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TOWARD DIGITAL TWINS: THE CASE OF THE PALMAVERA NURAGHE (ALGHERO) FOR A STRUCTURAL VULNERABILITY ASSESSMENT

1. Introduction[1]

The use of computational models represents a noteworthy approach to investigating degradation phenomena affecting historic structures vulnerable to environmental factors, both natural and anthropogenic. Through numerical simulation and predictive analysis, these models enable a deeper understanding of material deterioration dynamics and the interactions between structure and environment, providing valuable tools for the prevention, maintenance, and targeted restoration of architectural heritage (Cicalò, Solci 2016). In this context, the digital twin – a virtual representation of a physical object updated in real time with data from sensors (Hernández, Hernández 1997; Zhou *et al.* 2022) – is emerging as a strategic tool for the protection, conservation, and enhancement of cultural heritage (e.g. Hou *et al.* 2021, 2024; Vuoto *et al.* 2023). The digital twin assesses parameters such as structural stability by identifying areas prone to degradation, evaluates interactions with environmental factors (e.g. climate or seismic events), and validates restoration strategies through simulated intervention scenarios (Ćosović, Maksimović 2022). Consequently, it represents a key element in developing guidelines that integrate ancient knowledge with modern technologies to improve risk prevention and preserve structures.

Among the distinctive features of digital twins is the real-time analysis of the archaeological architecture under investigation: virtual modelling and simulation, grounded in a solid understanding of the archaeological architecture concerned, can be developed through an information transmission system that enables continuous monitoring of the object's condition (Hernández, Hernández 1997).

In Sardinia, there is a growing interest in applying computational models to the study of nuraghi structures, examining both their architectural features and their long-term resilience (Tran *et al.* 2025). Several factors have contributed to the development of computational models focused on nuraghi. First of all, their typological recurrence (Lilliu 1962, 1963, 136-232, 1982; Contu 1985; Blake 1998; Ugas 2005, 35-44; Depalmas 2009, 2015, 2018;

[1] Although the result of a joint research effort, sections 1, 2.1 are to be attributed to I. Trivelloni; sections 2.2, 2.3 to R. Busonera; section 3, along with its subsections, to M.E. Yildizdag, E. Barchiesi and E. Turco. Unless otherwise indicated, the contribution shall be considered as jointly written by all authors.

Vanzetti *et al.* 2013; Tanda 2015; Melis 2017) and widespread distribution[2] – whether referring to complex structures or simpler forms (Vanzetti *et al.* 2013, 86-92; Melis 2017, 29-48; Depalmas 2018, 76-81) – facilitate large-scale testing of model reliability, predictive degradation analyses, and structural vulnerability assessments. From an architectural perspective, the distinctive construction patterns of nuraghi (Contu *et al.* 2004, 383-388; Melis 2017, 29; Depalmas 2018, 57-58) provide an additional rationale for their suitability as case studies.

Another key aspect is the effort to achieve World Heritage recognition for Nuragic culture, supported by initiatives enhancing selected sites[3]. In addition to legislative measures and dedicated resources for protection and preservation, the significant number of nuragic towers still in good condition strengthens confidence in the reliability and durability of their architectural structure.

The central aim of this study is to establish the theoretical basis for a digital-twin approach to the analysis of dry-stone masonry structures using the discrete element method. In this model, individual stones are represented as rigid blocks connected by nonlinear spring interfaces, allowing the simulation of load transfer, damage evolution, and overall structural response. By integrating CAD-based geometric data with a computationally efficient solution strategy, the proposed approach allows the assessment of structural behaviour and local vulnerabilities under representative loading conditions. In this context, the Nuraghe Palmavera complex is selected as a representative case study due to its relatively simple architectural configuration, which facilitates accurate modelling; the extensive archaeological research providing a well-documented dataset; and recent restoration initiatives supported by targeted funding (Doro *et al.* 2019, 301-302), offering updated insights into conservation practices. Ongoing research by the Department of Architecture, Design and Urban Planning at the University of Sassari focuses on digital documentation and interpretation of the site, supporting conservation planning and advanced digital-access strategies for Sardinian cultural heritage (Cicalò *et al.* 2025).

[2] Although widespread across the island, nuraghi are especially concentrated in the Marghine region, a central-western area characterized by durable basaltic rocks. These offer high resistance and optimal physical-mechanical properties for supporting heavy structures subjected to compressive forces (Moravetti 1998; Melis 2017, 49-53).

[3] The initiative is sponsored by the association Sardegna verso l'UNESCO. Currently, the only UNESCO World Heritage site in Sardinia is the Su Nuraxi complex in Barumini. For an analysis of the limitations and prospects of applying UNESCO guidelines within the archaeological field, see Azzena *et al.* 2017.

