it one of the preferred methods within the practitioners' community.

KEYWORDS

historical aggregates, interactions between buildings, equivalent frame modeling, nonlinear static analyses.

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INTRODUCTION

Europe's vast Cultural Built Heritage, composed of monuments and historical city centers, plays a crucial role in tourism, contributing significant cultural and economic value. Preserving this heritage requires structural safety assessments, particularly in seismically active regions. In accordance with ISO 13822 [1] and the ICOMOS/ISCARSAH committee [2], conservation, strengthening, and restoration demand a multidisciplinary approach, integrating history, architecture, engineering, and topography. Understanding a structure's construction phases, materials, and geometry is essential before conducting structural analysis or implementing rehabilitation measures.

A major challenge in evaluating existing structures is determining the mechanical properties of masonry, which exhibit significant variability. In-situ experimental tests, both semi-destructive and non-destructive, are critical for reducing epistemic uncertainties, particularly in historic buildings lacking original construction records. Previous studies, including those by [3], have compiled masonry databases from in situ tests in Tuscany, while others have characterized masonry in Umbria, Abruzzo, and beyond ([4], [5], [6]). These studies highlight the significant regional and structural variations in masonry properties. In Portugal, while flat-jack tests have been conducted on traditional residential masonry (e.g., [7] and [8]), their application to monuments remains limited.

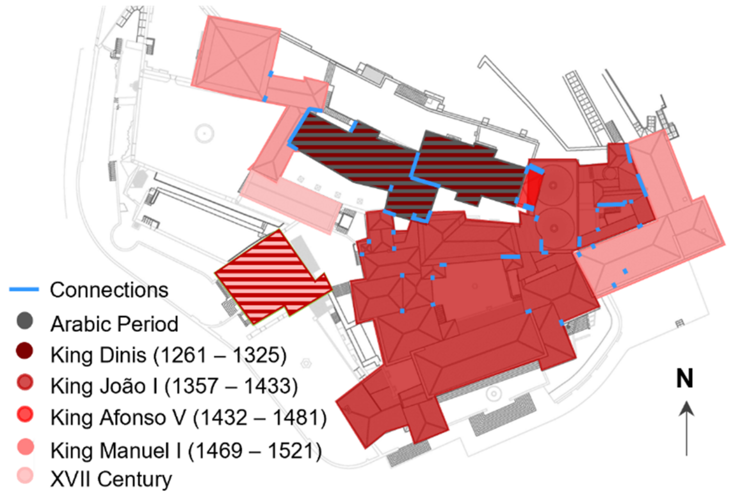
The National Palace of Sintra (NPS), a UNESCO World Heritage Site since 1995, serves as a case study for seismic vulnerability assessment. Managed by Parques de Sintra – Monte da Lua, S.A. (PSML), the Palace's conservation strategy includes structural evaluations to ensure visitor and personnel safety and mitigate seismic risks. This study follows a multidisciplinary methodology [9], involving: (i) historical research, (ii) seismic action characterization, (iii) an experimental testing campaign, (iv) numerical modeling and calibration, taking into account the aggregate interaction, and (v) performance of nonlinear analysis. This approach identifies vulnerabilities and collapse mechanisms.

CASE STUDY DESCRIPTION: THE NATIONAL PALACE OF SINTRA

The first step of the seismic assessment of the case study was the study of its construction and evolution The main periods of construction of the Palace are presented in Figure 1, together with the identification of the possible connections between structural units built in different times. The Palace's history dates back to the Muslim period in the Iberian Peninsula, with references from as early as the 11th century to an Arab Palace and mosque built in the NPS's current location. It became Portuguese royal property in 1147 and underwent significant expansions under Kings Dinis (1281), João I (15th century), and Manuel I (16th century). Its distinct architectural evolution, including influences from Christian and Arabic cultures, remains largely intact. The 1755 earthquake caused damage, but subsequent restorations preserved its authenticity. Since the 20th century, the Palace has served as a national monument and a venue for diplomatic events, maintaining its historical significance and tourist appeal. This Palace is nationally known for its two very large and iconic chimneys of a conic shape, sent to be built similarly to the chimneys in England from where the queen ruling at that time was originally born. Besides the kitchen with the large chimneys, the Palace presents a palatine chapel, residential areas, very large reception rooms and saloons.

