The mechanics of *opus reticulatum: Reticulata structura, qua frequentissime Romaestruunt, rimis opportuna est!*

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Reasons for the choice of an arrangement of small stones at 45 degrees are still unknown. However, over the centuries, contrasting explanationshave alternated, converging, in modern times, in the following two main justifications: (i) aesthetics of its facing (Adam [1994] 2010) (figure 1), and (ii) astructural reliabilitydue toa special bonding between facings and the inner core (Giuffré [1991] 1999).

Regarding the latter,Giuffré (1991)observed thatthe mortar in the facings and within the inner core harden and cureat different rates on account of a dissimilarity in the ratioof aggregate to mortar between the inside (*ceamenta*) and the outside (*cubiliae*). Here, *cubilia* and bricks are expected to limit vertical concretion of mortar by physically breaking into the concrete mass[1] –thus, creating a strong bond between the ingredients.

It is crucial to note that Vitruvius (Krohn 1912), in Roman times, described this type of building technique as vulnerable and weak on account of the unstable configuration of its bed joints (45 degrees) and poor bonding of its constitutive ingredients[2]. On the other hand, Pliny the elder reported that «*Reticulata structura, qua frequentissime Romaestruunt, rimis opportuna est*» (Plinii 1844, 1347).

This well-known dichotomy was resolved in practice. This shows an extensive use of *opus reticulatum*. Many examples can be found in central and central-southern Italy (Lugli 1957, Lancaster, 2009), where, numerous surviving buildings ranging from rural Villas to Monumental constructionsthat have stood the test of time.

On the reading of old treatises: *Vitruvius*, *Perrault* and *Galiani*

By analyzing the text of Vitruvius, it is apparent how two different building techniques were considered as typical for Roman standards in building construction, and in common use during his life. These are: *Opus incertum* and *Opus reticulatum*. Vitruvius compared the two techniques and came to a negative judgment of the *reticulatum* as opposed to the *incertum* which he considered *Imbricatus*[3].

In this regard, it is interesting to follow the debate around the inexact use of the word *imbricata* in codes, which led over time[4] to a misinterpretation of this passage from Vitruvius. In particular, it was the word *Incerta* was replaced with *Inserta* (Perrault1684[5]) and *imbricate* with *implicata* (Galiani 1790),and identical grammatical forms were translated with contrasting meanings (Cesariani 1521; Caporali 1536).

According to Galiani, Perrault altered the word *Incerta* in *Inserta* when used in relation to the term *imbricata*. This aimed at providing readers with an idea of masonry that was similar to brickwork, i.e. *Inserta Imbricata*[6], suggesting alternating courses of headers and stretchers cut into small pieces and probably ashlar dressed. This is mainly due to the fact that the word *Imbricata* was derived from the Latin term *Imbrices*. Imbrices are clay elements commonly identified with tiles or hollow ceramic components.

Galiani drew attention to this mistaken interpretation by Perrault noting the contrasting aesthetic of

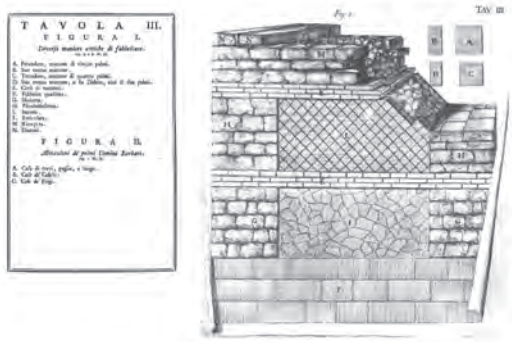

Figure 1
Different Type of Opuses(Galiani 1790,vol. 2, Tav.III)

the masonry he described which would correspond to isodoma or pseudo-isodoma masonry [7] rather than an irregular bond.

Caporali thought that *Inserta Imbricata* referred to terracotta tubes[8] laid in a masonry-like pattern –thus being given this name. Cesariani, on the other hand, believed that tiles were set at specific points to regularize the masonry to achieve uniform courses.

It is crucial to observe that this idea of a sequence of clay elements aligned to a horizontal line was pursued on account of the Latin word *Imbricatus* which describes a pattern of overlapping tiles having a curved profile and progressing along a line.

