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Pompeii's Stabian Baths. Mechanical behaviour assessment of selected masonry structures during the 1st century seismic events

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ABSTRACT

Eruption of Mount Vesuvius in AD 79 buried and preserved the Stabian Baths building in the exact configuration which the archaeological excavations carried out in the second half of the nineteenth century recovered. By combining archeologists' studies with the analysis of deformations and cracking pattern due to 1st century seismic, in this paper numerical models have been formulated which allowed to form some hypotheses coherent on the timeline of the events, the damages as well as the change of the shape and stylistic language of the thermal building. Specifically, through global seismic analyses and kinematic analyses of masonry portions of the "destrictarium" block, it is proven that during the 1st century not only a sole catastrophic earthquake occurred but, at least, two important seismic events took place.

The purpose of this paper is to identify and parameterize the responsible earthquake by the analysis of seismic effects detectable in the damages and archaeological remains of Stabian Baths masonry walls. The identification of the earthquake and the grading of provoked damages represent an useful knowledge tool that provides information about *ancient buildings vulnerability and can be suitably used also to safeguard architectural heritage from seismic risk.*

KEYWORDS: Stabian Baths, masonry structures, 1st century Pompeii's earthquake, kinematic analysis, seismic vulnerability, safeguard, ancient damage analysis.

1. Introduction

A very strong earthquake, gauged at the IX level of the Mercalli intensity scale (La Greca, 2007) and felt also in Naples, Herculaneum and Nocera, struck Pompeii on 5th February 62 AD. This date is long-debated among philologists, split between the witness of Tacitus and Seneca. In the *Annales,* Tacitus includes this earthquake among the events in AD 62. Instead Seneca refers in his Liber VI, 1, 2 (Corcoran, 1971): *"Pompeios, celebrem Campaniae urbem … consedisse terrae motu uexatis quaecumque adiacebant regionibus ... Nonis Februariis hic fuit motus Regulo et Verginio consulibus … (Pompeii, the celebrated city in Campania, has been overwhelmed in an earthquake, which shook all the surrounding districts as well… On 5th February, during the consulship of Regulus and Virginius…)",* namely the two duumvirs which governed Pompeii in AD 63.

Several scholars (Lecocq, 1949; Hine, 1984; Andreau, 1973; Maiuri, 1942; Henry, 1982) took place in the discussion. Pivoting on a clear contradiction in Seneca's treatise, the majority of them is inclined to the later dating. Indeed, in Liber VI the Latin author dates the earthquake that struck Achaea and Macedonia in AD 61 with reference to the *anno priore* (year prior) to that of Pompeii, thus confirming Tacitus' statement and his *"… témoignage irrefutable (incontestable proof)"* (Lecocq, 1949).

AD 62 is a dating that has now been accepted by the entire scientific community in which the works of Lecocq (1949), Hine (1984) and Andreau (1973) stand out. Instead, Maiuri (1942) has a discordant opinion. Even if he does not deal with this topic in detail, he states that Pompeii was struck by the earthquake in AD 63 in his work entitled "L'ultima fase edilizia in Pompei". Henry's opinion (1982) is peculiar, which interprets Seneca's contradiction as the information that two different earthquakes occurred: the first took place at the end of AD 62, according to Tacitus' witness, and the second on February 63 AD, according to Seneca.

The computation of the amount of energy released by the earthquake based on the damage analysis suffered by the buildings was the topic of another heated debate between the 19th and 20th century. It is a *vexata quaestio* attended by famous seismologists split both in the intensity assessment and in the seismogenic sources detection. Baratta (Baratta, 1901) fully agree with Mercalli's assumption "*… di un gran terremoto avvenuto il 5 febbraio … (che) fu disastroso ad Ercolano, Pompei, Stabia, Nocera e Pozzuoli (…of a strong earthquake occurred on February 5th (which) destroyed Herculaneum, Pompeii, Stabia, Nocera and Pozzuoli)"* (Mercalli, 1883). Modern research developments (Marturano and Rinaldis, 1995) would lead to assert that the magnitude of AD 62 earthquake in Pompeii was of high intensity and a consequence of the Tectonics of the central-southern Apennines (Ruggieri, 2017). In Boschi et al.'s opinion (Boschi et al., 1995), it was the strongest seismic event occurred in the Vesuvian site. This conviction is supported by the great damages on buildings, caused by a seismic sequence of high magnitude, currently detectable both in the post-earthquake restorations (Ruggieri, 2017) and cracks and deformations certainly caused by dynamic actions. Another meaningful witness is the precious iconography of the two reliefs of the *lararium* in the house of Caecilius Iucundus that depict some public buildings on the point of overturning and collapsing.

As a consequence of such an interpretation, the damages on the buildings could be the result not only of a single strong earthquake but of subsequent shakes that, even if of lower intensity, stressed constructive elements previously damaged and strained. This hypothesis is also validated by Seneca's witness: *"…Non desiit enim assidue tremere Campania, clementius quidem sed cum ingenti damno, qui aquas saquatiebat, quibus ad cadendum male stantibus non erat impelli sed agitari… (…In fact the Campania region went on trembling continuously, more gently it is true, but still causing great damage, because what it shook was already shaken and crushed. Things stood so insecurely as to require only a slight shake, but not a push, to bring them down…)"* (Corcoran, 1971) Liber VI, 31,1.

In fact, other earthquakes followed the AD 62 one, such as that recorded by the chronicles of that period in AD 64. Suetonius and Tacitus tell about it relating that Nerone was surprised by that event during his show in the theater of Naples.

In his *Vita Neronis* (the Liber VI, 20, 2 of *Vita Caesarum*), Suetonius (AD 119-122) tells: *"Et prodit Neapoli primum acne con-cusso quidem re-pente motu terrae theatro ante cantare destitit, quaminco-hatum absolveret nomon (He made his show for the first time in Naples and did not stop singing before he finished his song, despite a sudden earthquake had shaken the theater)".*

Furthermore, in the *Annales*, Tacitus (AD 114-120) reports*: "C. Laecanio M. Licinio consulibus acriore in dies cupidine adigebatur Nero promiscas scaenas frequen-tandi … Non tamen Romae incipere ausus Neapolim quasi Graeca murbem delegit ... (When C. Lecanio e M. Licinio were consuls [AD 64] the intense desire of Nero to show off in the scenes increased day by day more and more… Since he did not dare to perform in Rome, he chose Naples, as a Greek town…)", XV, 33. "Illic, plerique ut arbitra[ba]ntur, triste, ut ipse, provi dum potius et secondi numinibus evenit: nam egresso qui ad fuerat populo vacuum et sine ullius nox a theatrum collapsum est. (There occurred a fact that most people thought to be of ill-omen, and that Nero, at the contrary, considered fortuitous and a sign of a divine present: as soon as the viewers came out, the empty theatre collapsed without consequences for anyone)", XV, 34.*

The magnitude and the epicenter location of that earthquake are not known and, as a consequence, not even the effects and damages on Pompeii's buildings. Other sources, such as various epigraphs (Guidoboni, 1989), tell of restorations and reconstructions executed in Pompeii during different events. It is the proof of a real earthquake swarm. The seismic shakes lasted up to AD 79, certainly forerunning the eruption of Vesuvius, and compatible with the seismicity that characterizes this area and the volcanic ones in general. Furthermore, the existence of many construction yards in Pompeii is clearly explicable just considering the seismic sequence occurred during the 1st century. Maiuri himself (Maiuri, 1942) wrote: *"…non c'è casa che non abbia in corso riparazioni… (…there is no house without repairs…)"*.

Along with the analysis of the above mentioned historical sources (historical seismology), the study of seismic damages and the restorations of ancient buildings (historical seismography) are also of utmost importance. Indeed, every ancient building carries a trace of its seismic history, highlighting the damaged buildings and the structures that better resisted.

By crossing data provided by the seismological surveys with those provided by the seismographic surveys as well as the archaeological studies, in this paper the timeline of events was retraced, thus providing a more accurate and complete knowledge tool of an ancient building. This can be a useful instrument for its seismic prevention and protection. This type of research, based on a non-conventional use of the numerical model (Pugi and Galassi, 2013; Galassi and Paradiso, 2014), investigates the effects of seismic events on the archaeological ruins (shear, deformations, dislocations of structures) allowing to detect and parametrize the responsible earthquake in terms of intensity and dating and provides a guidance on the possible location of the epicenter (La Greca, 2007).