Extensive historical research, including analysis of Duarte D'Armas' 1507 drawings, 19th- and 20th-century plans, and archival records, supported the structural assessment. Field surveys and experimental campaigns were crucial in characterizing the Palace's structural elements, masonry typologies, and potential vulnerabilities. The integration of historical, experimental, and numerical data enhances the understanding of the Palace's seismic behavior, contributing to its long-term preservation. In aggregate constructions such as this, historical knowledge will help identify the connections between structural units, which is essential for adequately modelling the structure.

a)



b)

Figure 1: The National Palace of Sintra, Portugal: a) side view picture, b) plan view with construction timeline and identified connections between buildings

INSPECTION AND DIAGNOSIS ACTIVITIES

Geometry and damage survey

The geometry and damage were initially assessed by visual inspections and a topographical survey using total station equipment. However, the aggregate presented a variety of structural elements, like irregularly shaped walls, interior pillars connected by arches, vaults, different types of floors and the existence of floor misalignment. To address this, a laser scan and drone survey were conducted [10] using a Faro S70 laser scanner, capable of achieving a 1 mm resolution at 70 m. This methodology ensured a highly detailed representation of the Palace's geometry, particularly its congested and difficult-to-access areas. The data was integrated into an H-BIM model [10] by the IST architectural team (Figure 2), to allow subsequent inclusion of the experimental and numerical results. This approach aligns with recent applications of digital modeling in Cultural Heritage studies ([11], [12], and [13]).

The Palace's irregular geometry, resulting from its construction on a hillside, presents unique structural characteristics. The complex consists of multiple interconnected structural units with varying heights and entrance levels. The elevation difference between the lowest foundation and the highest roof reaches 44 m. Building footprints range from 28.4×26.1 m² to 15.5×5.9 m², with floor counts varying from one to five. The ground-floor walls, constructed of rubble stone masonry with air lime mortar, range in thickness from 0.35 m to 2.2 m, with the thickest walls being double-leaf stone masonry with infill. The masonry quality and composition differ between buildings and even within individual structural units due to the various construction phases in-plane or in-height. Horizontal diaphragms consist of timber floors made of Portuguese Pine or masonry vaults, while the roofs are primarily timber trusses, except for the kitchen building, which supports the Palace's iconic brick masonry chimneys. In large rooms, tie-rods provide strengthening against out-of-plane facade wall mechanisms. In general, the NPS has been kept well maintained, and the strengthening of some structural units has been carried out in recent years; however, at the time of the survey, light damage was found on the top floor of the most ancient unit (damaged timber floors and cracking on the walls, possibly due to settlements and out-of-plane mechanisms of the façades).

Figure 2: Section view of the NPS from the H-BIM model [10]

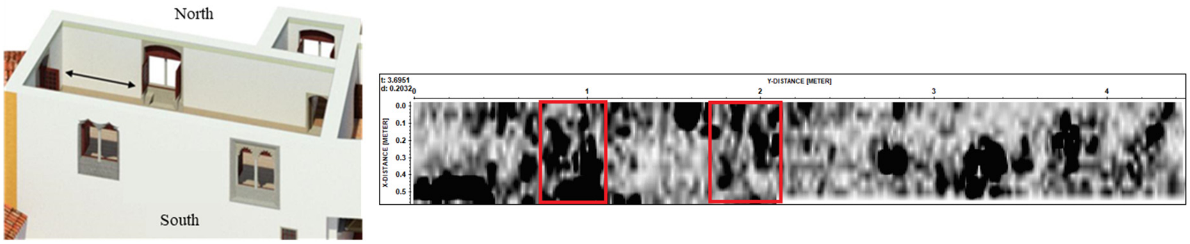
Experimental investigations

The experimental campaign was designed based on the structural and historical survey [9], considering both semi-destructive and non-destructive tests while respecting the historical value of the Palace. The campaign aimed to assess the mechanical properties of masonry, construction techniques, and the geometry of structural elements. The tests were carried out on the main structural units that represented a key construction period in the Palace. The main results are presented in the following subsections and provide critical data for the numerical modeling phase, ensuring an accurate representation of the Palace's structural behavior under seismic loading.