The *opus* described by Vitruvius –in comparison with the *reticulatum*– is intended to be neither made out of tiles norto have regular courses which, in fact, he described as a pattern of very small stones. However, this observation cannot exclude the possible use of reinforcing brick courses.

In fact, it might also be that Vitruvius was providing us with a comparison between the simplest type of *opus reticulatum* and its mixed form, usually referred to in the literature as *opus mixtum*. As reported by Lugli(1957) the term was invented by moderns[9], and it would thereforenot be surprising if no specific term is used by Vitruvius in his code to differentiate this type of masonry from others.

In the past, the term *opus mixtum* was often used to describe any Roman building typology that cannot be fitted into the standard categories. Nowadays, it refers strictly to reticulate construction –rarely *opus incertum*– which are box-enclosed into patterns of bricks functioning as quoins and/or regulatory courses (figure 1).

In this light, it is possible that the translation provided by Cesariani was mostly exact. While, Perrault and Galiani were both altering at least one word in order to make the text more intelligible to readers. However, Perrault clearly understood the underlying meaning of this passage of Vitruvius, which aimed at providing an idea of interlocking masonry which failed to comply with the described typologies of masonry. Galiani, however, did not succeed in identifying the significance of the word *Imbricata* as signifying a mechanical interlock, and being responsible for the supposed superior performance of *opus incertum* over the *reticulatum*. In particular, Galiani exchanged the word *Imbricata* with *Implicata*[10] implying that the *opus incertum* incorporates stones set *alla confusa*[11] –leading to its unattractive appearance[12].

However, we do not know whether Vitruvius is here referring to the basic form of *opus incertum* or to the mixed type. As mentioned above, the term *opus mixtum* was conceived in modern times. In this paper, we therefore propose translating the word *Incerta* rather than *Inserta*, and *Imbricata* rather than *Implicata* deriving the word *Imbricata* from the Latin term *Imbricatus* –rather than *Imbrices*. In so doing, we aimed atsuggesting a mechanical interlock between irregularities of small sized stones[13] having similitude with the one existing between overlapping tiles as well as recalling the practice of setting regulatory courses to reinforce walls.

We would here complement Vitruvius in observing that this mechanical interlock will, as a general rule, be as strong as stones that are set with corresponding faces which are irregular and shapeless (Fonti et al. 2017).

The mechanics of *Opus reticulatum* in the words of Choisy, Lugli and Giuffré

Vitruvius observed that reticula façades can fail on account of some defects in execution which lead to a lack of bonding between wythes[14] and that this is common for this type of building technique.

If this is accurate, why did Romans progress from a rather solid and structurally safe system such as *opus incentum*, or its reinforced form, to an *opus*which often had defects?

The majority of authors seem to agree that this was mainly on aesthetic grounds as well as reduced

construction time[15] and costs[16]. The latter was especially significant for Romans because of their need for standardization and fast and simplified building procedures[17]. In fact, according to Choisy (1873) the use of this building technique led to a new technique of masonry construction[18]. It enabled the use of concrete having little compaction which is suitable for construction making limited use of formwork[19]. Formwork was replaced by the external withes in the various standard opuses. Depending on the strength of the wythes, compaction of the inner core was alternately applied. Due to the increasingly reduced thickness of the external wythes, compaction was often impracticable[20] as they became unable to withstand the out-of-plane horizontal actions produced by compaction processes.

Choisy informed us that, due to this issue, the inner cores of Roman masonry often showed hollow regions and unfilled vertical joints[21]. The problem was exacerbated by unequal distribution of sand, gravels and mortar which were neither pre-mixed in advance, and poured between wythes, nor laid and progressively compacted in situ, which was normal for the construction of foundations. To find a solution for this common type of failure, Choisy observed that the Romans regularly piled up sand, gravels and mortar in regular sequences of courses using a shovel[22] in order to increase strength to walls.

Despite this, according to Lugli, walls generally had a limited resistance to compressive vertical loads. This is because of the strength of *opus reticulatum* arises from the cohesive properties of its mortar. Lugli is not explicit about the issue of poor compaction. Nevertheless, this seems apparent to us. He also observed that Romans limited the height of reticulate facades to avoid constructions that were too slender.[23]

However, Lugli considers the stones (*cubilia*) of the reticulate façades pointing towards the inner core to contribute significantly to increasing stability[24] and load-bearing capacity.