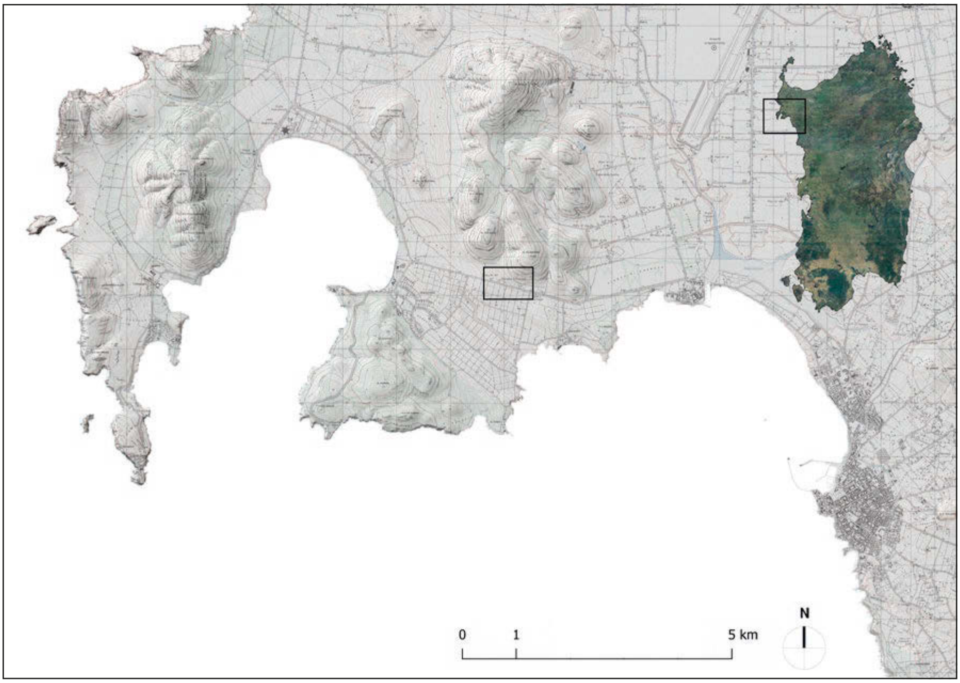

Fig. 1 – Framework of the site of Palmavera (Alghero).

2. The Nuraghe Palmavera in Alghero: a case study between archaeology and engineering

2.1 *Topographic context and archaeological evidence*

The complex stands on the southern slopes of the mountain of the same name, composed of layers of compact limestone used as building material. It is located at an elevation of approximately 65 m and less than 2 km from the Lazzaretto coastline. Positioned along the road connecting Alghero and Porto Conte, the site occupies a dominant and sheltered location, offering excellent visibility over the surrounding landscape and facilitating access (Fig. 1). Not far from the nuraghe, in the small valley stretching between the mountainous group of Monte Doglia and the heights of Punta del Giglio, lies an area known as Pozzo Patagone, where a spring described by A. Taramelli as «abbondante e discreta» was found (Taramelli 1908, 226). The morphological conditions of the territory favoured human settlement as early as the Early Neolithic period, and it is plausible that the nearby mining areas of Calabona, Canaglia, and Argentiera were known and exploited. The Nuraghe

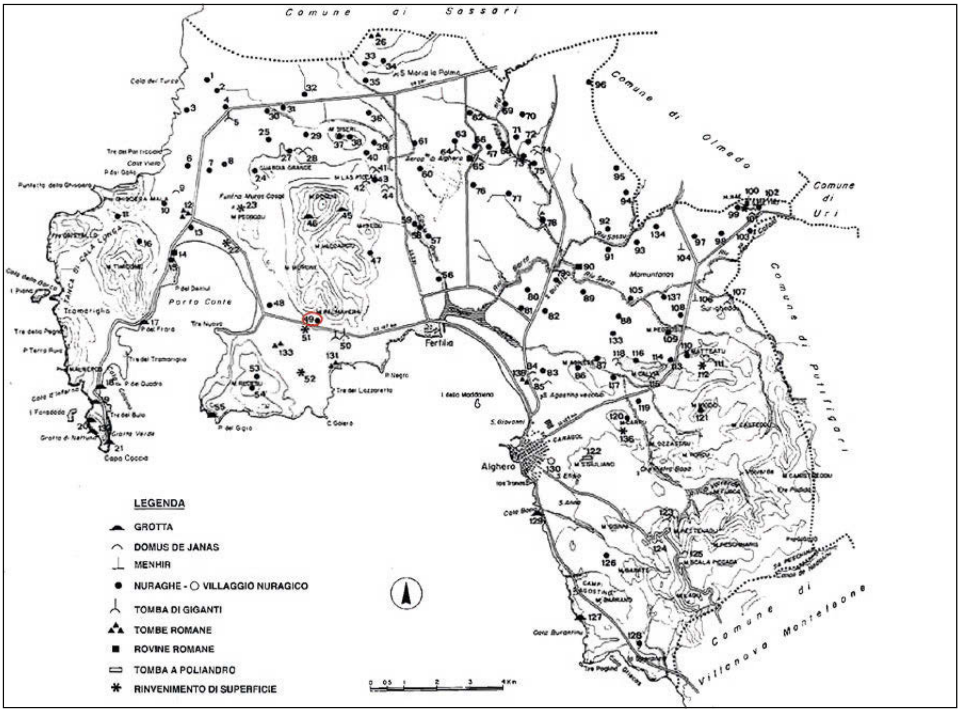

Fig. 2 – The map highlights the density of archaeological remains around the Palmavera Nuraghe (n. 49) (after Moravetti 1992).

Palmavera site does not represent an isolated complex; rather, it is part of a dense network of archaeological evidence, among which stand out the Anghelu Ruju necropolis, the single-tower nuraghe Sa Lattara, and the Giants' Tombs, located SE of Palmavera in the flat area at the foot of the mountain, near the modern road system (Fig. 2).

The site underwent multiple construction phases between the 15th-14th centuries BCE and the 9th-8th centuries BCE, marked by the progressive introduction of sandstone and limestone as building materials, structural reconstructions, and the expansion of domestic and communal spaces (Moravetti 1992, 121-122)[4].

