# HISTORY OF CONSTRUCTION CULTURES

VOLUME 2


edited by

**João Mascarenhas-Mateus**
and **Ana Paula Pires**

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HISTORY OF CONSTRUCTION CULTURES

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# History of Construction Cultures

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# Introduction: *History of Construction Cultures*

We are what we build and how we build; thus, the study of Construction History is now more than ever at the centre of current debates as to the shape of a sustainable future for humankind. Embracing that statement, the present work takes the title *History of Construction Cultures* and aims to celebrate and expand our understanding of the ways in which everyday building activities have been perceived and experienced in different cultures, times and places.

This two-volume publication brings together the communications that were presented at the 7ICCH – Seventh International Congress on Construction History, broadcast live from Lisbon, Portugal on 12–16 July 2021. The 7ICCH was organized by the Sociedade Portuguesa de Estudos de História da Construção (Portuguese Society for Construction History Studies – SPEHC); the Lisbon School of Architecture, University of Lisbon; its Research Centre (CIAUD); and the College of Social and Human Sciences of the NOVA University of Lisbon (NOVA FCSH).

This is the first time the International Congresses on Construction History (ICCH) Proceedings will be available in open access format in addition to the traditional printed and digital formats, embracing open science principles and increasing the societal impact of research. The work embodies and reflects the research done in different contexts worldwide in the sphere of Construction History with a view to advancing on the path opened by earlier International ICCH editions. The first edition of ICCH took place in Madrid in 2003. Since then, it has been a regular event organized at three-year intervals: Cambridge (2006), Cottbus (2009), Paris (2012), Chicago (2015) and Brussels (2018).

7ICCH focused on the many problems involved in the millennia-old human activity of building practiced in the most diverse cultures of the world, stimulating the cross-over with other disciplines. The response to this broad invitation materialized in 357 paper proposals. A thorough evaluation and selection process involving the International Scientific Committee resulted in the 206 papers of this work, authored by researchers from 37 countries: Australia, Austria, Belgium, Brazil, Bulgaria, Canada, China, Dominican Republic, Ecuador, Egypt, Estonia, France, Germany, India, Iran, Ireland, Italy, Japan, Mexico, Netherlands, New Zealand, Norway, Peru, Poland, Portugal, Puerto Rico, Russia, Serbia, Spain, South Africa, Sweden, Switzerland, Thailand, United Arab Emirates, United Kingdom, United States of America, and Venezuela.

The study of construction cultures entails the analysis of the transformation of a community's knowledge capital expressed in the activity of construction. As such, Construction History is a broad field of knowledge that encompasses all of the actors involved in that activity, whether collective (contractors, materials producers and suppliers, schools, associations, and institutions) or individual (engineers, architects, entrepreneurs, craftsmen). In each given location and historical period, these actors have engaged in building using particular technologies, tools, machines and materials. They have followed specific rules and laws, and transferred knowledge on construction in specific ways. Their activity has had an economic value and belonged to a particular political context, and it has been organized following a set of social and cultural models.

This broad range of issues was debated during the Congress in general open sessions, as well as in special thematic sessions. Open sessions covered a wide variety of aspects related to Construction History. Thematic sessions were selected by the Scientific Committee after a call for proposals: they highlight themes of recent debate, approaches and directions, fostering transnational and interdisciplinary collaboration on promising and propitious subjects. The open sessions topics were:

- Cultural translation of construction cultures: Colonial building processes and autochthonous cultures; hybridization of construction cultures, local interpretation of imported cultures of building; adaptation of building processes to different material conditions;
- The discipline of Construction History: Epistemological issues, methodology; teaching; historiography; sources on Construction History;
- Building actors: Contractors, architects, engineers; master builders, craftspeople, trade unions and guilds; institutions and organizations;
- Building materials: Their history, extraction, transformation and manipulation (timber; earth, brick and tiles; iron and steel; binders; concrete and reinforced concrete; plaster and mortar; glass and glazing; composite materials);

- Building machines, tools and equipment: Simple machines, steam operated-machines, hand tools, pneumatic tools, scaffolding;
- Construction processes: Design, execution and protective operations related to durability and maintenance; organization of the construction site; prefabrication and industrialization; craftsmanship and workshops; foundations, superstructures, roofs, coatings, paint;
- Building services and techniques: Lighting; heating; ventilation; health and comfort;
- Structural theory and analysis: Stereotomy; modelling and simulation; structural theory and structural forms; applied sciences; relation between theory and practice;
- Political, social and economic aspects: Economics of construction; law and juridical aspects; politics and policies; hierarchy of actors; public works and territory management, marketing and propaganda;
- Knowledge transfer: Technical literature, rules and standards; building regulations; training and education; drawings; patents; scientific dissemination, innovations, experiments and events.