As is well known, *cubilia* are stones perfectly dressed to form square-based pyramids, with the point penetrating into the wall. In adopting this technique, masons were bridging the gap which existed between the *opus incertum – imbricate* - and the unreinforced *opus reticulatum* providing the *reticulatum* with a mechanical interlock between the stones and the inner core.

Adam ([1994] 2010) suggested that «the masons noticed that the cementation brought about by good mortar made the arrangement of the stones irrelevant» (Adam [1994] 2010, 131).

On this point, the authors partially disagree; if this were true, stones would have been easily aligned with their edges horizontal and vertical to avoid the need for the more complex orientation of stones, which is as typical for *opus reticulatum*. Of course, the aesthetic argument also here applies.

In this regard, it is worth observing that such walls were often coated with fine pictorial surfaces and stucco. Because of this, some authors have supposed that reticulate surfaces were protected using rendering on the inside and external surfaces were left exposed[25]. We observed in Villa Arianna[26], amongst many other cases, that apparently reticulate façades were coated on both faces using very fine decorative pictorial surfaces (figure 2).

One can argue that decorative coatings were uniformly applied to mask a lack of homogeneity of the masonry placed at different times during the various construction phases of a Villa[27].While this might be a useful observation, it does not provide us with reasons for putting so much effort into building with *opus reticulatum*[28] given its supposedly structural weakness and beauty hidden beneath decorative rendering[29].

The authors believe that using wythes with such a special arrangement gives a clear technical advantage, over and above any aesthetic qualities.

To resolve this line of enquiry, the texts of Choisy, Lugli, Giuffré (1993) and Ceradini (1992) are analysed and compared.

Choisyin particular noted that external wythes were unable to stand upright without the aid of the inner core. This opens up the idea of an interdependence between wythes. Despite this, Choisy referred to the external wythesas a facing, merely use-

Figura 2
Reticulate façade protected using rendering at Villa Arianna (Stabiae) – outdoor face of walls

ful to protect the inner core from being left exposed. However, he explicitly refers here to *opus testaceum*[30] which he considered slightly superior to the *reticulatum*.

From *opus quasi-reticulatum* to *mixtum*

It is fundamental to the purpose of this paper to observe that while ancients were commonly addressing *opus reticulatum* as a single building type, four different subcategories can be identified which show increasing degrees of structural solidity: (i) *Opus quasi-reticulatum*; (ii) *Opus reticulatum*; (iii) *Opus reticulatum* having quoins and (iv) *Opus reticulatum* having both quoins and regulatory courses made with bricks.

In agreement with Lugli, Giuffré and Ceradini, we believe that regulatory courses were laid with the aim of reinforcing the opus with regard to out-of-plane actions[31]. Lugli addressed this issue especially for the *opus reticulatum* focusing on possible overturning of the facings on account of large vertical loads applied on top. Here, in contrast to the monolithic column of Coulomb which is failing along the tangent of least resistance to cracking[32] (figure 3,a), walls are supposed to act as multi-wythe masonry – thus, behaving as three different walls having different ratios of slenderness with regard to out-of-plane actions. Likewise, Choisy illustrates a similar mechanism of collapse which, in ancient times, persuaded the Romans to use formworks (figure 3,b).

However, Lugli does not study the mechanical behaviour of masonry walls. Rather, he provides us with interesting observations based on his deep knowledge of Roman building techniques. Giuffré and Ceradini, are the authors who address mechanics.

They start from the assumption that masonry members are assumed to act as rigid[33] or semi-rigid bodies, demonstrating that the out-of-plane response behaviour of a wall is mainly governed by geometry[34] (Heyman 1966, 2:249–279). Therefore, the height, thickness, and number of the different wythes are the parameters that must be considered to assess the out-of-plane vulnerability of an historical masonry wall. For this reason, there is a limiting height which defines the threshold value above and below which a wall will start to either slide or overturn –for a given externally-applied, out-of-plane horizontal force. It is apparent how the Romans strictly limited the height of their walls by introducing courses in the reticulate façades– thus, matching the above mentioned geometrical parameters[35].

