IAMON Workshop
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PROCEEDINGS

July 10th 2024, Athens, Greece




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ΠΡΑΚΤΙΚΑ

10 Ιουλίου 2024, Αθήνα, Ελλάδα

The research project is supported by the Hellenic Foundation for Research and Innovation (H.F.R.I.) under the "3rd Call for H.F.R.I. Research Projects to support Post-Doctoral Researchers" (Project Number: 7340).

IAMON Workshop
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Vasiliki Palieraki, Principal Investigator NTUA and Research Responsible of IAMON and Charalambos Mouzakis Associate Professor NTUA and Research Responsible of IAMON have organized the workshop on "Seismic response of column and colonnade - the role of vertical connectors".

The event has taken place on July 10, 2024 in the Multimedia Amphitheater, NTUA, Athens, Greece (Zografou Campus). The participants have been provided with the possibility to present and attend the workshop remotely.

The scope of the workshop was to create an interactive forum with academics, researchers, professionals, other stakeholders for presenting the work done and have feedback from the real needs of practice. Reinforced interfaces between structural members in ancient monuments have been promoted.

Objectives of the workshop:

1. Experimental investigation of ancient monuments
2. Structural analysis of ancient monuments with FEM or DEM
3. Connectors in ancient monuments
4. Examples of field applications

The Organizers,

Vasiliki Palieraki Charalambos Mouzakis

Το ερευνητικό έργο υποστηρίζεται από το Ελληνικό Ίδρυμα Έρευνας και Καινοτομίας (ΕΛ.ΙΔ.Ε.Κ.) στο πλαίσιο της Δράσης «3η Προκήρυξη ερευνητικών έργων ΕΛ.ΙΔ.Ε.Κ. για την ενίσχυση Μεταδιδακτορικών Ερευνητών/τριών» (Αριθμός Έργου:7340.)

IAMON Workshop
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Η Βασιλική Παλιεράκη, Μεταδιδακτορική Ερευνήτρια ΕΜΠ, Μη-Ιδρυματική Επιστημονική Υπεύθυνη του ερευνητικού έργου IAMON και ο Αναπληρωτής Καθηγητής Χ. Μουζάκης, Ιδρυματικός Υπεύθυνος για το ΕΜΠ διοργάνωσαν το workshop με θέμα «**Σεισμική απόκριση κιόνων και κιονοστοιχιών ή Σεισμική απόκριση αρχαίων μνημείων – Ο ρόλος των κατακόρυφων συνδέσμων**», στο πλαίσιο του ερευνητικού έργου IAMON : Reinforced interfaces between structural members in ancient monuments.

Η διοργάνωση έλαβε χώρα στις 10 Ιουλίου 2024 στην Αθήνα, Ελλάδα στο Αμφιθέατρο Πολυμέσων του ΕΜΠ (Πολυτεχνειούπολη, Ζωγράφου). Δόθηκε η δυνατότητα συμμετοχής-παρακολούθησης της συνάντησης εξ αποστάσεως.

Σκοπός του workshop ήταν μία διαδραστική συνάντηση με ακαδημαϊκούς, ερευνητές, επαγγελματίες και λοιπούς ενδιαφερόμενους όπου παρουσιάστηκε η έρευνα που έχει γίνει στο αντικείμενο των αρχαίων μνημείων. Ιδιαίτερη έμφαση δόθηκε σε διεπιφάνειες με κατακόρυφους συνδέσμους μεταξύ δομικών μελών σε αρχαία μνημεία.

Αντικείμενα/ Θεματικές ενότητες του workshop:
1. Πειραματική διερεύνηση αρχαίων μνημείων
2. Αναλυτική διερεύνηση αρχαίων μνημείων με πεπερασμένα (FEM) ή διακριτά (DEM) στοιχεία
3. Σύνδεσμοι σε αρχαία μνημεία
4. Πρακτικές εφαρμογές ενισχυμένων με συνδέσμους διεπιφανειών σε αρχαία μνημεία

Οι διοργανωτές,

Βασιλική Παλιεράκη — Χαράλαμπος Μουζάκης

The research project is supported by the Hellenic Foundation for Research and Innovation (H.F.R.I.) under the "3rd Call for H.F.R.I. Research Projects to support Post-Doctoral Researchers" (Project Number:

IAMON Workshop- Programme of the event

Reinforced interfaces between structural members in ancient monuments

10 July 2024, Athens, Greece
Hybrid format: on Zoom or at Zografou Campus NTUA (Multimedia Amphitheater)

09:30-11:00	**Introduction and in-situ Investigations**
	• Introduction to the IAMON Workshop **Vasiliki Palieraki,** *National Technical University of Athens* • Information from investigation **Manolis Korres,** *National Technical University of Athens* • Innovative Approaches for Structural Health Monitoring of Restored Elements of Stone Monuments **S. K. Kourkoulis,** E. D. Pasiou, I. Stavrakas, D. Triantis, *National Technical University of Athens* • Digital technologies for the inspection and assessment of historic structures **Vasilis Sarhosis,** *University of Leeds* • Investigation Works of the Structural System of the Hadrian Reservoir in Athens **Chrissy-Elpida Adami,** Alexandros Ranios, Aikaterini Kalouda, *EYDAP* • The use of Distinct Element Method for the preservation and reconstruction of archaeological free-standing columns **Matteo Salvalaggio,** Jacopo Bonetto, Maria Rosa Valluzzi, *University of Padova*
11:00-11:30	**Coffee break**
11:30-13:30	**Laboratory Investigations**
	• Tracking moving targets from video images **Eleftherios Tournas,** *GEOVISION IKE* • Real Scale Shaking Table tests for the investigation of the influence of the use of vertical connectors between the drums in columns and colonnades **Vasiliki Palieraki,** Eleni Tavouktsi, Konstantinos Arvanitis, Haralampos Mouzakis, *National Technical University of Athens* • Shaking table examination of the Prothyron monument model **Pavao Marović,** Željana Nikolić, *University of Split* • Seismic protection of multi-drum columns with the use of particle dampers **Angeliki Papalou,** *University of Peloponnese* • Seismic behaviour of dry-stack masonry structures: results from a recent experimental and numerical campaign **Georgios Vlachakis,** Carla Colombo, Dario Vecchio, Anastasios I. Giouvanidis, Nuno Mendes, Nathanaël Savalle, Paulo B. Lourenço, *University of Minho, ISISE, ARISE* • Reduced-scale testing of historical monuments under explosions: application to the Parthenon