[4] The final abandonment of the settlement likely occurred in the 8th century BCE, possibly due to a fire. The discovery of Punic and Roman materials in upper stratigraphic layers suggests that the site continued to be sporadically frequented in later periods, although without a true systematic reoccupation (Moravetti 1992, 122). For an analysis of the materials recovered during the excavations, see also Taramelli 1908 and Doro *et al.* 2019.

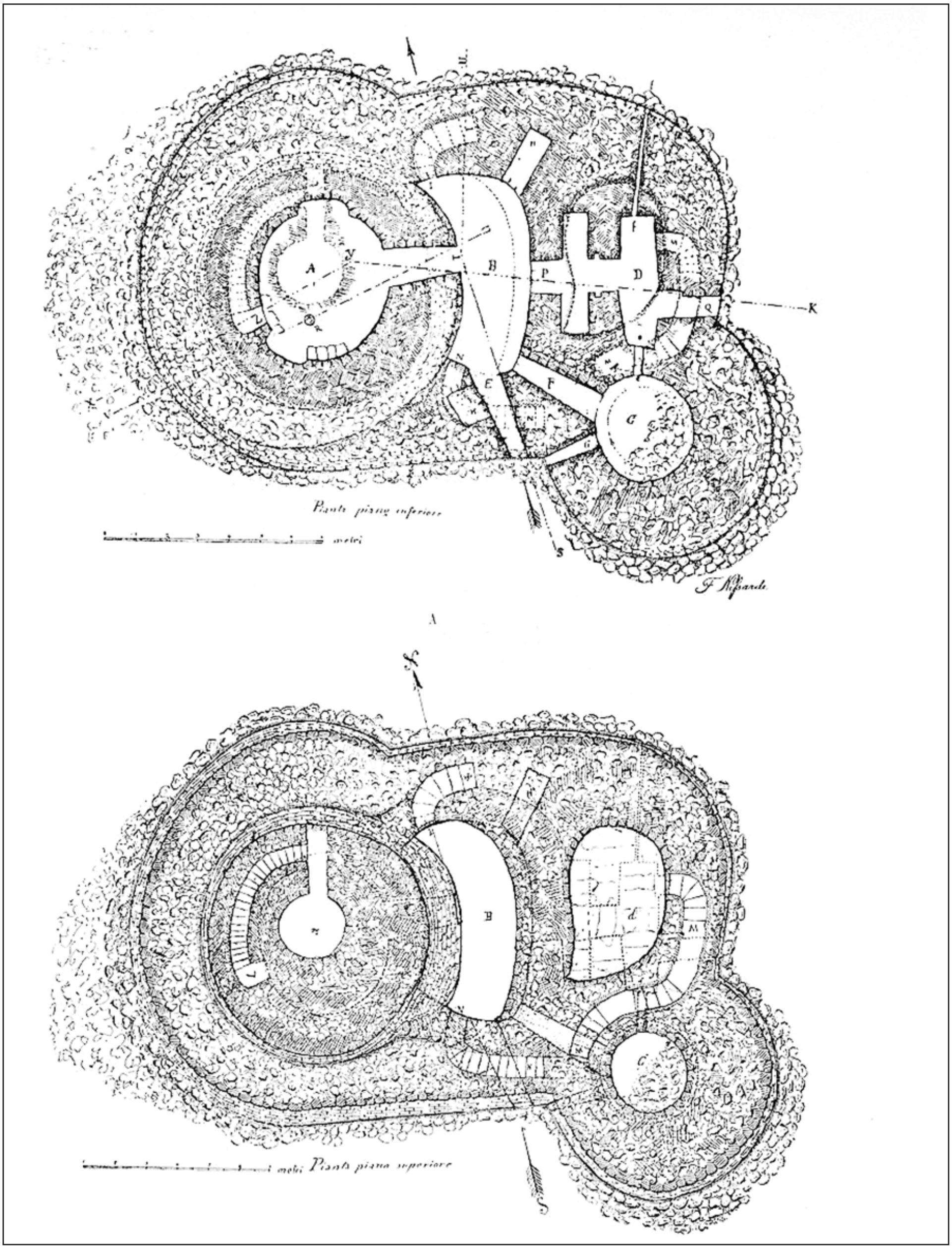

Fig. 3 – Plan of the nuraghe. The letter A indicates the plan of the lower floor, while letter B refers to the plan of the upper floor (after Taramelli 1908). The tower marked with the letter 'C' is the focus of the structural assessment presented in this study.