Ground penetrating radar (GPR) tests

GPR testing was carried out with different frequency antennas (500 MHz, 800 MHz, and 1.6 GHz) to determine wall thickness where unknown, to investigate the structural configuration of the Palace's vaults, determine construction techniques, types of materials and anomalies (e.g., voids, cracks, water). This non-destructive test has been proven to be very useful in the study of heritage buildings, as mentioned by [14] and [15].

The GPR survey results confirmed that most thicker walls consist of two stone leaves with an infill core, with exterior leaves typically measuring approximately 0.3 m thick. The stone's size identified was about 30 to 40 cm. Some tests showed the presence of former windows and doors that were later filled with different masonry. In fact, in one situation, this finding prevented the planned flat-jack test at that location, ensuring a more informed testing strategy. Two distinct masonry types were identified in one room on the top floor of the oldest part of the Palace: one more organized and the other less structured. The latter contained several significant voids correlated with visible multiple cracks. Figure 3 highlights the results, marking two large voids in red. GPR was also used to assess walls that lacked adjacent rooms, helping determine whether they were built directly against the bedrock or if an empty space existed between them. This information was crucial for defining boundary conditions in the numerical model, particularly in evaluating constraints that may block wall displacements or rotations due to strong connections with the bedrock. The survey further revealed that all analyzed vaults contained infilling material, a critical factor for assessing their load-bearing behavior and seismic response.



a) b)

Figure 3: GPR tests performed on one building: a) location of the reading, b) results. Adapted from [16]

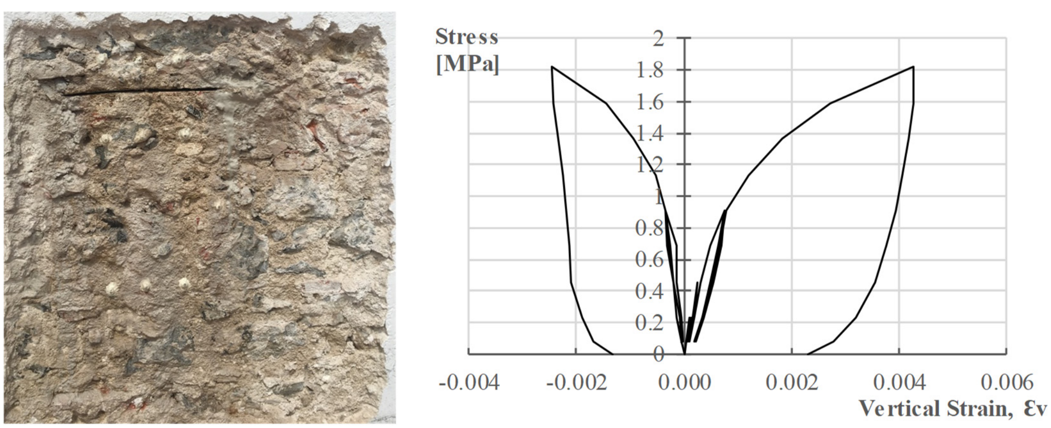
Collection of samples and flat-jack tests

Samples were collected from primary structural walls representing different construction periods, avoiding areas with decorative tiles or paintings. In cases where sampling was not possible, alternative locations were selected on adjacent walls. The retrieval of these samples provided valuable insights into the structural composition and material quality of the Palace's walls. The extracted samples had a diameter of 10 cm and a length between 20–30 cm, which allowed for the collection of material from a single leaf in double-leaf walls. However, due to the low cohesion of the mortar and difficulties in extracting intact cores, many samples were not retrieved in their entirety. Given the high heterogeneity of the masonry, the extracted samples were only representative of their local conditions, making it crucial to complement these results with broader experimental tests.

The survey results indicated a correlation between masonry quality and historical construction phases. The highest-quality masonry corresponded to structures built during the João I and Manuel I periods, whereas lower-quality masonry was predominantly found in the oldest sections of the Palace, dating back to the Arabic and King Dinis periods. This information was fundamental for assigning mechanical property values to numerical models, ensuring a realistic representation of the different construction techniques used across centuries. Moreover, among all collected samples, only those from the chimneys were brick masonry. However, many other samples contained brick fragments, suggesting that various available materials—predominantly limestone—were incorporated into the walls. Large voids were noted in several samples, while the best masonry quality was observed in the chimneys. This was a critical finding, given that the two monumental chimneys serve as the iconic image of the Palace. Their preservation and structural integrity are particularly significant, as they form part of the Cultural Landscape of Sintra, designated a UNESCO World Heritage Site since 1995.

