STRUCTURAL ASSESSMENT OF THE PROPYLAEA CHURCH ARCHAEOLOGICAL REMAINS IN JERASH (JORDAN) USING 3D DISCRETE ELEMENT MODELLING

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Abstract – The study presents the structural analysis of the remaining portion of the wall of the *diaconia* attached to the Church of the Propylaea in Jerash (Jordan), dating back to the 6th century AD. A 3D Distinct Element Modelling (DEM) approach was used with 3DEC software. A photogrammetric survey provided a dense three-dimensional point cloud, which was subsequently optimised for geometric modelling. The 3D DEM model, consisting of rigid blocks and non-linear contacts, was generated using a parametric script in Grasshopper and imported into 3DEC for numerical analysis. The physical-mechanical properties of the materials were chosen based on the literature and on the state of degradation. A quasi-static analysis was conducted to identify the equilibrium configuration under gravity loads, followed by a dynamic simulation under a seismic input. The results highlight the critical role of discontinuities and damage state in the structural behaviour of archaeological heritage and the contribution provided by 3D discrete element models for assessment and rehabilitation design.

Keywords: Cultural heritage; Historic masonry; Distinct Element Modelling (DEM); Digital survey; Parametric modelling.

I. INTRODUCTION

The evaluation of the dynamic behaviour of discontinuous structures, such as those consisting of stone blocks or masonry elements, represents a significant challenge in structural engineering, particularly for historic buildings. Such structures present a complex mechanical response due to the non-linear interaction between elements at the joints, the presence of discontinuities due to cracks, and the variability of the mechanical properties of materials and interfaces. Under dynamic actions, the behaviour is dominated by opening and closing contacts, rolling, sliding, which are difficult to model efficiently.

The seismic response of historic masonry structures can be analysed by means of finite element models (FEM), which allow an accurate assessment of the behaviour under dynamic actions [1, 2] but are developed for continuous systems, which complicates the representation of the highly non-linear phenomena concentrated at specific locations, such as joints and cracks, in inherently discontinuous structures. For these latter ones, a particularly effective alternative is numerical analysis based on the discrete element method (DEM), which allows each block to be explicitly modelled as a separate rigid or deformable entity, simulating the interactions between joints in terms of contact, friction and cohesion [3, 4, 5, 6]. The DEM is able to realistically represent historic masonry and dry-stone structures, being particularly suitable for the study of damage evolution, collapse mechanisms and the influence of geometric and mechanical characteristics on the global response of the system. Effective support for geometric modelling is provided by [7]. The application of this approach to historic structures allows the limitations of traditional methods to be overcome, offering a deeper understanding of seismic behaviour and intrinsic vulnerabilities.

The present work deals with the dynamic behaviour of the *diaconia* attached to the Church of the Propylaea (Jerash, Jordan) through a numerical approach based on 3DEC. The geometric modelling of the structure is developed from a high-density point cloud obtained by means of a photogrammetric survey, in order to accurately reconstruct the three-dimensional layout of the *diaconia* and the arrangement of the blocks. The integration of digital survey and numerical modelling provides a realistic representation of the geometric conditions, which is fundamental for assessing the structural behaviour. For the mechanical properties, reference is made to the data available in the literature, adapting them to the specific characteristics of the structure under examination. After an initial settlement phase, conducted by means of quasi-static analysis, a dynamic response evaluation is performed to simulate the effect of seismic stresses. The objective is to investigate the influence of the mechanical properties of the joints and geometry on the global response of the structure, providing indications for possible reinforcement interventions.

