A Detailed Structural Classification of Cross Vault in Ostia

In ancient Rome, the use of vaulted structures built by using Roman concrete allowed for the construction of high-rise buildings. This architectural influence can be evident in Ostia, the Roman port city. During the first half of the 2nd century C.E., clusters of buildings in Ostia were constructed with barrel vaults and cross vaults, reaching two or more storeys in height. Unlike the residential complexes in Pompeii and Herculaneum, some of the insulae in Ostia could have been reconstructed to have been as high as four storeys. However, these vaulted structures in residential buildings are often overlooked in mainstream research on Roman architectural vaults due to their perceived lack of architectural finesse. This study focuses specifically on the surviving cross vaults within Ostia, aiming to uncover the practical aspects of constructing high-rise buildings in the city. By carefully examining the form of these cross vaults, the study seeks to understand the reality of vaulted structures in the clusters of residential buildings. Extensive three-dimensional data measured by laser scanner of the city block units is utilized to analyze how these cross vaults interacted as a cluster.

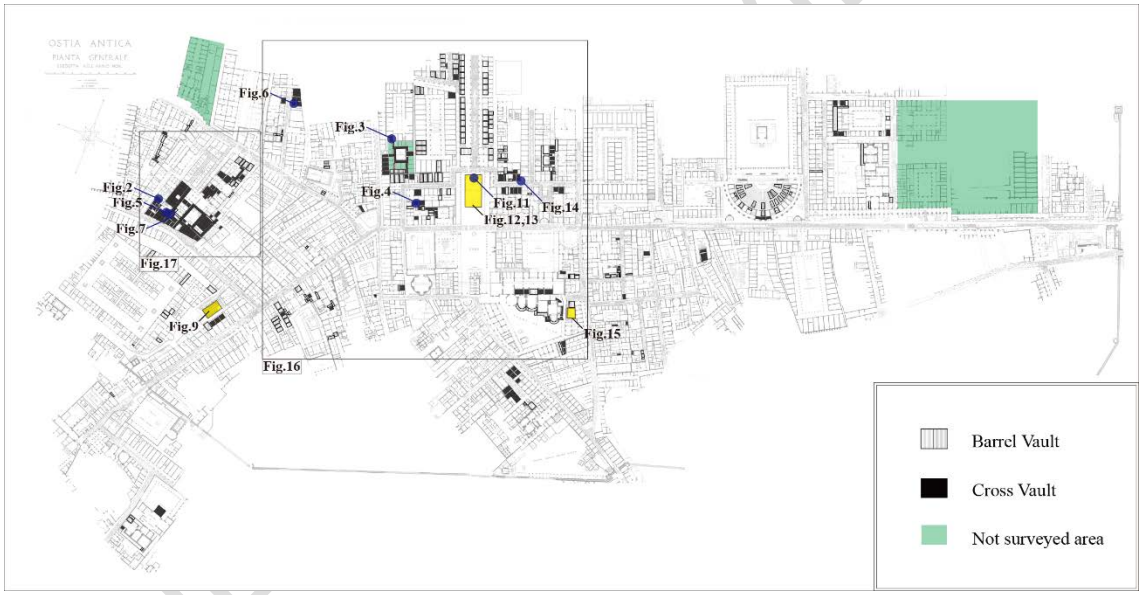
Introduction

In ancient imperial Rome, vaulted structures made it possible to raise the height of buildings which were constructed with Roman concrete, and the influence of these structures can be observed in the Roman port city, Ostia. The most significant building activity in Ostia occurred in the first half of the 2nd century C.E.[1], when two or more storey-high buildings with barrel vaults and cross vaults were constructed. When it comes to constructing high-rise buildings like apartment complexes, known as insulae in this context, two approaches can be employed: high-wall-erected approach and vault-stacked approach. In high-wall-erected approach, several storey-high walls are erected

[1]R.Meiggs, et al. Roman ostia. Oxford: Clarendon Press, 1973.p.111-148.

from the ground level to the top of the building, and floors can be supported by either wooden beams or vaulted structures that are integrated into the walls. On the other hand, the vault-stacked approach entails the stacking of multiple layers of vaulted structures. In some instances, a combination of both approaches could be employed within the same buildings. While the study of vaulted structures in ancient Roman buildings often focuses on large barrel and cross vaults, which are well-preserved, provide spacious interiors without the need for posts, and have no upper floors, relatively little information is available regarding the smaller-scale vaulted structures that are piled up to build multi-storey insulae in Ostia.[2]

Figure 1. *Distribution of Vaulted Structure in Osita*



[2]In the following papers, Lancaster discusses the Ostia vaults. They are all references associated with brick linings. Lancaster, L. Building Trajan's Markets. American Journal of Archaeology, 102.1998. Also see Lancaster, Lynne C. "Auguste Choisy and the economics of Roman construction." Auguste Choisy (1841-1909) l'architecture et l'art de batir (actas del Simposio Internacional celebrado en Madrid. 2009.

224 barrel vaults and 270 cross vaults have been identified in each of the remains in Ostia (see Figure 1).[3] This paper initially reviews the studies on vaults in ancient Roman buildings and subsequently presents the distribution and characteristics of barrel and cross vaults in Ostia. These findings, which have not been previously addressed, provide insights into the discussion points regarding high-wall-erected and vault-stacked approaches. Furthermore, the cross vaults are further categorized based on the presented information, and the interplay between these subdivisions, building height, and construction activity is explored on a larger scale, considering building complexes and city blocks. It is important to note that the majority of the barrel and cross vaults examined in this paper have already collapsed, and the observations are primarily based on the remnants of lunettes and springers found within the walls (see Figure 2).

Figure 2. *Example of Collapesed Cross Vault (House of Annius)*

Overview of Previous Research Conducted on Cross Vault of Roman Building

Studies on cross vaults in ancient Roman building can be broadly categorized into three main areas. Firstly, there are studies that focus on

[3]It is based on the author's own research.

form-based typologies, examining the different forms and shapes of cross vaults. Secondly, there are studies that explore information related to the construction process, including the reconstruction of wooden centring and formwork. Lastly, there are studies that analyse the composition of cross vaults, including the outer formwork as brick lining and ribs in concrete core.