The thematic sessions selected were:

- Form with no formwork (vault construction with reduced formwork);
- Understanding the culture of building expertise in situations of uncertainty (Middle Ages-Modern times);
- Historical timber constructions between regional tradition and supra-regional influences;
- Historicizing material properties: Between technological and cultural history;
- South-South cooperation and non-alignment in the construction world 1950s–1980s;
- Construction cultures of the recent past: Building materials and building techniques 1950–2000;
- Hypar concrete shells: A structural, geometric and constructive revolution in the mid-20th century;
- Can engineering culture be improved by construction history?

Volume 1 begins with the open session “Cultural translation of construction cultures” and continues with all the thematic sessions. The volume ends with the first part of the papers presented at the open sessions, organized chronologically and the introductory texts by the chairs for each thematic session. Volume 2 is dedicated to the remaining topics within the general themes, also in chronological order.

Four keynote speakers were chosen to present their most recent research results on different historical periods: Marco Fabbri on “Building in Ancient Rome: The fortifications of Pompeii”; Stefan Holzer “The role of temporary works on the medieval and early modern construction site”; Vitale Zanchettin “Raphael’s architecture: Buildings and materials” and Beatriz Mugayar Kühl “Railways in São Paulo (Brazil): Impacts on the construction culture and on the transformation of the territory”.

The editors and the organizers wish to express their immense gratitude to all members of the International Scientific Committee, who, despite the difficult context of the pandemic, worked intensively every time they were called on to give their rigorous evaluation of the different papers.

The 7ICCH was the first congress convened under the aegis of the International Federation of Construction History, founded in July 2018 in Brussels. Therefore, we are also very grateful to all the members of the Federation, composed of the presidents of the British, Spanish, Francophone, German, U.S. and Portuguese Societies and its Belgian co-opted member. A special thanks is due for all the expertise and experience that was passed on by our colleagues who have been organizing this unique and world significant event since 2003, and in particular to our predecessors from all the Belgian universities who organized 6ICCH.

The editors wish to extend their sincerest thanks to authors and co-authors for their support, patience, and efforts. This two-volume work would not exist but for the time, knowledge, and generosity they invested in the initiative.

Our sincere thanks also go out to Kate Major Patience, Terry Lee Little, Kevin Rose and Anne Samson for proofreading every paper included here, and to the team at Taylor & Francis (Netherlands), in particular Germaine Seijger and Leon Bijnsdorp.

Finally, we are grateful to all members of the Local Committee and to the institutions that have supported both the 7ICCH event and the publication of these proceedings.

The Editors
*João Mascarenhas-Mateus and Ana Paula Pires*

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IFCH
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FCT
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Construction History Society of America

*Open session: Construction processes*

*History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)*


# Experimental analysis to define the stability conditions of the temple of Vesta in *Forum Romanum*

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ABSTRACT: The round temple of Vesta - located in the Roman Forum and connected to the House of the Vestals on the Via Sacra – was the site of religious practices predating the founding of the city. The temple was reassembled by the Fascist regime in 1936 as background for the Via dell'Impero. This reconstruction was made by anastylosis with significant additions. The few original marble elements were composed with travertine pieces to partially restore the ancient image recovered from coins and descriptions. Investigating the building's structural condition verified the reconstruction methods for the N-W sector. Here, two rows of three columns are arranged in concentric circles in a system of pendular elements, which is made asymmetrical by the presence of partition walls between the inner columns. The reduced-scale model - commensurate with the prevailing building conditions - highlighted the behaviour of collapse and the possibilities for improvement.

## 1 HISTORICAL OUTLINE

The restoration of the Temple of Vesta was based on recompositing the ancient building remains by anastylosis. Today, this operation appears questionable due to the low percentage of original elements and the partiality of the reconstruction compared to the entire monument. However, this intervention brought about the creation of an easily recognizable visual and ideal identity-node in the Forum central area crossed by the Via Sacra. The cult of Vesta – dedicated to the conservation of the sacred fire – was, in fact, an essential aspect of the most ancient history of the city, linked to the myth of the founders.

The original temple, probably already rebuilt several times in the classical period, was closely connected to the House of the Vestals overlooking the Via Sacra. This was inspired by the tholos typology that constituted an impenetrable envelope in which fire burned perpetually, guarded by the Vestals. From the outset, the architectural form is not configured as a *templum* but as a *sacrarium* as evidenced by its original name "Aedes Vestae" (sacred residence of Vesta). In the 1st century configuration, after one of the most important reconstructions, the cell was formed by columns inserted in the inner circular wall and surrounded by the colonnaded perimeter covered with a lithic ceiling.

The classical profile was recovered both from ancient coins and descriptions that allowed for recompositing the building components found during the extraordinary excavation campaign supported by the fascist government.

This campaign belongs to an exceptional period in the history of archaeology and restoration that transformed the faces of a neighbourhood and the modern city; this was a vast operation that led to the demolition of an entire Renaissance sector to bring to light what remained of the ancient monuments and obtain the current layout of the archaeological area of the Roman Forum.


Figure 1. Two imperial coins of Tiberius (14–37) and Titus (79–81) preserved in Oxford's Ashmolean Museum (RIC I, 99, 74 and RIC II 34 n.162) (a); Bas-relief from Lateran, ascribable to the temple of Vesta, currently preserved in the Florence Uffizi Gallery coming from Villa Medici (b).