	Ahmad Morsel, Filippo Masi, Panagiotis Kotronis, **Ioannis Stefanou,** *ECN* • Reliability analysis of ancient columns **Spyridon Diamantopoulos,** Michael Fragiadakis, *National Technical University of Athens*
13:30-14:15	**Lunch break**
14:15-16:30	**Numerical investigations**
	• Seismic Vulnerability Assessment of a Historical Monument **Ozden Saygili,** José V. Lemos, *AtkinsRealis* • Numerical investigation of the seismic response of classical multi-drum and monolithic columns **Stella Karafagka,** Grigorios Tsinidis, Kyriazis Pitilakis, *Aristotle University of Thessaloniki* • Seismic performance evaluation of the Roman Temple of Évora in Portugal **Daniel V. Oliveira,** Paulo B. Lourenço, *University of Minho* • Application of a Tendon System to Protect Classical Columns against Earthquakes **Ioannis N. Psycharis,** Evangelos Avgenakis, Maria-Eleni Dasiou, *National Technical University of Athens* • Can we use the seismic response of free standing monuments to verify Probabilistic Seismic Hazard estimates? **Anastasios Sextos,** *National Technical University of Athens* • Quantifying the developing forces of clamps and dowels used for the anastylosis of the N.E. tower of the Aegosthena fortress in W.Attica **Eleni-Eva Toumbakari,** *Ministry of Culture, Ephorate of Antiquities of Western Attica* • Modelling drum columns with discrete elements – Practical issues **José V. Lemos,** *LNEC* • Numerical investigation of the role of iron dowels in the stability of multi-drum columns **Olympia Panagouli,** *University of Thessaly* • Discrete Rigid Block Analysis of The Stone Masonry Temple: Exploring the Effect of Ancient Retrofitting Technique **Bora Pulatsu,** Ece Erdogmus, *Carleton University*
16:30-17:00	**Coffee break**
17:00-18:00	**Interactive discussion- Conclusions**

Session 1:

Introduction and in-situ Investigations

Introduction to the IAMON Workshop

Vasiliki Palieraki*[1]

[1] School of Civil Engineering, National Technical University of Athens, 9, Iroon Polytechneiou Str., Athens, Greece

e-mail: vasopal@central.ntua.gr

ABSTRACT

The current workshop is part of an extensive research project, aiming to investigate the effect of interfaces, reinforced using vertical connectors (gomfoi) on the seismic behaviour of ancient monuments. The research focuses on the seismic behaviour of columns and colonnades, where shear connectors cross the interfaces between consecutive drums.

In order to design the experimental tests, and to simulate the monuments, it is necessary to document the use of vertical shear connectors in columns in monuments located in the city of Athens, as well as outside of the city. The investigation was carried out in monuments where the use of connectors is already known (Olympeion- from in-situ work of members of the Research Team, Thrasyllus monument- from the literature), as well as in monuments for which there is insufficient information (Hadrian's Library, Roman Agora), while monuments for which it is assumed that there are no connectors (Temple of Hephaestus) have also been studied, to confirm the hypothesis. On-site observation, as well as the application of non-destructive investigation methods (geo-radar), have led to the documentation of the use and location of connectors, in the monuments under study. It is noted that, even though intended, the study of some monuments, has not been possible, because of the difficulty and the lack of safety in the access.

The initial idea behind the proposed project is that gomfoi are mainly known to connect horizontal members. In some cases they are used for the connection of the drums of the columns, in the Hellenistic and Roman Era.

As concluded by the members of the research team, in most cases, the reinforced columns have a slenderness ratio greater than 1.0. The documentation of vertical connectors, based on Literature and on in situ documentation of vertical connectors and related pathology, as well as the detailed literature review of the available experimental and analytical works, have led to the selection of a typical monument, namely the Gymnasium in Ancient Messene.

Shaking Table tests of real scale columns and colonnades, with and without vertical connectors, have been performed. Modelling of the columns and the test assemblies has been performed before testing, and then the models have been calibrated, based on the test results. Parametrical parameter analyses are currently performed. The results of the project are presented in conference and journal papers, as well as in a workshop and a seminar.

Keywords: IAMON research project, free-standing columns, subassemblies, vertical connectors

Information from investigation

Manolis Korres*[1,2]

[1]Emeritus Professor, School of Architecture, National Technical University of Athens, 42, Patission Str., Athens, Greece

[2]Member of the Academy of Athens

**e-mail: dr.korres@gmail.com*

ABSTRACT

Nowadays many scholars, theoretical and practical, respectively conclude or believe that a column made of well fitted drums has advantages over a monolithic one, as allowing a more favorable energy absorption during a seismic event. This is not confirmed by the buildings and is not justified as an ancient criterion in favor of multidrum fashioning. In fact, the ancients preferred monolithic columns under the self-evident condition of being able to extract corresponding sizes without geological defects. Given the rarity of the combination of size and quality, the second choice was the 2- or 3-piece formation, and the third choice was the much more expensive multi-drum formation. In any case the intermediate joints of the columns were more perfect than the other joints of the building including the horizontal joints below the column. Therefore and given a deep circumferential notch at the bottom and top of the column shaft, free-standing multi-drum columns rock just like monoliths and very rarely (extremely solid high-mass foundations and peak accelerations) show any small drum displacement. Given the size of the friction bond, this displacement is only possible during the momentary impact reduction of friction. Column-drum displacements are more common only when several columns are connected to each other and/or to nearby walls, through architraves and beams, in which case the seismic movement of the column is accompanied by the action of external forces in its upper part with an almost dominant direction. During the seismic testing of such columns, column drums that are more liable to shifting are those in which, at their lower or upper edge, there are already, or manifest, fractures, even small ones. Some large shifts of drums attributed to seismic forces have actually caused by the impact upon them of falling beams or other large stones (during an earthquake or an explosion or a demolition).

Earthquake collapse is a phenomenon more common in rows of small columns and rarer in rows of large or very large columns. Some collapses of massive colonnades that had been attributed to an earthquake are now arguably understood as a special form of demolition.

During the construction of the multi-drum columns precisely centered empolia (ΕΠ), usually wooden, ensured the exact placement, while metal dowels (ΜΓ) were applied to increase the shear resistance of the column. Regarding these, cases can be distinguished: a) Columns without ΕΠ and ΜΓ, b) columns only with intermediate ΕΠ, c) columns with ΕΠ and on the stylobate, d) columns with ΕΠ and ΜΓ (usually 2 per joint), e) columns only with ΜΓ. The classification of the above a, b, c, d, e mostly corresponds to a historical development and certainly to causal relationships of architectural style (Doric, Ionic/Corinthian), building material (limestone, marble), building type (high column drums, low column drums, hollow column drums) and size (small, medium, large, giant).