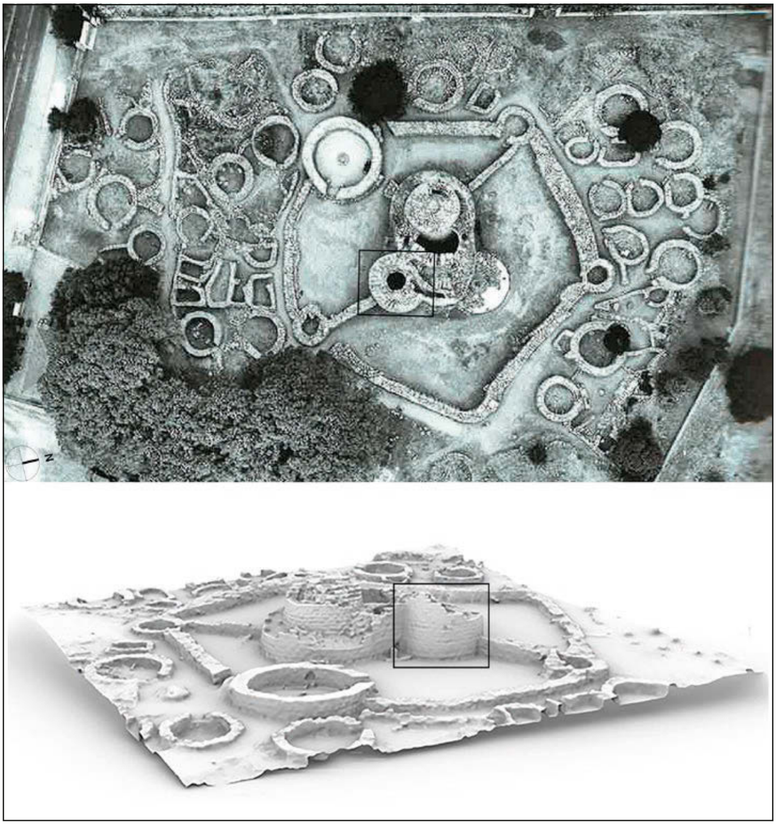

Fig. 4 – The site of Palmavera following the 2018-2019 excavations and restoration works (after Doro *et al*. 2019). Below, the rendered CAD model of Nuraghe Palmavera (courtesy of Michele Valentino). The tower under study is highlighted in black.

The complex of Palmavera is organized around a main central fortified tower, flanked by two secondary towers[5], a bastion with two entrances, an open-air courtyard, and a corridor with niches. The main tower, with a circular structure, has a preserved maximum height of approximately 10 m and a diameter of 8 m (Taramelli 1908, 237-248; Moravetti 1992, 51-58). Its entrance faces E and leads through a passageway into the tholos

[5] Recent excavations carried out between 2018 and 2019 near the bastion in the northwestern area led to the discovery of a third tower (Tower C), which mirrors the second (Tower B). Tower C was either demolished or collapsed due to significant structural failures during the Final Bronze Age (Fig. 4). Despite the collapse, the nuraghe continued to be used, and the breach in the bastion was sealed (Doro *et al*. 2019, 302).

chamber. The building includes a stairwell that once provided access to the upper levels, which are no longer preserved. The inner courtyard and the corridor with niches are additional elements that define the architectural articulation of the structure (Fig. 3). This nucleus, enclosed by a wide outer wall incorporating tower-huts and the so-called Meeting Hut (Moravetti 1992, 85-121; Vanzetti *et al*. 2013; Doro *et al*. 2019), was surrounded by a settlement of numerous huts arranged in an irregular pattern. The village, today visible in about fifty huts, suggests a much larger original settlement, though part of the area remains unexplored and has been compromised by modern interventions (Fig. 4).

Within this context, the secondary tower flanking the central one on the southeastern side constitutes the most relevant structure for computational modelling (see below, §3). With a circular plan (diameter 3.40-3.50 m) and a preserved height of about 5 m, it is accessed from the courtyard through a tall, splayed corridor with trapezoidal cross-section (length 2.90 m; width 0.90-1 m). The tower has three outward-facing slits and a fourth in the northern wall, aligned with a similar slit in the bastion. Unlike the central keep, it is mainly built with finely worked sandstone blocks in regular courses. However, from the bastion entrance across a large part of the outer perimeter, the facing is limestone, a feature that points to subsequent modifications, possibly linked to partial restoration work (Moravetti 1992, 58-59).

2.2 *Architectural and structural analysis*

As with other nuraghi of the island, the structural principle is that of a non-thrusting system, overall capable of transferring loads and stresses toward the ground along vectors that are nearly vertical. Nuraghi are composed of polygonal stone blocks arranged in concentric rings with progressively decreasing diameters: each ring projects slightly over the one below, culminating in the closure of the structure with a single keystone block. As for the masonry, its main characteristic is the absence of binding agents between the lithic elements that compose it[6]. The characteristics of the construction materials, selected for their availability and degree of workability, contribute to the overall structural resistance of the architecture. The use of limestone and sandstone has ensured good resistance to compressive forces, which is essential for the specific compositional solution of the nuraghe. On the other hand, a certain degree of porosity in these materials has led to inherent weaknesses, particularly in terms of sensitivity to atmospheric agents (which are especially significant given the site's location), as already observed during the earliest phases of investigation and restoration.

[6] Occasional evidence of mud between the stone blocks has been documented (Melis 2017, 29).

Fig. 5 – Southern front of the nuraghe. The main entrance and tower B (on the right) can be seen.

Regarding compositional principles, careful attention had to be paid to the choices regarding the placement of elements within the architectural structure: the larger blocks, with higher specific weight, were positioned in the lower sections. As the structure rose, lighter elements were progressively used, culminating at the top of the towers. The same solution is used for Tower B, a more recent architectural element added to the central core, as to a bastion guarding the two entrances to the building (Fig. 5). The construction technique appears more regular than that of the older tower, probably due to the more careful choice of building materials and the attention to the placement of the blocks. Furthermore, significant care has been taken in the processing of the blocks, that have been cut and machined for joining with the main tower (Taramelli 1908, 247-253)[7].