It was a process in which the political objective, aimed at opening the Via dell'Impero and the scenographic preparation of the Forum area, was

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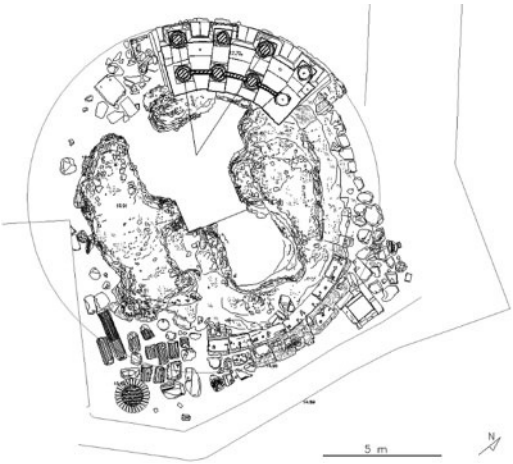


Figure 2. Site plan showing the temple with the remains of the foundations, the erratic pieces and the reconstructed sector formed of three columns. The original building must have been of 22 columns per row.

Figure 3. Photographic documentation (1929). Analysing the background, we can presume that the gypsum model is rotated compared to the current placing of the elements.

tightly interwoven with archaeological purposes. Great archaeologists such as Giacomo Boni, Corrado Ricci and Alfonso Bartoli himself, who was to support the reconstruction project of the Temple of Vesta through to its completion, all contributed.

The reconstruction of a portion of the temple was debated. The choices underlying the current relocation of erratic parts on the remains of the classical foundations also stemmed from the environmental context contrary to the first positioning proposed only according to the archaeological study. In a photograph taken by architect Torquato Ciacchi, Bartoli's collaborator, the prototype appears to display a different placement to that of the actual reconstruction. In fact, in the background, we may depict the Palatine structures which are currently on the southern side. Despite the different position, the real reconstruction maintains the same components of the prototype, with double rows of three columns, the wall partition between the inner intercolumns and the ceiling on the trabeation, with the dark colouring of the additions highlighting the original parts. The re-composition was completed in 1936 after a phase of proposals, rethinking and modelling. Nowadays, the intervention represents a classic example of partial reconstruction through anastylosis with significant additions.

Political needs presumably favoured a reconstruction made with a few marble elements and many travertine blocks and bricks. The execution was entrusted in two phases to the firm of engineer G. Cozzo; technical control, which was not attributed to the archaeologist Bartoli, was first based on the contributions of the architects G. B. Milani and T. Ciacchi and, in the execution phase, the engineer L. Crema, but especially on the advice of Gustavo Giovannoni.

The base was completely rebuilt with massive new masonry, lined with travertine slabs in which the fragments of the original covering materials are set.

The reconstruction was justified by the need to reposition the columns in an elevated position. This allows for a correct perception of the monument and the site's scenography, recalling the high podium in the tradition of Roman sacred building.

The columns are largely original but integrated with cabled shaft sections which, according to some scholars, re-proposes the lathwork of the archaic hut and symbolizes the idea of closure and protection. The two trabeation sections and the ceiling were also obtained by assembling the original marble portions with local travertine additions well-distinguishable from the originals, which were probably imported from eastern quarries.

The integrative portions were obtained by replicating in travertine the model made with gypsum during a preparatory phase. In fact, gypsum makes it possible to quickly obtain shapes that blend perfectly with the original stones but does not guarantee resistance and durability due to its typical hydrophilic behaviour.

Once the prototype was finished, the elements to be reproduced in stone were obtained from those in gypsum. In order to connect the different elements mortars and metal pins were chosen. During assembling, bronze connectors fixed with lead casting were certainly used while small concrete reinforcements with smooth steel bars could not be avoided.

Reinforced concrete inserts were applied to put together the trabeation where new portions joined the historical remains that would otherwise have been unable to sustain themselves.

