Roman Construction and Seismic Damage. Insights from the Capitolium of Ostia Antica

Laura Pecchioli
laura.pecchioli@tuwien.ac.at
Institut für Kunstgeschichte, Bauforschung und Denkmalpflege,
Technische Universität Wien, Austria

pagina a fronte

Fig. 1
Ostia Antica Archaeological Park. Capitolium, east façade. Detail of the eastern buttress, 2025, (Photo by L. Pecchioli).

Abstract
The study presented here forms part of an ongoing, more detailed research project and represents an initial step toward its broader development. It examines the interactions among structural logic, material degradation, environmental factors, and successive restoration phases, focusing on the cumulative nature of pathologies affecting walls, arches, vaults, and supporting elements. Rather than attributing deterioration to a single cause, the Capitolium is interpreted as a stratified architectural system in which material heterogeneity and post-constructional transformations are closely intertwined. Within this framework, the analysis of deformation patterns and equilibrium mechanisms in both vaulted and trabeated systems allows the identification of structural vulnerabilities while avoiding deterministic interpretations of failure. Particular attention is paid to the ambiguity of damage signatures in archaeological contexts, where seismic and non-seismic processes often overlap and are difficult to distinguish. The research integrates archaeological evidence, historical documentation, and structural analysis, highlighting the need for multi-criteria approaches in archaeoseismological interpretation and supporting an understanding of Roman architectural heritage as a dynamic and evolving system.

Keywords
Capitolium of Ostia; Roman construction techniques; Archaeoseismology; Masonry structures; Structural behaviour; Conservation methodology.

Introduction

The study of Roman monuments has progressively developed within an interdisciplinary framework encompassing architectural archaeology, the history of building practices, and conservation science, moving beyond typological interpretations toward a process-oriented understanding of the built environment. Roman construction systems, particularly opus caementicium combined with brick-faced masonry, should not be regarded as standardised technical solutions alone, but as the material expression of a complex structural logic in which material selection, building sequence, and interaction between components generate heterogeneous and time-dependent mechanical behaviours (Lancaster, 2005; Adam, 1994).

RA 1|2026, pagg. 66 - 91 | ISSN 1724-9686 (print) | ISSN 2465-2377 (online)


REG I
CAPITOLIVM

Recent scholarship has therefore emphasised the need to consider Roman architecture as a system in which material and procedural dimensions are closely interconnected. Within this framework, the Capitolium of Ostia Antica represents a significant case study due to both its urban and symbolic relevance and the complexity of its construction history and subsequent transformations. Despite this importance, systematic studies linking constructional aspects to structural behaviour and long-term decay processes remain limited, as research has traditionally focused on architectural reconstruction and chronological definition rather than on the relationship between material transformation and structural performance over time (Albo, 2002). This gap between archaeological interpretation and structural analysis is addressed here through an integrated reading of the monument.

Ostia Antica provides an especially relevant context for investigating long-term architectural behaviour (Pensabene, 2007). The preservation of standing remains allows direct observation of interactions between building systems, decay processes, and later modifications within a context shaped by environmental conditions, abandonment and reuse phases, and possible natural hazards, including seismic events (Pecchioli et al., 2024). However, interpreting these processes remains challenging, particularly in stratified urban environments where different phases of transformation are materially intertwined. Within this methodological framework, archaeoseismology provides valuable tools for identifying possible earthquake-related evidence while requiring a critical approach that avoids deterministic conclusions (Guidoboni, 1994; Stiros, 2001). This contribution forms part of an ongoing research project integrating field observation, analytical documentation, and historical reconstruction. The study interprets the Capitolium as a structure shaped by successive phases of construction, transformation, repair, and conservation. The analytical approach combines the study of Roman building systems, archaeological evidence, historical documentation, and the assessment of structural damage patterns.

The aim is to develop an interpretative framework linking structural logic and inherent vulnerabilities without reducing deterioration processes to a single cause. Historical and documentary sources, including archival photographs, excavation records, and previous restoration documentation, are essential for reconstructing this diachronic development. Seismic interpretations based on specific damage features must therefore be evaluated within a broader framework of contributing factors, including constructional, structural, environmental, and historical transformations. Urban dynamics related to the orthogonal Roman grid (Pecchioli et al., 2021), the proximity of adjacent buildings, and interactions among structural systems further influence stress distribution and deformation patterns at both the monument scale and the wider urban fabric.

The primary research question addressed is how the constructional logic of the Capitolium can be integrated with archaeological, historical, and structural evidence to achieve a more comprehensive understanding of its current condition and the mechanisms responsible for observed damage. Specifically, the paper examines how original construction methods, subsequent modifications, restoration interventions, and long-term deterioration processes have interacted over time, shaping both the structural behaviour and the conservation condition of the monument. Through these successive transformations, the Capitolium has developed a particular equilibrium between its structural configuration and its environmental context, one that cannot be fully reduced to or evaluated solely through standardised criteria of stability.

Methodological approach

The interpretation of structural damage presented in this study builds upon a previous archaeoseismological research project supported by the Gerda Henkel Stiftung. Its outcomes provided the scientific basis for integrating diagnostic investigations and establishing a long-term monitoring plan within the podium of the Capitolium as part of the current restoration programme. Within this framework, surveys have been carried out to assess material degradation, structural behaviour, and the monument's state of preservation, allowing the archaeoseismological approach to support and complement the restoration project from its initial diagnostic phase[1].

Focusing on the Capitolium of Ostia Antica, the methodology combines archaeological, structural, geotechnical, historical, and digital approaches to investigate damage patterns and long-term repair processes. The analysis adopts a multi-scalar perspective, ranging from individual structural elements to the wider urban context in which the monument was built (Pecchioli 2023; Giuliani 2018). To avoid deterministic interpretations, a multi-criteria archaeoseismological approach is applied, integrating:

- deformation patterns and cracking systems;
- archaeological and stratigraphic investigations for identifying construction phases, repair episodes, and later modifications;
- historical, archival, and restoration research, including excavation records, historical photographs, technical and archaeological reports, and documentation of previous interventions;
- diagnostic investigations assessing material degradation, structural conditions, subsurface characteristics, and possible seismic effects, including the MASW (Multichannel Analysis of Surface Waves) survey;
- digital documentation and monitoring activities, including terrestrial laser scanning, drone-based photogrammetry, three-dimensional modelling, spatial analysis, and the long-term monitoring programme;
- structural and archaeoseismological interpretation through the integration of constructional evidence, observed damage patterns, and contextual information to evaluate possible seismic and non-seismic mechanisms.

Structural mechanics principles, including masonry arch behaviour and the virtual arch model, are employed to reconstruct thrust lines, equilibrium conditions, and collapse mechanisms under horizontal loading. Comparison with experimentally and historically documented masonry failure mechanisms further contributes to distinguishing possible seismic effects from other processes, such as settlement, material fatigue, and environmental deterioration (Cangi, 2005). Within the Forum of Ostia Antica, several monuments exhibit masonry damage patterns that have been interpreted as possible evidence of seismic effects (Pecchioli et al., 2018). These include diagonal fractures, corner cracking, localised detachments, out-of-plane deformations, and rotational and torsional phenomena affecting walls and piers, all of which are commonly associated with seismic loading in masonry structures. Although none of these features can be regarded as individually diagnostic of an earthquake, their recurrence across different buildings provides an important comparative context for the present investigation, whose primary focus remains the Capitolium (fig. 1).