Flat-jack tests were performed to determine the in-situ mechanical properties of masonry following ASTM and RILEM standards and incorporating recommendations for highly irregular masonry, with results processed and analyzed for numerical modeling [9]. Single-flat-jack tests were conducted to determine the in-situ stress state of the walls, while double-flat-jack tests were used to assess the material's stress-strain behavior, including Young's modulus and load capacity [17]. However, since these tests assess only the first masonry leaf, Young's modulus values may be overestimated and should be considered as upper-bound estimates. Due to the historical significance of the chimneys, no flat-jack tests were conducted in these structures. The Young's modulus values obtained range from 0.20 GPa to 6.76 GPa, highlighting significant variability due to the heterogeneous nature of the walls and their thicknesses, which vary between 0.8 and 2.2 m. Notably, both the highest (5.03 and 6.76 GPa) and lowest (0.20 GPa) values fell outside the range proposed by [18]. The maximum values were likely influenced by boundary conditions, as the tested walls were built against the bedrock—particularly those from the King Dinis construction period. Conversely, the lowest value was attributed to the poor construction quality of the analyzed wall. An example of an inspection window and the stress-strain curves obtained with the double flat-jack test carried out at that location are presented in Figure 4.

Ambient vibration tests
To study the dynamic behavior of the Palace's main bodies, including natural frequencies and vibration modes, ambient vibration tests were performed in selected structures with different dynamic characteristics. The selection of testing locations was based on both the cultural significance of these spaces and their importance for numerical model calibration. In some more complex units, like the chimneys, preliminary numerical models were carried out to help define the position of the sensors, choosing the points with higher displacements in their first fundamental modes. The dynamic response was recorded using high-sensitivity force-balance accelerometers (80V/g) with a frequency range from DC to 200 Hz. The setup included six uniaxial EpiSensor ES-U2 and one triaxial EpiSensor ES-T from Kinemetrics Inc., connected via Belden signal transmission cables to a 36-channel Granite data acquisition system. A triaxial sensor, used as a reference, remained fixed while uniaxial sensors were repositioned in different test setups, primarily in orthogonal pairs to measure in-plane and out-of-plane accelerations of the façades. The reference sensor was placed at the highest point of each building, where the largest displacements were expected. Each setup involved three 10-minute recordings with a 200 Hz sampling frequency. Data acquisition and control were managed using Rockhound software [19]. Frequencies were calculated according to the Enhanced Frequency Domain Decomposition (EFDD) method, using the ARTeMIS Modal Pro [20] software ([9]), and the main results are presented in Figure 5.



a) b)

Figure 4: a) Inspection area, b) stress-strain curves obtained from double flat-jack tests.