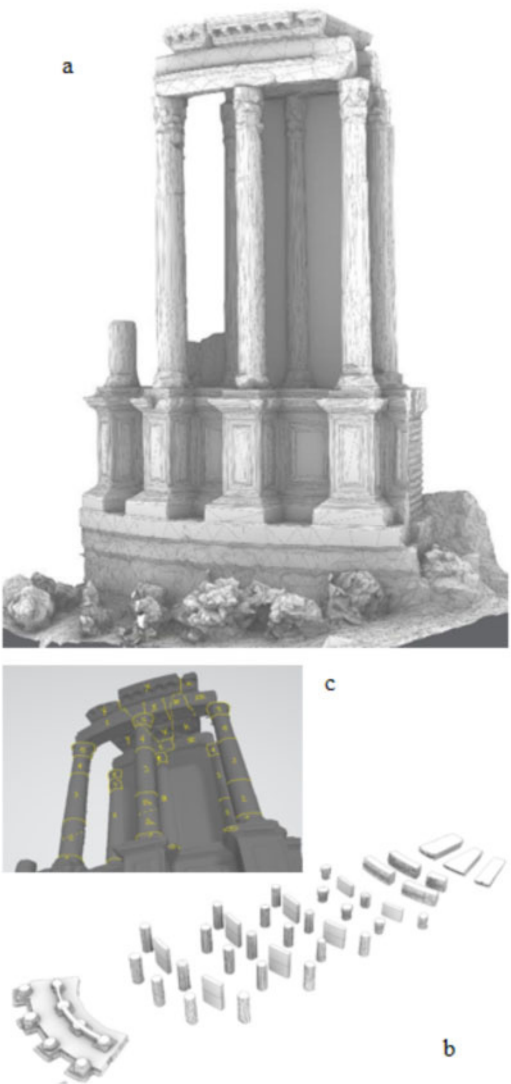


Figure 4. Perspective view of the laser scanner 3D model (a). The physical model was obtained by printing all the pieces separately (b), according to coded numbering, as shown in the study scheme (c).

Mostly, it emerged that these concrete works were widely used to recompose the lithic ceiling coffers by modelling them by moulding the ancient pieces.

We assume there are pins between pieces even in the columns, where they are inhomogeneous but are able to exclude the insertion of continuous metal cores. The wall partitions between columns are composed of slabs in which there are metal blocks at the edges, connecting them to the columns and the upper plates.

Tests conducted with electromagnetic instruments (georadar) have confirmed the use of connectors, which had already emerged from analysis of archival documents. However, the shapes and sizes remain undefined.

The binders present good consistency and toughness, both in the small additions and in the castings that give continuity to the elements. In the ceiling, you can see the connections obtained with small beams carved into the stone and cast with a concrete conglomerate, with small aggregates, which protects and connects the reinforcements. The connection of the architraves was obtained with similar reinforced castings put in fluting dug into the extrados of the old and new stone elements so they do not appear on the intrados. An understandable choice to preserve the image and to reunite the architraves with the ceiling, but apparently less effective than the similar and more common intrados reinforcements.

Although more than eighty years have passed since the building's completion, no significant signs of deterioration appear, neither to the mortars and conglomerates nor to the metal elements.

## 2 AIM OF THE EXPERIMENTATION

During the last few months, a monument maintenance cycle has been activated by the Parco Archeologico del Colosseo. No structural interventions are proposed and only conservation actions on the surfaces are planned as no symptoms of structural decay have been detected. However, we simultaneously gained the chance to verify – with instrumental investigations - the execution construction methods, the structural stability of the building and the potential of theoretical solutions for increasing its capacity.

Non-invasive investigations were carried out aimed at determining the state of conservation, identifying the presence of hidden connections and their state of conservation. Furthermore, the structure's behaviour was determined by means of accelerometers able to capture the effects of environmental micro-tremors.

Indeed, the structure - greatly reduced compared to the original intact building - appears as a pendular system consisting of two series of almost aligned columns and an important mass on top that connects them; the wall podium is instead solid and rigid, perfectly stable, so much that it can be considered equivalent to rigid ground.

As previously mentioned, it is a sector that represents about one seventh of the entire peristyle, consisting of two rows of three columns arranged radially on two concentric rows. The entire columns (3 out of 22 of the entire perimeter), made of original marble portions and reinstatement pieces, constitute the system of pendular elements that is symmetrical in the radial direction, but strongly asymmetrical in the frontal direction tangent.

The partition wall in travertine blocks, occupying the spaces between the inner columns, makes the internal colonnade more stable in the tangential direction; at the same time, however, this modifies the behaviour of the inner row of columns compared to the external row. In fact, it strongly differentiates the structural response of the two main axes by strengthening the

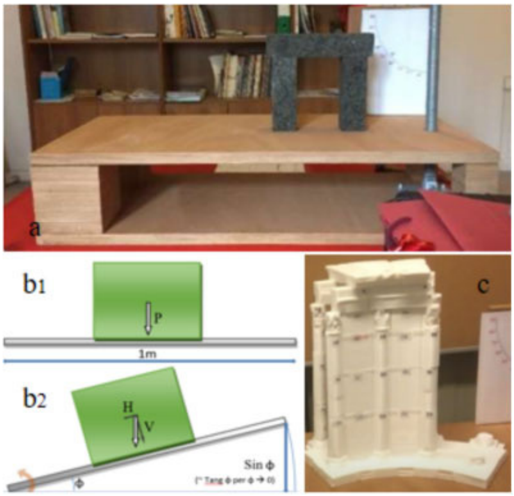


Figure 5. The inclinable table in horizontal position with a model placed on (a). Increases in inclination are obtained by screwing a bolt onto the vertical threaded bar on the right side of the table. (b). The 3D model used during the tests (c).