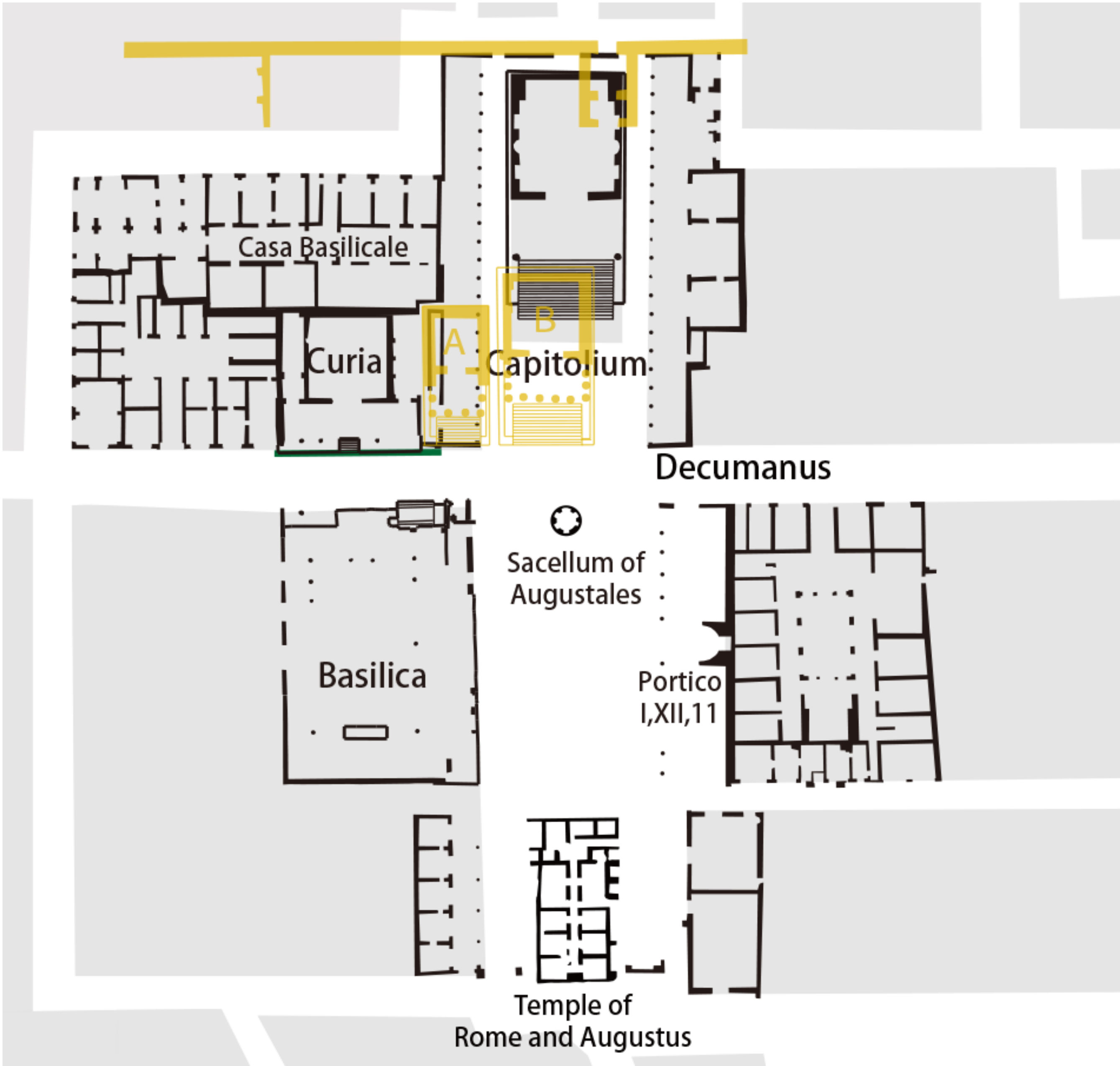
Historical and archival research, including excavation reports, restoration documentation, engineering records, and historical photographs, provides chronological constraints for reconstructing phases of deformation, repair, modification, and reuse. Archival imagery is particularly relevant for distinguishing ancient damage from modern interventions and post-depositional alterations.

1 This contribution forms part of the author's Habilitation research at the Institute of History of Art, Building Archaeology and Restoration (Institut für Kunstgeschichte, Bauforschung und Denkmalpflege), Technische Universität Wien. The author gratefully acknowledges the support and collaboration of the Archaeological Park of Ostia Antica, the Gerda Henkel Foundation, the excavation team of the Ostia Forum Project at Humboldt University, Kyushu University (Takuro Ogawa and Yoshiki Hori), the University of Urbino Carlo Bo (Fabio Cavallero and his team), and the Fondazione Lanciani (INASA-Rome).

At the urban scale, the methodology considers the influence of the Roman orthogonal grid, building clusters, foundation variability, and interactions between adjacent structures. This perspective allows evaluation of how seismic energy may be transmitted, amplified, or dissipated through the urban fabric and how local failures may develop into larger collapse phenomena. Alternative processes, including long-term decay, flooding, soil instability, and post-abandonment transformations, are also assessed by comparing their spatial and structural characteristics with documented seismic patterns, thereby reducing interpretative uncertainty and improving the evaluation of possible seismic contributions to the observed damage (Vafadari et al., 2017).

Historical development

The Capitolium is a monumental Hadrianic complex located within the Forum of Ostia Antica. On the eve of the major imperial interventions in the city, the urban layout was already highly consolidated, requiring substantial modifications to introduce new monumental structures. The most significant works concerned the area north of the Decumanus, including the demolition of two late first-century BCE temples and the incorporation of the space behind them (fig. 2; Paschetto, 1912).
The working methods of Roman builders demonstrate advanced knowledge of masonry techniques, structural consolidation, and repair strategies, allowing many constructions to remain structurally stable despite centuries of transformation. On these ancient structures, traces remain of events influenced by environmental and anthropogenic factors, enabling the reconstruction of long-term sequences of modification, as observed at the ancient Roman harbour and the Capitolium of Ostia (Boin, 2013). The Capitolium was part of Hadrian's urban programme and represents an opus testaceum structure of refined technical quality, in both construction methods and building materials, as well as in the use of characteristic architectural devices such as walls articulated by courses of bipedales. The monument was the city's main temple, dedicated to the Capitoline Triad (Jupiter, Juno, and Minerva), and was erected around 120 CE on the northern side of the Forum. It stands on a preceding cult building dating to the first century BCE, probably also dedicated to the same deities, located at the intersection of the cardo and decumanus. This earlier temple was itself built over an even older public structure, the remains of which are still visible in an open excavation trench protected by a grate in the Forum square.
From a conservation perspective, Ostia is one of the most significant case studies in the history of Italian archaeological restoration in the first half of the twentieth century, with its methodological approaches clearly reflected in the Capitolium itself. The monument provides evidence of the relationship between ancient construction techniques and successive restoration strategies. At Ostia, guiding principles such as minimum intervention and recognisability coexist with approaches aimed at reconstructing lost monumentality and restoring the intelligibility of the archaeological landscape.
Following the late nineteenth-century debate, a range of restoration techniques were developed to translate theoretical principles into practice. Among the most recognisable methods used to distinguish modern interventions – also documented in the Capitolium – are the hammered treatment of brick surfaces (figs. 3-4). Further repairs between 1873 and 1892 involved the restoration of niches and entrance structures (antae), likely weakened by their reduced structural consistency and possibly affected by seismic events, as suggested by traces of lateral 'slippage' visible in the western spur masonry. In several areas near the podium's offset, res-



toration techniques appear to rely on mimetic infill strategies, including toothed bonding (addentellato or saw-tooth joints). Another identifiable method is the so-called sottoquadro, visible at the left entrance pier of the cella, where restoration surfaces are deliberately set back from the original face to ensure material legibility and differentiation.