II. THE CASE STUDY

The case study analysed concerns the surviving wall of the *diaconia* attached to the Church of the Propylaea, located in Jerash (Jordan). The building, datable to the 6th century AD, belongs to the Byzantine period and was built

on the remains of an earlier Roman structure, of which it still retains clear traces of the original architectural configuration (Fig. 1). The *diaconia* consists of a circular room, later lowered and decorated with a mosaic floor. On the basis of the inscription in the floor mosaic, it is plausible to assume that the room was intended for the collection of offerings, thus constituting significant evidence of the liturgical function and spatial reorganisation characteristic of late antique architecture in the Christian sphere [8].
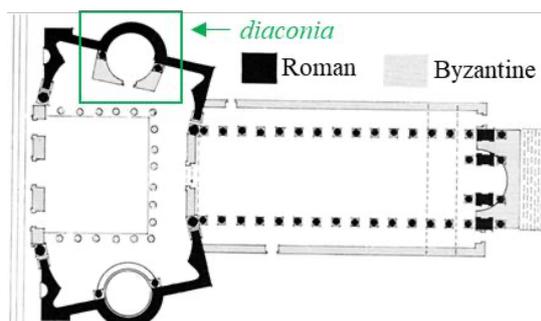

Fig. 1. Plan of the Church of the Propylaea. The black portions represent Roman-era structures, while the grey areas correspond to Byzantine additions. The diaconia is highlighted in the top left corner. From [8]

The geometry of the *diaconia* was detected by a three-dimensional digital survey based on photogrammetric techniques. A commercial camera was used for the acquisition, while image processing was conducted with Agisoft Metashape Professional software. The process returned a dense point cloud consisting of approximately 690.5 million points, with a total size of 10.5 GB.

III. DEM NUMERICAL MODEL

A. The Discrete Element Modelling (DEM) method

The structural analysis was conducted using the 3DEC calculation software. Originally developed by Cundall in 1983, 3DEC is a three-dimensional numerical programme designed to simulate the behaviour of rock clusters [9-10]. Subsequently, the code was extended to the study of masonry structures, described as an assembly of blocks [11-12]. This software is based on the discrete element method (DEM), a numerical approach that represents the mechanical behaviour of systems consisting of separate blocks, which interact through localised contacts at their interface surfaces (joints). This method makes it possible to simulate finite displacements, including complete separation between blocks, and to automatically update the geometry of the model by identifying new contacts formed during the analysis. The equations of motion are integrated in the time domain using an explicit central difference method, ensuring efficient integration, considering the non-linear behaviour of discontinuities and the high

relative displacements between blocks [13-14].

B. Modelling of the block structure

The acquisition of the dense point cloud in the digital survey phase provided essential support for geometric modelling, representing a key resource for the reconstruction of the geometry of the archaeological site. The point cloud was preliminarily optimised to obtain a more manageable version, from which the model used for the structural analyses was then derived. In particular, the original cloud was subjected to cropping and subsampling operations to improve computational efficiency. Sub-sampling was performed by imposing a minimum distance of 1 mm between points, resulting in a final cloud composed of 48.7 million points and a total weight of 700 kB. These operations were carried out with CloudCompare open-source software, which is specifically dedicated to the management and processing of point clouds.
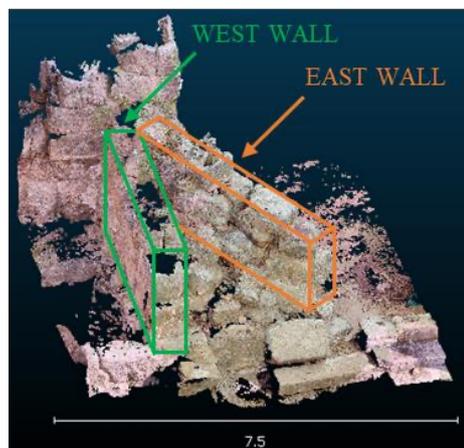

Fig. 2. Point cloud of the diaconia obtained in the post-processing phase. The West Wall and the East Wall are highlighted in green and in orange, respectively.