In this way, the study of historical buildings in seismic prone areas is no longer merely aimed at detecting heritage buildings to be protected but it is also a knowledge source of the site hazard aimed at protection from the seismic risk.

For this reason and with this purpose, in this paper a meaningful portion of the Stabian Baths is investigated. Indeed, on one hand (historical seismology) this building represents a significant example that proves the first earthquake occurrence, most likely that of AD 62, followed by a second one after few years, occurred in an uncertain date. On the other hand (historical seismology), the building was used as an open air construction site where it is possible to read in the ruins the damages caused by the earthquake and the subsequent restoration and securing interventions (Paradiso et al., 2013) of the crumbling structures.

In such a way, the archaeological site of the Stabian Baths in Pompeii is used, in this paper, as a research lab where the cooperation of scholars of different subjects (archaeologists, historians, architects, structural engineer) contributes to the reconstruction of a complete pattern of the events which occurred in sequence in the limited period of just seventeen years, that is from the AD 62 earthquake to the eruption of Vesuvius in AD 79.

The pattern of the events is here obtained crossing the data provided by the archaeological studies, taken from the scientific literature (Maiuri, 1942; Marturano and Rinaldis, 1995; De Simone, 1995; Fiorelli, 1862; Trümper et al., 2016; Eschebach, 1979; Mau, 1899; Fiorelli, 1875), with the site inspections, measurement surveys, cracking patterns and the structural investigations carried out by the authors.

2. The Stabian Baths

The Stabian Baths are the oldest thermal building in Pompeii, whose original nucleus, placed in the north-west area and consisting of the swimming pool, cells and individual bathrooms, is dated from the 4th century BC. This dating already was to appear evident in

1855 when during *"… il cavamento …* (fu ritrovato un) *orologio solare colla iscrizione osca sul suo basamento… (excavations … a solar clock was discovered provided with the inscription on its basement…)"* (Fiorelli, 1862). Recent studies (Trümper et al., 2016) have confirmed Fiorelli's hypothesis and also questioned the existence of archaic structures before the Sannitic age. The discovery of an inscription of the duumviri Uulius and Aninius (CIL X, 829), would assign to the 1st century BC important and wide enlargement works during which *laconicum* and *destrictarium* were built and the colonnade and the swimming pool were repaired (Mau, 1899), so as to assume a distribution of functions very similar to the current one. Other important interventions, concerning new rooms on the west side of the baths, decorations and repairs can be placed in Julio-Claudian age.

The central core of the baths (Fig. 1), in its current configuration, is formed by a trapezoidal *palaestra* which laterally provides access to the women's and men's baths, divided by a common *praefurnum*, composed of three *caldaria* (i.e. boilers). The two male and female sectors are composed of the *apodyterium*, the room where bathers could undress, *frigidarium*, *tepidarium* and *calidarium*. The *calidarium* is facing south-east according to Vitruvius' suggestions. It is very interesting the presence of the *Hypocaustum*, still in situ and clearly visible, where the technical recommendations proposed by the architect of August, are perfectly observed so as to award to the Pompeii's Stabian Baths also an exceptional educational value.

On the west side of the *palaestra* there is the *natatio*, a very large swimming pool, between two rooms, to the south and to the north, devoted to *destrictarium*, where bathers could clean their bodies after exercises, and *palaestra* service rooms.

3. Roman seismic strengthening interventions

Certainly, the many clues relative to the effects of 1st century seismic events were also patent during the excavation campaign carried out between 1854 and 1858 just in the site of the Stabian Baths, such as the finding of ancient interventions based on *"… opere di sostegno alle fabbriche cadenti, con l'abolizione di talune località più vetuste e con molte nuove decorazioni… (works for supporting the falling buildings, with the removal of some more ancient places and with a lot of new decorations…)"* (Fiorelli, 1875).

Wide portions of the baths architectural structures were very damaged, to the extent that several and extensive repairs were necessary which continued unfinished until the AD 79 eruption. At the eruption time the baths could not work; the lack of the principal pipeline for water conveying (Maiuri, 1942) proves that the baths could not be used. In addition, the obvious state of ruin of some rooms in the period of excavation so as to require suddenly the need of impending restorations (Fiorelli, 1862) would confirm that the whole building or a part of it was out of use during the last phase of Pompeii.

Some supporting and safety works carried out on the building used as *destrictarium* and its service rooms (*nymphaeum*), such as the two buttresses built on the building peripheral walls (Fig. 1,2,3), are particularly explicative.

Specifically, the buttress near the south-east corner of the building, aligned with the wall plan facing the *palaestra* (Fig. 2), is doubtless intended to oppose to the possible collapse of masonry portions near the cantonal.

Instead, the massive masonry buttress, built orthogonally to the inner surface of this same wall, is obviously aimed at opposing to the overturning beginning of a large portion of the peripheral wall. Placed at the intersection with the masonry wall on the colonnade of the peristyle, beginning from the height of approximately 3 meters, the wall of the *destictarium* shows a considerable inward rotation, pointed out by two parallel vertical cracks (the left one is more clearly detectable), provoked by different displacements of the masonry portions from the original wall surface. The buttress arrangement[1] seems to be built in two subsequent phases, characterized by the use of different constructive techniques, more disordered in the first sector and better arranged in the southernmost sector, made of a coursed stone masonry (Fig. 3). Furthermore, this supporting structure still shows plaster remains on the north and south sides.

Made of *opus latericium,* the infill of two pre-existing windows (Fig. 4 and 5) on the same wall is clearly visible inside. Also this intervention, which in the authors' opinion (it will be discussed in the following) was made during the restoration works as a consequence of a first seismic event, seems to be aimed at strengthening the masonry wall under study to restore both its continuity and consistency, due to its noticeable loss of stability onset. Among the interventions executed immediately after seismic events occurrence, it is also necessary to highlight those made in correspondence to the masonry wall north of the *nymphaeum* and the corner near the *palaestra* (Fig. 5). The masonry arrangement, which clearly stands out from the adjacent one with brick courses arranged according to the typical constructive technique (*opus latericium*) used during the last Pompeii's phase, clearly proves that a wide portion, comprising the same corner and masonry portions connected to it, had entirely collapsed, so that the total reconstruction was necessary.

Others important clues useful for timeline assessment of the seismic events which have damaged the building can be deduced by observing the exterior façade of the main wall facing the *palaestra* (Fig. 5, 6 and 10). Indeed, the façade shows its surface entirely coated by painted stucco decorations that depict Hercules, Jupiter and Apollo and generally some mythological figures framed by fantastic architectures, dating back to the IV style, in vogue during the 1st century, in accordance with Maiuri's assumption. This

[1] In Escheback's opinion (Fiorelli, 1862), this buttress can be dated to the Borbone's period. However, in his studies the German archaeologist does not highlight the two constructive phases. In authors' opinion, one of these could be dated back to the Julio-Claudian age.

coating intervention, which couldn't exist before the AD 62 earthquake, was obviously made after the execution of the infill of the two pre-existing windows and, almost certainly, also after the first masonry walls reconstruction which cross in the north corner of the *nymphaeum*. As stated in the following paper, this fact is meaningful to correctly interpret the seismic events timeline.

Another sign of an intervention criterion aimed at securing and strengthening the structures after the earthquake occurrence, is represented by the increase of the diameter of the peristyle columns from 0.42-0.5 meters to 0.56-0.80 meters (Maiuri, 1942). Even if it makes the columns stubby emphasizing the drum diameter disproportion in relation to the limited height (Fig. 7), this intervention seems clearly aimed at improving the overall stability of the structural system which certainly had pointed out its inherent vulnerability just during the seismic events occurred in that period.

4. Analysis of "destrictarium" and its damage pattern

As mentioned above, the catastrophic earthquake that on 5th February 62 AD struck the city of Pompeii, Herculaneum and many other towns on the Vesuvian coast caused great damages to the structures of the Stabian Baths, involving specifically the building composed of the *destrictarium* and the *nymphaeum*.