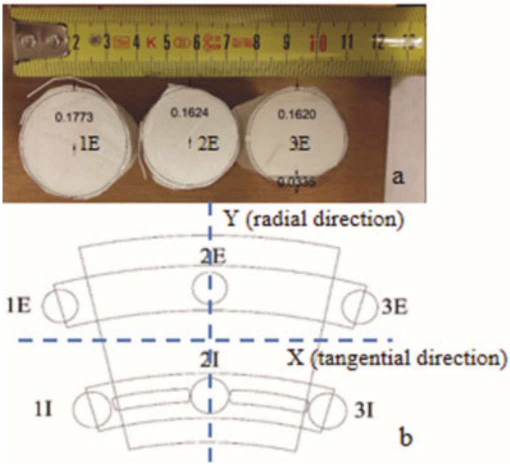


Figure 6. The column bases with their dimensions in the model representation scale (1:14.5) and the chipping of column 1E (a). The planimetric diagram with the elements coded (b).

in-plane behaviour of the internal columns compared to the others.

On the other hand, the structural response in the radial direction is not particularly enhanced by the walls, which are very thin compared to the columns.

The sustain system of the columns is linked at the top by curved trabeation sections and by the recomposed lithic coffered ceiling which is laid - sometimes in an apparently 'adventurous way' - on the capitals. Actually, the supports are constrained by means of special anchoring devices that are only visible close-up from scaffolding.

The original portions of the columns show flaking and deterioration due to aging and previous damage. Defects in the lithic material appear relevant, especially when corresponding to the nodes expected to contain hinge formations. In these cases, any lacking can strongly influence the kinematic behaviours of the entire system.

The first analysis identifies the structure's seismic vulnerability while remaining, however, almost intact despite the earthquakes occurring in Rome over the last century.

## 3 DEFINITION OF THE STUDY MODEL

This structure is unusual because it is an incomplete portion of a building that would find its own stability in a closed conformation based on the circumference. This is thus an almost real 'macro-element' extracted from the ideal integral structure.

This portion can behave as a rigid body. The radial action is well-defined but - due to the aforementioned asymmetry - it is difficult to delineate the response to actions tangential to the peristyle and perpendicular to the radial direction.

The definition of the kinematics implies the determination of the nodes in which the hinges form, and their positioning can be influenced by the fragmentation of the recomposed elements.

To deepen the study, the behaviour of the structure brought to collapse also involved a physical model produced by printing the results of a 3D laser scanning survey.

The model was obtained from a three-dimensional printer making all the pieces separately, following the discontinuity lines between the historical elements and modern additions.

The model's scale of representation is 1:14.5. The printing was carried out by depositing a filament of synthetic material - layer-upon-layer - until the object was fully formed. This material has a density of about 13 kN/m3, obviously different from the travertine and marble of the lithic elements, but the shapes are effectively simulated. The physical model presented some problems relating to the reconstruction of pieces in the posterior portion and the coplanarity of the overlapping bases.

These problems were partially solved by correcting the discretization of the non-matching pieces and re-printing them. A progressively inclinable plane served to check system behaviour. The gradual leaning increase makes it possible to evaluate, – as in some experiments begun in the late 1980s – the model's behaviour in comparison with a horizontal stress equivalent to the component of its own weight parallel to the plane.

The inclination transforms the weight into stress corresponding to the horizontal static action ($H = V \text{ tg } \phi = V \alpha$) proportional to the inclination and to load multiplier $\alpha$.

Contextually, some theoretical calculations related to limit-behaviour schemes based on the application