The optimized point cloud was then imported into Rhino for modelling. The three-dimensional model of the structure was realised by means of a parametric script developed in Grasshopper, which enabled the generation of regular blocks based on the dimensions of individual building elements. Only the well-defined blocks belonging to the East and West Walls of the ancient structure were modelled, whilst those in the intermediate area were excluded from the structural analyses, as they are in an inadequate state of preservation and are not sufficiently defined for modelling. Furthermore, the geometric model was further refinemed, to adapt it to the actual shape of the blocks and provide a more realistic representation of the structure. This step proved to be fundamental to consider the state of degradation, the geometric irregularities, and the crack pattern, which significantly affect the structural behaviour. The survey of the state of preservation (Fig. 6 and Fig. 7) shows that the majority of the blocks are in

good to mediocre condition, although there are severely degraded elements that need supports to ensure their stability. The East Wall is the most critical, due to a deteriorated ashlar at the base that compromises the balance of the blocks above it. The West Wall appears to be generally more stable, with the exception of the upper row of ashlars, which is also in a very deteriorated condition. Consequently, the refinement mainly concerned the East Wall, and consisted in cutting the blocks, shifting some faces, and inserting the discontinuities. At the same time, the position of the vertices of the damaged blocks was changed to obtain a more refined geometric representation of the structure. These operations allowed a more accurate reproduction of the blocks and a more realistic modelling of the joints.

Finally, the model developed in Rhino was exported in *.wrl format and subsequently imported into 3DEC for structural analyses. 3DEC model (Fig. 3) consisted of 47 blocks, some of which - particularly those of the East Wall - have a geometry derived from the refinement process described above. Furthermore, in order to ensure a correct simulation of the structural behaviour and to prevent free movement of the blocks under the action of gravity, a constraining block was introduced at the base. This element acts as a one-sided constraint, preventing the free fall of the blocks.

C. Properties of blocks and joints

In the 3DEC model, the blocks were modelled as rigid elements, assuming that their internal deformations were negligible with respect to rigid movements. In order to improve the representation of the interactions between blocks, the contact surfaces were discretized by triangulation, with the introduction of a central node on each face. This configuration allows for more accurate contact calculations, overcoming the standard approach based solely on vertices and edges, and permits a more realistic distribution of interface forces [15]. The blocks were given a density of 2200 kg/m³, an indicative value for a soft limestone. For the mechanical modelling of the joints, an infinitely rigid behaviour was adopted in compression, while in tension and shear an elasto-plastic relationship was considered. The normal joint stiffness was calculated by representing the dry-stone masonry to a spring system arranged in series, according to the following expression [16]:

$$k_n = \frac{E_b E_w}{(E_b - E_w)h} \quad (1)$$

where E_b, E_w represent the elastic modulus of the block and the wall, respectively, while h indicates the height of the block. Moreover, thanks to the relationship $G = E/[2(1 + v)]$, the shear stiffness of the spring can be expressed as a function of the normal stiffness as follows:

$$k_s = \frac{k_n}{2(1+v)} \quad (2)$$

For rigid blocks, assuming $v = 0$, the previous equation becomes $k_s = k_n/2$. A friction angle of 30° was assumed, according to the scientific literature for dry masonry structures [17-18]. The mechanical properties were suitably reduced to consider the surveyed state of degradation, which can compromise the structural performance. This choice allows for a more realistic representation of the behaviour of the material under current conditions. The physical-mechanical properties of the model are summarised in Tab. 1.
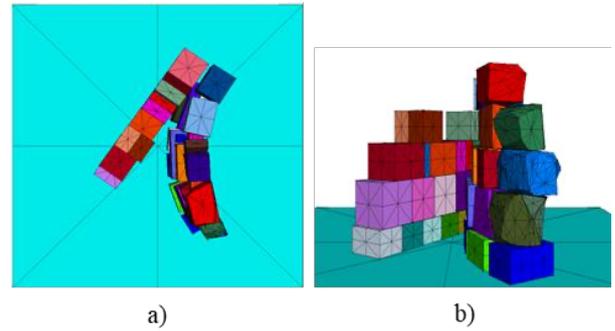

Fig. 3. Structural model in 3DEC: a) plan view; b) front view.