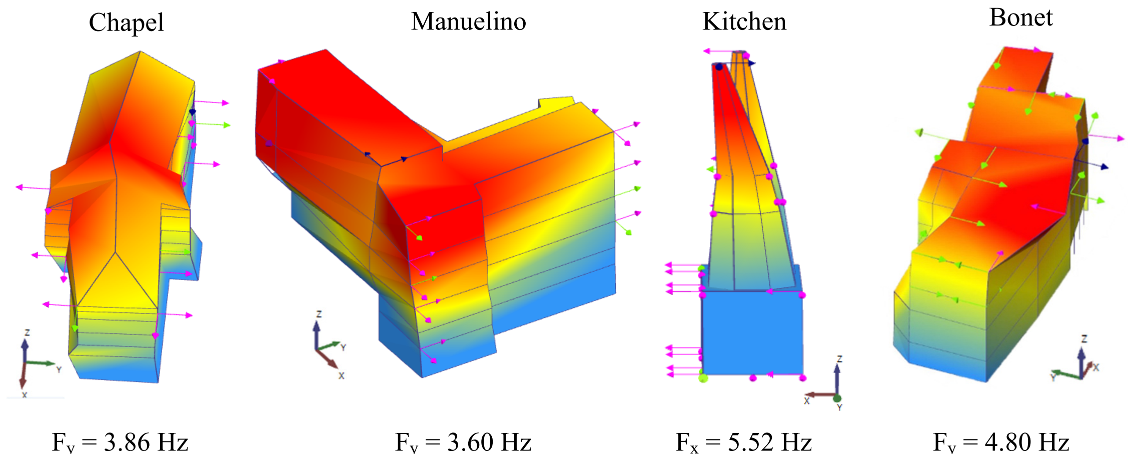


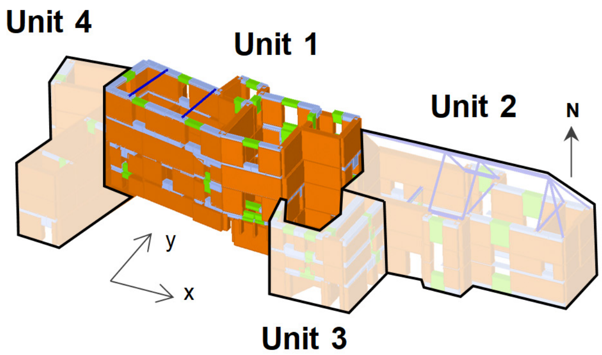
Figure 5: First frequency and modal shape of the main tested structural units (from [9])

NUMERICAL MODELING

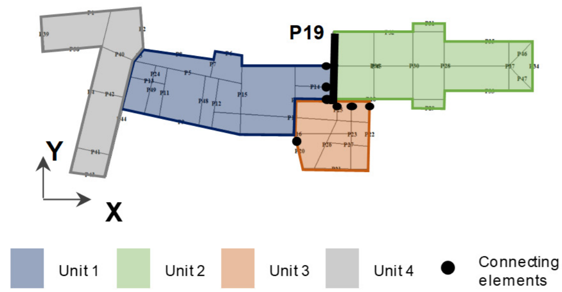
The global in-plane seismic performance of this historical unreinforced masonry (URM) complex aggregate was carried out by adopting the Equivalent Frame (EF) modeling approach, using 3Muri commercial software [21] for the geometrical modeling and Tremuri [22] for the mesh refinements and analysis processing. In this approach, masonry walls were defined by a mesh of macroelements with nonlinear behavior, piers and spandrels, connected by rigid nodes. The EF modeling was used instead of more refined approaches, such as Finite and Discrete Element methods, due to the lower computational effort. Besides, EF modeling has proven to provide realistic nonlinear static analysis results for URM structures.

Due to the large size and complexity of the Palace, which is composed of aggregate units built in different time periods with distinct dynamic behaviors influenced by the aggregate effect, the analysis of the monument was carried out in separate models of the structural units ([9], [23]). One of the key challenges in modeling aggregate structures was the definition of boundary conditions. This study focused on the seismic behavior of part of the aggregate (Unit 1) while examining the influence of different connection types with the adjacent units (Units 2, 3, and 4), presented in Figure 6. Three models were created considering perfect, partial and no connections within the aggregate. The first case was simulated by sharing nodes between adjacent units, while the last consisted of isolated models of the structural units. In the intermediate case, the partial connections between units (identified in Figure 6b) were introduced through spandrel elements, which resist compression and shear forces but not tensile stresses. The material properties attributed to these spandrels were the same as those of their adjacent piers. Floor misalignments were also considered when modeling full or partial connections by dividing the pier at the height of each floor.

The mechanical properties of the masonry were determined through the extensive experimental campaign presented previously and are presented in Table 1. The Young's modulus (E) and shear modulus (G) were calibrated on the perfect connections aggregate model using dynamic characterization from ambient vibration tests since for low-amplitude vibrations it is assumed a monolithic behavior between units. The tensile strength (f_t), compressive strength (f_c), and weight (w) were defined based on the Italian Standard [18] for the identified masonry types. The last story of Unit 1, which was found to have significant cracks, had its masonry strength and stiffness properties reduced by half.



a)



b)