The *opus quasi-reticulatum* and *Villa Arianna at Stabiae*

Direct observation of out-of-plane damage to Roman masonry has been conducted at Villa Arianna. Walls are found to have been affected by different kinds of

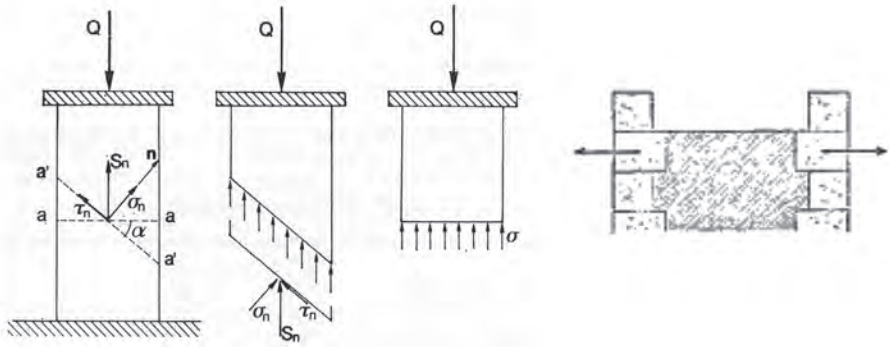

Figura 3
a) monolithic column which is failing along the tangent of least resistance to cracking (Benvenuto 1981, 303; b) facing failing out-of-plane on account of exceedingly vertical compressive stresses (Choisy 1873, 20)

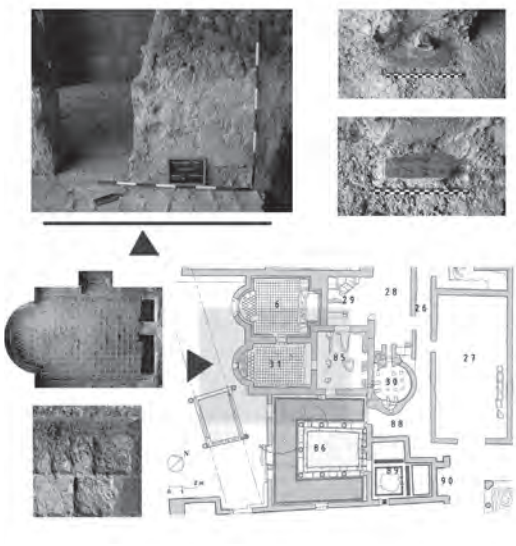

Figure 4
Villa Arianna walls in opus quasi-reticulatum lacking one external wythe and being covered by rendering. This is applied directly upon the inner core

damage, partial reconstruction and works of addition which most probably were a consequence of the Campania earthquake in 62 AD[36]. Although there is no common understanding on the exact date of this earthquake, it is possible that more than one seismic event shocked Campania region (Harry 1984, 53: 266-269) in a relatively short period of time, anticipating the eruptionof Vesuvius in 79 AD.

In particular, during the last excavation campaign (Gardelli et al. 2011, 209–216), several key observations were made regarding the historical damage that had occurred to the masonry structures of the baths of the villa. Here, walls which are positioned in the same row, were recognized as lacking one of the external wythes (figure 4).Furthermore, parallel walls located in a different row show similar damage resulting, at times, in full reconstruction of sections of masonry displaying different building techniques within the same façade.

By analysing the structure of the *tepidarium* (room 31), it was possible to observe an integration of the original floor in historic times on the NW side of the opus sectile floor.The work of addition runs alongside the missing wythes on the front of the wall (Gardelli et al. 2016, 439-48). Here, an unusual layering of the rendering can be recognized which was applied directly onto the inner core of the walls that had been left exposed after the earthquake. On the rear face of the wall an opus quasi-*reticulatum* was used. It is, therefore, apparent that originally,the walls were not lacking external wythes as these are necessary to construct walls. This observation allowed us to reasonably consider this to be post-earthquake historical damage.