This building holds a very clear series of signs that allows to retrace a plausible timeline of damages which involved the overall building, through the analysis of the interventions mentioned above, the analysis of the constructive techniques, the interpretation of the effects on the structures explained by the cracking patterns.

Following this way of interpretation, it's also possible to justify quite clearly the correspondence of these interventions with the seismic events which had required them to safeguard the structures.

The collapse of a wide portion of the masonry walls near the north-east side of the *nymphaeum* can be referred to the first seismic event occurred in AD 62 (Fig. 8).

Within this collapse mechanism, the collapse had certainly involved the entire wall facing the swimming pool, a portion of the longitudinal façade (with an extension approximately comprised between the corner and the inner transversal partition wall) and the whole corner. Indeed, the corner was not only exposed to the thrust increase due to the hip rafter of the roof, but also had an inherent weakness due to the existence of the two wide arched doors placed exactly in correspondence to the corner.

Following the line which divides the materials forming the masonry arrangement and the differences in the laying out (Fig. 5, 6 and 9), the portion which was rebuilt can be exactly identified and, consequently, its correspondence to the masonry walls involved in the overturning collapse mechanism. The seismic analysis discussed in the following section, carried out considering an earthquake with magnitude similar to that of AD 62 (almost certainly acting in the south-west north-east direction), will clearly show the collapse mechanism occurrence of the structures coherent and coincident with that mentioned above.

In the authors' opinion no other important damage was recorded at the date of the first earthquake, because the collapsed masonry portions were suddenly rebuilt and, at the same time, the longitudinal masonry wall facing the *palaestra* was strengthened (through the infill of two pre-existing windows) and its exterior façade was successively decorated in painted stucco.

In a sense, the interventions carried out on the structures can be considered not only works aimed at securing the building, but also aimed at a final restoration of the structures and the overall architectural elements. The increase of the diameter of the peristyle columns (whose stucco coating recalls that in the façade decoration) could belong to the same intervention strategy to improve their stiffness, consistency and look.

The restoration works of the baths were not concluded because, some years later, another important earthquake struck the Vesuvian site.

Reading the effects provoked by this second earthquake, it can be assumed that the seismic action was probably east-west directed.

The collapses detected on the façade of the wall facing the *palaestra*, in correspondence to the colonnade line of the peristyle, are attributable to this second earthquake, as well as those on the south-east corner of the building, which comprise the wide cuneiform portion, subject to the thrust of the hip rafter of the hip roof, increased by the seismic acceleration, and a portion of the longitudinal masonry wall connected to it (Fig. 10).

From the analysis of several signs visible on the structures, it can be assumed that the damage mechanisms which certainly occurred in a fast sequence involved in chronological order (Ruggieri, 2017):

- the south-east corner collapse of the building also involving adjacent masonry portions;
- the activation of the overturning, towards the inside of the *destrictarium*, of the wide wall portion facing the *palaestra* between the corner and the greater vertical crack which still today clearly shows the beginning of a rotational movement.

Referring to the second point, it can be easily hypothesized that, due to the loss of the link with the corner, the peripheral masonry wall suffered a high vulnerability condition subject to the hammering action of the wall above the peristyle colonnade, orthogonally oriented and perfectly situated at the centre of the wall portion involved in the overturning activation. About that, it can be noticed that the axis of the wall rotational hinge has settled at the height, approximately 3 meters, which exactly corresponds to the level of the timber frame placed above the capitals of the columns.

The resultant cracking pattern (Fig. 11) highlights a vertical crack at the height of approximately 2.5 meters from the floor, which provoked a meaningful out of plumb which at the top reaches the value of 35 cm.

Therefore, the maximum rotation has involved the masonry wall portion which was directly subjected to the hammering action of the peristyle colonnade and the wall above it. Another crack (Fig. 11) involved that masonry wall at a distance of 1.5 meters from the previous one. Even if it is clearly readable, it is a minor crack since in correspondence to it the wall portion has taken advantage of the existence of the transversal inner brace wall which was able to act as an intermediate restraint even if it is not linked to the wall under study (Fig. 4a e 12).

Analyzing this second sequence of damages and observing the relation between these damages and the strengthening interventions carried out at the moment, it is clear that the strategy adopted in this case was only aimed at securing the structures. The buttresses, specifically those executed in correspondence to the *destrictarium* wall towards the east, seem to be aimed at suddenly preventing further collapses, waiting for more targeted and final interventions that, unfortunately, could not be executed due to the eruption in AD 79.

5. Numerical Model of the Stabian Baths

Aimed at assessing the *destrictarium* block response to the historical earthquake in AD 62, a 3D-numerical model of the north-west portion of the Stabian Baths has been carried out. The portion composed of the block along the Abbondanza Street has been detected, where there are the main entrance to the baths, the shops on the street and the colonnade, and the buildings facing the Lupanare Alley, where there are other shops, the two blocks devoted to *destrictarium* and *nymphaeum* and the swimming pool. Indeed, the portion analyzed can be considered as an independent structural unity, since it is separated from the adjacent blocks by the presence of the main entrance and a secondary entrance from the Lupanare Alley.

The analysis has been performed using the commercial software Aedes-PCM (Aedes Software, 2000), suitably developed for the analysis of existing masonry buildings, according to the present Italian Building Code NTC2008 (DM.LL.PP., 2008) and/or the Eurocodes (CEN, EN 2006).

The numerical model has been subjected to two types of analysis: the global seismic analysis under a design response spectrum and the local kinematic analyses for the assessment of damage or collapse mechanisms due to masonry portions overturning detected in the block under study.

For the global analysis, the architectural model has been carried out (Fig. 13) and transformed into the equivalent frame structural model, where all the wooden floors have been assumed as deformable and the wooden roof as thrusting on the peripheral masonry walls. The deformability hypothesis is coherent with the statement that the floor structure was composed only of very little spaced joists (approximately 20 cm), as it can be noticed observing the holes which are still present in the masonry walls (Fig.14).

The double-height blocks of the *destrictarium* and the northernmost *nymphaeum*, between which there is the swimming pool, certainly had a sloping roof. Through the damage analysis of the corner between the masonry wall facing the *palaestra* and the wall between the *destrictarium* and the shops on the Lupanare Alley, one can easily hypothesize, also according to several historical reconstructions in literature, that the roof was a hip roof and that the corner overturning had just been caused by the thrust exerted by the hip rafter. For this reason, the hip roof has been assumed in the numerical model.

In the numerical model, all the floors have been considered as load distributors on the masonry walls both in the vertical direction and the horizontal direction in the case of the roof.

As observed during inspections of the site and from the carried out relief campaign, the storey floors of the shops were warped in the direction of the two street axes. Therefore, in the model such a warping has been considered in order to correctly distribute the loads above the transversal walls between the shops. In order to give account to the thrust from the sloping roof, the roof warp has been defined orthogonally to the shops walls facing the streets and orthogonally to the peripheral walls of the *destrictarium* and the *nymphaea* blocks.

Regardless of the variable loads, the gravity loads of the floors assumed in the model have been directly obtained from historic information on the constructive technologies and the amount of the materials used in the layers of the deck (mixture of lime, straw and wooden planks).

Regarding the load-bearing masonry walls, with an average thickness of 0.55 meters, the mechanical parameters taken from sheets of the materials present in the Italian NTC 2008 have been adopted as reference values, considering the minimum values of a coursed rubble masonry which is sufficiently representative and coherent with the Pompeian brickwork. The mechanical parameters, the strengths and the elastic modulus adopted in the model are presented in Tab. 1.

In order to perform the local analyses, related to the study of the mechanisms activated by the seismic sequence in the 1st century AD, the structural software has been used to develop a suitable kinematic model from the architectural one, in which all the overturning mechanisms have been defined by cutting the masonry wall portions involved in each mechanism. Such mechanisms have been deduced by observing the existing cracking patterns and the lack of masonry portions due to the collapses.