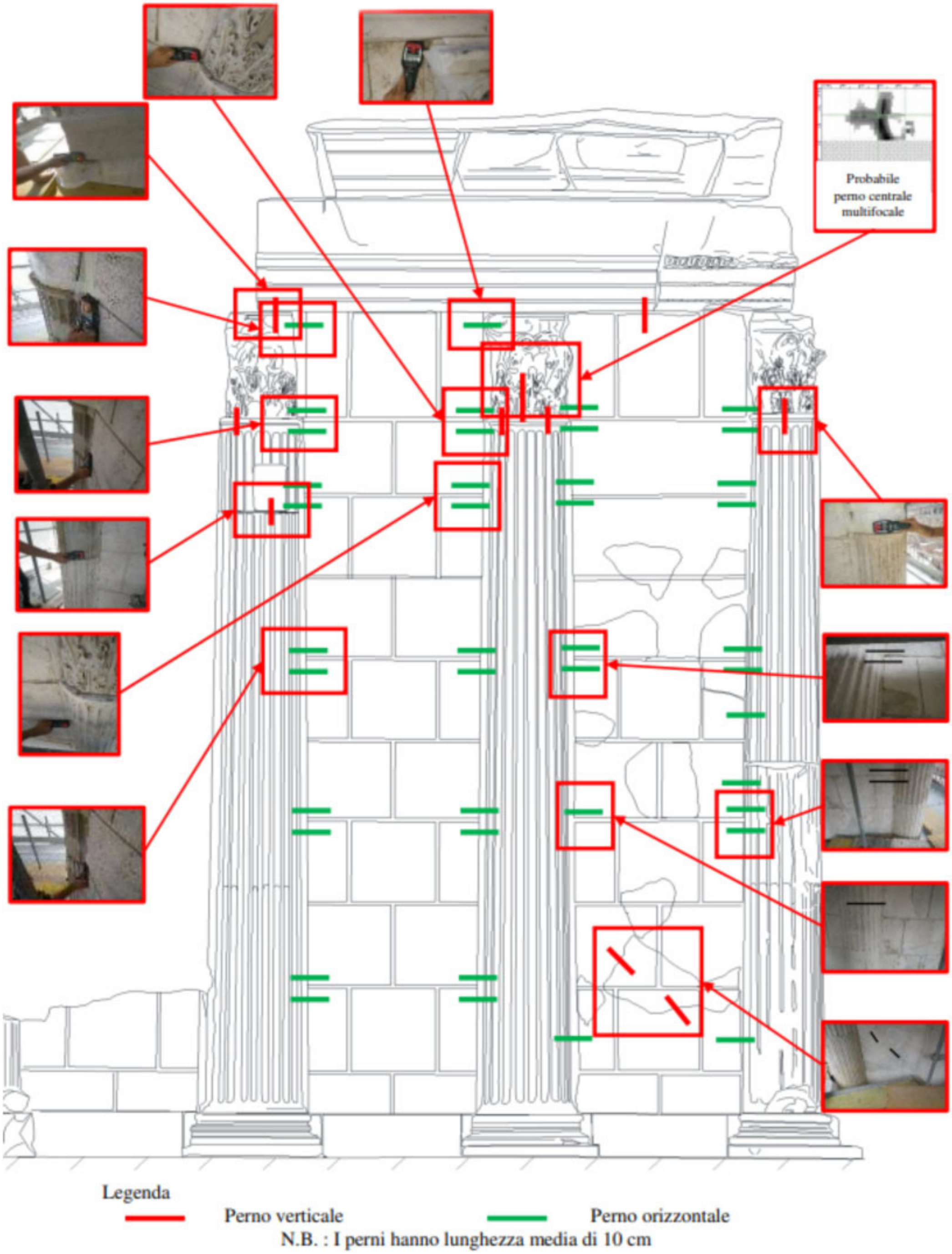


Figure 7. Working notes on the connections reported by magnetometric and thermal instrumental analysis.

of the PLV were made and also defined according to the results achieved in physical modelling.

The physical model underwent minor adaptations to make it more similar to the real monument in keeping with the research outcomes on the presence of metal connections and the registration of the response methods to environmental vibrations.

Analysis and the study of site documents highlight the presence of connection devices largely not visible from the outside: concrete castings with steel

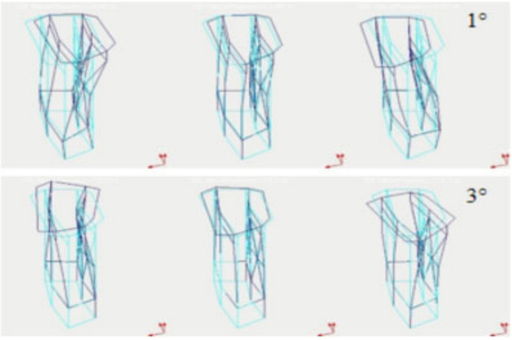


Figure 8. Wire frames of the structure with its vibration modes produced by environmental micro-tremor. The main modes (1° , 3°) are compatible with the behaviour of the model.

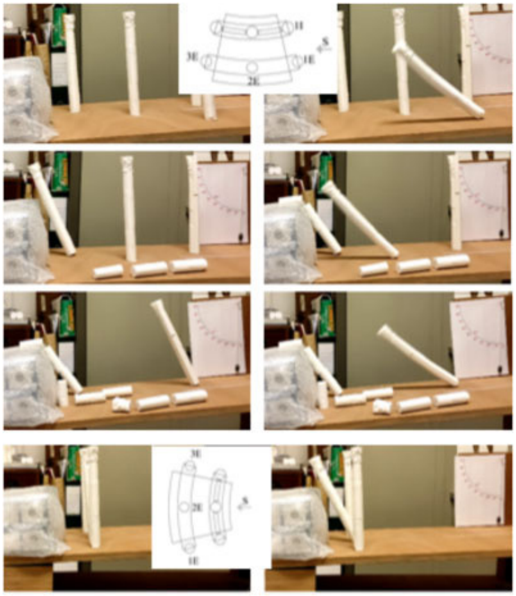

Figure 9. Results of the experimentation on single columns.

reinforcements that strongly constrain elements of the ceiling and portions of the entablature anchored to the capitals, especially at the ends where the connection appears less solid. The wall partition between the internal columns is provided with cramps that bind the single travertine panel to the upper section. It is presumable that pins have been inserted centrally between the elements composing the columns.

In the physical model, the elements were simply placed against each other and so the results are thus highly preliminary. Strings were inserted only in the horizontal planes of the inner row to simulate the actual massiveness of the wall obtained with the cramps.