These building strategies are rooted in static mechanics and are easily justified. On the one hand, the larger elements contribute to forming a solid foundation; on the other, the builders of the Nuragic period must also have considered the challenges related to the shaping, transport, and lifting of the structural components. Unfortunately, the frequent collapse of the upper portions prevents a clear understanding of the articulation of the summit area. Overall, the structural stability and mechanical resistance of the masonry rely solely on the mass and self-weight of the individual elements. An additional solution emerges, whereby architectural form and masonry composition work together to ensure the solidity of the entire construction. The use of

[7] In Taramelli 1908, the tower is referred to as Tower C (pl. II A, B; Fig. 3 in this article).

a truncated conical shape for the towers gives the masonry an inclination of approximately 10°, which reduces the risk of overturning and ensures a balanced distribution of loads (Melis 2017, 29). The considerable weight of the nuragic structure clearly influenced both the design and construction phases. The need to direct the load of the masonry along vertical axes has favoured the adoption of the post-and-lintel system, characterized by two vertical elements supporting a horizontal beam placed above them. The intense flexural-compression stresses required particular care in determining the width of openings, leading to the choice of relatively narrow entrances. At times, the trilithic system of the nuraghi is further enhanced by a small opening created in the upper course, serving as a relieving window. Moreover, given the complexity of the stresses the structure had to withstand, the selection of construction materials became a crucial factor in the success of the building. For this reason, the inevitable challenges related to quarrying activities, as well as those concerning the transport of materials, cannot be overlooked.

2.3 *Conservation measures and consolidation strategies*

Several operations aimed at safeguarding the Nuragic site of Palmavera have made it possible to address and solve many structural issues affecting the complex. The site was, in fact, undergoing a progressive deterioration of its original masonry, whose static capacity was gradually undermined by the action of atmospheric agents and by the high degree of salinity in the area, due to its proximity to the sea. Following the first archaeological investigations carried out at the site (Taramelli 1908, 231-262; Moravetti 1992, 49-84) and after years of severe abandonment, the first structural consolidation works were conducted by G. Maetzke, who at that time was head of the Superintendency of Sassari. His action was characterized by anastylosis and structural integration carried out through modern techniques and materials (a meaningful choice, even for the purposes of the present study). The gaps in the masonry of the nuraghe were treated using concrete, bricks, and plaster, while the simpler repositioning of collapsed blocks was limited to smaller areas that posed fewer structural problems (Fig. 6). These solutions were adopted mainly for Tower B, where it was necessary to restore structural continuity, requiring the renovation of several sandstone courses laid in an isodomic arrangement (Tomassetti 2018, 333).

Given the construction features of the architectural complex, a specific attention was devoted to the entrances and to the connecting chambers around the central courtyard, where the original materials were in an advanced state of decay and could no longer fulfil structural functions. Through new masonry and the use of cementitious materials, the vertical supports for the architraves were rebuilt and, in some cases, iron beams were inserted to absorb the tensile stresses that stone materials are usually unable to withstand.

Fig. 6 – Some examples of the recent restoration works carried out on the masonry at the main entrance of the nuraghe.

Due to the natural decay of the original structures and the deterioration of the interventions carried out under Maetzke's supervision, new and more recent structural consolidation operations became necessary in 1990 and again in 2010-2011 (Boninu 1991; Doro *et al.* 2019). In several parts of the monument, the earlier restoration work was removed, and a lithological study was undertaken to perform a structural assessment, as well as to allow for the more precise planning of future actions. The presence of plants on the upper part of the structure had caused evident displacements of the blocks, which required the cutting and drying of the vegetation. In addition, stabilisation actions were carried out, including structural integrations that also helped to restore the original configuration of the masonry.

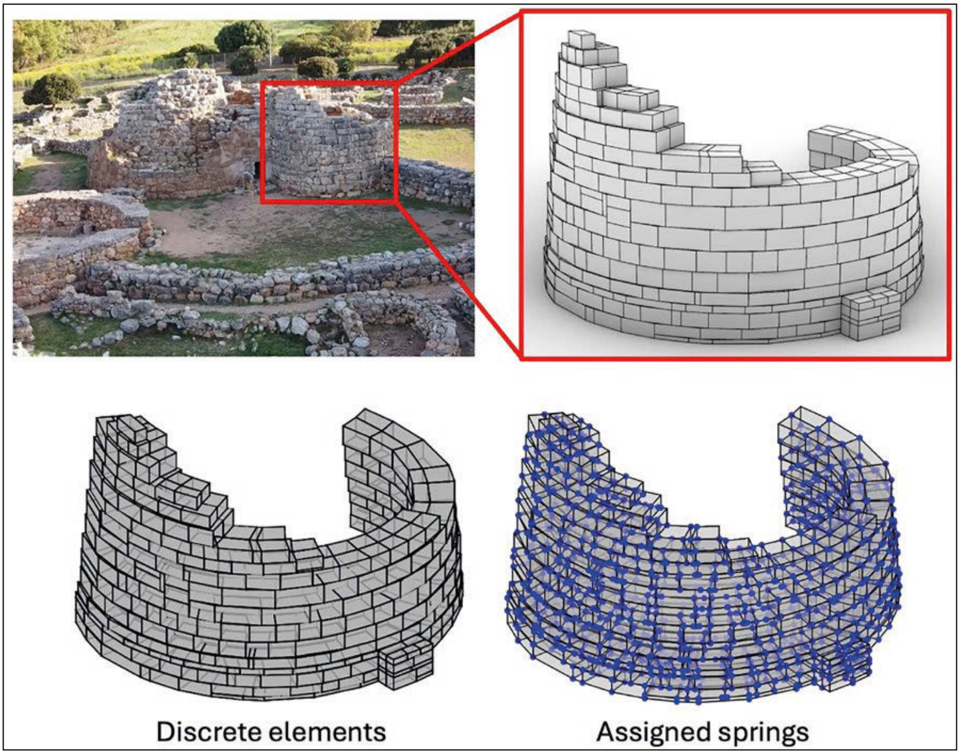

Fig. 7 – Discrete modeling of historical stone masonries.