Specifically, considering the events which were supposed to occur in sequence during the earthquake, two groups of mechanisms have been analyzed. The first one refers to the events provoked by the earthquake in AD 62 and deals with the damages of the *nymphaeum* room of the *destrictarium* block. The second group, instead, refers to the following earthquake and deals with the masonry walls of the *destrictarium* facing the *palaestra* and the shops.

The first group mechanisms, activated by the earthquake that almost certainly acted in the north-south direction, are:

- the north-east corner overturning of the *nymphaeum* (mechanism 1), at the intersection between the longitudinal masonry wall facing the *palaestra* and the transversal one facing the swimming pool, which are both pierced by the two wide arched gates. This mechanism was facilitated by the high vulnerability level of the actual state of the corner, due to the thrust action exerted by the hip roof and the hammering of the hip rafter, in addition to the thrusts resultant of the two arched gates;
- the two peripheral masonry walls overturning (mechanisms 2 and 3) which were weakened by the lack of the link provided by the corner before the collapse. Also this mechanism was certainly facilitated by the thrusting roof, in addition to the fact that the thrust action is exerted at the top of a double-height wall without an intermediate floor.

The second group mechanisms, activated by the earthquake that almost certainly acted in the east-west direction, are:

- the overturning beginning, towards the inside of the *destrictarium*, of a wall macroblock facing the *palaestra*, between the corner and the major vertical crack visible in Fig. 11, not prevented by any horizontal retaining structure since it is a double-height block without an intermediate floor, as mentioned above (mechanism 4). It is hypothesized that the wall overturning, due to the hammering action exerted by the masonry wall above the colonnade, could also have involved a portion of the wall better linked to it, thus generating a retaining effect. Probably, the presence of the retaining piece of the orthogonal wall is the reason why the overturning did not activate completely and the wall portion which displaced reached the intermediate equilibrium configuration that it is still visible. Considering that the vertical cracks begin approximately at the level of the wooden lintel which stands over the columns, it follows that the cylindrical rotational hinge should have created just at that level. In fact, the sequence of the columns is the weakest and most deformable part of the colonnade which, working as a sequence of vertical trusses, could not exert a hammering action against the lower portion of the longitudinal wall. On the contrary, the rotational hinge should have placed at the bottom of the wall which, probably, would also have entirely collapsed;

- the overturning of the corner between the first vertical crack of the *destrictarium* longitudinal wall and the first transversal wall which is perpendicular to the wall which divides it from the shops on the Abbondanza Street (mechanism 5). Also in this case, vulnerability of this element is due to the presence of the hip rafter of the thrusting roof;
- finally, the long masonry wall over the colonnade, by that time detached from the *destrictarium* wall and subjected to the thrusting action of the sloping roof, certainly collapsed suddenly thereafter following the overturning mechanism around at a cylindrical hinge in line with the wooden lintel over the colonnade, on which the masonry brickwork remains prove the presence of the wall (mechanism 6). Portions of the masonry brickwork are still visible in correspondence to the entrance and therefore at the beginning of the colonnade (Fig. 15).

The seismic input used to perform both the analyses is referred to a design spectrum according to the Italian Building Code contextualized to the building site in Pompeii. The design spectrum has been assumed equal to the elastic one, therefore the unit structure factor has been adopted, in order to implement the abnormal 1st century seismic event that, as proved by historians, was a catastrophic event.

6. Numerical analyses and results

The global seismic response of the structural unity detected in the whole Stabian Baths has been assessed performing the nonlinear static analysis (pushover), adopting a linear distribution of the horizontal seismic forces (proportional to the masses) and the centroid of the first floor as the displacement control point.

This type of analysis has not provided results coherent with the data actually detected. Figure 16, which shows the coplanar eccentric compression force verification, clearly reveals that the equivalent frame model is not able to interpret the actual local vulnerabilities of the buildings as well as each masonry wall. Indeed, the only masonry wall portions detected as elements prone to collapse are the storey spandrels above the shops doors on the streets and the storey spandrels above the dwelling windows which are on the upper floor.

Under these interpretative assumptions of the model, the *destrictarium* building does not seem to suffer damages. Indeed, except in the case in which the seismic action is hypothesized in the –Y direction, i.e. from west to east, in all the other cases the Ultimate Limit State verification for life saving limit state (hereafter SLV) highlights a risk factor, computed as the ratio between capacity and demand as a function of the Peak Ground Acceleration (hereafter PGA), comprised between 1.075 and 1.089 (Table 2).

Ascertained that the catastrophic damages provoked by the 1st century historic earthquake are not highlighted by results of the global analysis performed in accordance with the conventionally proposed modeling procedure, local analyses of the damage or failure mechanisms of the masonry wall portions have been performed.

Six kinematic models have been developed (Fig. 17) in order to define the mechanisms related to the first and second seismic event. The linear kinematic analysis results are presented in Table 3, where α_0 is the collapse load factor, M* the participating mass, a_0* the spectral acceleration which activates the mechanism, a_1* the acceleration required above a rigid body, a_2* the acceleration required above a deformable body, a* the maximum between a_1* and a_2*, PGA,CLV the capacity as a function of the PGA for SLV and PGA,CLV / PGA,DLV the seismic risk factor as a function of the PGA for SLV.

For each analyzed mechanism, the seismic risk factor computed is much lower than one, ranging from 0.35 to 0.73.This highlights the actual vulnerability of the masonry wall portions that, in effect, collapsed during 1st century seismic events. It is worth noting that only the overturning mechanism of the eastern masonry wall macroblock (mechanism 4) has a risk factor prone to one (0.969). Indeed, this condition is perfectly coherent with the fact that such a masonry wall portion, actually, has not completely overturned, but it has displaced in an out of plumb position towards the inside of the building.

7. Conclusions

Through a methodology which crosses data coming from seismological surveys, taken from the literature, with the seismographic surveys carried out by the authors, in this paper a damage analysis of the Stabian Baths in Pompeii due to the 1st century earthquake is presented. The analysis has been addressed to the *destrictarium* block, where sufficiently evident signs have been detected to formulate hypotheses coherent about the principals events timeline occurred in the period between AD 62 and AD 79, the year of Vesuvius eruption. The analysis of the cracking pattern, the collapses, the lacks and the historic restorations has been supported by the use of numerical modeling of the building which have confirmed the formulated hypotheses.

The historical sources tell about a catastrophic seismic event, occurred in AD 62, which caused great damages to the baths structures. From the analyses discussed in the paper it has been concluded that the earthquake mainly occurred in the north-south direction, causing wide masonry wall portions collapses of the *nymphaeum* adjacent to the *destrictarium*. It has also been ascertained that, in the following years, the inhabitants of Pompeii carried out not only reconstruction works of the collapsed masonry walls, but also generalized strengthening interventions. These interventions are specifically detected in the increase of the diameter of the colonnade columns, the infill of the pre-existing windows in the exterior wall of the *destrictarium* and the wall finishing by the use of plasters based of painted stucco decorations which also resulted in a general restyling of the baths that has obtained the formal aspect that is currently visible.

Furthermore, the analyses have proved that a following important seismic event occurred, causing new damages and collapses to the structures. From the damages analysis it has been concluded that the second seismic event, even if it had perhaps a lower intensity, caused more important damages than the previous earthquake. It can be clearly proved if one assumes that the earthquake mainly occurred in the east-west direction because, as confirmed by the performed numerical analyses, according to this condition it is possible that some resisting elements of the building orientated in the disadvantaged direction and, in this specific case, also the weakest, have gone out of use. The hammering of the east wall of the *destrictarium* exerted by the wall over the colonnade was able to break, through two perfectly vertical cuts, the same wall and to generate a macroblock. It didn’t fall down, but it suffered a rotation towards the inside of the building. It’s clear that this damage cannot be referred to the first earthquake, as proved by the two vertical cracks which involve also the stucco finishing, which is a work certainly executed successively. Also the south-east corner collapse was proved to be the consequence of this second event, facilitated by the trust exerted by the sloping roof and the double-height of the wall, without the aid of an intermediate floor capable to act as a restraint and oppose to the wall overturning.