Fig. 2
Remains of the Republican period overlapping the Capitolium, after I. Gismondi, drawing dated 1923-1951 (Scavi di Ostia I, fig. 19).

Archaeological investigations and documentary sources

Within this historical framework, the most legible evidence, chronological markers, and traces of interventions relevant to the project are introduced. The excavation

Figg. 3-4
Details of interventions employing a bush-hammered surface finish (1964) and a sawtooth profile (south exterior of the cella), 2025, (Photo by L. Pecchioli).

journals (*Giornali di Scavo - GdS*) preserved in the archives contain numerous reports on past clearance activities around the building, often referred to as the Temple of Vulcan. Throughout the 19th century, scholars including Guattani, Gilbert, and Nibby contributed to defining the monument's architectural configuration (Guattani, 1805; Glibert, 1912; Nibby, 1819), generally identifying it as a Corinthian prostyle hexastyle temple, while excavation and clearance activities continued, particularly under Cardinal Pacca (1831-1834). In the second half of the 19th century and the early 20th century, systematic clearance operations progressively uncovered the structure from its earthen deposits; however, these same deposits, which reached the level of the podium crown, likely generated the erosion band that remains visible today. In 1868, C.L. Visconti proposed its identification as the Temple of Vulcan, an interpretation later superseded. The excavations carried out by Borsari (1880-1892) further highlighted the structural unity between the temple and the adjacent complexes. The removal of soil beneath the cella occurred in several phases (fig. 5). During the excavations under Pius IX (1846-1878), the lower chamber of the temple was emptied. In the *Giornale di Roma* of 9 June 1864, Pietro Ercole Visconti reports a papal visit to these spaces, while in the *Notizie degli Scavi di Antichità* of 1912, Dante Vaglieri notes the completion of the earth removal operations. Through the clearances of the second half of the nineteenth century and the first decades of the twen-

tieth century, the monument was progressively, and ultimately fully, exposed from the soil that had partially concealed it. The presence of these deposits up to the podium likely contributed to the severe disintegration of mortars and brickwork. Excavation journals from around 1892 also record a Tiber flood, which necessitated restoration and reorganisation of the backfill layers (Bersani et al., 2021; Marini, 2000). Around the mid-twentieth century, archaeological investigations continued, culminating in the significant campaigns conducted between 1947 and 1952 by Italo Gismondi on the surrounding Republican and early Imperial structures.
More systematic studies emerged only in the early 20th century with F.O. Lawrence and, above all, D.C. Badgeley (1929), who definitively identified the monument as the Capitolium and proposed a comprehensive reconstruction. From the 1920s onwards, restoration practice became increasingly intertwined with archaeological research, leading to the introduction of new materials and techniques, including bituminous mastics and surface patination treatments. During the 1930s, increasingly mimetic interventions were adopted in connection with the excavations and enhancement programme undertaken for the E42. During this period, archival documentation preserved in the *ACS, Soprintendenza Archeologica di Ostia-EUR, bb. 51-55* provides evidence of weekly workers' records and site organisation.
Between the unification of Italy and the mid-20th century, restoration practices were largely based on the reuse of ancient bricks recovered during excavations, while 19th-century interventions tended to be deliberately mimetic. Additions were often carried out in brickwork with exposed edges and high-quality pozzolanic mortars, frequently allowing the recognition of construction joints (*addentellati*) where walls were intended to continue. Among the technical staff supporting Gismondi during the E42 interventions, the name Domenico Scarfagna has been identified; he appears to have had extensive knowledge of the works and remained active in Ostia throughout the 1950s and 1960s. In the post-war decades, particularly during the 1960s and 1970s, further restoration campaigns – documented in the *Bollettino d'Arte* (1965) and archival photographic records – were carried out by external contractors, including Impresa Adolfo Grutter and architect Alberto Davico, with technical support from figures such as Domenico Scarfagna, who maintained continuity in site management. These interventions confirm the continuity of conservation strategies and the ongoing reinterpretation of the monument through successive methodological approaches.

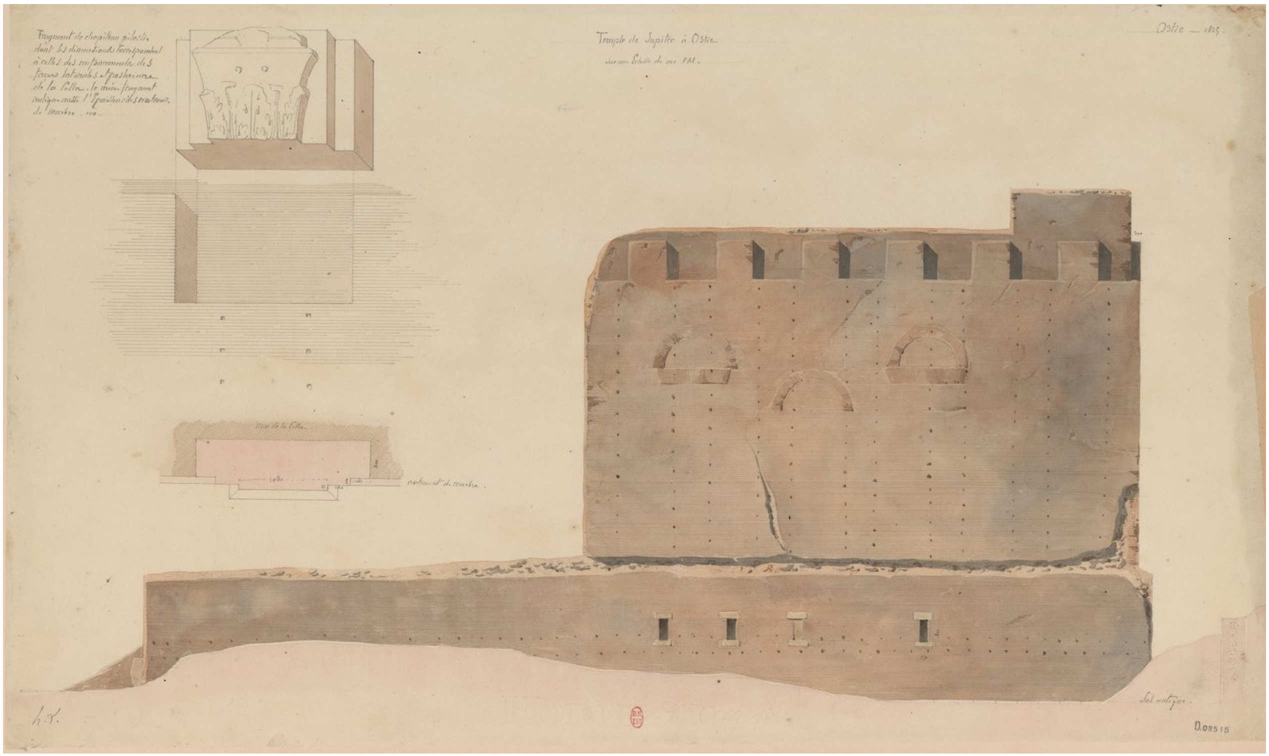
Constructional Analysis of the Capitolium