Innovative Approaches for Structural Health Monitoring of Restored Elements of Stone Monuments

S. K. Kourkoulis*[1], E. D. Pasiou[1], I. Stavrakas[2], D. Triantis[2]

[1]School of Applied Mathematical and Physical Sciences, Department of Mechanics, National Technical University of Athens, 9, Iroon Polytechneiou Str., Athens, Greece

[2]Department of Electrical and Electronics Engineering, Division of Materials and Electronics, University of West Attica, Ancient Olive Grove Campus, 250 Thivon Ave., Athens, Greece

**e-mail: stakkour@central.ntua.gr*

ABSTRACT

Among the key issues in the restoration of stone monuments are the structural integrity of the restored elements and their Structural Health Monitoring. In this study experience gained from series of research projects related to the restoration of emblematic monuments of the Greek Cultural Heritage is exploited. These projects aimed to enlighten critical aspects of the pioneering restoration technique (introduced by the scientific teams working since the early eighties for the restoration/conservation of the Athenian Acropolis monuments) which is based on the combined use of titanium elements and proper cement-based pastes.

This technique generates three-materials complexes (marble-cement-metal) with two interfaces (marble-to-cement, cement-to-titanium). Given that these interfaces are the locations where damage mechanisms are activated, any attempt to model the response of the restored structural elements necessitates data from these interfaces. Such data can be only obtained with the aid of novel sensing techniques, like Acoustic Emissions (AE), Pressure Stimulated Currents (PSCs), Optical Fibers, Carbon NanoTube (CNT) based electrically conductive pastes etc.

In this direction, complexes/specimens consisting of Dionysos marble blocks joined together by means of titanium connectors and suitable cementitious materials were tested under various loading schemes achieved by in-situ improvised set-ups, assuring either multi-point bending of the elements or pure shear and direct tension of the connections. The specimens were monitored by a system of eight R15α AE sensors, two electric sensors (recording the PSCs with the aid of extremely sensitive electrometers) and a 3D-Digital Image Correlation (DIC) system. In parallel, traditional sensing tools (clip gauges, LVDTs and dial gauges) were also used.

The data gathered indicate that both the AE and PSC techniques "follow" the mechanical response of the restored elements according to a quite satisfactory manner, and their outcomes are in good accordance with these of the 3D-DIC system. Moreover, the AE and PSC techniques provide clear signs warning about upcoming entrance of the restored element into its "critical stage", namely that of impending failure. It appears that the combined use of these two techniques enlightens the level of damage of the restored element and the challenge is now to standardize this combination, in order for it to become a flexible and easy-to-use tool in hands of engineers working in the field of Continuous Structural Health Monitoring of restored stone monuments.

Keywords: Stone Monuments, Marble, Acoustic Emissions, Pressure Stimulated Currents, 3D-Digital Image Correlation

Digital technologies for the inspection and assessment of historic masonry structures

Vasilis Sarhosis[1,2]

[1]University of Leeds, Civil Engineering, United Kingdom

[2] Chair of Committee on the Analysis and Restoration of Structures of Architectural Heritage (ISCARSAH-UK), ICOMOS UK

**e-mail: v.sarhosis@leeds.ac.uk*

ABSTRACT

Although one of the oldest construction methods, masonry is still commonly used due to its reliability and sustainability that it offers. Most of our historic structures are made of masonry. Apart of that, a large portion of the existing critical infrastructure stock in the UK is consisting of masonry arch-bridges, many of which were constructed well beyond 100 years ago. Weathering, demands of increasing load intensity and axle loads, plus factors such as increased frequency of flood events brought about by climate change have introduced an uncertainty on the long term performance of such infrastructure assets. Also, significant heritage and cultural identity within masonry infrastructure fabric exists (e.g. the Grade II-listed Hungerford Canal Bridge, in Berkshire, England) and the UK has a policy to "retain and repair", rather than "demolish and replace" them. Failure of such infrastructure could lead to direct and indirect costs to the society and economy and hamper rescue and recovery efforts. Therefore, there is a timely need to effectively inspect the condition and assess the performance of ageing masonry infrastructure stock and provide detailed and accurate data that will better inform maintenance programmes and asset management decisions

Frequent inspection of masonry structures and infrastructure is important to ensure their serviceability, which is often a manual process characterised by its high cost in terms of workforce, subjectivity, tedious health and safety precautions and time requirements. For those reasons, improvements in automation and simplification of visual inspection have acquired large scientific and commercial interest. Recently, the use of terrestrial laser scanning using LiDAR and structure from motion using images have been successfully used to create accurate digital records in the form of 3D point-cloud or reality-mesh of existing structures at millimetre or even sub-millimetre level of accuracy. However, the output of such applications requires post-processing to be used to automate engineering workflows, such as classification of the generated point-cloud or reality-mesh objects.

This talk presented recent developments and future directions towards the resilience of historic masonry structures subjected to different environmental conditions and loads. In particular, novel ways for the identification of defects using photographs taken from UAVs coupled with machine learning and structural assessment using high fidelity numerical models have been discussed. It also put emphasis and brought together information from proven techniques and illustrated these technologies through case studies.

Keywords: masonry, DEM, machine learning, point clouds, photogrammetry, automation, inspection, defect detection

Investigation Works of the Structural System of the Hadrian Reservoir in Athens

Chrissy-Elpida Adami*[1], Alexandros Ranios[1], Aikaterini Kalouda[1]

[1]EYDAP SA, 9 Ilission str, 15773

**e-mail: chadami@eydap.gr*

ABSTRACT

The Hadrian's reservoir, in Athens, Greece is part of an 25km aqueduct that was originally built around 140 A.D.. The aqueduct was functional until the years of Ottoman domination in Greece, when it was partially destroyed. In 1870 A.D. the reservoir was rebuilt and used as a source of water supply for modern Athens until the mid-20th century. This reservoir belongs to EYDAP SA, that is the water utility of the city of Athens. The ceiling of the tank of the reservoir consists of cross vaults that are supported by columns, whereas the perimeter walls are made of brick masonry. The vulnerability of its structural system against seismic actions and the structural deterioration of perimeter walls, led EYDAP SA to numerically investigate and assess the current state of the reservoir, as well as the effect of several intervention techniques. Within the framework of restoration works, the documentation of the structural system of the reservoir was carried out by the Authors using ND and SD Techniques. The results of this study are presented here. The investigation was focused, mainly, on areas where the interventions would be applied. To this end, in-situ application of boroscopy technique and in-lab mechanical characterization of the constitutive materials were carried out. The systematic boroscopy observations offered the possibility to identify the thickness of masonry leaves constituting the perimeter masonry walls in most of the regions of the tank, as well as to document the presence of steel connectors in the upper part of the columns. It should be noted that the interventions based on this study were recently completed successfully.