From the authors' direct investigation on the building, in its present state, which is the result of centuries of "freezing" after the Vesuvius eruption in AD 79, it has also been deduced that the inhabitants of Pompeii had obviously been caught off guard by this second seismic event and that, as a consequence, implemented emergency measures exclusively aimed at preventing new mechanisms and further collapses. This was also due to the succession of frequent seismic shocks that prevented the execution of final interventions. As a clear example, the existence of the buttress inside the *destrictarium* is the proof of it. Indeed, these interventions could not be compatible with the public use of the rooms. A further proof is the lack of the pipe for water conveying, ascertained during the nineteenth century archaeological excavations; therefore the baths building was out of service in that period.

Therefore, the results of the structural analyses must be considered as a support for timeline reconstruction of the events and have provided useful information to parameterize the earthquake, in terms of seismic action direction but also of PGA. Data obtained from the analyses, the vulnerabilities detected in the constructive Pompeian system, the parameters obtained to qualify the earthquake form a source of knowledge that can also be used to deal with the current problem of the protection of the Pompeii's archaeological site from the seismic risk.

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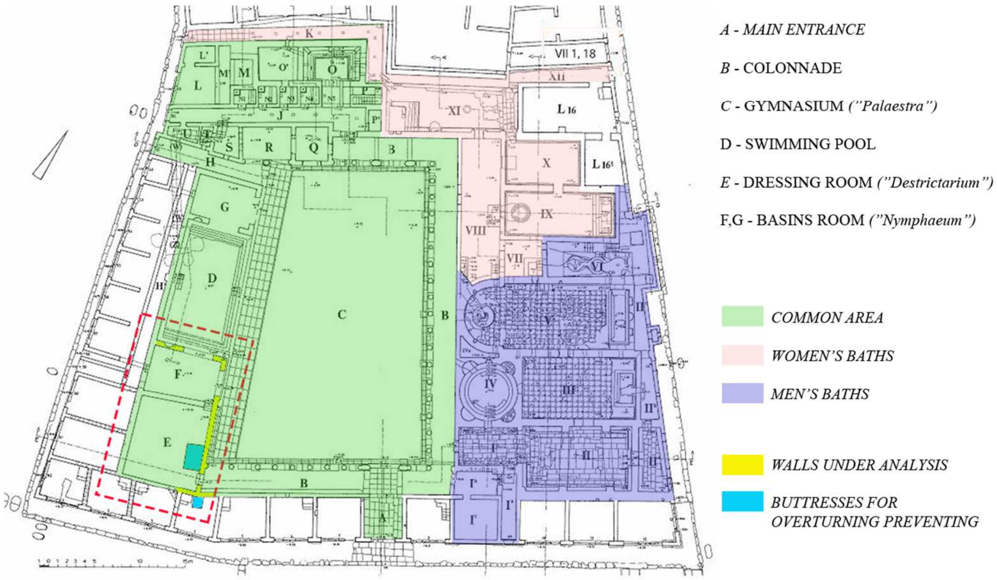

Fig. 1. Stabian Baths site plan. Elaboration of Hans Eschebach (1979) original drawing to distinguish the women's baths from the men's baths as well as the common area and to highlight the use of the main blocks which have been structurally modelled. The destrictarium masonry wall damaged by AD 62 earthquake is also indicated together with the strengthening interventions carried out consequently

179x103mm (200 x 200 DPI)

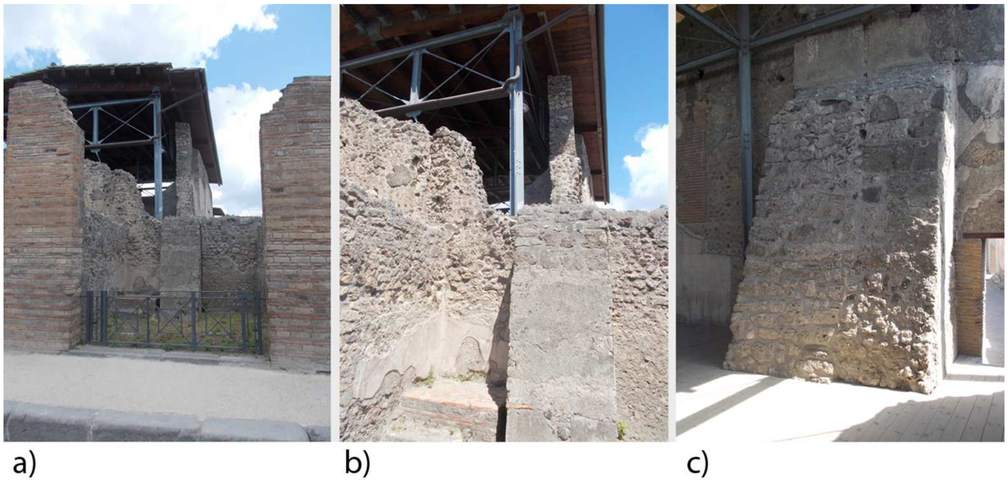

Fig. 2. a), b) Masonry buttress at the south-east corner of the destrictarium block in line with the longitudinal wall; c) masonry buttress inside the block placed in correspondence to the colonnade

173x83mm (200 x 200 DPI)

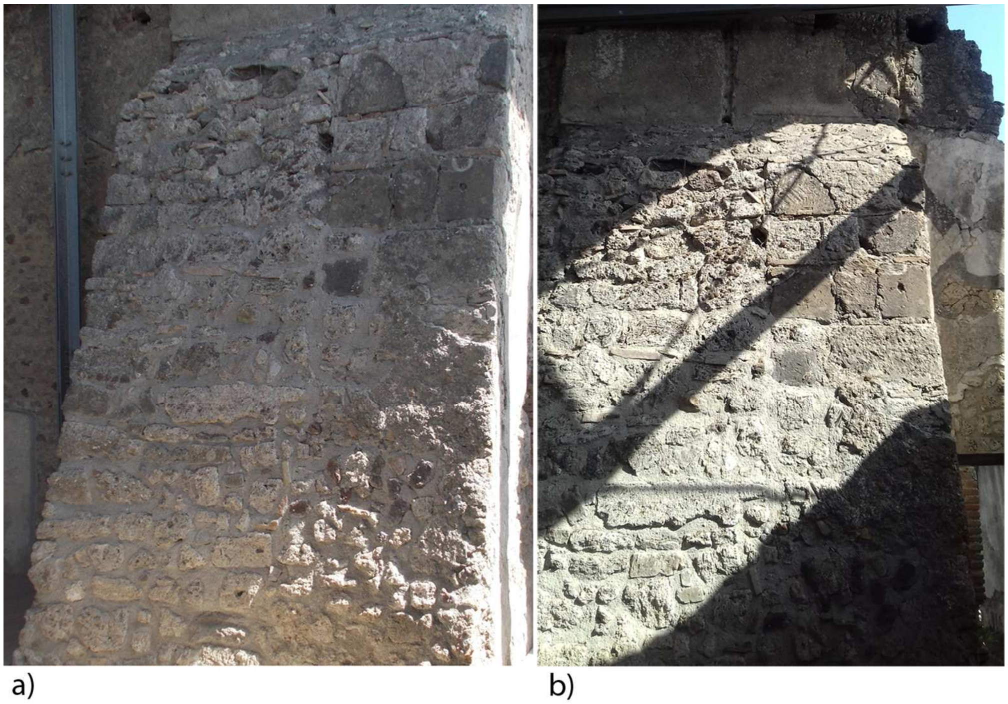

Fig. 3. a,b) Detail of the two different constructive techniques adopted to build the masonry buttress inside the destrictarium block

179x125mm (200 x 200 DPI)