Before analysing the damage affecting the monument, it is necessary to outline its constructional organisation and structural logic, as these govern the distribution of loads and influence the development of subsequent deformation patterns. The building is oriented along a north-west/south-east axis and is located on the northern side of the Forum. Along its longitudinal sides, it adjoins two porticoed buildings, of which only the remains of perimeter walls, access steps, and column bases survive, although these have undergone substantial restoration. The Capitolium was built using a combination of opus caementicium and brick-faced masonry, a construction system highly representative of Imperial Roman architectural practice. The wall structure is characterised by a complex interaction between a heterogeneous concrete core and external brick facings, resulting from successive construction phases often marked by subtle discontinuities that reflect both original building procedures and later structural adaptations. Rather than constituting a uniform, monolithic system, the masonry fabric reveals a constructional logic based on successive phases, in which each stage contributes to the structure's overall mechanical behaviour.

opposite page

Fig. 5
Capitolium (date as reported in the archival source, 1828): damage to niches and masonry curtain; staircase not yet constructed. Source: Istituto Nazionale di Archeologia e Storia dell'Arte, Fondo Lanciani, colloc. Roma XI, 31, 39861.


39861
1828



previous page

Fig. 6
Aerial drone photograph documenting survey and laser scanning operations (2025). Source: PAOA. Survey conducted by the Università di Urbino Carlo Bo (Fabio Cavallero and his team).

on this page

Fig. 7
One watercolour by H. Labrouste (1802) illustrating the state of preservation of the Capitolium. Source: Istituto Nazionale di Archeologia e Storia dell'Arte, Fondo Lanciani, colloc. Roma XI, 31, 2025 , (Photo by L. Pecchioli).

The Hadrianic Capitolium, erected on a high podium, was entirely constructed in brick and originally clad in marble, of which significant traces remain in the bedding mortar and in the numerous clamp holes still visible on the walls. The cella was preceded by a pronaos with six frontal columns and two on each side and preserves its monumental threshold in African marble. Inside, the statues of the three deities were originally placed on a podium set against the rear wall (fig. 6).
The Capitolium represents an exemplary case of high-quality opus testaceum masonry, both in craftsmanship and in the quality of the construction materials employed. A stratigraphic reading of the wall fabric reveals multiple phases of intervention, including restorations and repairs of varying visibility, that have progressively contributed to the structure's preservation over time. Typologically, the building belongs to the classical temple tradition and consists of a raised platform (podium or stylobate) accessed by a frontal staircase leading to the upper chamber (cella). Within the podium, four internal spaces extend across the entire footprint of the building; they were constructed in sequence and interconnected by simple axial passageways at their midpoints.

Restoration History
The comparative analysis of archival photographs preserved in the Parco Archeologico di Ostia Antica and the Fondazione Lanciani (INASA-Roma) archives has identified several restoration phases affecting the Capitolium. These interventions are distinguishable through differences in conservation condition, construction techniques, material quality, and intervention strategies. Their reconstruction is based on the integration of in situ observations, archival documentation, construction records, dated inscriptions stamped directly on the masonry, and the study

of brick stamps, among them those recorded on the bipedales of a relieving arch within the podium.

The structural crack pattern indicates that the monument underwent reinforcement and repair interventions from its earliest documented phases[2]. These operations are recognisable through differences in masonry fabric, narrow openings in the podium masonry subsequently sealed with brick infill, material characteristics, and their relationship with the original Roman construction. However, the stratigraphic interpretation remains complex due to the systematic reuse of ancient materials and the recurring adoption of restoration strategies based on visual mimesis and the attempt to render interventions indistinguishable from the ancient fabric.

Nineteenth-century interventions

Early travellers and archaeologists visiting the Capitolium during the nineteenth century produced drawings, watercolours, and field sketches that represent essential documentary sources for reconstructing the monument's condition before major restoration campaigns. Among these, reconstructions of the original marble flooring of the cella, including giallo antico, pavonazzetto, and African marble, are particularly significant. Scholars such as Henri Labrouste, Èmile Narcisse-Jacques Gilbert, and Giuseppe Antonio Guattani proposed different interpretations of the lost pavement, of which only limited traces survive today along the eastern inner perimeter of the cella (fig. 7). The same documentation provides evidence of significant structural damage. Nineteenth-century drawings and photographs record severe fissuring along the northern side of the monument, particularly at the corners, both before and after consolidation works. Several repair phases can be recognised by differences in mortar composition and masonry execution, with some nineteenth-century interventions characterised by high-quality mortars frequently associated with red pozzolana.

Partial collapses also occurred as a consequence of attempts at intrusive access to the monument (Trockels, 2025). By 1825, structural failures were recorded in the vaults of chambers II and III within the podium, together with breaches in the overlying pavements of the cella and pronaos and damage to the six niches of the cella. Between 1872 and 1874[3], the staircase underwent an initial partial reconstruction, later completed under Dante Vaglieri, who used reused ancient material for the stair treads. During the same period, reconstruction of the southern cella perimeter walls was initiated.

Early twentieth century

Archive excavation journals (GdS) document restoration activities in the mid-1920s, identifiable by changes in flooring materials, including the replacement of cocciopesto surfaces with conglomerate layers composed of tuff and brick fragments, bound with pozzolanic mortar. From the mid-1930s onwards, restoration practices at Ostia increasingly adopted flush mimesis techniques, particularly in preparation for the 1942 World Exhibition (E42). These interventions were often characterised by lower material quality and by the substitution of traditional lime putty with hydrated lime. The documentation of the early twentieth century also confirms the persistence of structural problems. Notes published in the Bollettino d'Arte (1965), referring to previous interventions, mention major fractures at the corners of the monument, repaired through cement injections and reconstruction of wall crests. The same sources describe unstable bricks anchored from the interior and integration works carried out using dressed-brick replacements, demonstrating the continuous need for structural consolidation.

[2] Notably, a reinforcement inserted at the entrance on the north side, near the corner blocks, was constructed within the first chamber of the podium. This consists of an ancient concrete vault, dated by a brick stamp, which resulted in the closure of the earliest narrow openings in the original masonry.