With regard to form-focused typologies, the position of cross vault form with respect to the barrel vault is discussed about. For example, W.L.MacDonald considers cross vault as one of the typologies of erection as a structural form developed from the intersection of two barrel vaults.[4] L.C.Lancaster also considers cross vault as a type of erection, but after acknowledging the possibility that each building had its own specific formwork,[5] she analyses regional differences in cross vaults separately, focusing not only on Rome but also on northern Africa and the Middle East.[6] On the other hand, J.P.Adam takes a negative view of the typology of cross vault itself and states that cross vault is a special form that can only be established when barrel vaults of the same diameter cross orthogonally, and if this condition is not met, it is defined as a groin vault.[7] In recent years, the author has analysed cross vaults of Ostia focusing on the ridge lines of them, and the results of analysis, to which was applied laser scanning, indicate that they are not intersecting cylinders, but are composed of four arcs of lunettes on the four sides of the room and the other four arcs springing from the corners that meet together at the centre of the room, and that they are not intersected by cylinders, but it can be recognized as the newly defined typology is a "quasi-cross vault", whose ridge lines resemble the shape of that of an intersecting cylinders, and reconstruct its centring and formwork from a practical point of view.[8]

[4]W.L.MacDonald, *The architecture of the Roman Empire: An introductory study*. Vol. 1. Yale University Press, 1982.p.15-18.

[5]L.C.Lancaster, Concrete vaulted construction in Imperial Rome: innovations in context. Cambridge University Press, 2005.p.34-40.

[6]Lancaster, Lynne C. Innovative Vaulting in the Architecture of the Roman Empire: 1st to 4th Centuries CE. Cambridge University Press, 2015.p.70-98.

[7]Adam, Jean-Pierre. Roman building: materials and techniques. Routledge, 2005.p.390-400.

[8]Ogawa, Takuro. and Hori, Yoshiki."ANALYSIS OF CONSTRUCTION PROCESS OF CROSSING VAULT IN OSTIA ANTICA."J. Archit. Plann., AIJ, Vol. 87, No. 793,

The reconstruction of centring and formwork is based on imprints of removed wooden planks on mortar on intrados of vault structures, which have been rarely preserved, and paired corbels and sockets of wooden beams on the opposite walls. However, as no wooden centrings or formworks have been excavated, most of the images of them are based on the bridge span inscribed on Trajan's post, the wooden bridging receivers on the Pont du Gard stonework, and modern construction techniques.[9] In addition to Adam and Lancaster, who compile information from an architectural point of view, there is Ullrich, who compiles information from the point of view of timber frame structures. Although not a cross vault, there is the work of J.J. Rush, who has elaborately precisely measured the dome structures of mausoleums in and around Rome.[10]

Lancaster researches detailed on compositions, including outer formwork and ribs. With regard to the formwork on *intorados*, the most common composition, with the exception of wooden formwork, is called brick lining. In this method, *bipedales* or *sequipedales* are laid against the formwork, followed by a grid of *bessales*, which are then concreted.[11] In the remains of Ostia, brick lining is identified in 55 of 224 barrel vaults and 60 of 270 intersecting vaults.[12] Examples of ribbing as reinforcement built into the concrete core have been typified by Lancaster.[13]

In the above-mentioned previous studies, the analysis of vaulted structures is limited to well-preserved large buildings, and group of buildings in Ostia, which is not so high architectural quality, is rarely included.[14]

644-655, 2022.

[9] See Taylor, Rabun. Roman builders. Cambridge: Cambridge University Press, 2003: 178-190. and C.E.am, 2005, p.356-362. Also See Lancaster,2005, p.22-40. and Ulrich, Roger BrC.E.ley. Roman woodworking. Yale University Press, 2007,p.172-177.

[10] Rasch, J.J. Zur Konstruktion Spätantiker Kuppeln Vom 3. Bis 6. Jahrhundert. Neue Ergebnisse Photogrammetrischer Untersuchungen. 1991.

[11] bessales, sequipedales, bipedales are standardised fired bricks, with different names depending on their dimensions.

[12] It is based on the author's own research. It is based on the author's own research.

[13] Lancaster, 2005, p.22-40.

[14] Adam only presents a photograph of House of Serapis.

Overview of vaulted structures in Ostia

Distribution of Vaulted Structure

Ostia, originally established as a Roman naval fortress called Castrum in the 4th century BC, underwent significant expansion beyond its fortifications during the 1st century BC.[15] It was encompassed by walls, including the Roman, Laurentina, and Marina gates, and bordered by the Tiber River. The tufa stone initially used for the castrum's construction was repurposed for the walls of the surrounding buildings. Most of the present-day appearance of Ostia comprises structures from the 2nd century C.E., which marked a period of extensive building activity. Subsequent constructions and additions continued, and the current appearance is estimated to date back to the 4th-5th centuries. It is important to note that the distribution map of the vault structures resulting from the comprehensive survey does not encompass all the vaults in the city because unlike Pompeii and Herculaneum, the upper remains are not as well preserved. The southern part of the city is primarily characterized by domus, and only a few vaulted structures are found in that area. Notably, the vaulted structures around the forum and those around Region III Insula X and XIV are particularly prominent.

The two methods indicated above seem to have been used in the construction of the higher structures at Ostia: high-wall-erected can be understood as a common construction method not only in Ostia, but also in Pompeii and Herculaneum. It should be noted that this method applies to both wood-beam and vaulted ceiling. Most importantly, walls should be free-standing from ground level to building height in an uninterrupted and continuous manner. In many cases, plan of building is divided by the construction of second-storey high walls, and the first floor is supported by passing wooden beams against these walls. In special case, the first floor is supported by a vaulted structure, which is discussed below. Vault-stacked is a method of stacking upper storeys on the vault for the ground floor, so below and upper structures are separated both in building process and in structure. For example, ground level of a series of cross vaults is built on the ground. Then, on the first floor supported by these cross vaults is built.

[15]Pavolini, Carlo. Ostia. Bari: Laterza, 2006.p.20-41.

Inductive explanation, in the case of a three-story building, it is conceivable that the ground floor is predominantly built by vault-stacked while the first and higher floors are built by high-wall-erected. Taking into account the information provided above, the specific details of Ostia's vaulted structures will be presented and subdivided. Against the background of the above information, the details of vaulted structure in Ostia will be discussed.

Findings from Lunette

Cross vaults in Ostia feature various types of lunette. For instance, pyramid-shape blocks composed of *opus reticulatum* are placed along the arc of the lunette when the wall is constructed using a combination of *opus reticulatum* and *opus testaceum*, where arches are placed along the lunette's arc or fired bricks are cut to match its shape (see Figure 3). Examples of lunette arcs can also be found in structures built applying only *opus testaceum* (see Figure 4). These lunettes could represent walls played a role in showing the four arcs of the cross vault during its planning and construction. In these cases, walls with an arched shape are constructed first, then a vault is built on top of them. These processes are along with the vault-stacked approach, and even if outlines of lunette are different on the reverse side of the same wall.[16] There are also cases where the partition walls are added later, as seen in Figure 5, which illustrates the closure of four-way openings covered over cross vaults. These processes are also along with the vault-stacked approach.