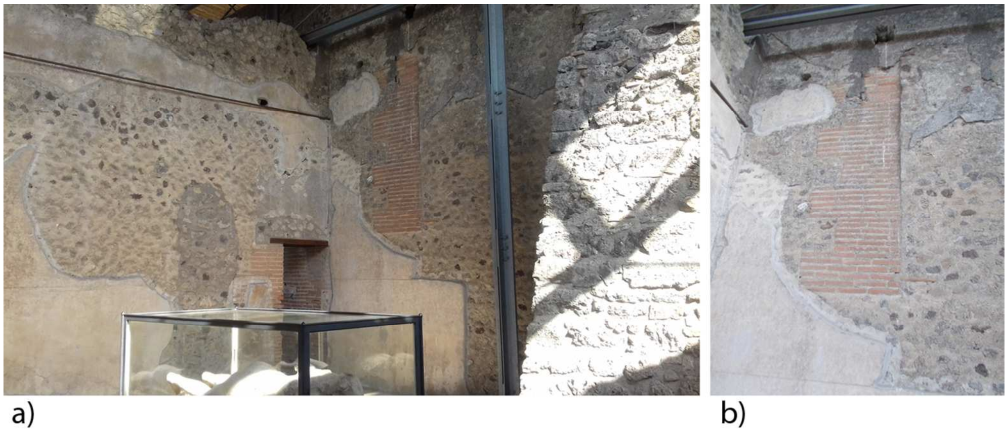

Fig. 4. Detail of the masonry arrangement of the destrictarium walls, seen from inside the block. In a) the inner wall separating the destrictarium from the nymphaeum and in b) the infill of two pre-existing windows on the east wall facing the palaestra

179x76mm (200 x 200 DPI)

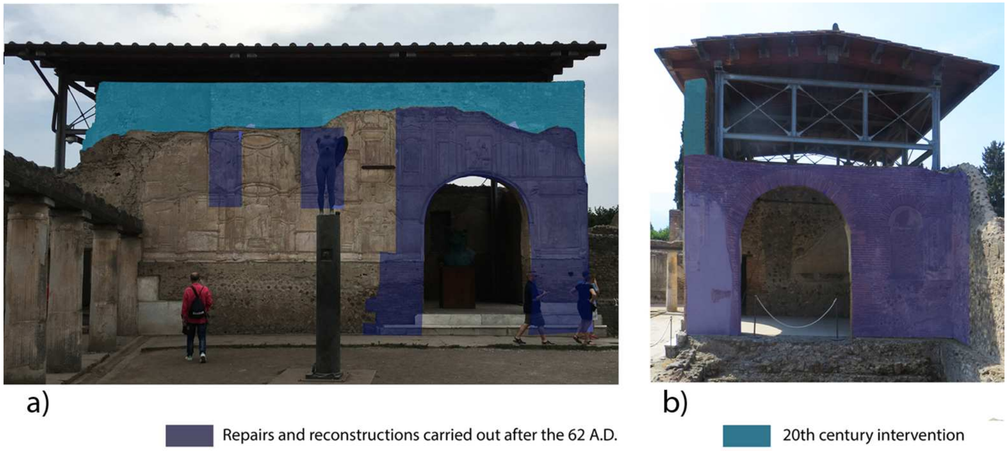

Fig. 5. Post-earthquake reconstruction interventions of some masonry wall portions collapsed and infill interventions of the windows on both the east (a) and north (b) wall of the destrictarium-nymphaeum block. The photo shows also the top of the east wall reconstruction, carried out in the mid-twentieth century

179x81mm (200 x 200 DPI)

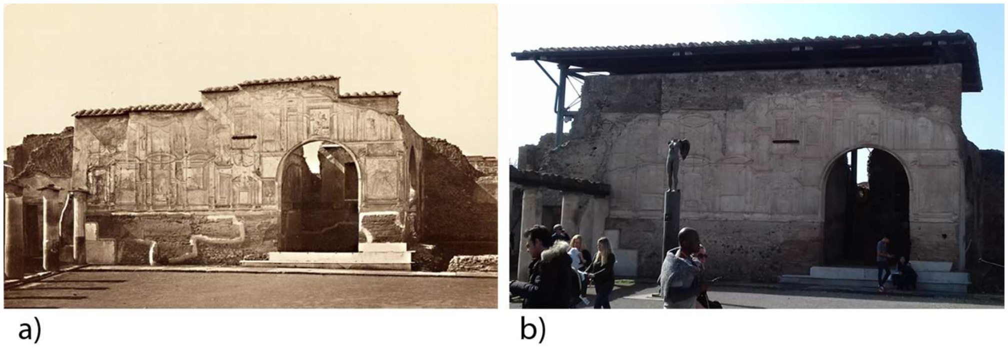

Fig. 6. Destrictarium block seen from the palaestra: a) historical photo; b) current photo (February 2017)

178x61mm (200 x 200 DPI)

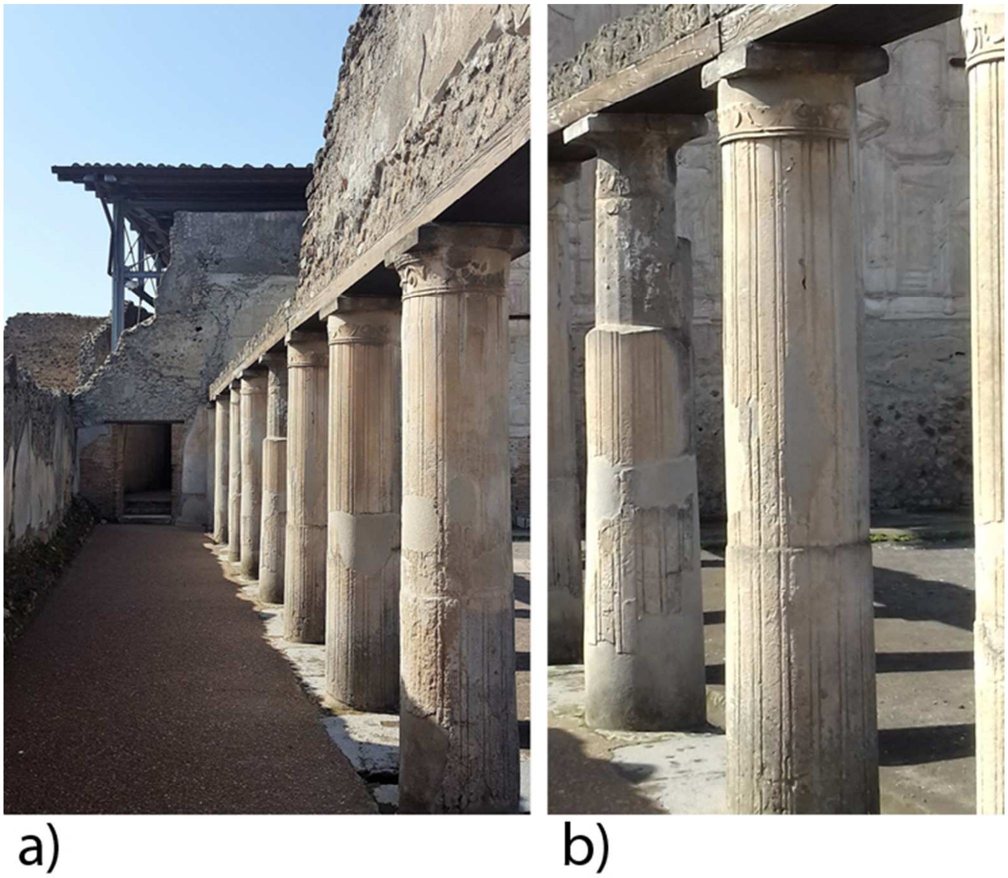

Fig. 7. a) Portico leading to the destrictarium block; b) detail of the columns which highlights the strengthening interventions based on the increase of their diameter

93x82mm (200 x 200 DPI)