3. Mechanical digital twin of ancient stone masonry

We describe the main aspects for building a digital twin of ancient stone masonry building able to predict the mechanical behaviour of such structures. The keynotes of this kind of structures (Fig. 7) are the following: 1) irregular stones; 2) absence of mortar; 3) irregular organisation. These characteristics suggested to conceive a mechanical model where the fundamental brick is the single stone considered as rigid and to model the interactions in-between stones by means of simple springs. The structure is represented as a discrete assembly of interacting rigid blocks, thus avoiding the use of continuum discretisation approaches such as finite element modelling. In this way, the whole construction is modelled as a series of rigid blocks whose position is perfectly determined, in the three-dimensional space, by six Lagrangian parameters. As usual in structural analysis, to each configuration, i.e. the positions with respect to a reference system of all its blocks, can be associated the total potential energy of the elastic springs and, by using the principle of minimum of total potential energy, the problem solution. The overall modelling strategy is particularly suited to dry-stone masonry systems such as nuraghe structures, where the global mechanical response is mainly governed by block arrangement, self-weight, and contact interactions rather than by the deformability of individual stones.

Naturally, the analysis of a relevant number of stones is not simple but, nowadays, is manageable even with a cheap laptop. The fundamental brick of the proposed method is the definition of the strain energy in a generic configuration of two adjacent blocks. In this direction, we first define a block as formed by the stone and by the possible mortar around the stone. In such a way, the whole construction is made of rigid parallelepipeds whose current position in a three-dimensional space can be described by six geometrical parameters. For instance, three parameters indicating the position of the centroid and three parameters indicating the Euler angles (for further details, see Tran *et al.* 2025; Yildizdag *et al.* 2025). We remark that each stone is represented by a hexahedral polysurface modelled in Rhinoceros, with its size and position determined directly from the CAD geometry. The adopted idealisation focuses on reproducing the overall block arrangement and contact topology governing the structural response, while detailed surface irregularities are intentionally neglected within the scope of the mechanical analysis. The vertex coordinate data of these polysurfaces are extracted using RhinoScript and then imported into MATLAB for further processing. In MATLAB, the centroids and volumes of all stones are computed, forming the geometric foundation for contact detection and spring assignment in the discrete element model.

In the present study, the digital twin is developed based on a physics-based mechanical representation of the monument aimed at predictive structural assessment rather than real-time monitoring. The geometric model of the structure was reconstructed through photogrammetric survey (Cicalò *et al.* 2025). Although direct real-time data coupling is not implemented at this stage, the framework can be initialized from observed damage conditions and used to simulate plausible deformation and failure scenarios under representative loading actions.

3.1 *Strain measure and strain energy*

Considering two adjacent blocks both in the reference and in the current configurations, it is possible to define the strain energy associated with a spring linking two points on the i and j blocks. We denote with X_i and X_j and with x_i and x_j the position vectors of the considered points in the reference and current configurations, respectively. The stretch of the spring connecting the two considered points can be written as:

$$\Delta s = (u_j - u_i) + (R_j - I)(X_j - \overline{X}_j) - (R_i - I)(X_i - \overline{X}_i), \qquad (1)$$

where we distinguish two contributions: the first is related to the relative translation $x_j - x_i$ of the block centroids indicated in the reference configuration with $\overline{X}_i$ and $\overline{X}_i$ and the second to the relative rotations $(R_j - I)(X_j - \overline{X}_j) - (R_i - I)(X_i - \overline{X}_i)$ of these blocks. The rotation tensors R_i and R_j are constructed by means of products of three successive rotations about the reference axes in terms of Euler angles of the two blocks (Yildizdag *et al.* 2026).

The strain energy associated to the aforementioned kinematics can be written as sum of two contributions

$$U = \frac{1}{2}(k_n(\Delta s \cdot n)^2 + k_t(\Delta s \cdot t)^2), \qquad (2)$$

the first linked to the normal unit vector and the second to the tangent unit vector both referred to the two considered adjacent faces.

The stiffness parameters, k_n and k_t, can also be used to introduce damaging in a very simple form. Damaging indicates the degradation of the elastic mechanical behaviour as the loading increases. In formulae, the stiffness parameters assume the form

$$k_n^d = f_s\left(k_n^T(1 - d_n^T)H(u) + k_n^C(1 - d_n^C)H(-u)\right), \qquad (3)$$

$$k_t^d = f_s k_t(1 - d_t),$$

where damage parameters range between 0 and 1 and are different for traction d_n^T, compression d_n^C and shear d_t. Also, the term f_s is the surface scaling factor. The Heaviside function $H(u)$ is used to switch on the appropriate branch based on the relative displacement in-between blocks.

It is possible to describe precisely the progressive degradation of the spring stiffness by using the definition of the dissipated energy functions for normal, tensile and compressive, and tangential modes. Within the hemivariational framework (Yildizdag *et al.* 2022) the damage laws satisfying the Karush-Kuhn-Tucker conditions yield:

$$d_n^T = 1 - \exp\left(-\frac{|\Delta \mathbf{s} \cdot \boldsymbol{n}|}{B_n^T}\right),$$

$$d_n^C = \frac{2}{\pi}\arctan\left(-\frac{\Delta \mathbf{s} \cdot \mathbf{n}}{B_n^C}\right), \qquad (4)$$

$$d_t = 1 - \exp\left(-\frac{|\Delta \mathbf{s} \cdot \mathbf{t}|}{B_t}\right),$$

being the quantities B_n^T, B_n^C, and B_t the characteristic damage lengths associated with normal, tensile and compressive, and tangential directions, respectively.