The use of Distinct Element Method for the preservation and reconstruction of archaeological free-standing columns

M. Salvalaggio*[1], J. Bonetto[1], M.R. Valluzzi[1]

[1]DBC-Department of Cultural Heritage, University of Padova, Padova, Italy

**e-mail: matteo.salvalaggio@unipd.it*

ABSTRACT

Free-standing columns and colonnades were recurring typologies in ancient architecture, nowadays often found in archaeological sites in complete, decayed, or remains forms. Their preservation and restoration are critical due to their susceptibility to rocking and overturning under strong seismic activity. The prediction of such seismic behaviour by modelling strategies tailored on material composition, construction technique, and conservation status.

This study investigates the use of the 3-D Distinct Element Method to simulate the rocking behaviour of free-standing columns, also addressing the reconstruction design (i.e., anastylosis) of fragmented remains, considering the use of fasteners to guarantee adequate connection between columns parts. The methodology is applied to the remains of the Temple of Apollo Pythios in Gortyn (mid-7th century BC), which currently comprises six fragmented stone columns (third century AD) lying within the naos. Potential reconstruction scenarios are proposed based on the remains layout and geometric features, increasing the size of titanium fasteners until the achievement of a seismic behaviour and capacity compliant with the expected ground motions for the site.

Keywords: free-standing columns, Distinct Element Method, Archaeological remains, seismic assessment, anastylosis, reconstruction

Session 2:

Laboratory Investigations

Tracking moving targets from video images

Eleftherios Tournas[1]

[1]GEOVISION IKE

**e-mail: ltournas@gmail.com*

ABSTRACT

The determination of 3D trajectories of moving objects under seismic action is always a challenging task. Several methods, using both contact and non-contact sensors have been proposed, but for large scale objects composed of many blocks, vision-based systems are of great potential. Since the objects to be modelled are moving quickly, video image sequences acquired from high-speed cameras are used.

Videogrammetry is a measurement technology in which the 3D coordinates of points on an object are determined by measurements made in two or more video images taken from different sensors and different angles. Accurate synchronization to ensure that a distinct model is generated at each frame epoch is very important. The 3D coordinates of a point on the objects surface are estimated using photogrammetric techniques. A video camera maps a 3D object space to its corresponding 2D image. The image coordinate observations are performed on simultaneous views of the object. The solution is known as photogrammetric "two-camera triangulation".

Rigorous system calibration is essential for vision applications, when accurate measurement is required. Several photogrammetric techniques are available, but the most convenient is the simultaneous, iterative solution for camera position, orientation and distortion parameters by Least Squares Adjustment. The obtained accuracy depends on several parameters, including the distance from the object, the image resolution, the distance between cameras, the camera synchronization and the accuracy and repeatability of the image coordinate measurements.

The hardware configuration used in IAMON experiments consists of 4 grayscale CMOS cameras of 5MP resolution at 64 frames per second, 4 high resolution lenses of 8 mm, 2 USB controllers for camera communication, 2 synchronization cables and 2 personal computers for camera control and camera acquisition. The distance between cameras was set to 80 cm and the distance from the object was about 6.5 m. The system calibration is accomplished by using about 30-35 control points.

A significant number of signalized targets are placed on the objects surface. The use of circular black targets on a white background is ideal because they are not distorted considerably from different points of view. Image processing tools are applied for noise reduction and then initial target positions are determined by cross-correlation. To improve the accuracy a centroid detection algorithm is finally used which computes the center of gravity of the black target with sub-pixel accuracy. The object coordinates for each target are estimated using photogrammetric two-camera triangulation.

To further improve the efficiency of the developed system, proper synchronization between the seismic table and the cameras should be implemented using external triggering. Cameras placed closer to the object could lead to increase the system accuracy. Camera lenses with wider field of view may be acquired therefore. The possibility to place the cameras on the seismic table to compensate for table movements may be also investigated.

Real Scale Shaking Table tests for the investigation of the influence of the use of vertical connectors between the drums in columns and colonnades

Vasiliki Palieraki[1*], Eleni Tavouktsi[1], Konstantinos Arvanitis[1], Haralampos Mouzakis[1]

[1]School of Civil Engineering, National Technical University of Athens, 9, Iroon Polytechneiou Str., Athens, Greece

**e-mail: vasopal@central.ntua.gr*

ABSTRACT

In the framework of the IAMON research project, the following tests are carried out:

• Tests on three free-standing columns in scale 1:1, without connectors;

• Test on subassembly, consisting of three columns without connectors. The columns are positioned to form a corner, with the use of two epistyles-beams;

• Tests on three free-standing columns in scale 1:1, with connectors between the successive drums, and between the base and the first drum;

• Test on subassembly, consisting of three columns with connectors between the successive drums, and between the base and the first drum. The columns are positioned to form a corner, with the use of two epistyles-beams.

The tests are performed in order to study the seismic behaviour of columns with and without connectors between the consecutive drums, and compare the experimental results, make conclusions on the improvement of the behavior when epistyles are used, and finally, get the necessary information for the calibration of the analytical models.

Triaxial (X, Y and Z direction) tests are performed. The columns of the Gymnasium in Ancient Messene have been selected for testing. The selection is based upon the following advantages: (a) The available information that could be obtained for the monument and its construction, (b) The large number of columns and drums that remain in-situ, (c) The seismicity of the area in which the monument is situated, (d) The rather small size of the monument, that allows testing in scale 1:1, which, according to the studies of the Researchers has never been done before, for monuments.

All columns are constructed using three drums and one capital. The dimensions are based upon the Gymnasium. The three columns are identical in terms of dimensions and preparation of all the interfaces. In case of subassemblies, two epistyles were used.

When the drums are connected with vertical connectors, connectors made of titanium, with dimensions 15mm*15mm*60mm, namely with a length of 30mm in each drum, are positioned. The connectors are positioned in grooves, with dimensions 30mm*30mm*35mm. The material used for the positioning is a grout of very high strength.