[3] P. Rosa, op. cit., 1873: "Prima però di por mano ai lavori di sterro si ebbe a cura la pulizia e manutenzione degli edifizi già anteriormente scoperti, i quali per l'abbandono in cui erano rimasti da qualche anno, un'altra volta eransi ricoperti di sterpi, e divenuti di malagevole accesso. La vasta via dei sepolcri fu sottoposta a completa e radical pulitura [...] Similmente il grandioso tempio [...] fu liberato dalle macerie e dagli sterpi, che occupavano specialmente la sua gradinata. Ma una cura speciale fu rivolta alla manutenzione di quel vasto edifizio che si stende in vicinanza del Tevere presso la moderna Tor Bovacciana [...] per i guasti naturali prodotti dalle intemperie nonché dalle frequenti inondazioni, parte dei musaici..erano stati fortemente danneggiati, e qualche muro eziandio era caduto [...] Per cui fu data opera innanzi tutto a ripigliar le parti rovinose, rivestendole superiormente di struttura che resistesse all'infiltrazione delle piogge; [...] si rafforzarono quindi con appositi cementi i musaici che per l'umidità s'erano gonfi e sfasciati, colmandone con opera signina le più piccole lacune". I giornali di scavo relativi ai lavori di Rosa (ACS I vers. B 146), confermano che gli operai venivano periodicamente destinati (specie la domenica, quando si lavorava mezza giornata) al taglio della vegetazione ed alla fermatura di intonaci e pavimenti negli edifici già scoperti: maggio 1874, "[...] altro operaio per tagliare i cardi nelle vicinanze del Tempio di Giove (ndr. Capitolium)"; giugno 1874, "[...] il muratore [...] per legare le stabiliture ed i mosaici negli scavi di ponente (ndr. Palazzo Imperiale e Terme Marittime)".

Post-war restoration

In the 1950s, restoration approaches increasingly reflected Vaglieri's interpretative principles, following existing fracture lines in order to reconstruct their presumed original trajectories. These interventions sought to integrate structural evidence with archaeological interpretation, although further field verification is required to precisely attribute individual masonry sectors to specific chronological phases. During the 1960s and 1970s, conservation works focused increasingly on waterproofing and structural protection. Cementitious screeds and hot-applied bituminous layers were introduced and remain visible today in the flooring of the cella and pronaos. Reconstructed wall crests (*bauletto*) in cement mortar, together with the underlying brick courses treated with hammer-dressed finishing, can be securely dated to 1964 through stamped inscriptions impressed directly on the masonry. The 1964 intervention represents a crucial phase in the conservation history of the Capitolium. The technique, already employed by Vaglieri, demonstrates continuity in twentieth-century restoration practices. At the same time, this intervention provides significant evidence of the persistence of pre-existing structural deformation patterns: the original crack system remains traceable through the reconstructed upper masonry profile and gradually disappears within the cement coping. This continuity suggests that the restoration did not simply conceal previous damage but preserved stratigraphic evidence of the monument's long-term structural evolution.

Recent conservation works

Recent conservation activities have focused on improving understanding of and monitoring the monument's structural condition through integrated documentation, diagnostic investigations, and preventive conservation strategies. These interventions are based on the recognition that the current state of preservation reflects the interplay among ancient construction phases, historical damage, and successive restoration campaigns. The current analysis therefore considers restoration history as an essential component of damage interpretation. The distinction between original structural behaviour, ancient repair strategies, and modern interventions is fundamental for assessing the present configuration of the Capitolium and identifying the mechanisms responsible for observed deformation patterns, particularly along the eastern side, the southern cella wall fabric, and the upper portions of the northern interior piers.

Environmental context and current conservation condition

The environmental context and orientation of the Capitolium have influenced the monument since its construction. Its original position, overlooking the river and the ancient coastline, increased its exposure to natural processes, further conditioned by the alluvial nature of the subsoil, as demonstrated by the stratigraphic units identified in the Forum area. Over time, the coastline shifted, and the river meander facing the complex disappeared after the 1557 flood. These transformations contributed to the formation of a marshy zone in the former riverbed area, known in late Renaissance and modern toponymy as *Fiume morto* (Vött et al., 2020). The long-term interaction between environmental conditions and catastrophic events – including repeated Tiber floods (documented at least until the 1950s), shallow groundwater levels, intense rainfall, and possible seismic events – has significantly affected the monument's preservation and structural behaviour. These factors likely contributed to the need for reinforcement and repair interventions from ancient times onwards.

Recent monitoring activities, including environmental surveys and laser scanning (fig. 8), indicate that the groundwater level is located approximately 2.40 m below ground level and that the monument may be affected by long-term soil subsidence phenomena (Hori et al., 2017). Since 2016, the Parco Archeologico di Ostia Antica has implemented a dedicated monitoring strategy for the Capitolium, providing continuous information on its conservation condition and on geometric and morphological variations over time. These data are essential for distinguishing active deformation processes from stabilised damage patterns and for supporting the interpretation of crack evolution. The Forum area, where the Capitolium is located, lies at a slightly higher elevation than the south-western sector of the archaeological site. This difference, together with the heterogeneous characteristics of the alluvial deposits, may influence water circulation and contribute to localised deterioration processes.

Fig. 8
High-resolution laser scanning survey by Kyushu University (Takuro Ogawa | Yoshiki Hori) for PAOA.

Several parts of the structure exhibit common forms of deterioration. These include biological patinas, widespread dissolution of mortar joints, efflorescence, water percolation, and extensive degradation of the brick facing, particularly concentrated at the podium offset (*risega di spiccato*). This loss of external protection

Fig. 9
Shows a close-up of the vault surfaces with different corroded iron cramps attached to wooden elements. These cramps are probably remnants of an old suspended system, potentially used for lighting or storage, rather than for structural support.

exposes the masonry's inner core, increasing vulnerability to water infiltration and environmental agents. A persistent presence of invasive vegetation is also recorded, with species such as *Herba parietaria* and *Ficus carica* developing even inside the podium spaces. Despite numerous restoration campaigns and later modifications, large portions of the original Roman masonry remain preserved. However, these areas are affected by surface alterations, including thick crusts and plaster residues forming compact layers of concretion. The effects of efflorescence and carbonation are particularly evident in the restoration works of 1892, especially in the repaired niches and the cella wall piers, where a whitish patina is visible in both historical photographs and the present condition. These interventions reused ancient bricks laid flush with the original facing and employed traditional lime and pozzolanic mortars.
A continuous erosion band affects three external sides of the monument (north, east, and west), mainly corresponding to the intermediate zone of the podium offset. This phenomenon appears to be related to the prolonged partial burial of this portion of the structure, which originally emerged only to the level of the niche intrados. The brick facing was therefore exposed for a long period to environmental action and anthropogenic processes, including the reuse of the monument as a source of building material (*spolia*). The conservation condition differs significantly between the exterior and interior spaces. Internally, the eastern and western sides show spoliation-related losses, including missing lintels and thresholds,

along with widespread disintegration of the masonry fabric, exposure of the concrete core, vegetation growth, rainwater infiltration, and biological colonisation.
A recent detailed inspection of the vault surfaces revealed several heavily corroded iron cramps associated with small wooden elements. In previous research, these features were interpreted as reinforcement devices for the structural consolidation of the vaults (Pecchioli et al. 2024). However, a more detailed analysis of their distribution, morphology, and relationship with the masonry indicates that they do not correspond to a systematic reinforcement system. Their position and arrangement are instead more consistent with traces of a later suspended installation, possibly related to lighting, storage, or museal use of the subterranean spaces. Current archival research is being conducted to clarify their chronology and function, including the possibility that these elements belong to electrical installations dating to the mid-twentieth century, when the podium spaces may have been adapted for simple storage. The evidence suggests a suspended system of wires or supports arranged longitudinally and across the vaults, possibly intended for lighting fixtures or other functional elements (fig. 9). This reinterpretation underscores the importance of distinguishing between structural interventions and later functional adaptations when assessing the monument's conservation history. It also demonstrates how direct observation, archival investigation, and contextual analysis are essential for revising previous interpretations and avoiding misleading readings of constructional evidence.