This discovery confirms both the observations of Lugli and Giuffré as no regulatory courses were executed to reinforce walls, and *quasi-reticulatum* façades include relatively small sizes for the part of the *cubilia* which was meant to interlock within the concrete mass.

A further observation should be added here regarding the use of the word *quasi-reticulatum*. As reported by Lancaster (2009), this term is similar to *opus mixtum* being of modern origin. Wetherefore need to be cautious when applying this term. As shown in Figure 7, *quasi-reticulatum* referrs to a type of facing showing a precise rhomboid shape,and is clearly differentiated from both the *opus incertum* and *reticulatum*. Examples of all three different types are found within the boundaries of this Villa.

While the observations noted by Lancaster on the *opus reticulatum* are significant, technological aspects of Roman building techniques are beyond the purpose of this paper. Therefore, no observations on the history of building technology have been pursued unless strictly related to the structural aspects.

Giuffré and Ceradini also theorized that quoins contribute to the in-plane stability of walls – resisting horizontal actions while tightening the masonry in between. In the case of *opus reticulatum*, those are deemed to counteract the lateral forces generated by the *cubilia*. In fact, regulatory horizontal courses also redistribute vertical loads along the length of a wall. This load acting on stones with an oblique setting will redistribute forces laterally; therefore, the use of solid quoins, along with horizontal courses to enclose *cubilia* into a box-blocked scheme. Quoins are also crucial to resisting in-plane actions generated by earthquakes.

A reason for arranging stones at an oblique angle

Based on established theoriesthe previous discussion has addressed the reasons why reticulate structures were structurally reliable. However, it is still unclear why the stones are set at an oblique angle.

Manieri Elia (2003 [20]) thought this setting to be suitable avoid defectsin execution due to ageing of the exceedingly layers of mortar[37].

The authors consider that the opus of the facing has the double function of both stiffening the front face against out-of-plane overturning, and redirecting inclined loadsand achieving equilibrium by virtue of their inclined bed joints.

Analysis of studies conducted by Giuffré on a different matter has revealed material information to support our theories. In particular, he investigated the distribution and transmission of inclined vertical loads and applied at specific points on top of a wall built in *opus quadratum*. He demonstrated that by changing the dimensions of stones and reducing the surface area of contact between them, the equilibrium at any point of the block will be possible only if the direction of the reaction on each element is within the geometrical limits of its base, and that the inclination of this reaction is less than the one arising from friction[38](figure 5,a).It is apparent to the authors that this case also applies to a wall loaded in-plane by the thrust of an arch.

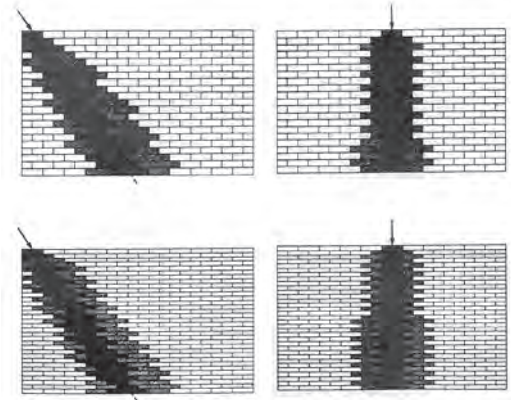

Figure 5
Wall of opus quadratum vertically loaded by a vertical dead load a) inclined; b) orthogonal (Giuffré [1991] 1999)

Giuffré also analysed and compared the case of a wall of *opus quadratum* vertically loaded by a concentrated dead load orthogonal to the top of the wall (figure5,b).

We here theorized that, by turning stones with an inclination suitable for responding to inclined loads arising from semi-circular arches,and orthogonally to those, the equilibrium is assured at any point of the wall making this much stronger to statical thrusts applied within itsprincipal plane.We believe this to be the reason for using patterns of stones laid within a diagonal grid pattern.The angle of 45 degrees can be easily associated with the direction of thrusts arising from semi-circular arches.

Conclusions

By analysing the different theories and observations devised by many authors over the centuries,the authors have proposed a new idea of structural behaviour of the *opus reticulatum*, which is a reasonable consequence of several studies on this topic. However, while we consider our conclusions to be significant, they are somewhat restricted to theoretical observations which need to be experimentally proven in the future.