The instrumentation consists of accelerometers and cameras, for the continuous monitoring of the movement of the specimens. The results of the measurements are presented herein.

Keywords: IAMON research project, free-standing columns, subassemblies, vertical connectors, shaking table tests

Shaking table examination of the Prothyron monument model

Pavao Marović*[1], Željana Nikolić[1]

[1]University of Split, Faculty of Civil Engineering, Architecture and Geodesy,
HR-21000 Split, Matice hrvatske 15, CROATIA

e-mail: marovic@gradst.hr

ABSTRACT

Nowadays, there is an increasing need and interest in the preservation of cultural heritage, i.e. ancient buildings and monuments. Considering the time of their construction, when the main building material was stone or brick, they belong to masonry constructions. With the increase of mobile loads in the vicinity of such objects as well as by the action of natural forces (earthquakes, winds) they become increasingly endangered. In order to preserve them for the future, we need to protect and/or strengthen them, and to do so we need to know their present state of both the installed materials and their possibilities of withstanding various loads. We can get the most accurate information about their condition by carrying out on-site tests under natural, ambient, loads. As such constructions we cannot examine by loading them to failure, we then test their models until failure. With this intention, this article will describe the creation of a model of the Prothyron monument, which is located on the Peristyle of Diocletian's Palace in Split, Croatia, and its examination until failure on the shaking table. The Prothyron monument closes the south facade of the Peristyle, the central square of Diocletian's Palace in Split, Croatia. It was built from 295 to 305 AC for Roman Emperor Diocletian. The construction of Prothyron consists of four massive granite columns brought from Egypt, approximately 8 meters high with Corinthian capitals, on which rests a 12-meter-long gable with an arch in the middle, i.e. between the two middle columns. The original structure was built of stone blocks (limestone from the island of Brač) in dry construction. Iron anchors are only found between bases and columns, columns and capitals, and capitals and gables. Throughout history, due to various actions, most likely earthquakes, there has been movement between gable blocks as well as between columns and gables.

Keywords: Roman monument, examination, shaking table, model

References:

[1] Ž. Nikolić, L. Krstevska, P. Marović, H. Smoljanović: **Experimental investigation of seismic behaviour of the ancient Protiron monument model**, *Earthquake Engineering and Structural Dynamics*, Vol. 48, Issue 6, pp. 573-593, 2019.

[2] Ž. Nikolić, L. Krstevska, H. Smoljanović, N. Živaljić: **Modelling of the influence of metal connectors on the resistance of historical dry-stone masonry structures**, *Int. Journal of Architectural Heritage*, Vol. 14, Issue 10, pp. 1468-1483, 2020.

[3] L. Krstevska, Ž. Nikolić, M. Kustura: **Shake table testing of two historical masonry structures for estimation of their seismic stability**, *Int. Journal of Architectural Heritage*, Vol. 15, Issue 1, pp. 45-63, 2021.

[4] H. Smoljanović, N. Živaljić, Ž. Nikolić, A. Munjiza: **Numerical analysis of 3D dry-stone masonry structures by combined finite-discrete element method**, *Int. Journal of Solids and Structures*, Vol. 136-137, pp. 150-167, 2018.

[5] H. Smoljanović, Ž. Nikolić, N. Živaljić: **A finite-discrete element model for dry stone masonry structures strengthened with steel clamps and bolts**, *Engineering Structures*, Vol. 90, pp. 117-129, 2015.

Seismic protection of multi-drum columns with the use of particle dampers

Angeliki Papalou[*1]

[1]School of Civil Engineering, University of Peloponnese, 1, Megalou Alexandrou Str., Patras, Greece

**e-mail: papalouang@gmail.com*

ABSTRACT

Preservation of monuments is of great importance for all countries with historical heritage. Multi-drum columns are significant parts of monumental structures. These columns consist of drums that have been placed precisely one above the other without any mortar. Past seismic activity and harsh environmental conditions have usually caused damage to monumental structures leaving them more vulnerable to earthquakes. Predicting the dynamic behavior of multi-drum columns is a difficult task due to their complex geometry and existing imperfections. Finite element models can provide a good estimate of their response if key model parameters are selected properly. Strengthening monumental structures is also challenging since the techniques that can be adopted have to respect their architectural features. Innovative techniques that include the installation of devices like particle dampers can be used to control the vibration of multi-drum columns without altering their appearance. Particle dampers consist of particles that move freely inside a container. Their effectiveness is attributed primarily to the dissipation of energy through collisions of the particles among themselves and with the walls of the container. In the case of multi-drum columns, the container can take the form of a drum replacing a missing one or one that has been damaged, preserving their appearance. Our experiments with scaled column-models show that the damper can increase the multi-drum columns seismic safety if it is placed above the mid-height where the motion is higher increasing the number of impacts. In addition, when particles are placed in a single layer occupying 40- 60% of the container's empty space with a mass ratio (mass of particles with respect to mass of the column) 1-3% the dynamic response of the column can be reduced by up to 40%.

Keywords: Multi-drum columns, particle dampers, passive control

Seismic behaviour of dry-stack masonry structures: results from a recent experimental and numerical campaign

Georgios Vlachakis[1*], Carla Colombo[1], Dario Vecchio[1], Anastasios I. Giouvanidis[2], Nuno Mendes[1], Nathanaël Savalle[3], Paulo B. Lourenço[1]

[1]University of Minho, ISISE, ARISE, School of Engineering, Campus de Azurém, 4800-058, Guimarães, Portugal

[2] Department of Civil and Environmental Engineering, University of Auckland, Auckland, New Zealand

[3] Université Clermont Auvergne, Clermont Auvergne INP, CNRS, Institut Pascal F-63000 Clermont-Ferrand, France

**e-mail: giorgovlachaki@gmail.com*

ABSTRACT

Monumental masonry structures are particularly vulnerable to earthquakes. Their vulnerability stems mainly from their high mass, low tensile strength and weak connections among the structural elements. As a result, cracks develop easily that lead to the formulation of structural mechanisms, which are prone to collapse (i.e. collapse mechanisms). Nevertheless, the majority of these collapse mechanisms are composed of a kinematic chain of macro-blocks which owe a non-negligible dynamic stability beyond their force capacity. Essentially, these structures might avoid collapse during an earthquake, even if a mechanism is completely formed. Nonetheless, masonry structures are usually analysed and assessed statically, while their dynamic stability is neglected. Moreover, this could lead to excessive or unnecessary interventions on monumental structures, in contrast with the principles of conservation. To this end, the STAND4HERITAGE project (new STANDards for seismic assessment of built cultural HERITAGE) has developed an extensive experimental and numerical campaign concerning the dynamic behaviour of dry-joint masonry structures. This work presents the main research topics of the project, together with a summary of the associated key findings. More specifically, the experimental investigation includes the characterisation of the dry-joint interfaces and the shaking table tests of single- and multi-block masonry assemblies. Furthermore, the numerical campaign focuses on the dynamic modelling of the experiments by resorting to both rigid and compliant rocking models. Merits and shortcomings of the modelling techniques are discussed, with particular emphasis on the damping mechanisms. Finally, the work indicates open issues and future challenges towards a comprehensive understanding of the dynamic response of block-based masonry structures.