Tab. 1. Physical and mechanical properties used in 3DEC model for structural analyses

Density	$\rho = 2200 \ kg/m^3$
Elastic modulus of the block	$E_b = 2000 \ MPa$
Elastic modulus of the wall	$E_w = 100 \ MPa$
Normal stiffness	$j_{kn} = 105 \ MPa$
Shear stiffness	$j_{ks} = 53 \ MPa$
Friction angle	$\phi = 30°$

D. Analyses and results

A preliminary gravity load analysis was conducted to assess the equilibrium configuration that the structure assumes under its self-weight, based on the physical and mechanical properties assigned to the blocks and joints. This quasi-static analysis was performed by introducing a viscous damping coefficient of 0.8, with the aim of facilitating the achievement of the equilibrium state by limiting numerical oscillations. This initial step is fundamental for defining a static reference state, from which to start in the subsequent phases of the analysis. The results obtained indicate that the model reaches a stable condition, confirming the validity of the hypotheses adopted with regard to materials and constraints.

The seismic action was applied to the base block of the model, through the three components of velocity. The signal used corresponded to a seismic event that occurred at an epicentral distance of 17.6 km from the site, with a

duration of the strong motion of about 20 seconds, a peak ground acceleration (PGA) of 0.15 g in the East-West direction and 0.13 g in the North-South direction and 0.08 g in the vertical direction. The velocity time histories are shown in Fig. 4. In the analysis, the viscous damping coefficient was neglected, since energy dissipation occurs mainly due to friction between the blocks. The seismic input was applied to the numerical model to analyse the dynamic response of the wall and verify its stability under the ground motion. In order to focus on the most significant effects of the earthquake base motion, the signal was introduced starting from the tenth second, leaving out the initial phase characterised by low velocities. The results of the analysis showed a progressive damage of the structure, with the activation of local collapse mechanisms in specific portions. In particular, the top blocks of the East Wall exhibited displacements and rotations such as to compromise their equilibrium, leading to the loss of stability and the consequent partial collapse (*Fig. 5*). Four blocks detached and collapsed at an angle, while the other blocks of both walls underwent relative sliding. The analysis made it possible to understand the progressive evolution of the damage and to identify the most vulnerable parts, providing useful elements for the assessment of structural safety and for the possible definition of reinforcement works.

E. Restoration measures

The project stems from the survey of the state of deterioration and the result of the stability analysis to guarantee the safety of the walls and preserve their memory. In fact, it is a question of restoring some of the stone ashlars that are crucial to guarantee the stability of the wall, and which are severely degraded and/or fractured in several places and therefore no longer able to fulfil their load-bearing function. It is also necessary to restore the position and stability of those ashlars that have shifted, slipped or rotated, which, according to analyses, are in danger of falling.

Firstly, it will be necessary to remove the stonework that has accumulated between the east and west walls of the church, presumably the result of previous collapses. Subsequently, it will be possible to work on both the East and the West Walls, dismantling the portions that are severely degraded or unstable due to large dislocations, and then reassembling them in their original position, after replacing some degraded ashlars that can no longer be recovered and bolting together one of the fractured ashlars with carbon fibre reinforced polymer (CFRP) bars.
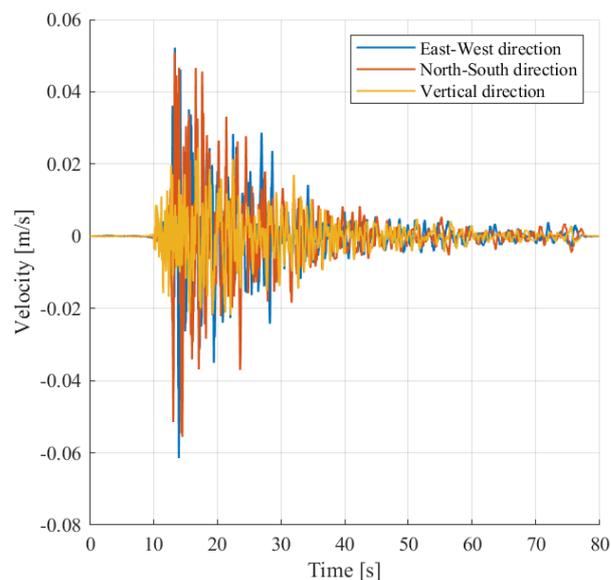