Some simplified experimental tests were initially conducted to calibrate the reliability of the model. These took into consideration the columns individually and they displayed fewer resistant behaviours than the corresponding theoretical schemes. Nevertheless, the most macroscopic defects were considered only in the schemes. On the other hand, the re-proposal of the exact geometry of the columns, including the irregularities in shape and verticality, leads us to consider the experimental result as more realistic than the theoretical, abstract and simplified model.

Subsequently, the behaviours of the entire model were tested alternately on the two main axes and in the two opposite directions. Finally, having identified the greatest criticality, improving the resistance capacity was tested by inserting a holding device consisting of two stays placed in the rear section of the building.

## 4 VERIFICATION RESULTS

Comparing the results obtained experimentally with the physical model with the results of the theoretical calculations reports a decent level of convergence; however, certain numerical differences must be highlighted between the homologous values determined with the different methods. We presume this difference is attributable to the simplification of the theoretical model and to the eventual limitations of the physical model.

The overall result in determining the modalities of the final behaviour remains reliable with the limitations of a test conducted only with equivalent static stress. For this reason, we intend to verify the dynamic behaviour of the model in the future. Both methods have their own trustworthiness and a real intermediate behaviour between the two series of results obtained can be considered valid. The greater attention paid to the individual external columns came from their significant influence on the behaviour of the entire model.

Frames 1 to 6 in Figure 9 concern the three external columns and one of the internal columns when the inclination solicits the tangential direction. In the same figure, frames 7 and 8 resume the three external columns arranged in a radial direction, 90° rotated by the previous position. The mechanism is firstly activated in column 2E; columns 1E and 3E follow. Based on the results obtained by theoretical calculations and by considerations about the geometry of these columns and the defects that we incorporated into the test, we decided to repeat the test for column 2E only.

The result confirmed expectations: the mechanism is activated firstly for column 1E, then for column 2E and finally for 3E. This response mainly links to the presence of chipping at the base of column 1E. Therefore, this anomaly determines a decrease in the width of the support with a consequent reduction in the stabilizing work. The columns of the internal peristyle - stabilized by the dividing wall - exhibit a distorted behaviour in the tangential direction for which they were tested separately only in the radial direction. Figure 10 details how the anterior columns precede the movement with less contribution from the column located in a prominent position, which initially follows

Table 1. Single column.

| Code | numerical meth. | experimental meth. |
|---|---|---|
| Tangential direction | | |
| 1Ex | $\alpha = 0.096$ | $\alpha = 0.047$ |
| 2Ex | $\alpha = 0.090$ | $\alpha = 0.087$ |
| 3Ex | $\alpha = 0.102$ | $\alpha = 0.070$ |
| 1Ix | $\alpha = 0.096$ | $\alpha = 0.090$ |
| Radial direction | | |
| 1Ey | $\alpha = 0.063$ | $\alpha = 0.049$ |
| 2Ey | $\alpha = 0.093$ | $\alpha = 0.058$ |
| 3Ey | $\alpha = 0.102$ | $\alpha = 0.090$ |

*E = external peristyle I = inner peristyleigure 10. Model response when stressed in the radial direction.

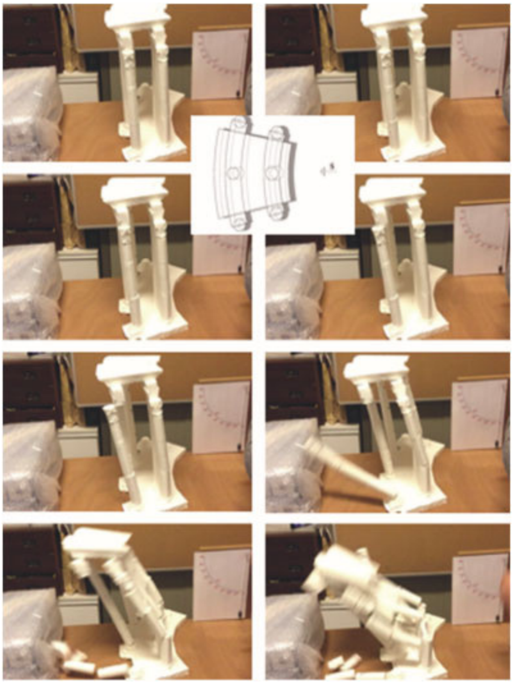

Figure 10. Model response when it is stressed on the radial direction.

the global movement and then releases. Recording the experimentation with continuous photographic shooting allowed us to study the collapse mechanism by extrapolating the most significant frames. In fact, the collapse occurs with extreme rapidity which sometimes does not consent to fully observe its evolution and, particularly, its trigger.

The tests all considered the two directions - radial and tangential - and the horizontal multiplier values of load $\alpha$, which involve the activation of the mechanism, were determined. The most significant values are collected in Tables 1 and 2. This column anticipates the kinematic collapse that involves all the elements except for the base of the inner peristyle which, linked to the base and to the wall, does not participate in

Table 2. Complete model summary.

| | | |
|---|---|---|
| Tangential North | numerical meth. $\alpha = 0.145$ | experimental meth. $\alpha = 0.090$ |
| Radial East | numerical meth. $\alpha = 0.096$ | experimental meth. $\alpha = 0.090$ |
| Radial West | numerical meth. $\alpha = 0.096$ | experimental meth. $\alpha = 0.081$ |

*we consider the force acting towards the cardinal point.