Keywords: Dry-joint masonry, rocking dynamics, shaking table tests, numerical model, contact mechanics

Reduced-scale testing of historical monuments under explosions: application to the Parthenon

Ahmad Morsel[1], Filippo Masi[1], Panagiotis Kotronis[1], Ioannis Stefanou[1*]

[1]ECN, GeM, France

**e-mail: ioannis.stefanou@ec-nantes.fr*

ABSTRACT

The Parthenon was severely damaged by an explosion in 1687, and since then, many other monuments have faced partial or complete destruction due to blast loads, whether accidental or intentional. Protecting such valuable cultural assets from blast impacts is crucial. However, understanding how they respond to explosions requires more than just numerical and analytical tools (cf. [1]-[4]). Experimental tests are essential for enhancing our current understanding and validating existing models. Large-scale experiments, although valuable, are limited by their requirement for specialized testing areas, safety concerns, and issues with repeatability. An effective alternative is to conduct reduced-scale experiments in controlled laboratory settings. These experiments could offer high repeatability, moderate costs, and significantly reduced safety hazards.

In this study, we present a novel experimental setup designed to investigate the response of masonry structures to blast loads using reduced-scale experiments. This setup simulates blast shock waves by detonating wires triggered by high-voltage discharges from a capacitor. Our approach ensures both safety and repeatability. Our experimental setup is based on recently derived scaling laws [5] and allows for detailed analysis of the fast dynamics of the structures through optical measurements. As a notable example, we attempt to replicate the explosion of the Parthenon within this laboratory setting. Preliminary results are promising and, in the future, could provide new insights into this historical event.

References

[1] Masi, F., Stefanou, I., Vannucci, P., & Maffi-Berthier, V. (2020). A Discrete Element Method based-approach for arched masonry structures under blast loads, Engineering Structures, 216, 110721. https://doi.org/10.1016/j.engstruct.2020.110721

[2] Masi, F., Stefanou, I., Vannucci, P., & Maffi-Berthier, V. (2020), Resistance of museum artefacts against blast loading, Journal of Cultural Heritage, 44, 163-173, https://doi.org/10.1016/j.culher.2020.01.015

[3] Masi, F., Stefanou, I., Vannucci, P., & Maffi-Berthier, V. (2019). Rocking response of inverted pendulum structures under blast loading. International Journal of Mechanical Sciences, 157–158(May), 833–848. https://doi.org/10.1016/j.ijmecsci.2019.05.024

[4] Masi, F, Stefanou, I. & Vannucci, P. (2018), A study on the effects of an explosion in the Pantheon of Rome, Engineering Structures, 164, 259-273. https://doi.org/10.1016/j.engstruct.2018.02.082

[5] Masi, F., Stefanou, I., & Maffi-Berthier, V. (2021). Scaling laws for the rigidbody response of masonry structures under blast loads. 1–38, ASCE's Journal of Engineering Mechanics, https://doi.org/10.1061/(ASCE)EM.1943-7889.0001986

Keywords: Blast loads, Exploding wires, Fast-dynamics, Masonry, Scaling laws

Reliability analysis of ancient columns

Spyridon Diamantopoulos[1], Michael Fragiadakis[1*]

[1]School of Civil Engineering, National Technical University of Athens, 9, Iroon Polytechneiou Str., Athens, Greece

**e-mail: mfrag@mail.ntua.gr*

ABSTRACT

Modern methods for the assessment of the seismic vulnerability of ancient columns are presented. Initially, the simulation methods are discussed and, at a second step, the framework for the reliability analysis of these methods is presented. The proposed methods are applied for the reliability analysis of colonnades as well as for individual, free-standing, columns, while the possibility of using satellite InSAR measurements for risk assessment is also presented.

Session 3:

Numerical Investigations

Seismic Vulnerability Assessment of a Historical Monument

Ozden Saygili[1*], José V. Lemos[2]

[1]AtkinsRealis, TK LS15 8ZB, Leeds, United Kingdom

[2]LNEC, LNEC, Av. do Brasil, 1700-066, Lisboa, Portugal

**e-mail: ozden.saygili@atkinsrealis.com*

ABSTRACT

The Western Anatolia Region of Turkey is a highly seismically active area, influenced by ongoing compression and expansion dynamics. This research investigates the seismic performance of the Frontinus Gate, an ancient Roman monument in Hierapolis of Phrygia, Southwestern Anatolia. Utilizing discrete element modeling, the study conducts nonlinear dynamic analyses to simulate the gate's structural response to seismic excitation. The analyses focus on identifying deformation, damage, and failure patterns under different seismic intensity levels. The findings reveal that an earthquake with a 475-year return period may inflict damage but not cause collapse, whereas an earthquake with a 2475-year return period is projected to result in the gate's collapse. These results provide critical insights into the structural vulnerabilities of the monument, informing preservation and restoration strategies.