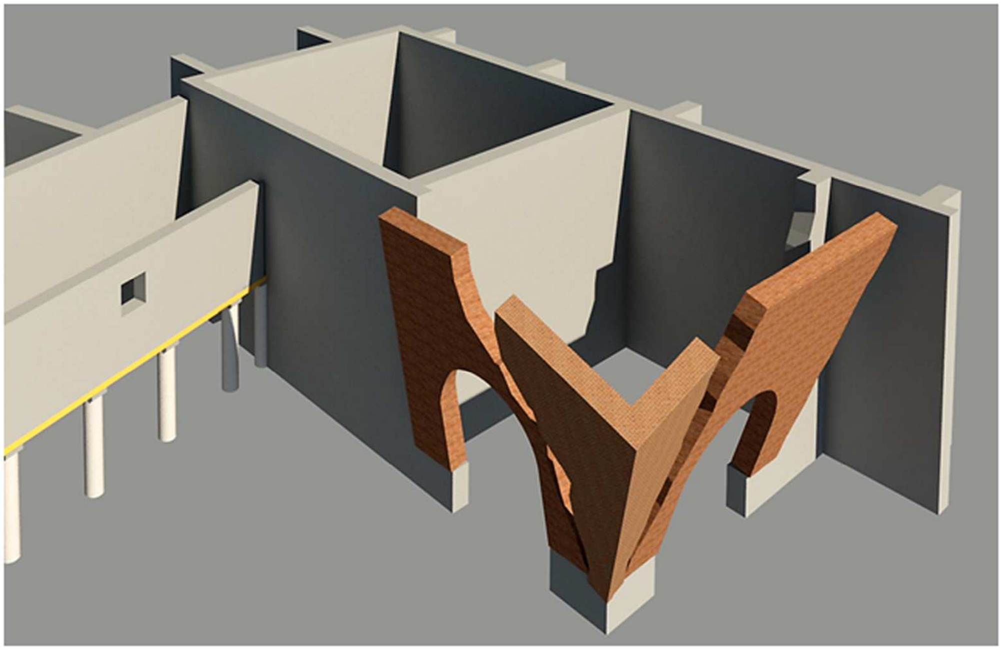

Fig. 8. Schematic representation of the collapsed nymphaeum masonry portions (north-east side) attributable to the first earthquake in AD 62

179x116mm (200 x 200 DPI)

Fig. 9. The nymphaeum of the destrictarium: a) east wall facing the palaestra; b) north wall facing the swimming pool

179x82mm (200 x 200 DPI)

Fig. 10. Schematic representation of the collapsed destrictarium masonry portions (south-east side) attributable to a subsequent seismic event

179x111mm (200 x 200 DPI)

Fig. 11. a) Cracking pattern which highlights two main vertical cracks on the destrictarium masonry wall; b) detail of the minor crack; c,d) detail of the major crack

179x66mm (200 x 200 DPI)

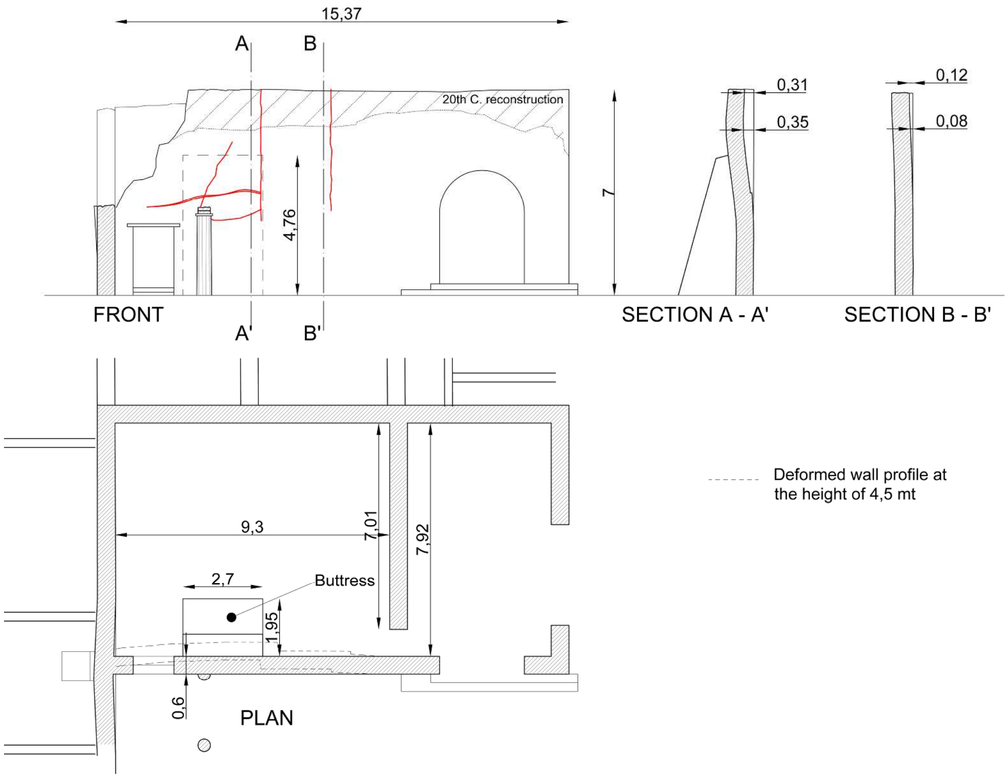

Fig. 12. The destrictarium block. Relief of the two rooms plan, elevation and cross sections of the masonry wall facing palaestra

370x284mm (200 x 200 DPI)

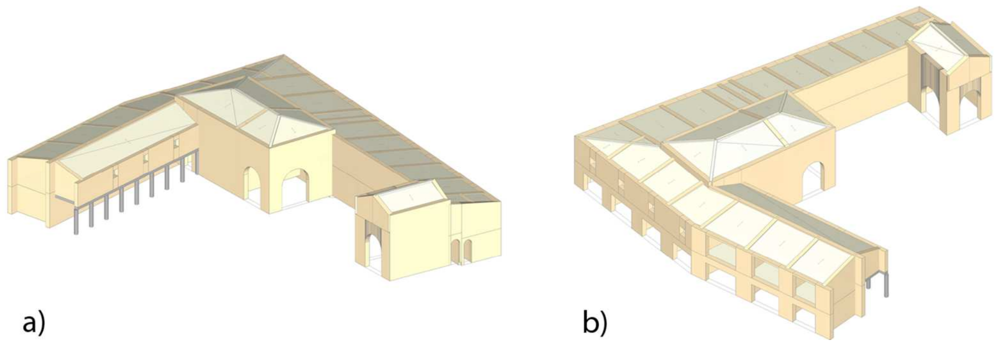

Fig. 13. Architectural model of the structural unity under study of the Stabian Baths, carried out by the software Aedes-PCM: a) view of the destrictarium and portico leading to it from inside the palaestra; b) view of the shops on the Abbondanza Street

179x60mm (200 x 200 DPI)

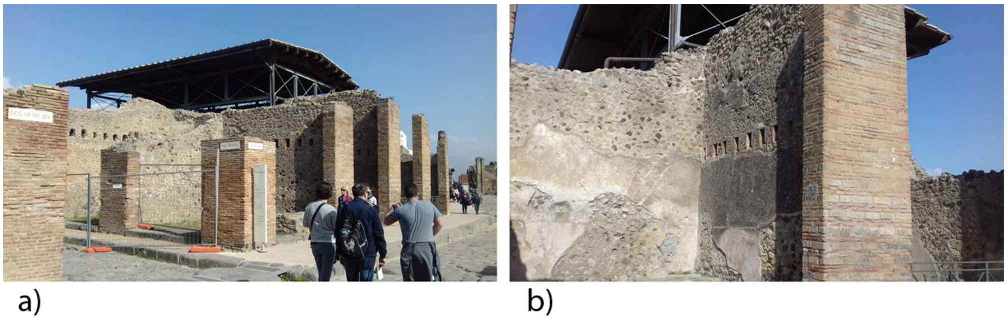

Fig. 14. a) Blocks of the shops at the corner between the Abbondanza Street and the Lupanare Alley; b) shops next to the destrictarium block and detail of the holes in the walls for the frames which supported the timber floor of the dwellings on the upper floor

178x56mm (200 x 200 DPI)

Fig. 15. Colonnade along the palaestra south side: a) overview from the palaestra courtyard; b,c) detail close to the baths entrance where remains of a continuous wall with windows above the wooden lintel of the columns is still visible

179x67mm (200 x 200 DPI)