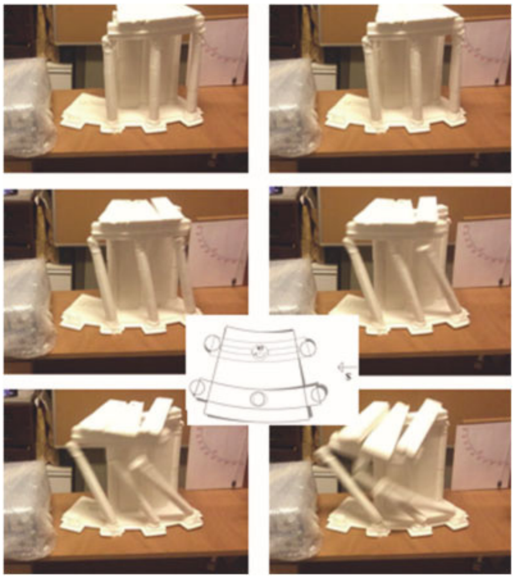

Figure 11. Model response when the pushing direction is tangent to the peristyle.

the collapse. The ceiling and the architraves follow the movement of the columns although remaining substantially compact.

Figure 11 depicts how the columns represent the weak part of the vertical bearing system and how the trigger of the kinematics begins with the overturning of the three columns in tangential directions to the horizontal trajectories with the centre in the median zone of the posterior wall; simultaneously, the left column of the inner peristyle folds towards the back. Subsequently, the failure of the floor due to friction brings about a release between the horizontal masses and the wall which loses its balance and collapses almost completely.

## 5 HYPOTHESIS FOR THE STRUCTURAL IMPROVEMENT AND CONCLUSIONS

The results obtained showed global stability but also a greater sensitivity of the structure in the radial direction. Therefore, we suggest inserting suitable devices

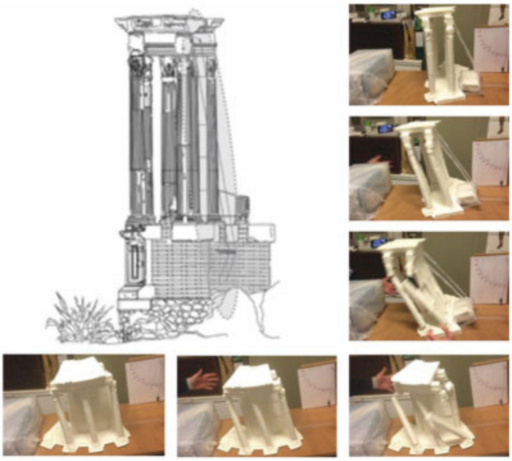

Figure 12. Lateral view of the reconstructed portion showing the stays designed to anchor the structure and to reduce its vulnerability especially in the radial direction which is that most exposed to a potential seismic event (a). Model response when stressed in the radial direction with the application of strings anchored to the ballast (b). Model response when stressed in the tangential direction with strings anchored to the ballast (c).

Table 3. Complete model summary experimental meth.

| | | |
|---|---|---|
| Tangential<br>North | without strength<br>$\alpha = 0.090$ | with strength<br>$\alpha = 0.110$ |
| Radial<br>West | without strength.<br>$\alpha = 0.081$ | with strength.<br>$\alpha = 0.105$ |

∗considered the force acting towards the cardinal point.

to improve resistance to overturning in this direction, especially towards the outer areas. In order to respect the construction and the historical documents and because of its special location, we decided to verify the possible positive contribution of a minimal intervention. This can consist of a stayed system formed with two ropes placed on the rear face, out of sight from the gaze of observers, distinct from the stone artefact and totally reversible. These devices can be fitted with minimal alterations to the existing material, while also capable of significantly improving the resistance to overturning in this direction, especially outside.

The upper anchoring could be placed on the internal entablature, in correspondence with the less exposed face, limiting the invasiveness to the two holes that would be necessary for the passage of the wire ropes. To allow for a suitable inclination of the stays (increasing the horizontal component of the constraint) two battens inclined on the bisector of the two linear sections were hypothesized. The advantage obtainable with this device is summarized in the table above. This was verified in the model applying two strings corresponding to ropes anchored to a ballast. We presume that the positive effect would be greater than in the model, which is made of lighter materials than travertine and does not reproduce the real limit conditions for sliding. The expected advantage is thus obtained in both directions, radial and tangential. In the second case, the tensioned stay helps delay the triggering of rotation due to the torsional effect, while the other one remains inert. Overall, the experience was useful to deepening the study of archaeological artefact reconstruction techniques with metal connections and well-preserved reinforced concrete mortars; the experiments highlighted the behaviour generated by the geometric shapes of the perfectly reproduced masses and guided the analysis carried out numerically by applying the principle of virtual work on mechanisms determined by physical modelling.


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