Acknowledgments

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Notes

1. «La realizzazione delle facce esterne mediante … i tufarelli troncopiramidali a base quadrata dell'opus reticulatum … per quanto costituiscano una inessenziale crosta esterna che oggi vediamo spesso distaccata o del tutto scomparsa, pure presentano, appena costruito il muro, una diversa tendenza al ritiro rispetto alla concrezione e la maggiore irregolarità di posa dei caementa produce nell'interno del muro un ritiro, in fase di presa e indurimento della malta, maggiore di quanto non avvenga nella manifattura più serrata delle facce

esterne. Il riempimento tende quindi a scorrere, concentrandosi verticalmente per effetto del ritiro, ed a distaccarsi dagli apparecchi esterni. La periodica interruzione della massa, collegando tramite i bipedali interno ed esterno del muro, riduce questo effetto dannoso» (Giuffré [1991] 1999, 23)

2. «Structurarum genera sunthaec: reticulatum quo nuncomnesutuntur, et antiquumquodincertumdicitur. Ex his venustiusestreticulatum, sedadrimasfaciendasideoparatum, quod in omnespartesdissolutahabetcubilia et coagmenta.» (Krohn 1912,41-2)
3. «Incerta vero caementa alia super alia sedentia inter seque imbricate non speciosamsedfirmioremquamreticulatapraestantstructuram.» (Krohn 1912,42)
4. L'ignoranza generale de' copisti, e molto più nel caso presente per la novità e scabrosità della materia ci hanno renduti scorrettissimi tutti i codici manoscritti, donde è necessariamente derivata l'imperfezione anche dell'edizioni; (Galiani 1790, IV)
5. Claudio Perrault, first edition, Paris, 1673. This was reviewed and published again in 1684. The first French translation of the Vitruvian Code was published by Giovanni Martin in 1547.
6. «Non vi è bisogno di mutare la lettura d'Incerta in Inserta, come vorrebbe il Perrault, ed altri, ... lo che può appropriarsi ...non alla Inserta Imbricata, o sia Intrecciata a similitudine della fabbrica di mattoni, la quale, oltre all'esser bella non può eseguirsi con pietre piccolissime, quali le richiede Vitruvio in questa Incerta.» (Galiani 1790, 37)
7. «Leggendosi Insertum, e relativamente Imbricata, verrebbe a indicare quella stessa specie di fabbriche, che poi chiama Isodoma, e Pseudoisodoma, ed avrebbe trascurata quella specie, che non può aver altro nome, che d'Incerta» (Galiani 1790, 37)
8. «Tegulae ad volutae veluti semi tuboli» (Capolali1536)
9. «In un secondo tempo si cominciarono a collocare filari di mattoni anche nel pieno del muro: dapprima alcuni filari isolati, poi fasce di 5 o 6 filari insieme, per l'altezza complessiva di un piede, le quali sostituiscono negli spigoli le ammorsature che si trovano al loro livello e si fondono direttamente col laterizio delle testate. Si forma così l'opus Mixtum, nome convenzionale dato dai topografi moderni a questo genere di muratura costituito da specchi, o riquadri, di opera reticolata – più raramente di opera incerta – di pietra, con legamenti o piani di posa in laterizio; in tal caso anche le testate sono in laterizio. A dire il vero, l'opus Mixtum è una qualsiasi muratura fatta di materiali diversi, ma per una tacita convenzione nei nostri studi, il nome è ormai limitato soltanto a questa.» (Lugli 1957, 515)