Fig. 10
Room IV, basement below the staircase, with localised masonry structural supports inserted shortly after construction, 2024, (Photo by L. Pecchioli).

Damage Assessment

Roman concrete technology, extensively studied by Lancaster (2005), enabled the development of complex spatial and structural configurations, but also introduced significant mechanical variability due to differences in aggregates, construction techniques, and chronological phases. At Ostia, this variability is further increased by the numerous construction and restoration phases documented archaeologically, which progressively modified the structural coherence and load-bearing behaviour of the monument (Pavolini, 2006; Meiggs, 1960). The Capitolium should therefore be understood as a stratified constructional system whose present mechanical response results from the interaction between original building techniques, material transformations, repairs, and long-term structural adjustments. Observed damage patterns cannot be interpreted as isolated mechanical failures but rather as the cumulative expression of processes that act over centuries. In archaeological contexts, seismic interpretation requires a multi-scalar and context-dependent approach that integrates morphological evidence with construction phases, stratigraphic relationships, repair sequences, and regional seismic history (Boschi, 1995; Marra et al., 2020; Milana et al., 2025). Within complex urban environments such as Ostia Antica, seismic attribution must therefore be considered a hypothesis arising from the convergence of multiple datasets rather than a direct inference from damage morphology alone (Pecchioli et al., 2018; 2022).

The Capitolium of Ostia Antica exhibits a complex pattern of structural damage involving cracking systems, masonry disaggregation, deformation, and partial collapses affecting both vertical and vaulted structural components. These phenomena do not correspond to a single failure process but reflect the interaction of different mechanisms acting over long periods. The observed evidence includes diagonal cracking, vertical and subvertical fissures, localised detachments, out-of-plane deformations, rotational mechanisms, and displacement of masonry elements. The presence of different cracking patterns indicates that the damage cannot be attributed to a single cause. While diagonal cracking, localised rotations, and out-of-plane movements may be compatible with seismic loading, vertical fissures and differential openings may also be associated with foundation settlement, soil movements, subsidence, material degradation, and progressive structural fatigue.

Geotechnical and environmental factors are particularly relevant to interpreting the present condition of the structure (fig. 10). Both the Forum area and Regio V are affected by subsidence related to the characteristics of the local subsoil, which consists of heterogeneous alluvial and coastal deposits with variable mechanical behaviour. These conditions may have contributed to differential settlements, foundation deformations, and gradual changes in the equilibrium of the masonry over time.

Possible Seismic Interpretation

The identification of seismic damage in archaeological masonry remains a complex issue, as similar deformation patterns may result from different mechanisms acting at different temporal and spatial scales. Interpretation, therefore, cannot rely on individual cracks or deformations alone but must consider their geometric organisation, distribution, kinematic coherence, and relationship to the structural system. Seismic actions may produce coherent deformation patterns involving multiple structural elements, including diagonal shear cracking, out-of-plane movements, and rotations potentially associated with horizontal loading (Hinzen, 2013; Stiros, 2001). Conversely, damage related to foundation movements, differential settlement, or subsidence tends to develop progressively and locally, reflecting variations in soil-structure interaction. In the Capitolium, vertical and subvertical fissures, par-

Fig. 11
North façade corner showing structural rotation and crack patterns with successive repair phases, 2025, (Photo by L. Pecchioli).

Fig. 12
Photo from the third chamber of the podium, showing the residual traces of the original central reinforcing arches preserved in the second chamber. The image highlights the exceptional quality of the opus caementicium vault construction.

opposite page

Fig. 13
Detail of the eastern buttress showing an ancient repair of damage potentially related to seismic activity, characterised by rotation and in situ sliding of the upper terminal masonry of the staircase; minor traces of the same mechanism are also visible on the western side, 2025 (Photo by L. Pecchioli).

ticularly within the podium, are therefore evaluated in relation to local structural conditions, foundation behaviour, and ongoing monitoring data rather than directly interpreted as seismic evidence (fig. 11).

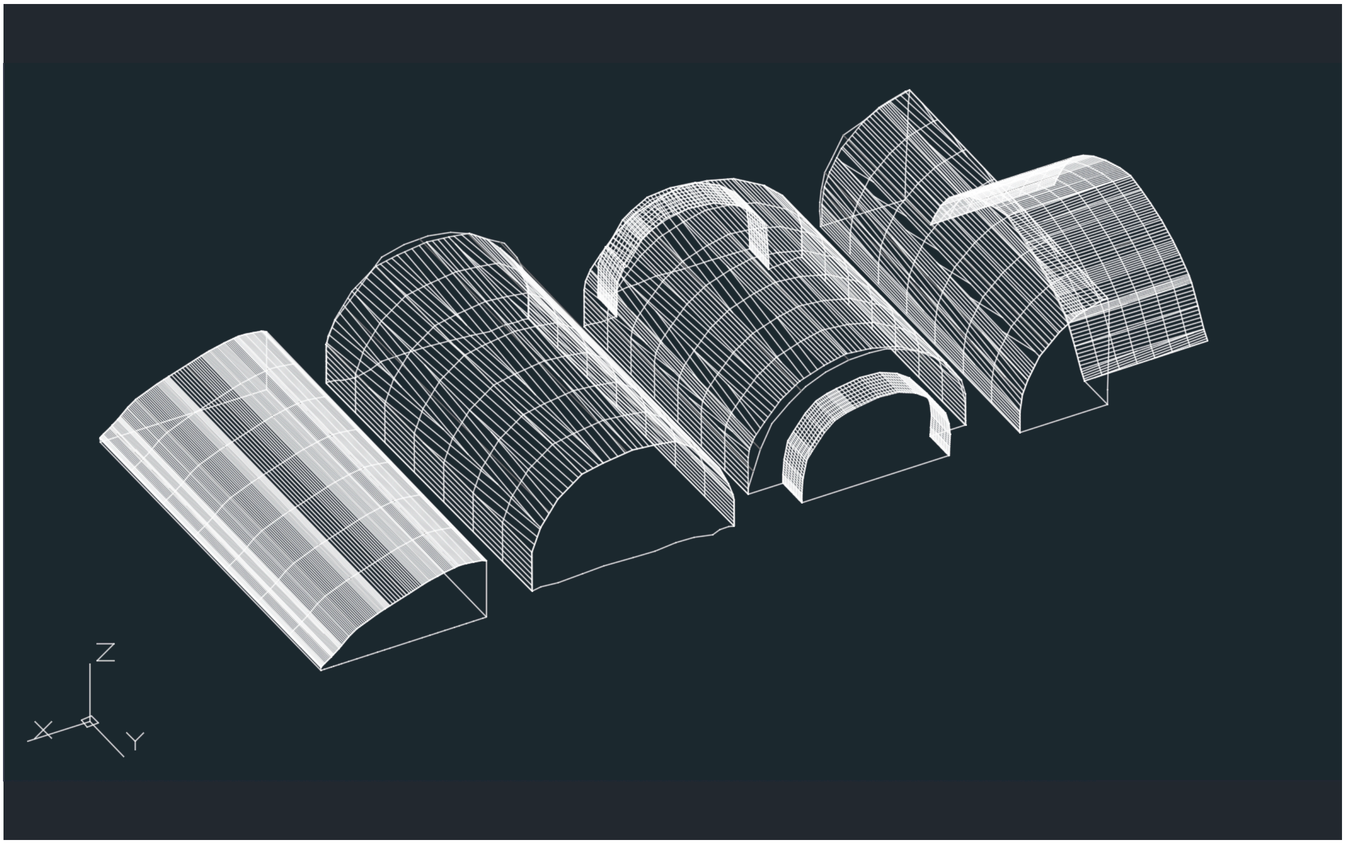
Following current archaeoseismological approaches, seismic hypotheses are assessed using a multi-criteria framework that evaluates the convergence of independent evidence, including stratigraphic relationships, construction phases, repair sequences, environmental conditions, and regional seismic history (Rodríguez-Pascua et al., 2011). At the Capitolium, some observed deformation patterns are compatible with mechanisms associated with seismic loading; however, none can currently be considered diagnostic when analysed in isolation. The absence of a clearly identifiable and synchronised archaeological collapse horizon indicates that the present condition of the monument reflects the interaction of processes developed throughout different chronological phases rather than the consequence of a single catastrophic event (fig. 12).