Keywords: Seismic hazard, masonry structures, discrete element modeling

Numerical investigation of the seismic response of classical multi-drum and monolithic columns

Stella Karafagka[1], Grigorios Tsinidis[1], Kyriazis Pitilakis[1]

[1]Civil Engineering, Aristotle University of Thessaloniki, 54124

**e-mail: stellak@civil.auth.gr*

ABSTRACT

Ancient classical temples constitute common historic monuments of great architectural and archaeological value. Many of these monuments, which are found in high seismicity areas around the Mediterranean, remain nowadays as free-standing multi-drum columns. Despite their present typology and their high slenderness, these columns often remain intact through the centuries and proved to be resistant to strong earthquakes. Multi-drum columns exhibit a quite distinct seismic response compared to that of modern structures. Indeed, their seismic response is dominated by highly non-linear phenomena along the interfaces, including rocking and/or sliding of the drums during shaking, as opposed to modern structures, where the response is dominated by the hysteretic behaviour of the materials. In this study, the seismic response of classical multi-drum columns is investigated by means of rigorous numerical analysis. An Ionic multi-drum column that has recently been restored at the Akropolis of Lindos in Rhodes, Greece, is used as a case study. The numerical analyses are conducted using the Finite Element code ABAQUS. Three-dimensional solid elements are used to model the drums, while the nonlinear response of the interfaces is encountered in the analyses using special interface/contact algorithms embedded in ABAQUS. Additional analyses are conducted by bonding perfectly the drums of the column, to investigate the seismic response of free-standing monolithic columns and compare with multidrum columns of the same geometry. Through the presentation of representative results, critical parameters that affect the seismic response of this type of structures, such as the interface characteristics, are highlighted and discussed. Emphasis is given on the stresses developed along the interfaces during shaking. The structural performance and overall stability of both the multi-drum and monolithic columns are investigated in terms of the maximum displacement of the capital against various intensity measures of the base excitation. The study contributes towards the improvement of the knowledge of the seismic performance of free-standing rocking systems, such as the classical columns.

Keywords: Classical free-standing columns, Numerical dynamic analysis, Interfaces, Stresses, Rocking/sliding phenomena

Seismic performance evaluation of the Roman Temple of Évora in Portugal

Daniel V. Oliveira[1], Paulo B. Lourenço[1]

[1]University of Minho, School of Engineering, Campus de Azurém, 4800-058, Guimarães, Portugal

**e-mail: danvco@civil.uminho.pt*

ABSTRACT

Strong earthquakes frequently cause the destruction of classical monuments, particularly those structures that have previously sustained damage and are now incomplete. Thus, understanding the dynamic behaviour of these structures is crucial for their preservation for future generations. The dynamic response of such structures is characterised by a complex interplay of rocking and sliding motions, exhibiting highly non-linear behaviour. The Roman Temple in the historical centre of Évora, Portugal, serves as a case study to present its seismic behaviour. Initially, the stability of the structure is assessed using limit analysis and the pushover approach. These methods significantly underestimate the structural capacity due to their inability to account for the dynamic stability of blocks during an earthquake. Nevertheless, they accurately identify the failure mechanism of the structure. A discrete element model (DEM) of the structure is also analysed in the time domain. This model utilizes rigid elements with frictional joints, incorporating both geometric and material nonlinearity at the joints. Calibration of the model is achieved using results from an experimental dynamic identification. The structural response is evaluated across a range of earthquake intensities, considering both far-field and near-field scenarios. The findings indicate that the structure can sometimes accommodate large deformations while maintaining stability. Finally, a set of three damage indicators is proposed, and their results are discussed and compared.

Application of a Tendon System to Protect Classical Columns against Earthquakes

Ioannis N. Psycharis[1*], Evangelos Avgenakis[1], Maria-Eleni Dasiou[1]

[1]School of Civil Engineering, National Technical University of Athens, 9, Iroon Polytechneiou Str., Athens, Greece

**e-mail: ipsych@central.ntua.gr*

ABSTRACT

Multi-drum columns, made of drums placed one on top of the other without mortar, are found today either free-standing or within colonnades. The fact that many classical monuments built in seismic prone areas have survived for almost 2500 years shows that, despite the lack of any lateral load resisting mechanism except friction, classical columns are, in general, earthquake resistant. However, many have collapsed and the ones that have survived upto-date present many types of damage (cut-offs of drums, tilting due to foundation problems, dislocated drums, cracks) which reduce significantly their capacity to survive strong earthquakes. Thus, most of the today standing columns and colonnades are rather vulnerable to future earthquakes and interventions are deemed necessary in order to reduce the risk of collapse to an acceptable level, with the most common one being the addition of missing fragments of the drums. An innovative system, which consists of an unbonded steel tendon that passes through the drums and is anchored at the foundation and at the top of the column, is proposed herewith to enhance the seismic stability of classical columns and increase their ability to survive strong earthquakes. During the seismic response, the tendon is elongated due to the rocking of the drums and applies a compressive restoring force to the column. In this way, the deformation of the column and the rocking of the drums decrease and the collapse of the column is prevented. The restoring force increases as the deformation of the column increases, leading to a “controlled rocking” system. The application of the proposed ‘tendon system’ is conditioned on the approval of drilling a small hole along the column. Its efficiency is proven for the case study of the restoration of the columns of the temple of Pythios Apollo on the Ancient Acropolis of Rhodes in Greece.

Keywords: Classical columns, tendon system, restoration, rocking, seismic response

Can we use the seismic response of free standing monuments to verify Probabilistic Seismic Hazard estimates?

Anastasios Sextos[1,2*], Kosmas Stylianidis[2],

[1]School of Civil Engineering, National Technical University of Athens, 9, Iroon Polytechneiou Str., Athens, Greece

[2]Civil Engineering, Aristotle University of Thessaloniki, 54124

**e-mail: asextos@mail.ntua.gr*

ABSTRACT

This presentation aims at developing the tools and strategy for assessing the seismic performance of the Roman remains in the city of Thessaloniki, in Greece, as a means to back-evaluate and enrich the seismic micro zonation studies available for the Metropolitan area. At first, focus is made on the Walls that have been constructed at the end of the 4th century A.D.

In the reign of Theodosius the Great and numerous blocks remain intact widespread within the city grid. The study particularly focuses on a specific Wall residuum, whose small dimensions, simple morphology (free-standing, rocking dominated masonry block), availability of nearby strong ground motion recordings and good knowledge of the underlying soil conditions, constitute a well-controlled case-study with the minimum possible numerical modeling (i.e., epistemic), record-to-record and material uncertainty. Secondly, the study focuses on an ancient Roman column, which was reestablished in 1969 after extensive archeological works. For both historical structures, a refined probabilistic approach is adopted and the structural performance is examined, through a Monte Carlo Simulation scheme, for a number of realistic earthquake scenarios, accounting for geometric nonlinearities (i.e., sliding and rocking) and uncertainties in friction properties. Given the absence of damage, permanent displacement or collapse of the particular bodies, the probability of non-exceedance of a specific intensity measures (for the period that the structures remain intact) is assessed for the Wall residuum and the ancient colonnade, thus implicitly, for the city as a whole. It is also demonstrated that the fragility predicted without dully considering rocking and sliding of the two rigid blocks may lead to misleading results for particular sets of strong ground motions.