Some lunettes, which were formed along with the high-wall-erected approach, also can be observed. Figure 6 depict examples of wooden-beam-support converted into cross-vault-support, and Figure 7 shows the extension of cross vaults against the external wall of an existing building, respectively with the windows filled in to match the curve of lunette's outline, where applicable. These examples share a common feature in which the wall surface has been carefully removed to match the lunette's shape, preserving the face of the existing wall to which the cross vault was attached. They also could have provided guidance for the construction of the cross vault, as well as serving as an anchor for the structural material.[17] When the formwork on

16Examples of this are clearly identified, e.g. in House of Annius.

[17]A sequence of six semi-circular grooves remains in the travertine arches of the third level of

intrados was composed of brick lining, the grooves served as hooks for the fired bricks such as *bipedales*. It indicates that the extended cross vaults have shifted and collapsed from the existing wall surface. In other words, they were partially suspended by anchoring and thrusting mechanisms. Only two remaining structures clearly exhibit extensions to the existing wall surface, suggesting an expansion of the existing buildings through the use of cross vaults. These various feature of lunettes and ways to construct cross vaults influence the extension and alteration of buildings complex or city block.

Figure 3. *Outling Lunet Seen in opus reticulatum*

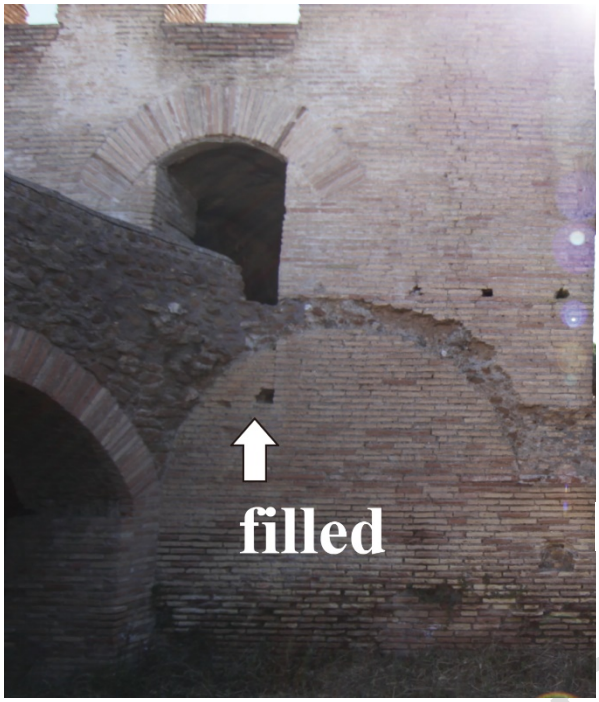
the Colosseum, which Lancaster attributes to the inclusion of a cross vault. While this example is fragmentary, they provide valuable insights into cross vaults of Ostia. See Lancaster, Lynne C. "Reconstructing the restorations of the Colosseum after the fire of 217." Journal of Roman Archaeology 11 (1998): 146-174.

Figure 4. *Outling Lunet Seen in opus testaceum*

Figure 5. *Building Partition Wall under Cross Vault*

Figure 6. *Conversion from wooden-beam-support to cross-vault-support*

Figure 7. *Addition of Cross Vault to Preexisting Wall*



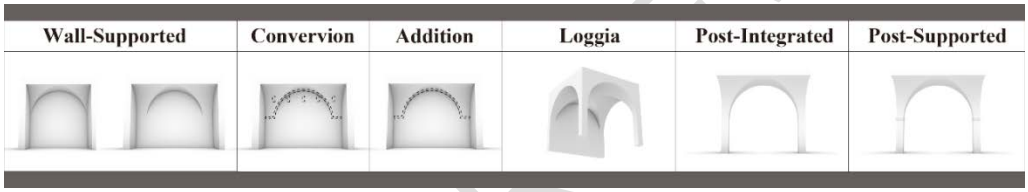
Subdivision of Cross Vault

The divisions of support methods for cross vaults can be broadly classified into wall and post support. When supported by walls, they can be further subdivided into two categories based on the construction method. The first category involves constructing the wall and cross vault as a unified unit, indicating a sequential construction process starting from the lower part of the wall. The other category is where the cross vault intersects the pre-exist wall. In many cases, the wall extends up to ground level or even the height of the first floor. Well-preserved examples of *opus testaceum* reveal a removed area of at a depth of approx. 10 cm max along the outline of lunette arc mentioned above. At this removed area, brick linings are hooked to construct a cross vault.

When supported on posts, cross vaults are subdivided based on how they release thrust forces. The primary emphasis lies in determining whether posts and concrete core of vault are integrated as a single unit. In this context, two types of posts can be seen in Ostia: one involves a continuous connection from posts to a cross vaulted structure, the other one involves separating posts from a vaulted structure placing *bipedales*. Secondly, the attention is directed towards understanding surroundings in which a post-support vault is

constructed. In this context, there is a distinction between constructing a vaulted structure as an independent entity or as part of a complex of structures. Post-support vault as an independent entity is erected at four corners of a room surrounded by walls on all sides, and the cross vault is sprung on top of these posts, with thrust forces received by the surrounding walls. On the other hand, the vault as part of a complex of structures involves a series of cross vaults like bays as arranging in row and grid, where the thrust forces are shared among these cross vaults, but the overall thrust forces of the connected space are borne by the buildings at both ends in the city block. Both categories of wall and post support are sometimes used in combination, especially in peristyle and colonnade. The following is a summary of the subdivisions of cross vaults and their characteristics (see Figure 8).