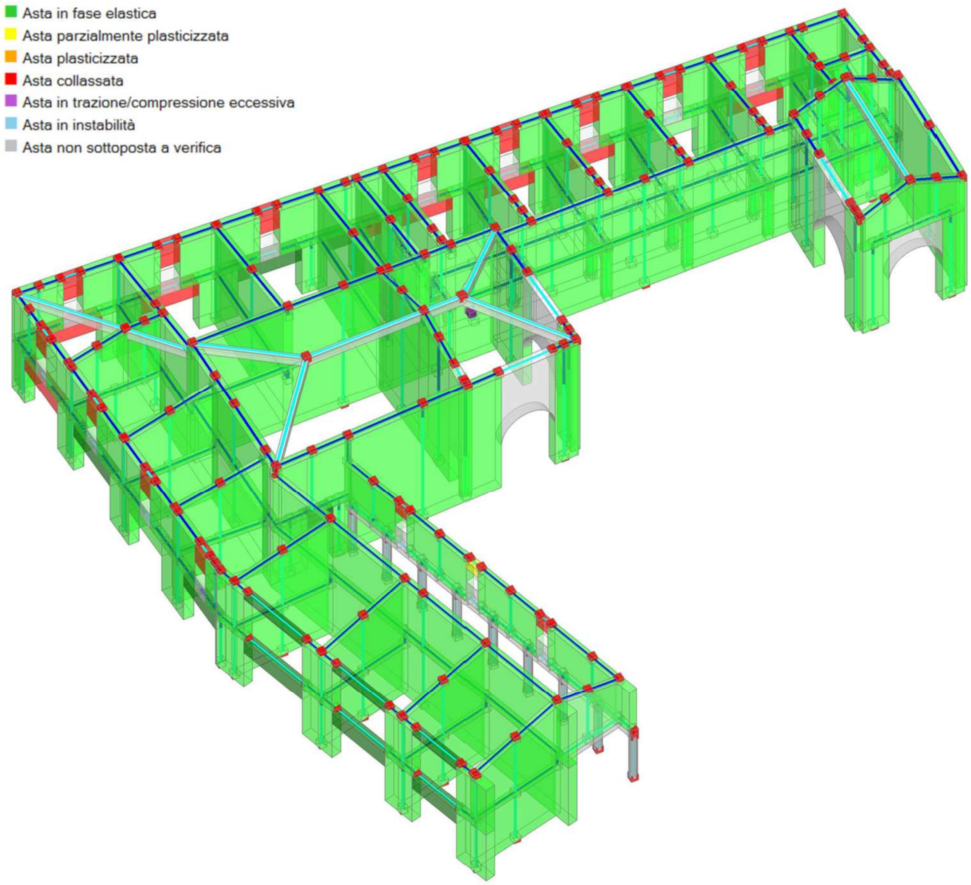

Fig. 16. Structural model: results of the coplanar eccentric compression force verification executed through the pushover analysis (Aedes–PCM)

179x162mm (200 x 200 DPI)

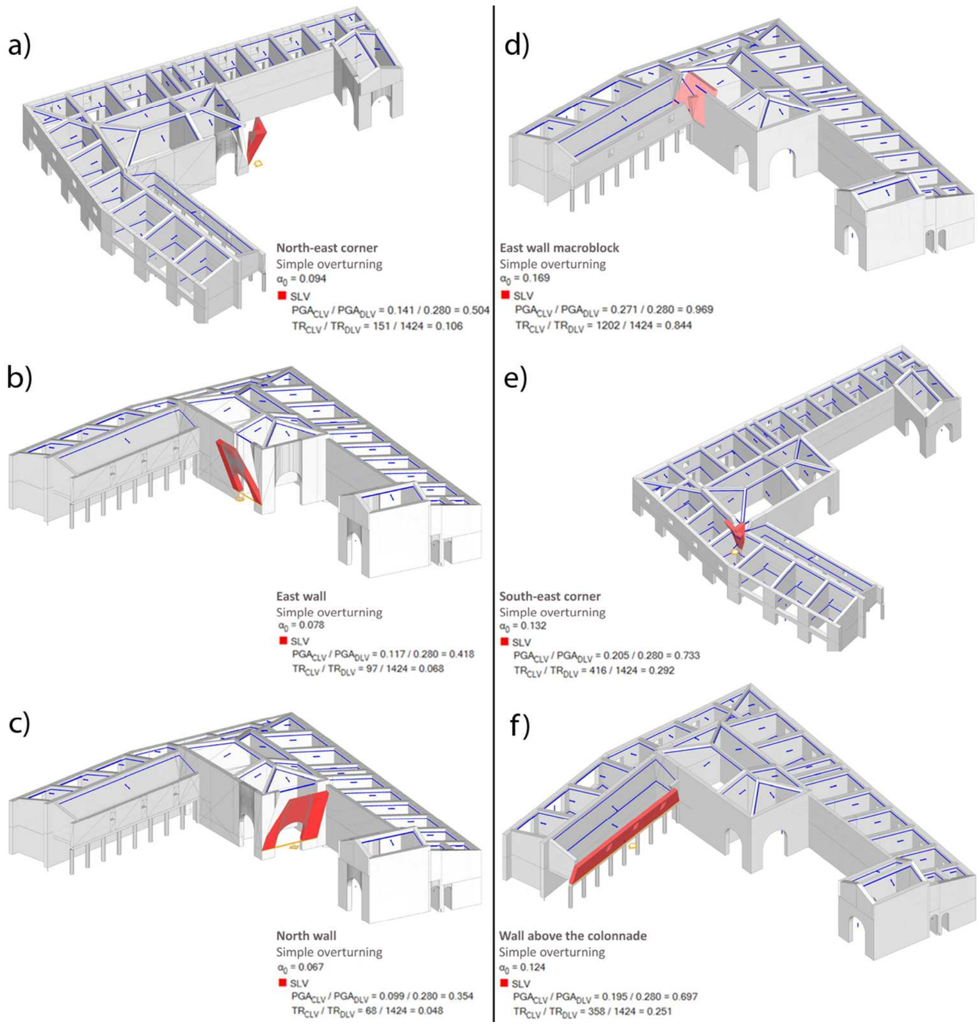

Fig. 17. Collapse mechanisms analysis (Aedes-PCM). First seismic event: a) north-east corner overturning of the nymphaeum; b) east wall overturning; c) north wall overturning. Subsequent earthquake: d) east wall macroblock overturning of the destrictarium; e) south-east corner overturning; f) wall above the colonnade overturning

179x183mm (200 x 200 DPI)

Type	Knowledge level	Elastic Modules [N/mm²]		Strenghts [N/mm²]				Specific Weight [kN/m³]	Friction Coefficient
		Young's Modulus	Tangent Modulus	Compression	Shear	Traction	Horizontal Compression		
Coursed rubble	LC1	1020	340	2.00	0.04	0.20	1.00	20.00	0.40

Table 1. Mechanical parameters of the load-bearing masonry walls used in the numerical model

180x29mm (300 x 300 DPI)

curve n.	Earthquake direction	PGA,CLV [a]	PGA,DLV [b]	PGA,CLV/PGA,DLV [c]
1	+X (south-north)	0.301	0.280	1.075
2	-X (north-south)	0.305	0.280	1.089
3	+Y (east-west)	0.305	0.280	1.089
4	-Y (west-east)	0.253	0.280	0.904

[a]Capacity as a function of the PGA for SLV; [b]Demand as a function of the PGA for SLV; [c]Seismic Risk Factor

Table 2. Pushover analysis results of the global structural model

180x47mm (300 x 300 DPI)

		Capacity			Verification				
n.	Mechanism	α_0	M* [kgm]	a_0^* (g)	a_1^* (g)	a_2^* (g)	a* (g)	PGA,CLV	PGA,CLV/PGA,DLV
1	North-east corner	0.094	12,229	0.07	0.14	0.136	0.14	0.141	0.504
2	East wall	0.078	22,259	0.058	0.14	0.136	0.14	0.117	0.418
3	North wall	0.067	26,584	0.049	0.14	0.136	0.14	0.099	0.354
4	East macroblock	0.169	29,552	0.136	0.14	0.136	0.14	0.271	0.969
5	South-east corner	0.132	11,664	0.103	0.14	0.136	0.14	0.205	0.733
6	Wall above the colonnade	0.124	46,650	0.097	0.14	0.136	0.14	0.195	0.697

Table 3. Results of the linear kinematic analysis related to the six collapse mechanisms under study

180x35mm (300 x 300 DPI)