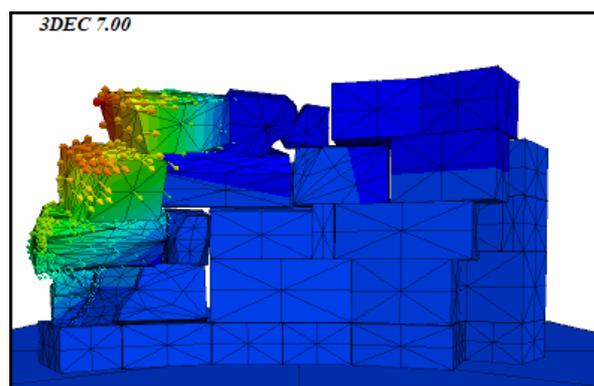Fig. 4. Velocity time histories used in dynamic analyses

Fig. 5. Collapse configuration of the East Wall under earthquake base motion.

The drawings below (*Fig. 6* and *Fig. 7*) show the portion to be dismantled and reassembled. The blocks that require replacement with stone elements similar in size and characteristics to the original stone are highlighted, as are the elements that require restoration of the missing portions and defects. Particular attention will be paid to the installation of the parts to be reassembled to guarantee the perfect stability of the elements and of the wall. The contact among the joints, if necessary, could be improved with wooden wedges and lime-based mortar. The ashlars that, although degraded, do not compromise the stability of the wall can be preserved and possibly filled with natural hydraulic lime mixed with the powder of the same stone, to protect the stone element, guarantee its durability and ensure its stability.
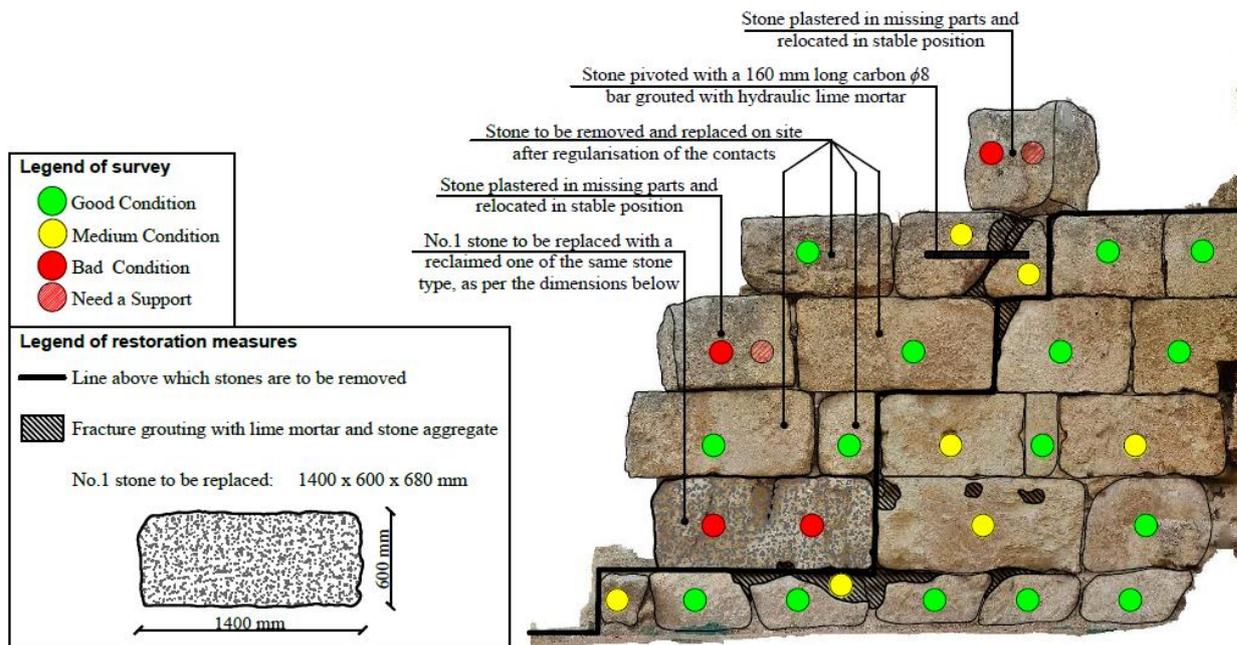
Fig. 6. Survey of the state of degradation and East Wall restoration.