10. «Leggo con Blado Implicata, riuscendo sempre oscuro il senso, se si leggesse Imbricata» (Galiani 1790, 37)
11. Mixed up/ blended
12. «Che abbia a leggersi Incertum, e Insertum, e Implicata, non Imbricata può anche dedursi dalle stesse parole di Vitruvio, ove dice, che questa fabbrica non è bella d'aspetto, non speciosampreastantstructuram: lo che puó appropriarsi all'Incerta, che è confusa» (Galiani 1790, 37)
13. «utraqueautem ex minutissimissuntinstruenda» (Krohn 1912,42)
14. «uti materia ex calce et haren acre briter parietes satiati diutius contineantur. molli enimet rara potestate cumsint, exsiccantsugendo e materia sucum; cumautemsuperarit et abundarit copia calcis et harenae, paries plus habensumoris non cito fientevanidus, sed ab hiscontinetur. Simulautem umida potestas e materia per caementorumraritatemfueritexsuctacalxque ab harenadiscedat et dissolvatur, item caementa non possunt cum hisco haerere, sed in vetusta temp ariete sefficiunt ruinosos.» (Krohn 1912,42)
15. «The choice of an arrangement of small stones at 45 degrees might at first appear odd, but it is in fact in line with the economic and social evolution of the Roman world, an evolution which led to the creation and expansion of new techniques. It has already been noted that the use of an abundant supply of servile labour from the end of the third century BC had encouraged the aediles to go in for the rapid manufacture of construction materials that could easily be worked after a brief period of specialized training. This was to lead to an even more precise standardization, bringing about a simplification of the mason's job as mentioned before» (Adam [1994]2010, 131)
16. «Et, en effet, les Romains étaient trop sagement économes pour préférer à la maçonnerie que nous venons de definer l'usage du béton, qui, sans offrir plus de solidité, les eûtentraînés à un sur croît notable de dépense :leur maçonnerie ordinaire, nous l'avonsdit, ressembleassez au béton pour qu'on l'ait confondue avec lui, maiselle devait être beaucoup moinschère. Le mélange des pierres avec le mortier exige une certain dépense de main d'œuvre, et représente un travail pénible dont les Romains cherchèrent à s'affranchir» (Choisy 1873,19)
17. «Ce que les Romains se proposaient avant tout, c'était de réduire les frais et de render l'exécution rapide; ils redoutaient dans leurs chantiers la moindre complication, la moindre entrave, et évitaient par principe, je dirais presque par système, tout travail menant d'une façon indirecte au but qu'ils avaient envue.» (Choisy 1873, 20)
18. Walls moved from massive blocks made out of stones having, at times, an inner core (Emplecton) to concrete members supposedly protected by a stone facings.
19. «Si donc les parements ne présentent pas par eux-mêmes une bonne stabilité, il faudra pour appliquer aux maçonneries qu'ils enveloppent une compression énergique, armer le mur d'une charpente de défense, d'une