The interpretation is therefore based on the integration of archaeological, structural, environmental, and historical evidence. Non-seismic factors, including foundation movements related to local soil conditions, subsidence affecting the Forum area, material deterioration, flooding, erosion, and prolonged exposure to humidity due to high rainfall and shallow groundwater levels, must also be considered. These processes may have progressively influenced masonry behaviour and contributed to the observed deformation patterns. Ancient repair interventions, such as the reinforcement of the eastern buttress – possibly related to a sliding mechanism – like a collapse dynamics hypothesised on the north-west side (Pecchioli et al., 2024 -

Fig. 14
Post-construction intervention involving the insertion of two relieving arches (Room 2, basement level, eastern side). The use of bipedales within the opus caementicium is clearly visible, along with traces of the wooden centring (centinatura), 2024-2025 (Photo by Laura Pecchioli).

fig. 8), demonstrate that structural movements had already occurred and were addressed in antiquity. Although these repairs cannot be considered conclusive evidence of seismic damage, they are compatible with deformation mechanisms that may also occur under seismic loading (fig. 13).
The distinction between seismic and non-seismic effects remains particularly challenging in a monument characterised by long-term transformation, repeated repairs, and environmental exposure. Recent studies on Ostia Antica have highlighted the difficulty of separating individual degradation processes within densely stratified urban contexts (Pecchioli and Cangi, 2021; Pecchioli et al., 2025). Based on the available evidence, the confidence level of seismic interpretation remains moderate and depends on the integration of multiple archaeological, structural, environmental, and historical indicators. The Capitolium therefore represents a case in which possible seismic effects must be evaluated within a broader framework of interacting processes that have shaped the monument's long-term structural evolution.

Conservation
The interpretation of the damage affecting the Capitolium of Ostia Antica raises significant theoretical and operational issues for conservation. The coexistence of multiple deterioration mechanisms, together with the uncertainty in identifying a single causative factor – particularly regarding possible seismic actions – requires a cautious approach based on stratigraphic analysis and critical evaluation of material evidence. Conservation strategies must balance structural safety with the preserva-



tion of material authenticity and the legibility of the monument's successive phases of construction, transformation, and repair (figs. 14-15). The Capitolium should therefore be understood as a structure shaped by continuous modification, in which original construction processes, later interventions, and restoration campaigns are closely interconnected.

Within this framework, the principle of minimum intervention remains fundamental, especially when available evidence does not allow unequivocal causal interpretations. For the Capitolium, this implies preserving the extensive Roman brick fabric while limiting replacements or integrations to areas where structural safety, material loss, or water infiltration may compromise the long-term integrity of the masonry. However, minimum intervention must also be considered in relation to preventive protection measures: actions aimed at reducing environmental exposure and limiting deterioration processes, such as controlling rainwater infiltration, may require priority when necessary to prevent irreversible damage. In such cases, conservation choices may need to balance strict philological approaches with the practical necessity of ensuring the conservation of the monument's historical fabric. Particular attention must therefore be given to the compatibility of materials and techniques in order to preserve the structure's original mechanical behaviour and maintain the legibility of archaeological evidence.

Monitoring systems provide an essential tool for identifying active deformation processes, evaluating environmental influences, and supporting adaptive conservation strategies supported by continuous monitoring data (Valluzzi, 2010). Laser

Fig. 15
The accompanying graphic shows the spatial development of the podium vault system and the position of the second chamber (elaboration by Laura Pecchioli and the Università di Urbino Carlo Bo (Fabio Cavallero and his team).

scanning and environmental monitoring contribute to the assessment of crack evolution, geometric variations, and changes in structural behaviour, enabling interventions to be planned based on observed conditions.

Current conservation planning is primarily oriented towards stabilisation, with particular attention to vulnerable structural connections, localised masonry weaknesses, and areas exposed to environmental deterioration. Targeted reintegration of brick facing is envisaged where necessary to protect exposed masonry and reduce water infiltration, together with additional measures to mitigate the effects of climatic and environmental agents. These interventions are developed in coordination with the Parco Archeologico di Ostia Antica within a framework aimed at preserving both the material integrity and the historical complexity of the Capitolium.

Conclusions

The study of the Capitolium of Ostia Antica demonstrates that the interpretation of structural damage in ancient masonry cannot be separated from the monument's constructional history and subsequent transformations. The observed deformation patterns are consistent with various mechanisms, including possible seismic effects, but their attribution requires a combined evaluation of structural behaviour, archaeological evidence, repair phases, environmental conditions, and soil–structure interactions.

The present condition of the Capitolium reflects a long-term process in which original construction strategies, ancient modifications, restoration interventions, and environmental influences have progressively shaped the structural response. Damage, therefore, represents not only a manifestation of deterioration but also a record of the successive stages through which the structure has adapted and changed over time. The research confirms the value of integrating archaeoseismological investigation with constructional analysis and conservation practice. In complex archaeological contexts, uncertainty is not a limitation to be eliminated but a condition that must be critically managed by evaluating multiple, independent sources of evidence.