Figure 8. *Subdivisions of Cross vault*

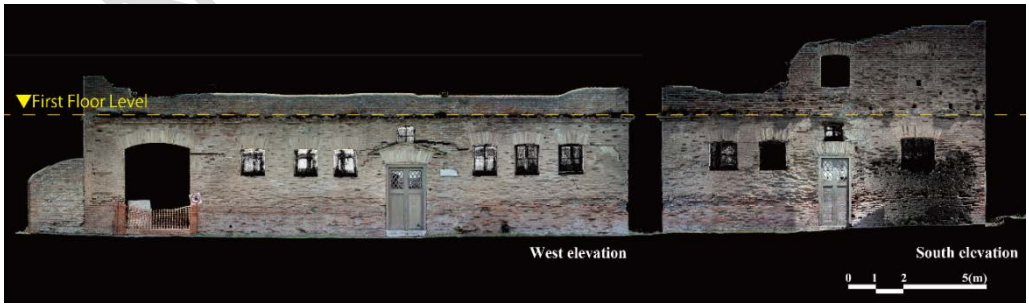


- **Wall-Supported**: This is a widely recognized type of cross vault in ancient Roman building. The vaulted ridge springs from the four corners of the room. It is included that cross vault, whose ridge lines do not spring from the four corners of a room, commonly found in rectangular rooms, prevalent in Ostia.
- **Convervion**: This represents structures that were originally supported by wooden beams for the upper storey but were later converted to support by a cross vault through reconstruction. Although not dominant in Ostia, there are surviving examples that serve as valuable evidence of the change in the upper floor support method.
- **Addition**: This method involves attaching a cross vault to an existing wall by creating a groove along the arc of the lunette and inserting large-format bricks such as bipedales as lower layer of brick linings. There are some remains, which could be built without applying brick linings and attached directly into the groove and surfaces of the wall. The existing walls predate the construction of the cross vaults in the building sequence, regardless of their original construction date.

- **Loggia**: Combination of wall-supported and post-supported construction. Commonly used in the Insula and Roman warehouse, Horrea in Ostia.
- **Post-Integrated**: Posts and springs of the cross vault are integrated.
- **Post-Supported**: Cross vault sprung from posts. Posts and springs of the cross vault are clearly distinguishable, often indicated by *bipedales*. In certain instances, the *bipedales* are slightly larger than the cross-section of the spring, suggesting that the *bipedales* could be used in facilitating the installation of wooden centrings.[18]

When applying vault-stacked approach for high-rise buildings, the first storey typically corresponds to the height of the ground floor. In House of the Painted Vaults, the ground and upper floors are separated by cornices made of fired brick (see Figure 9).[19] The upper edges of these cornices align with the first-floor level and represent a common example of vaulted support for the ground floor. However, while the wall structure of the first floor is still intact, the upper portion cannot be discerned, making it difficult to determine definitively whether the upper storey is supported by walls or vaults. In rare cases, the first floors were built in double height, and the first floor is usually supported by wooden beams or vaulted structures. Alternatively, there is unique example which is a structurally separate. One-storey-high vault structure is constructed within the double-high vault structure, and the load-bearing structures of the ground and the upper floor are independent of each other.

Figure 9. *Elevation of House of the Painted Vaults*

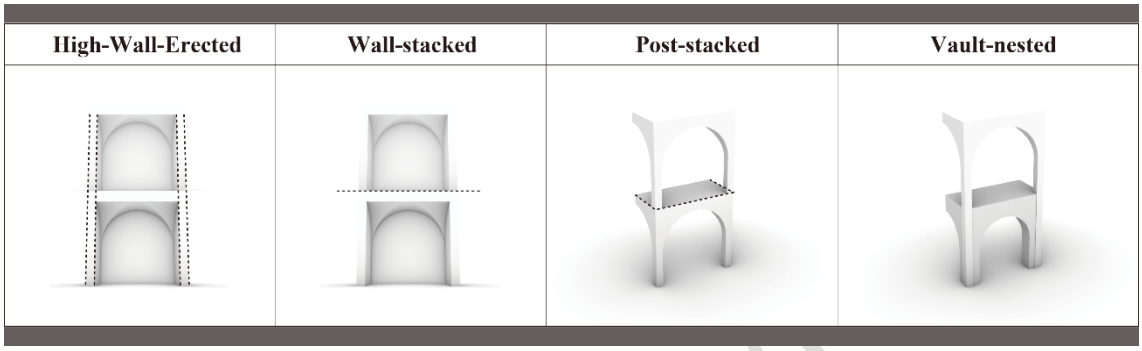


[18]It is clearly seen at House of Serapis.

[19]About detailed report of this building, see Felletti,Maj B.M. "Le pitture delle Case delle Volte Dipinte e delle Pareti Gialle", Monumenti della Pittura Antica 3,1-2, Roma, 1961.

These ones can be seen in only the house of the Charioteers (III,X,1).[20] The following is a summary of the subdivisions of construction method of high-rise building (see Figure 10).

Figure 10. *Construction Method of High-Rise Building*



- **High-Wall-Erected**: This method involves constructing walls that are more than two storeys high and supporting the cross vaults on these walls.
- **Wall-stacked**: This method entails constructing cross vaults by supporting wall elements on each level and stacking them sequentially from the ground floor. In two or three-storey buildings, a wooden beam structure with high-wall-erected structures could be stacked on top of the ground floor.
- **Post-stacked**: This method involves constructing cross vaults with post supports for each storey and stacking them sequentially from the ground storey. It has no evidence of preserved remains in Ostia, so it is not within the realm of estimation. In two or three-storey buildings, it can be assumed that a wooden beam structure with high-wall-erected elements is stacked on top of the ground floor.
- **Vault-nested**: This method comprises building a one-storey cross vault inside a double-storey high post-integrated or post-supported cross vault. In Ostia, this structure is observed in only house of the Charioteers, but information on upper than three-storey level remains is unavailable due to the lack of surviving remnants. A distinctive aspect of this method is that,

[20]A part of the first floor of House of the Charioteers could have been eventually used as waterway. See , Ricciardi, Maria Antonietta., and Valnea Santa Maria Scrinari. La Civiltà Dell'acqua in Ostia Antica. Roma: Palombi, 1996. Vol.1,164-167.

in relation to the load-bearing capacity of the building, it enables an additional storey to be constructed, despite maintaining the same load-bearing capacity as other methods. This implies that a three-storey building can be extended to a four-storey building, and a four-storey building can be expanded to a five-storey building.

Sub-conclusion

The former part of this paper has unveiled certain aspects of high-rise building construction in Ostia by examining the techniques employed in supporting and stacking cross vaults. These methods are occasionally combined, and the existing cross vaults exhibit a wide range of variations. The classification proposed in this part proves valuable not only for understanding the construction in Ostia but also for articulating the distinct features of cross vaults, enabling their identification even in cases where they have collapsed.