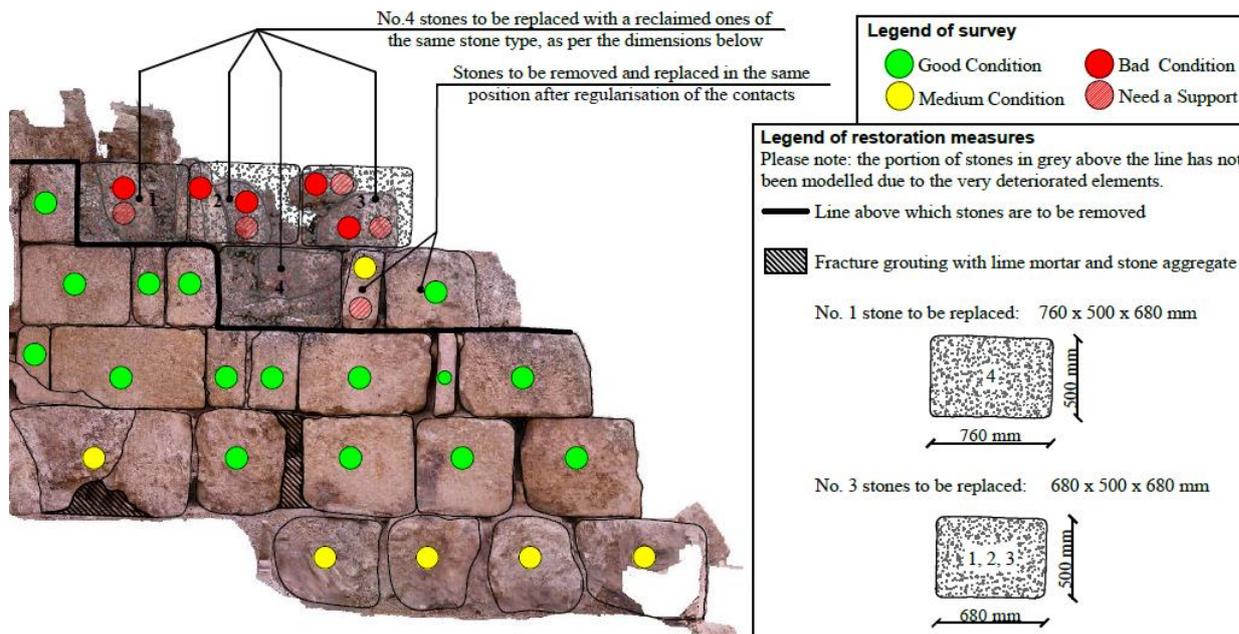

Fig. 7. Survey of the state of degradation and restoration design.

IV. CONCLUSIONS

The work investigated the seismic behaviour of the *diaconia* attached to the Church of the Propylaea in Jerash (Jordan), a historical masonry structure characterised by dry assemblies of stone blocks. The research adopted a numerical approach based on the discrete element method (DEM), implemented in the 3DEC software, which is particularly suited to the modelling of discontinuous structures where the contacts between the blocks play a central role in the mechanical response.

The geometric modelling of the structure was carried out from a high-density point cloud obtained by means of a photogrammetric survey, which made it possible to

render the three-dimensional layout of the *diaconia* with high fidelity, including the irregular shape of the blocks and their actual arrangement in space. The integration of digital surveying and numerical modelling represented a fundamental step for a realistic representation of the geometry and the assessment of the structural response to seismic actions.