For the Capitolium, this approach provides a framework for identifying vulnerabilities, distinguishing active processes from historical damage, and supporting conservation decisions that combine the preservation of archaeological authenticity with the preventive measures required to ensure the monument's structural safety and long-term survival. Ensuring future accessibility and interpretation of the Capitolium requires not only the conservation of its material evidence but also the development of strategies that balance protection, monitoring, maintenance, and compatible use. From this perspective, conservation becomes an active process aimed at preserving both the historical meaning and the monument's future role within the archaeological landscape of Ostia Antica.

Bibliografia

Adam J.-P. 1994, *Roman Building: Materials and Techniques*, Bloomington–Indianapolis, Indiana University Press.

Albo C. 2002, *Il Capitolium di Ostia: alcune considerazioni sulla tecnica edilizia ed ipotesi ricostruttiva*, «Mélanges de l'École française de Rome – Antiquité», 114(1), pp. 1-28.

Arrighetti A. 2016, *Archeosismologia e restauro in architettura*, «Restauro Archeologico», 23(2), pp. 16-31.

Bersani P., Bencivenga M. 2001, *Le piene del Tevere a Roma dal V secolo a.C. all'anno 2000*, *Roma*, Istituto Poligrafico e Zecca dello Stato.

Bianchini M. 2010, *Le tecniche edilizie nel mondo antico*, Roma, Editrice Dedalo.

Boin D.R. 2013, *Ostia in Late Antiquity*, Cambridge, Cambridge University Press.

Boschi E., Guidoboni E., Ferrari G., Mariotti D., Santoro A., Valensise G. 1995, *Catalogo dei forti terremoti in Italia dal 461 a.C. al 1980*, Roma-Bologna, ING–SGA.

Cangi G. 2005, *Manuale del recupero strutturale e antisismico*, Roma, DEI.

Gilbert É.N.-J. 1912, *Restauration d'un temple de Jupiter à Ostie*, in D'espouy H. (éd.), *Monuments antiques relevés et restaurés par les architectes pensionnaires de l'Académie de France à Rome*, vol. III, Paris, pp. 231-233.

Giuliani C.F. 2018, *L'edilizia nell'antichità*, Roma, Carocci Editore.

Guattani G.A. 1805, *Monumenti antichi inediti: notizie sulle antichità e belle arti di Roma per l'anno MDCCCV*, Roma.

Guidoboni E. 1994, *Catalogue of Ancient Earthquakes in the Mediterranean Area*, Roma, Istituto Nazionale di Geofisica.

Hinzen K.-G. 2013, *Archaeoseismic study of damage in Roman and Medieval structures in Cologne*, «Journal of Seismology», 17, pp. 647-660.

Hori Y., Ogawa T. 2017, *Visualization of the construction of ancient Roman buildings in Ostia using point cloud data*, «The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences», XLII-2/W3, pp. 345-352.

Lancaster L. 2005, *Concrete Vaulted Construction in Imperial Rome*, Cambridge, Cambridge University Press.

Marini F. 2000, *La grande escavazione ostiense di Papa Pio VII*, «Rivista dell'Istituto Nazionale di Archeologia e Storia dell'Arte», 53 (III serie, XXI, 1998), pp. 61-110.

Marra F., Milana G., Pecchioli L., Roselli P., Cangi G., Famiani D., Mercuri A., Carlucci G. 2020, *Historical faulting as the possible cause of earthquake damages in the ancient Roman port city of Ostia*, «Journal of Seismology», 24(3-4), pp. 833-851.

Meiggs R. 1960, *Roman Ostia*, Oxford, Clarendon Press.

Milana G., Cara F., Famiani D., Mercuri A. 2025, *Historical faulting as the possible cause of earthquake damage in the ancient Roman port city of Ostia*, in Pecchioli L., D'alessio A., Meneghini R., Holmes D.A. (eds.), *Hazard and Disaster Risk in Ostia: Between Hypothesis and Reality*, Oxford, BAR Publishing, pp.47-54.

Nibby A. 1819, *Viaggio antiquario ne' contorni di Roma. Escursione all'Isola Sacra e a Porto*, Roma.

Paschetto L. 1912, *Ostia, colonia romana: storia e monumenti*, Roma.

Pavolini C. 2006, *Ostia*, Roma-Bari, Laterza.

Pensabene P. 2007, *Ostiensium marmorum decus et decor. Studi architettonici, decorativi e archeometrici*, Roma.

Pecchioli L., Cangi G., Marra F. 2018, *Evidence of seismic damages on ancient Roman buildings at Ostia: an arch mechanics approach*, «Journal of Archaeological Science: Reports», 21, pp. 117-127.

Pecchioli L., Cangi G. 2021, *Interpretazione degli effetti sismici e analisi dinamica dei collassi in Ostia Antica*, «Restauro Archeologico», 29(1), pp. 80-93.

Pecchioli L., Betti M., Pintucchi B. 2022, *Archaeoseismological project in Ostia: tracking evidence of seismic damage by nonlinear numerical simulations*, «Developments in the Built Environment», 10, 100073.

Pecchioli L. 2023, *Archaeoseismology: Methods and Case Studies*, Cham, Springer.

Pecchioli L., D'alessio A., Casella V., Alati M.c., Russo C., Ogawa T., Hori Y., Milana G. 2024, *Monitoring methods as a preventive measure: the example of the Capitolium in Ostia Antica*, «Bollettino di Archeologia Online», XIV-XV, pp. 31-48

Pecchioli L. 2025, *Hazards vs Disasters and their Implications. The Value of Pre- and Post-Event Learning for Disaster Resilience*, in Pecchioli L., D'alessio A., Meneghini R., Holmes D.A. (eds.), *Hazard and Disaster Risk in Ostia: Between Hypothesis and Reality*, Oxford, BAR Publishing, pp. 9-19.

Rodríguez-Pascua M.A. et al. 2011, *A comprehensive classification of Earthquake Archaeological Effects (EAE) in archaeoseismology*, «Quaternary International», 242(1), pp. 20-30.

Stiros S. 2001, *Archaeological evidence for earthquakes: a review*, «Journal of Seismology», 5(3), pp. 397-414.

Trockels J. 2025, *Ostia's so-called Capitolium – A source on construction technology, seismic effects and damage by catastrophes*, in Pecchioli L., D'alessio A., Meneghini R., Holmes D.a. (eds.), *Hazard and Disaster Risk in Ostia*, Oxford, BAR Publishing, pp.81-90.

Vafadari A., Philip G., Jennings R. 2017, *Damage Assessment and Monitoring of Cultural Heritage Places in a Disaster and Post-Disaster Event – A Case Study of Syria*, «ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences», XLII-2/W5, pp. 695-701.

Valluzzi M.R. 2010, Strengthening of historical masonry structures, in Modena C., Da Porto F., Valluzzi M.R. (eds.), *Structural Analysis of Historical Constructions. Proceedings of the VII International Conference on Structural Analysis of Historical Constructions (SAHC 2010)*, London, CRC Press.

Vött A., Willershäuser T., Hadler H. 2020, *Geoarchaeological evidence of Ostia's river harbour operating until the fourth century AD*, «Archaeological and Anthropological Sciences», 12, 88.