Observation and analysis of high-rise wall, substantial load-borne vault, and vaulted complex

In the second half of this paper, the aim is to further deepen the understanding of the classification obtained from the observation of cross vaults and to analyse and discuss not only cross vaults but also barrel vaults. Firstly, attention is directed towards the challenges of constructing freestanding walls from the ground to the height of the building in high wall support. To examine the practical issues that arise when constructing tall structures using this method, the analysis focuses on the walls surrounding the *cella* of the Capitolium temple, which stands facing the central square and represents the highest walls preserved in Ostia. The analysis includes the wall thickness, foundation elements supporting it, and the connections between the walls. Next, the focus shifts to the difficulties of bearing and releasing large loads through the stacked vaults. By examining the enormous water tank in the Forum Bath, which houses the largest barrel vault preserved in Ostia, the analysis investigates the handling of significant loads observed in this structure. Lastly, attention is drawn to the characteristic feature of vaulted structures in Ostia, where a cluster of vaulted structures are constructed jointly within specific city

blocks, Regio III, Insula X and XIV. The study investigates how the load of the entire group of vaulted structures is transmitted to the ground using sectional drawings across the city block. The analysis of these structures and building groups is conducted using point cloud data obtained through laser measurements.

Figure 11. *Barrel vaults of Capitolium*

The Highest-Rise Wall

The Capitolium, constructed during the Hadrianic period as an expansion of the central square, is the largest temple, whose three walls encompassing the *cella* have the most extensive surface area in Ostia.[21] The temple is supported by three consecutive barrel vaults, one supports the platform, and the other ones support the *cella*. The rear of the *cella*, where walls are connected with each other, is reinforced by barrel vaults of different orientations (see Figure 11), and it could serve to distribute vertical loads and disperse thrust by overlapping the two barrel vaults rotated 90 degree.[22] However, it is important to note that

[21]The detailed research of Capitolium in Ostia, see Albo, C., 2002a. Il Capitolium di Ostia : alcune considerazioni sulla tecnica edilizia ed ipotesi ricostruttiva. Mélanges de l'Ecole française de Rome. Antiquité no. 114, 1, Rome, pp. 363-390.

[22]This structure can be considered as a variation of the barrel vault proposed by McDonald

apart from the Capitolium, there are no other instances in Ostia where a barrel vault is further reinforced by a rotated barrel vault inside it, so it should be regarded as a unique case. Thickness of three walls surrounding the calla measures approx.1.0m (see Figure 12). And their height measures 11.9m, which is approximately the equivalent of three or four storeys of the insula (see Figure 13). Additionally, thickness of these walls is unevenly from the bottom to top, and joints of these walls are reinforced by increasing in thickness.[23] That shows how difficult it is to build and also maintain high, self-standing walls. Good example about that can be seen near the capitolium, next to House of Jupiter and Ganymede, whose hight is expected to five storey,[24] and the wall in Figure 14 has tilted. These remains indicate that it would have been difficult to build such a high-rise wall in the insula without tilting.

Figure 12. *South Section of Capitolium*

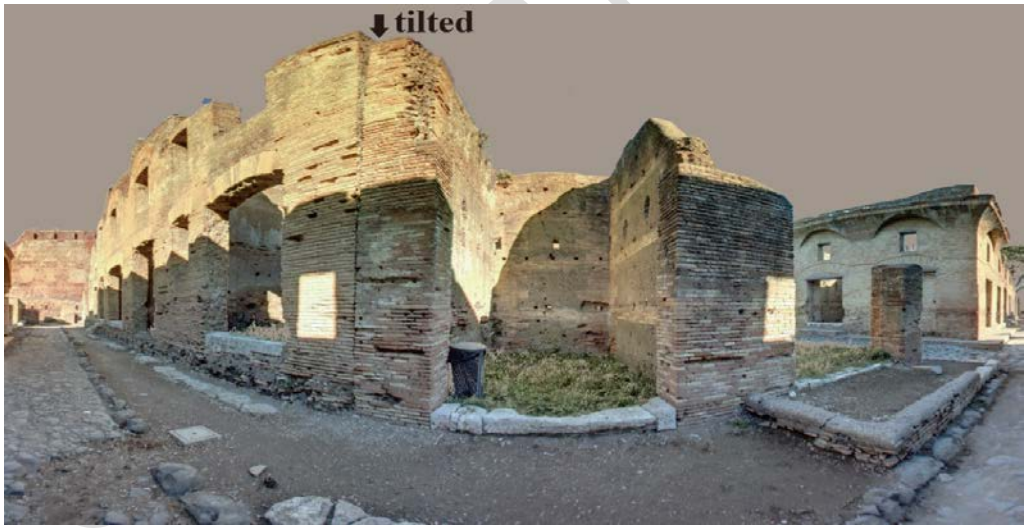
and others in prior studies. Nevertheless, it is important to note that, in contrast to this, the majority of Ostia's cross vaults are not a result of cylindrical crossings.

[23]Hori, Y., and T. Ogawa. "Visualization of the construction of ancient roman buildings in ostia using point cloud data." The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences 42 (2017): 345.

[24]The reconstructed model of House of Jupiter and Ganymede can be seen at the museum of Roman civilization.