Quantifying the developing forces of clamps and dowels used for the anastylosis of the N.E. tower of the Aegosthena fortress in W.Attica

Eleni-Eva Toumbakari[1*]

[1]Ministry of Culture, Ephorate of Antiquities of Western Attica, 16, Panos Str., Athens, Greece

**e-mail: etoumpakari@culture.gr*

ABSTRACT

The Aegosthena fortress was built at the eastern side of the Corinthian Gulf. It is dated at 340 B.C. and was part of the Athenian defensive system. The northeastern tower is one among the four towers that reinforced the fortress' eastern wall. It is a quadrangular construction, with external dimensions approximately 7.5m at the foundation level and total remaining height around 12m. The eastern and northern sides are founded directly on the rock, whereas the western and southern sides are founded on a deformable substrate. In the course of its life, the building has gradually suffered from local collapses and foundation subsidence. At the 1981 eastern Corinthian Gulf earthquake, the whole southeastern corner of the tower, including most of the eastern wall, collapsed. The study for the monument's structural restoration was carried out within the framework of the Directorate for Restoration of Ancient Monuments and comprised detailed constructional analysis of the tower and investigation of the mechanism of collapse. Moreover, modeling and analysis of the structural behaviour of the tower before and after the proposed interventions was carried out by means of spectral dynamic analysis as well as discrete element analysis. The first part of the presentation will briefly discuss the constructional analysis of the tower, the qualitative description of the four stages of the collapse mechanism and the justification of the anastylosis strategy and interventions. The second part will focus on the modeling of the "repaired" condition with the discrete element method in order to understand and quantify, as much as possible, the behaviour of the repaired structure. As is usual with ancient fortifications, the tower was built without connectors (clamps, dowels). One of the main anastylosis requirements has been their introduction at specific places inside the structural blocks. In this context, the rationale for the selection of the areas, where connectors were introduced, will be discussed. Moreover, the developing forces at the clamps and dowels will be discussed in detail as a function of their position inside the structure. The anastylosis of the northeastern tower of the Aegosthena fortress has been carried out between the years 2014-2019 by the Directorate for Restoration of Ancient Monuments of the Hellenic Ministry of Culture with funds from Greece and the European Union.

Keywords: Fortifications, anastylosis, clamps, dowels, discrete elements

Modelling drum columns with discrete elements – Practical issues

José V. Lemos[1*]

[1]LNEC, LNEC, Av. do Brasil, 1700-066, Lisboa, Portugal

**e-mail: vlemos@lnec.pt*

ABSTRACT

The modelling of drum columns with discrete elements is discussed, considering in particular the use of the 3DEC code. The main issues involved in the modelling of these structures are addressed, namely: the representation of deformability; contact discretization; geometric irregularities; block breakage; modelling reinforcement; efficiency in dynamic analysis; damping options. Some examples are presented to illustrate the available options.

Keywords: Columns, discrete elements, dynamic analysis

Numerical investigation of the role of iron dowels in the stability of multi-drum columns

Olympia Panagouli[1*]

[1]School of Civil Engineering, University of Thessaly, Volos, Greece

**e-mail: olpanag@uth.gr*

ABSTRACT

The seismic vulnerability of ancient free-standing multi-drum columns is an important issue for the preservation of archaeological monuments. Multi-drum columns show a complex and highly non-linear dynamic behavior, requiring specific structural analysis. Different numerical studies on the dynamic behavior of ancient multi-drum columns found that their response is sensitive to their geometry, as well as to the material properties, the coefficient of friction and the amplitude and frequency of the applied base excitation. Another parameter which influences the response of multi-drum columns is the existence of dowels between the drums. The aim of this work is to investigate numerically the contribution of the iron dowels to the overall stability of multidrum columns. For that, the complex 3D dynamic response of two different types of a multi-drum column is studied numerically, by using the FE code MARC. In the first type, the drums simply lie on top of each other, while in the second one a connection system which consists of two iron dowels is implemented. The studied columns, which consist of three drums and a capital on the top, are part of the colonnade system of the ancient Messene Gymnasium in Greece. In the 3D models, special attention is given to the modelling of the metallic dowels which were used to connect adjacent drums. The columns were subjected to sinusoidal base excitations having different acceleration amplitudes and different frequencies and useful results are derived concerning the role of the iron dowels to the overall stability of the studied multi-drum columns.

Keywords: Cultural heritage, multi-drum columns, iron dowels, 3D dynamic response

Discrete Rigid Block Analysis of The Stone Masonry Temple: Exploring the Effect of Ancient Retrofitting Technique

Bora Pulatsu[1*], Ece Erdogmus[2]

[1]Carleton University, Carleton University, Civil and Environmental Engineering, Canada

[2]School of Building Construction, Georgia Institute of Technology, Atlanta, GA, USA

**e-mail: bora.pulatsu@carleton.ca*

ABSTRACT

In the last several decades, with the advances in computational power, sophisticated numerical modelling techniques have been proposed to predict the seismic response of unreinforced stone masonry columns, colonnades, and heritage structures. The computational models have also been utilized to quantify the effectiveness of various retrofitting solutions by targeting the minimum intervention principle. Typically, the highly nonlinear and inherent discontinuous mechanics of dry-joint stone masonry structures have been predicted via various discontinuum-based analysis approaches in the literature. The discrete element method (DEM) has been utilized most, among others, in simulating various dry-joint block assemblages (columns, arches, walls, etc.) subjected to static and dynamic loading scenarios. To this end, the present research aims to predict the quasi-static and dynamic behaviour of an unreinforced stone masonry Temple located at the ancient Roman site of Antiochia ad Cragum using DEM. The adopted modelling strategy represents stone units via discrete rigid blocks interacting along their boundaries at the pre-defined contact points. The geometrical properties of the computational model, including the dimensions of the masonry units, are obtained based on the in-situ investigations and available studies. In the discrete block representation of the Temple, 488 blocks are employed, and non-cohesive frictional contact planes at the inter-block interfaces are considered. According to the computational investigations, the overturning collapse mechanism of the front façade and the vulnerable condition of the gable are noted based on quasi-static and dynamic analysis, respectively. Furthermore, the effect of iron clamps used to attach adjacent blocks is explored through discontinuum-based analysis, and its positive influence on the seismic response is simulated.

Keywords: DEM, Collapse Mechanism, Dry-Joint Masonry, Simulation