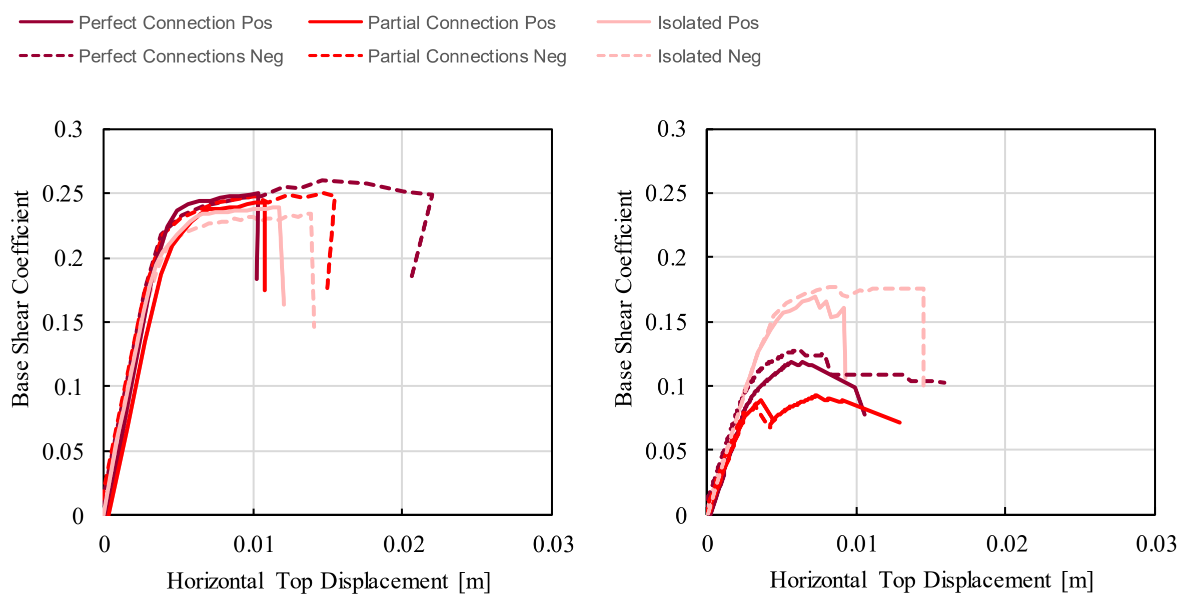
Figure 6: Numerical model: a) 3D view of the mesh, b) plan of the units and location of connecting elements

Table 1: Masonry mechanical properties (adapted from [9])

	Young's modulus, *E* (GPa)	**Shear modulus, *G* (GPa)**	**Tensile strength, f_t (MPa)**	**Compressive strength, f_c (MPa)**	**Unit weight, *w* (kN/m³)**
			Disorganized irregular stone masonry		
MIT (2019)	0.69 – 1.05	0.23 – 0.35	0.03 – 0.048	1.0 – 2.0	19
Unit 1	0.80	0.26	0.036	1.24	18
Unit 4	1.20	0.40	0.063	2.43	18
			Roughly dressed rubble masonry with varying leaf thickness		
MIT (2019)	1.02 – 1.44	0.34 – 0.48	0.0525 – 0.0765	2.0	20
Unit 2 / Unit 3	1.44	0.48	0.08	3.00	19