Figure 13. *West Section of Capitolium*

Figure 14. *Tilted Wall next to House of Jupiter and Ganymede*

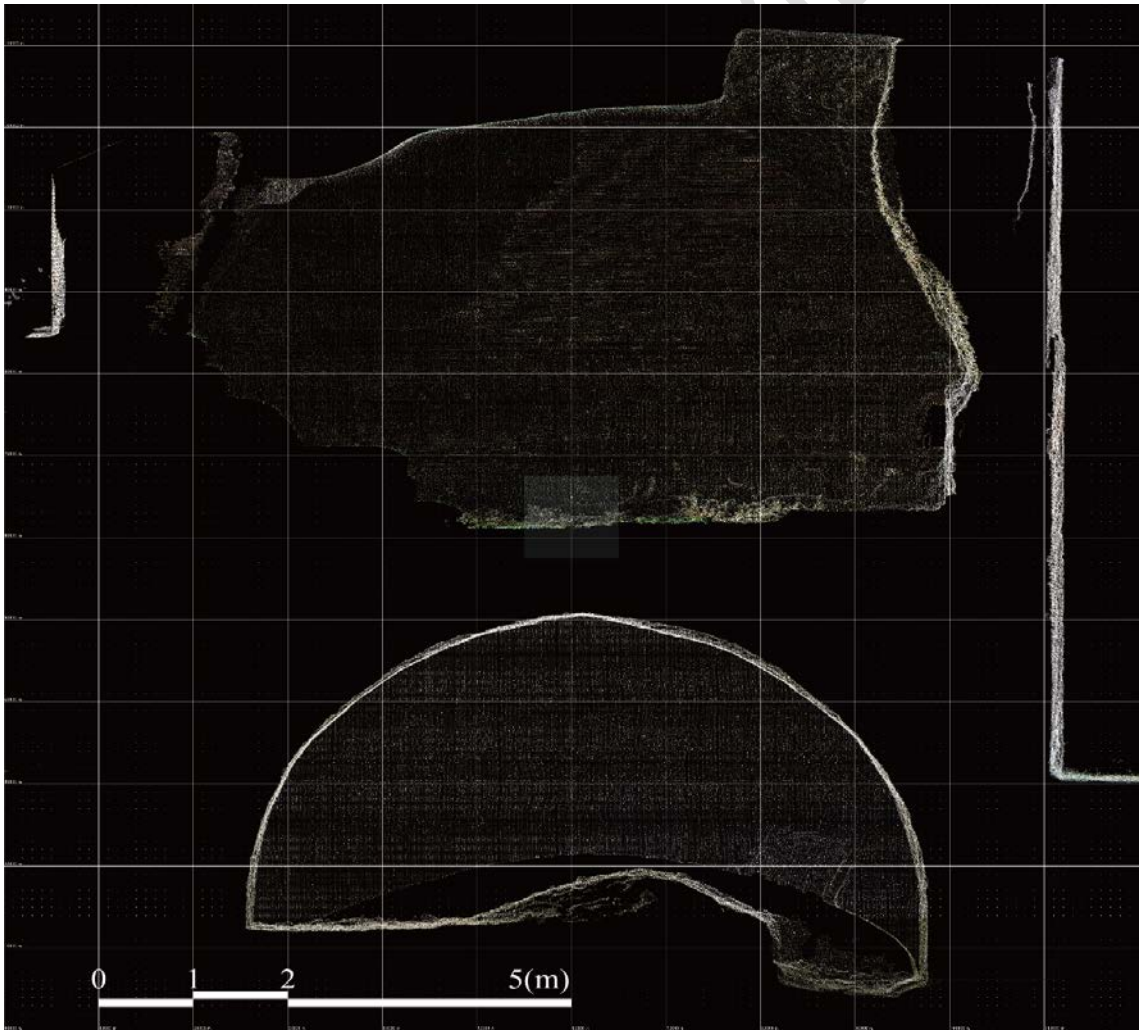


Substantial Load-Bearing of Vault

The Forum Bath, one of the largest bathing complexes in Ostia, is situated south of the forum. Inscriptions and brickwork suggest that it underwent construction and restoration in multiple phases, starting from the

mid-2nd century C.E..[25] Subsequent building activities took place during the early Severian period (C.E. 193-225) and the reigns of Maxentius and Constantine (C.E. 306-337), likely occurring in two phases. The notable feature, a large water tank which consists of two large barrel vaults, is located east of the bathing square, and the lower barrel vault was partially buried beneath the surrounding street level, with the spring of the vault noticeably lower than the street surface (see Figure 15). This indicates that thrust was transmitted to the ground. The first barrel vault has a diameter of approx. 7.14 m and a wall thickness of 1.42 m, while the upper barrel vault has a diameter of approx. 7.96 mm and a wall thickness of 1.19 m.

Figure 15. *Barrel Vaults of Cistren of Forum Bath*



25. Pavolini, 2006.p.107-110.

Vaulted Complex: Cluster of barrel vault

In Ostia, there are instances of a sequence of vaulted structures constructed on a city block scale (see Figure 16). Examples include House of the Grain Measurers (I, VII, 1-2), shops (I, VIII, 10), East and west porticus of Pius IX and loggias (I,V,2 - I,VI,1), and House of the Shops with Show-windows (IV, V, 18). In House of the Grain Measurers (I, VII, 1-2) , which is dated to 120 C.E.,[26] barrel vaults are employed in front of the building without being directly adjacent to each other. The longitudinal axis of the barrel vault built at the building's corner is connected to the transverse axis of the other barrel vault to the east of the building, where at least three rooms are continuously utilized. Cross vaults of House of the Balcony with Corbels (I,VI,2), which is dated to the Hadrian period,[27] are built in the rooms opposite this corner and across the street, which are similarly adjacent to the continuous barrel vaults. In shops (I, VIII, 10), which is dated to the early-Hadrian period,[28] eight out of the ten contiguous rooms, along with the adjoining buildings on both sides, employ barrel vaults, while cross vaults are built in the two rooms situated between barrel vaults. Concerning the ends of these sequences of vaulted structures, the old city wall castrum, consisting of tufa masonry, is connected on the west side, while two rectangular rooms with unidentified barrel vaults are connected on the east side along the longitudinal axis. Another example of a continuous barrel-vaulted structure in Ostia is East and west porticus of Pius IX and loggias (I,V,2 - I,VI,1), which links the Tiber direction to the Capitolium. As far as can be determined, it consists of a sequence of 16 rooms with barrel vaults, excluding the staircase rooms. However, the northern end of these loggias has been lost due to the River Tiber, and the southern end, which is four times the area of each loggia room, has largely lost its upper structure, making it impossible to confirm the details of the continuous barrel vaults and their ends, as previously mentioned. In House of the Shops with Show-windows (IV, V, 18), which is date to the Trajan period,[29] three continuous barrel vaults and one cross vault are adjacent to

[26]Pavolini, 2006.p.98.

[27]Pavolini, 2006.p.98.

[28]Calza, Guido. Scavi Di Ostia. Roma: Libreria dello Stato, 1953.p.233-238.

[29]Pavolini, 2006.p.190.

each other, and two rooms bridged by barrel vaults are connected to them in the longitudinal direction. However, it is not appropriate to consider this connection as a general approach for the vaulted structure, as it can be regarded as a consequence of placing the rooms squarely along the street, rather than solely for the purpose of supporting the vault structure.