To reproduce the inherent asymmetry between tensile and compressive responses in stone masonry joints, the tangential characteristic length B_t can be formulated as a piecewise function of the relative normal displacement $\Delta s \cdot n$ (Yildizdag *et al.* 2026 for technical details). The quadratic form of the strain energy is intended to represent the elastic response associated with small relative displacements between adjacent blocks prior to damage activation. Nonlinear interface behaviour, including stiffness degradation and sliding mechanisms, is indirectly captured through the adopted damage evolution laws.

It remains to define how the spring sets are defined by a contact algorithm that detects interfaces between neighbouring stones based on their geometric proximity and overlapping faces. When two stone surfaces are identified as coplanar and share a common area, springs are placed at the vertices of the intersecting region to represent the normal and tangential interactions. This procedure ensures a computationally-efficient and consistent mechanical linkage between adjacent stones, enabling accurate simulation of load transfer and damage evolution within the structure.

3.2 *Iterative scheme for solving nonlinear system of equations*

When a minimum principle – in our case the minimum of total potential energy – is used, a system of nonlinear equations, imposing the equilibrium conditions, is generated and its solution requires an ad hoc solution strategy. By referring the interested readers to Turco *et al.* 2016, here we describe only the main aspects of the Newton-Raphson method which can be improved in many ways, but it is however the keystone. We suppose to know the displacement vector of the whole discrete system $u = x - X$ and the residual vector $r(u)$ using the Taylor expansion we can write

$$r(u + \Delta u) \approx r(u) + K(u)\Delta u, \qquad (5)$$

where $K(u)$ is the gradient of $r(u)$, the so-called stiffness matrix, and the correction vector Δu can be computed by imposing that the residual vector becomes zero

$$\Delta u = -K(u)^{-1} r(u). \qquad (6)$$

After a suitable number of loops the residual vector becomes practically zero and we have a new solution. Performing a desired number of steps gives a sequence of points each one characterised by a practically null residual vector, therefore representing an equilibrium point.

3.3 *The case study of Nuraghe Palmavera*

To demonstrate the applicability and the performance of the proposed method, a series of numerical studies are carried out. The aim of this section

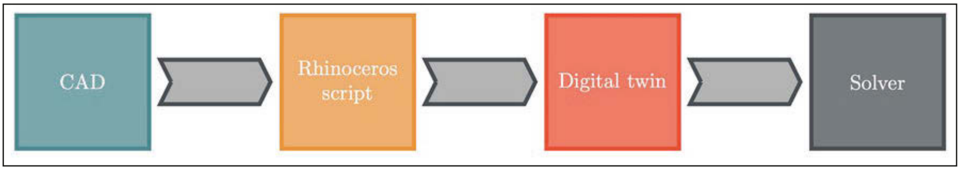

Fig. 8 – Workflow of digital twin construction.

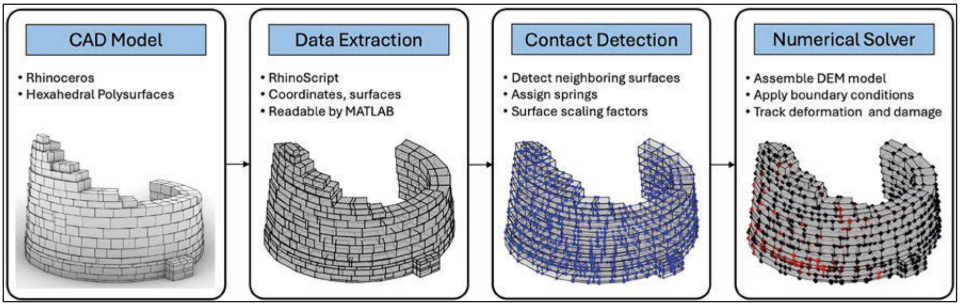

Fig. 9 – Flowchart of the developed 3D hemivariational DEM digital twin framework.

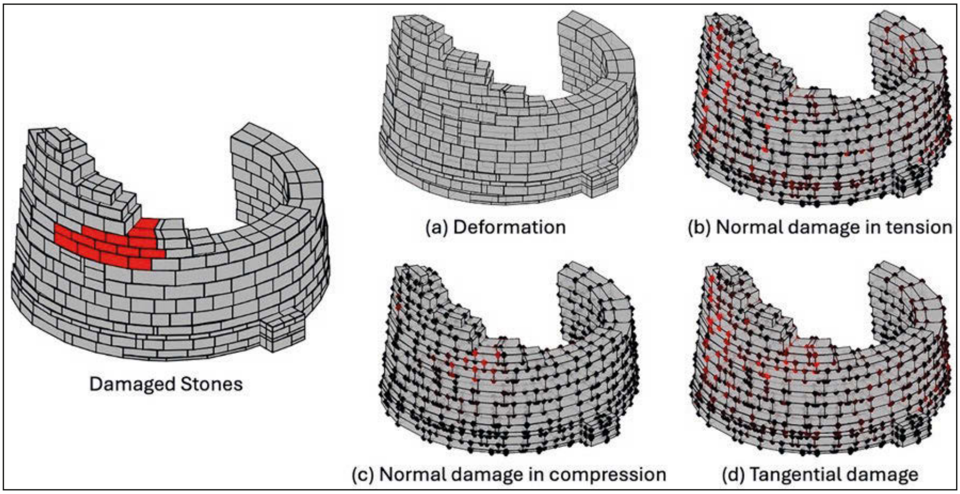

Fig. 10 – Discrete element model of the Nuraghe Palmavera tower segment used in the numerical study. Damaged stones (shown in red) indicate the damaged region, while the structure is subjected to a representative lateral load simulating environmental effects.