After a preliminary phase of settlement by means of quasi-static analysis, dynamic simulations were conducted to evaluate the structural response to seismic inputs. The results showed that the mechanical properties of the joints and the geometric configuration influence the global response, highlighting opening, sliding and rotation mechanisms of the blocks, which can lead to localised failure or progressive collapse of the structure.

The study represents a significant contribution towards the integrated use of advanced surveying techniques and numerical simulation tools for assessing the structural safety of historic buildings and supporting possible conservation strategies or reinforcement interventions compatible with the historical-architectural value of the artefact. Future developments may include the calibration of the numerical model using experimental data and the simulation of reinforcement interventions to evaluate their effectiveness.

REFERENCES

[1] A. Fathi et al, "Assessing Seismic Behavior of a Masonry Historic Building considering Soil-Foundation-Structure Interaction (Case Study of Arge-Tabriz)", Int. J. Arch. Heritage, vol.14, No.6, 2019, pp. 795-810.

[2] Turer et al, "Reverse-engineering evaluation and monitoring of Nemrut monuments", Int. J. Arch. Heritage, vol.6, No.4, 2012, pp. 373-395.

[3] A.Mordanova, G.de Felice, "Seismic Assessment of archaeological heritage using discrete element method", Int. J. of Arch. Heritage, vol.14, No.3, 2020.

[4] S.De Santis, "Structural Assessment of Late Neolithic Sa Covaccada Dolmen", Sardinia, Italy", Int. J. Arch. Heritage, 2024.

[5] R.Y.Chura et al., "Seismic assessment of churches through integration of digital survey, texture recognition and distinct element modelling", Journal of Building Engineering, vol.98, 2024

[6] Y.Hua, et al., "A computerized tool for the kinematic limit analysis of 2D masonry structures failing on a tilting table", SoftwareX, vol.30, 2025, pp.102180.

[7] M.Pourfouladi, et al., "PoliBrick plugin as a parametric tool for digital stereotomy modelling", Computers & Structures, vol.311, 2025, pp.107722.

[8] https://northeastinsulaeproject.org/a42-gerasa-church-of-the-propylaea/

[9] P.A.Cundall, "Formulation of a three-dimensional distinct element model - Part I. A scheme to detect and represent contacts in a system composed of many polyhedral blocks", Int J. Rock Mech. and Min. Sci. & Geomech. Abstr., vol.25, 1988, pp.107–116.

[10] R.Hart, P.A. Cundall, J.V.Lemos "Formulation of a three-dimensional distinct element model—Part II. Mechanical calculations for motion and interaction of a system composed of many polyhedral blocks", Int J. Rock Mech. and Min. Sci. & Geomech. Abstr., vol.25, 1988, pp.117–125.

[11] J.V.Lemos "Modeling of Historical Masonry with Discrete Elements", Proc. of 3rd European Conference on Computational Mechanic, 2006.

[12] J.V.Lemos, K.Bagi, "Discrete Element Modeling", CISM International Centre for Mechanical Sciences, Courses and Lectures, vol.609, 2023, pp.189–232.

[13] P.A.Cundall, O.Strack, "A discrete numerical model for granular assemblies", vol.29, 1979, pp.47–65.

[14] P.A.Cundall, R.D.Hart, "Numerical modelling of discontinua", Eng Comput, vol.9, 1992, pp.101–113.

[15] I.N.Psycharis et al., "Numerical study of the seismic behaviour of a part of the Parthenon Pronaos", Earthq Eng Struct Dyn, vol.32, 2003, pp.2063–2084.

[16] P.B.Lourenço, et al., "Dry Joint Stone Masonry Walls Subjected to In-Plane Combined Loading", Journal of Structural Engineering vol.131, 2005, pp.1665–1673.

[17] D.V.Oliveira, et al., "Seismic analysis of the Roman Temple of Évora", Proc. of 15th WCEE World Conference on Earthquake Engineering, 2012.

[18] A.Pappas, F.Da Porto, C.Modena "Seismic Vulnerability Assessment Form for Free-Standing Columns Based on a Simplified Numerical Analysis", Int. J. of Arch. Her., vol.10, 2016, pp.281–299.