Figure 16. *Clusters of Barrel Vauted structures*

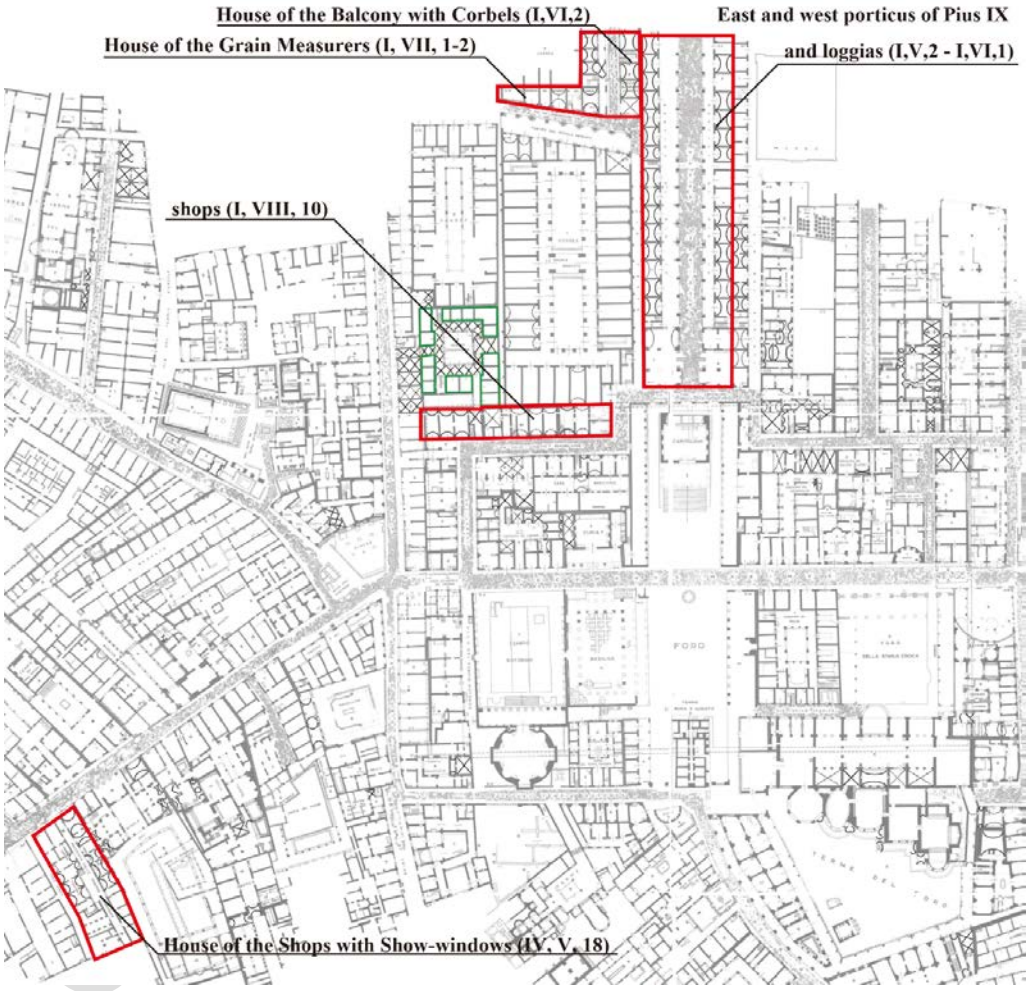
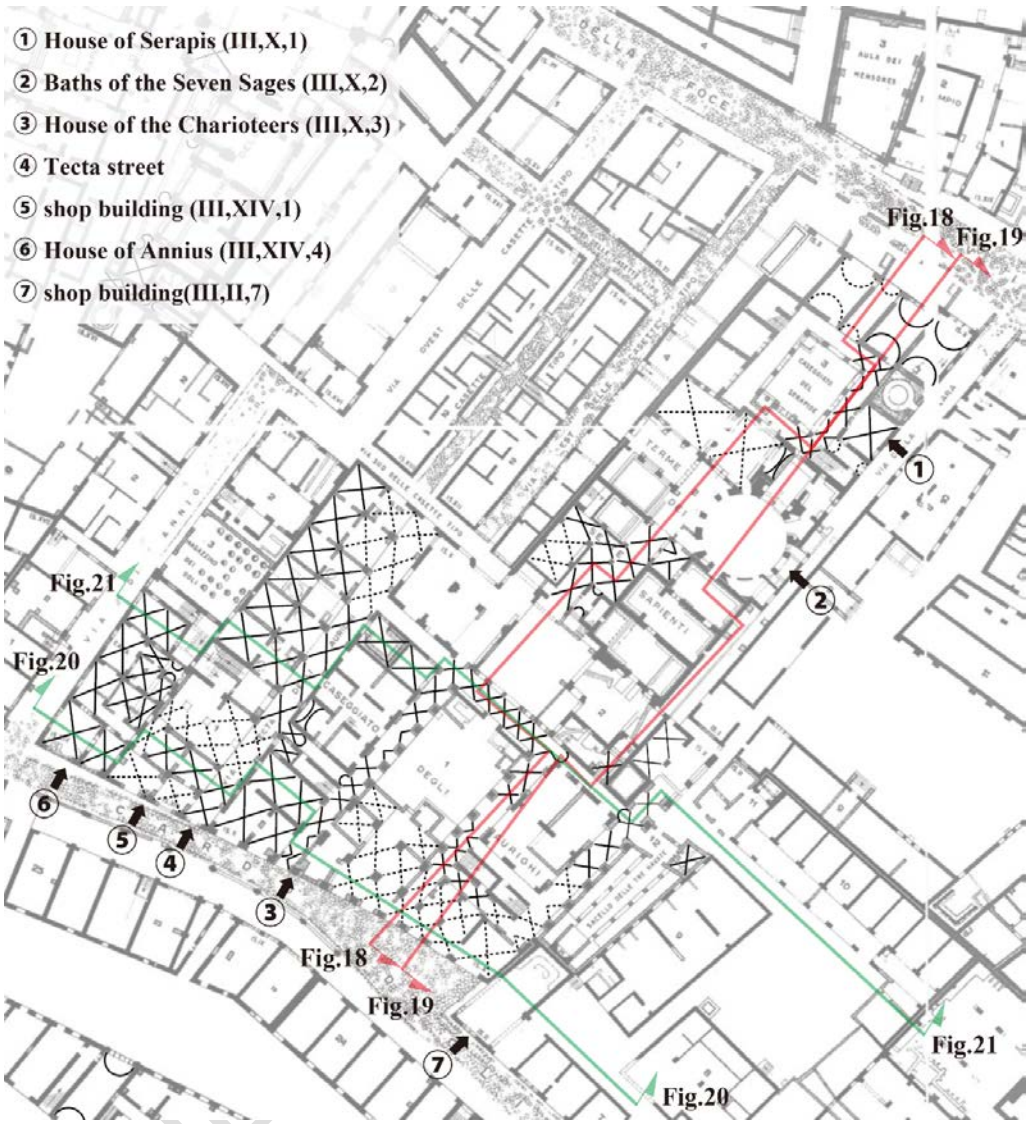


Figure 17. *Clusters of Cross Vauted structures*



Vaulted Complex: Cluster of Cross Vault

As evident from the distribution map of vaulted structures, the use of cross vaults on a town block basis is limited to Insula X and XIV, which were constructed around the same time (see Figure 17).[30] In Insula X, House of Serapis (III,X,1) was built in 126-127 C.E., followed by House of the Charioteers (III,X,3) in 140 C.E., resulting in three successive buildings