Parameter	Definition	Value
t_m	Equivalent interaction layer thickness	1×10^6 m
kT_n	Undamaged normal stiffness in tension	1×10^6 m
kC_n	Undamaged normal stiffness in compression	2×10^6 m
k_t	Undamaged tangential stiffness	1×10^6 m
BT_n	Characteristic normal damage length in tension	0.01
BC_n	Characteristic normal damage length in compression	0.05
$B\tau_0$	Reference tangential damage length	0.01
ρ	Density	2700 kg/m^3
α_1	Tangential stiffness parameter	10
α_2	Tangential stiffness parameter	14
u^*_η	Impenetrability potential threshold	$2t_m$

Tab. 1 – Simulation parameters.

is twofold: first, to illustrate the discrete element generator developed to create masonry geometries in a systematic manner; and second, to apply the framework to a representative case study involving a historic monument. These studies provide insight into the flexibility of the generator, the robustness of the solution algorithm, and the ability of the framework to capture the complex mechanical response of ancient masonry structures under different loading conditions. To build a discrete element model for the analysis of stone masonry structures, it is necessary to merge results deriving from different software. The workflow (Fig. 8) begins by importing the data deriving from the survey in a CAD model. Successively, using a Rhinoceros script routine data such as coordinates and surfaces are built in a format readable by MATLAB. Contact in-between neighbouring surfaces is detected and springs elements are coherently generated. Finally, the discrete element model is assembled and, after having assigned boundary conditions and loading processes, deformation and damages are computed.

Using the strategy sketched immediately above we have built the digital twin of the main tower of Nuraghe Palmavera (Fig. 9) and performed a numerical simulation freely inspired by an unsuccessful consolidation attempt some years ago. A large portion of the wall was reinforced by inserting a steel beam which, in turn, was deteriorated by a progressive corrosion process. This area was coloured in red in Fig. 10. As mechanical parameters for the digital twin we chose those reported in Tab. 1 both for the undamaged and damaged joints.

After the definition of this pre-damaged configuration, the structure is subjected to a lateral pressure intended to mimic realistic environmental actions such as wind loads, or long-term weather effects. The simulation (Fig. 10) captures the resulting deformation and damage evolution throughout the assembly. The predicted deformed configuration reveals that the most significant damage develops around the initially weakened zone, where local stiffness loss leads to concentrated displacements and progressive joint opening. Away from this region, the masonry remains comparatively stable, demonstrating the capability of the proposed hemivariational DEM framework to reproduce localised failure and global deformation in ancient stone structures under lateral loading.

4. Computational models for heritage protection: applicability and future scenarios

The study of nuraghi offers a compelling opportunity to apply the concept of the digital twin and computational modelling to the structural and degradation analysis of ancient architecture. These models, when integrated with high-resolution surveying technologies, enable a dynamic understanding of how dry-stone masonry structures, built without binding agents, respond to mechanical stress, environmental change, and long-term deterioration. The methodological framework developed through the analysis of nuraghi holds promise for broader application to similar heritage typologies, particularly those characterised by vernacular construction techniques and limited documentation. From this perspective, while construction chronology and architectural form may introduce variables in model calibration and interpretation, it is ultimately the construction technique and the geo-morphological context that exert the greatest influence on structural behaviour and determine the reliability of predictive simulations. The physical interaction between stone blocks, their geometry and arrangement, the mechanical properties of the lithic material, and the condition of the geological substrate all contribute to the long-term performance and vulnerability of these structures.

Thanks to their widespread distribution across Sardinia, relative architectural homogeneity, and rich archaeological documentation, nuraghi represent an ideal case study for testing and validating structural models. Their presence across diverse environmental settings enables comparative analyses, large-scale simulations of structural behaviour, and empirical validation of results. This also opens the possibility of developing typological classifications based on structural performance, degradation patterns, and resilience thresholds. The integration of computational models with advanced surveying technologies supports long-term monitoring of structural evolution, simulation of extreme events (e.g. hydrogeological instability, climate-induced stress), and analysis of degradation processes. These tools further aid the optimisation of restoration strategies, allowing interventions to be guided by objective, data-driven assessments rather than solely by visual inspection or historical precedent.

If proven effective in the case of nuraghi, this approach could be extended to a wide range of historic structures sharing similar construction principles. The proposed method relies primarily on high-resolution geometric survey data and basic mechanical parameter estimation, while computational analyses remain affordable in terms of time and resources. Such a scalable methodology could support a new paradigm in cultural heritage conservation, promoting sustainable strategies for structural assessment and risk mitigation.

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ABSTRACT

Starting from the archaeological and architectural analysis of the Nuraghe Palmavera, located near Alghero in northwestern Sardinia, this study presents a preliminary investigation into the application of digital twin methodologies and computational modelling for predictive structural analysis and risk assessment. The focus is placed on one of the towers within the nuragic complex, selected as a representative case for testing the integration of digital tools with archaeological data. The research explores the potential of mechanical digital twins to simulate structural behaviour over time, assess vulnerability to environmental and anthropogenic stressors, and support conservation strategies based on objective, data-driven insight.