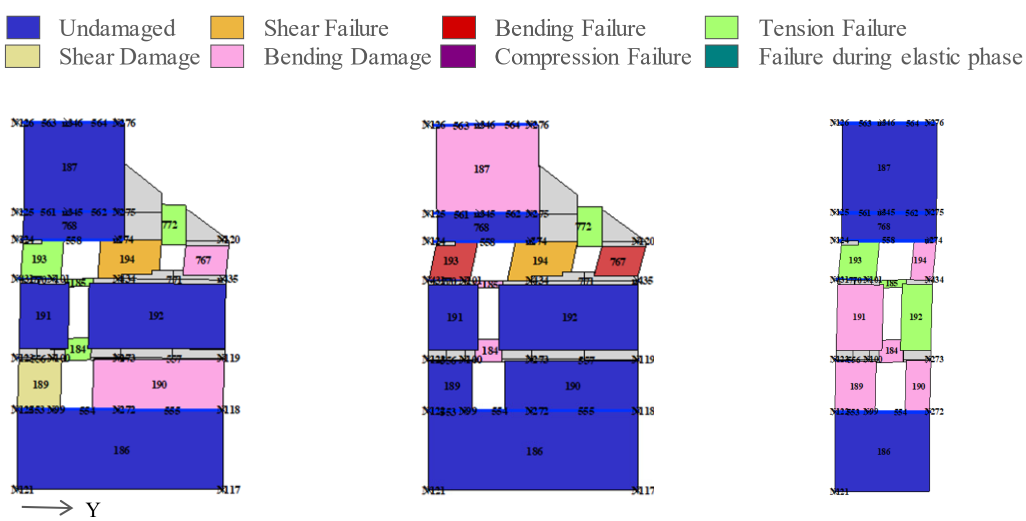
Pushover curves were generated to analyze the in-plane seismic response of the walls, as presented in Figure 7. A uniform force pattern, proportional to the nodal masses, was applied in the X (longitudinal) and Y (transverse) directions separately, until reaching the target displacement of the control node. The curves are presented in terms of base-shear coefficient and average top floor horizontal displacement, both regarding Unit 1, until the ultimate displacement, corresponding to a peak lateral strength reduction of 20% or the development of a collapse mechanism. For the X-direction, the aggregate effect had little influence on Unit 1's stiffness, suggesting that the aggregate tended to move together when pushed in this direction. The collapse of Unit 1 was caused by a soft-storey mechanism of one of the main façades, far away from the connecting elements. Although the in-plane capacity of walls in Unit 1 was similar between connection types, there were some changes in the damage pattern near the connecting elements.

For the Y-direction, the aggregate effect significantly influenced Unit 1's behavior. The isolated model showed the highest strength, followed by the models with perfect and partial connections. When in the aggregate, Unit 4 restrained Unit 1, causing slight torsion. In fact, the pushover curve of the wall shared by Unit 1 and Unit 4, when in the aggregate, presented low force values and remained in the elastic phase when the model started losing resistance. On the other side, the model with partial connections exhibited lower strength due to the soft-story collapse of wall P19 (identified in Figure 6b), as presented in Figure 8 for the tree models. It was possible to observe the changes in the damage pattern when considering the different types of connections. For the isolated model, the wall presented damage distributed throughout its height due to the lack of restraint from adjacent buildings, while the damage was more concentrated at the floor levels for models in aggregate. As mentioned before, the damage was concentrated at the top floor for partial connections, leading to a soft-storey mechanism of collapse. On the other side, with perfect connections, the wall also presents concentrated damage on the first floor.



a) b)

Figure 7: Pushover curves for Unit 1: a) x direction, b) y direction, considering a uniform loading



a) b) c)

Figure 8: Damage pattern of wall 19 in the Y direction shared between Unit 1 and Unit 2 for a top wall horizontal displacement of 0.02 m

Regarding the displacement capacity, in the positive X direction it was similar, independent of connection types, but it increased with the level of connection in the negative X direction. In the Y direction, the perfect connection model had a slightly higher displacement capacity than the isolated model. The partial connection model showed the highest displacement capacity in the positive Y direction, while the collapse of Unit 1 was not reached in the negative Y direction due to the early collapse of wall P19.

CONCLUSIONS

The paper presented an overview of the study conducted on the National Palace of Sintra, covering a variety of multidisciplinary activities finalized to its seismic assessment. The study involved historical and field surveys, non-destructive and semi-destructive testing, and the development and calibration of numerical models. The geometry survey was carried out not only using traditional methods but also using laser scanning to develop an H-BIM model. The results of the experimental testing campaign, including GPR, flat-jack, and ambient vibration tests, were used to identify the type of masonry in the building and to calibrate the numerical models.

The numerical modeling focused on one structural unit of the Palace and on the adjacent portions through an EF approach. Different levels of connections between these units were defined and their effects were assessed in terms of nonlinear pushover curves and damage patterns. The results show the significance of properly considering internal boundary conditions instead of modeling each unit as isolated. More study is needed to generalize the positive or negative influence of the aggregate effect on structural units, especially in relation to the position of the structure within the aggregate, and to quantify the degree of restraint provided by adjacent units.

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