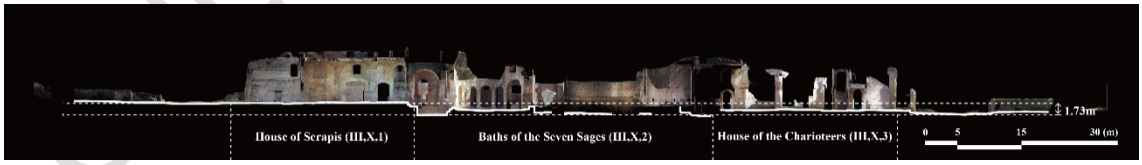
[30]Heres, Th.L. 1993, "La storia edilizia delle Terme dei Sette Sapienti (III X 2) ad Ostia Antica: uno studio preliminare", Meded 51-52, 76-113. Also see Pavolini, 2006.p.132-144.

erected over a span of approximately 13-14 years. Among the buildings in Insula XIV, House of Annius (III,XIV,4) on the western side was constructed in 128-129 C.E.,[31] around the same period as the House of Serapis, while the shop building (III,XIV,1) was built during the Antonine Empire.[32] Between the shop building and House of the Charioteers lies Tecta street, and cross vaults were constructed over this street, linking these structures together.

Although Insula X and XIV were built concurrently, there is a height disparity of approx. 1.8 meters between the north and south streets surrounding the city block (see Figure 18 and 19), and 0.8 meters between the east and west streets, resulting in varying floor levels for different buildings.[33] The height difference of 1.8 meters gradually transitions from north to south, but when examining another section, lower sections can be observed in Baths of the Seven Sages (III,X,2) compared to the House of Serapis and House of the Charioteers. The fact that part of Baths of the Seven Sages has a lower floor level than the neighbouring buildings is partly due to the semi-underground facilities of the bath. However, it is important to note that, among the three series of buildings, the middle building is the lowest.

Figure 18. *NS Section 1 of Insula X and XIV*

Figure 19. *NS Section 2 of Insula X and XIV*



[31]Pavolini, 2006.p.139.

[32]Calza, 1953.p.233-238.

[33]Detail description about the raising land around Baths of the Seven Sages (III,X,2) was presented the author. OGAWA,T., HORI,Y. ARCHAEOLOGY WITHOUT EXCAVATION?: LASER SCANNING IN OSTIA, 24th EAA Annual Meeting, 2018/9/6, Barcelona.

Next, when examining the east-west cross section across Insula X and XIV, starting from the west, various height differences become apparent (see Figure 20). These differences occur not only between buildings but also within the same building. The ground floor level of House of Annius is the highest and exhibits a height difference of approx. 20 cm within the structure. the shop building (III,XIV,1) is approx. 60 cm lower than House of Annius and an additional 15 cm lower within the same building. Moving further, there is a ground floor level increase of about 10 cm in Tecta Street. In House of the Charioteers next to Tecta Street, the ground floor level is approx. 10-30 cm higher. Furthermore, in the section with the northern street surrounding the city block, which is adjacent to Insula X, the floor level is higher than that of Insula X. Particularly in the east-west section, a significant barrel vault with a diameter of 5.5m is present in the shop building(III,II,7), which is approx. 50 cm lower than the neighbouring House of the Charioteers. In simple terms, the whole of building complexes are not constructed on level ground but are adapted to the irregularities within the city block. These characteristics are also observed in Figure 21, although some variations in ground floor level can be noted. The springs height of each vault also differs, particularly the framework of the cross vault in Tecta Street, which connects the springs of each neighbouring cross vault.

Figure 20. *EW Section 1 of Insula X and XIV*

Figure 21. *EW Section 2 of Insula X and XIV*

Sub-conclusion

In the latter part of the paper, elements were derived from the site to enhance the comprehension of the subdivisions established in the first half: the challenge of constructing a wall-support, necessitating the erection of a tall,

standalone wall, was confirmed at Capitolium, where an attempt was made to construct a high-storey building with a wall-support. Subsequently, the cross section of the barrel vaults encompassing the water tank of Forum bath, considered one of the structures bearing the heaviest loads, verified that the ground level of the vault was lower than the surrounding ground level due to the disparity in elevation. Attention was then drawn to the continuous utilization of vault structures. Barrel vaults possess longitudinal and transversal axis, contingent upon the orientation of the cylinder. In most instances, it was observed that barrel vaults of the longitudinal axis were employed in conjunction with barrel vaults constructed continuously in the transversal axis, or that ancient city walls of masonry construction or sizable rooms were situated at the extremities. In Insula X and XIV, where cross vaults are employed in clusters, the characteristic feature of the cross vaults being dispersed in a grid pattern of rows and posts, rather than exclusively rows, was noted. Furthermore, the variation in elevation of each building within these grid-like vault structures was highlighted, with each of these structures fitting into an uneven site configuration. The diverse elevation differences across the site, as well as the varying heights of the springs of the intersecting vaults, may have contributed to the effective transmission of thrusts to the ground, as observed in the substantial barrel vaults in the central square. In the context of Ostia, where all these elements are present within the same city, the construction of clusters of vaults spread out in a grid pattern of rows and posts, on sites characterized by contrasting elevation differences, may have played a crucial role in the actual construction of high-storey buildings.

Conclusions

Based on the information gathered from a comprehensive survey of Ostia, this paper summarises details that have not been addressed in vault studies and categorises Ostia's cross vaults. Additionally, the construction of tall, self-supporting walls, the capacity to bear substantial loads, and the clustering of vaulted structures were analysed and discussed by measuring the existing structures in Ostia, with the aim of facilitating the construction of high-storey buildings. Finally, based on the observation that cross vaults were clustered on sites with varying elevations in the city of Ostia, and that wall-support and

vault-support can be employed together, it was concluded that raising a building by one storey was a significant factor in achieving greater height. This study suggests that this may have played a crucial role in achieving the effect of high-rise buildings. In particular, a three-storey building can be understood as the construction of a two-storey building with high-wall-erected method.

While Ostia boasts the largest collection of preserved cross vaulted remnants in the city, most of the surviving remains are extensively collapsed at the upper levels, making it challenging to determine whether these structures originally had an upper storey and, if so, whether it was supported by wooden beams or barrel or cross vaults. Consequently, this paper does not present statistical data but rather provides a qualitative analysis based on observations made during site exploration. However, when referring to dimensions and numerical values, such as building cross-sections, point cloud data which were measured by laser scanner was employed. Ostia, as illustrated in this paper, is a complex city comprised of diverse elements. It is believed that this research will contribute to a better understanding of such a city.

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