sorte de blindage extérieur ou d'encaissement, et c'est là une complication dont les anciens cherchèrent à s'affranchir» (Choisy 1873,20-1)

20. «dans les murs ordinaires, les parements étaient trop minces et trop peu stables pour faire obstacle au renversement; aussi la compression ne jouait aucun rôle dans l'exécution de ces murs; il suffit de jeter un coup d'œil sur leurs parements pour comprendre qu'en effet le procédé par compression eût été impraticable. - Le revêtement d'un mur ordinaire en maçonnerie se compose de très-petits moellons cubiques arrangés de façon à dessiner par leurs joints des figures élégantes ou variées» (Choisy 1873,21)
21. «Une dernière remarque paraîtra peut-être plus décisive encore: les Romains, malgré le soin qu'ils y apportaient, ne sont pas toujours parvenus à remplir de mortier les joints verticaux qui séparent deux à deux les fragments de pierre formant une même assise;des fragments sont enveloppés de mortier d'une façon incomplète; autrement dit, la couche sur laquelle ils reposent et celle qui les recouvre n'ont pas pénétré assez profondément entre les joints verticaux pour les combler, et il reste à mi-hauteur du joint un vide, une soufflure.
De emblables lacunes ne se seraient jamais produites, si les matériaux avaient été mêlés d'avance et coulés d'un seul jet. — Ces lacunes sont rarement très-apparentes ; pourtant, elles ne sont point du tout des singularités ou des défauts exceptionnels» (Choisy 1873,18)
22. «au lieu d'opérer d'avance le mélange des matières, ils l'exécutaient sur place : les cailloux étaient peut-être moins bien unis au mortier, mais leur arrangement régulier rachetait en partie ce défaut» (Choisy 1873,19)
23. «Ma esisteva soprattutto una ragione tecnica che consigliava di evitare superfici troppo estese in reticolato: una parete lunga ed alta, costruita in questo modo, era facilmente suscettibile di frattura, qualora fosse stata gravata da un peso troppo considerevole. È noto come la spinta di una volta monolitica, come erano le volte romane nei primi tempi dell'impero, risulti prevalentemente verticale: ora il reticolato ha i piani di allettamento obliqui, sia pure limitatamente alla sola cortina, e tutta la sua resistenza è fondata sulla coesivitá della malta, mentre in una parete fatta con materiali disposti a piani orizzontali, i pericoli di frattura sono minori.» (Lugli 1957, 514)
24. «Se per caementa incerta dobbiamo ritenere il sistema da noi descritto innanzi, questa grande differenza di stabilità non esiste: la possibilità di frattura offerta dalle linee continue del reticolato è compensata pienamente dalla forma più allungata delle tessere piramidali, che si addentrano considerevolmente nel nucleo cementizio del muro» (Lugli 1957, 487-8)
25. «Merviglia certamente il pensare che, dopo aver fatto un lavoro così complicato, come era il reticolato lavorato a squadra, venisse poi ricoperto e reso invisibile; ciò ha fatto pensare ad alcuni che rimanesse a faccia vista.»(Lugli 1957, 489)
26. For further information about the excavations of Villa Arianna see: Camardo (2001, 75-83); d'Orsi (1996, 526); Ruggiero (1881, 366).
27. «In studying these polychrome masonry walls, however, one surprising thing is noticeable: the majority have the remains of rendering on them which would once have masked them completely. Indeed it is curious to think that, whatever trouble the masons took, it was doomed to be hidden by the application of a covering decoration for which more rough and ready masonry would have been sufficient. It is more satisfying to believe that these renderings were applied later to fit in with architectural fashion or the whims of successive owners» (Adam [1994] 2010, 133)
28. «Per un perfetto reticolato occorreva naturalmente che le tessere fossero squadrate con molta cura; in vari casi ho notato che le tessere erano cementate fra di loro con una malta di impasto più fine, più densa e di colore biancastro; inoltre le testate e gli spigoli dovevano essere fatti di blocchetti ben squadrati della stessa pietra, alti quanto la diagonale di una tessera e anch'essi accuratamente cementati. Di fronte alla difficoltà di costruire un muro reticolato viene fatto di domandarsi perché mai i Romani facessero il paramento a piramidi tronche anziché a blocchetti parallelepipedi, quelli stessi che ponevano negli angoli e negli archi prima dell'uso del mattone» (Lugli 1957 vol.1, 488)
29. «maceriam lapide fabricata et expolitatectoriispedalia in quadratumcubilia» (Columella vol.8,15)
30. «Ce système permettait d'obtenir, moyennant une dépense insignifiante, une liaison très-intime entre ces briques triangulaires et le noyau de maçonnerie brute; mais le parement, bienloin de pouvoir arrêter un effort d'écartement exercé par ce noyau de maçonnerie (fig. 3), ne se tenait debout que par l'effet de son adhérence avec les rem plissages : c'était une simple enveloppe, excellente pour protéger le mur contre les pluies, d'ail leurs absolument incapable de résister à une poussée agissant du de dans au dehors» (Choisy 1873, 21)
31. «La presenza di listature e/o corsi regolari atti a definire le bancate ed irrobustire la muratura è relazionata alla specifica tipologia eventualmente presa in esame e va considerata come un elemento migliorativo delle rigidezza complessiva del pannello murario» (Ceradini 1992)
32. «Che le due parti di questo pilastro siano unite in questa sezione da una coesione data, mentre tutto il resto della massa è perfettamente solida, ovvero unita da un'aderenza infinita: se il pilastro è caricato di un peso, questi tenderà a far scorrere la parte superiore del pilastro è realmente uguale in tutte le parti, affinché il pilastro possa sopportare un peso, occorre che vi sia alcuna sezione di

questo pilastro per la quale l'intensità della componente di pressione possa far scorrere la parte superiore. Pertanto, per determinare il più grande peso sopportabile da un pilastro, si deve cercare tra tutte le sezioni quella la cui coesione è in equilibrio con un peso che sia un minimo; poiché in tal caso ogni pressione superiore a quella determinata da questa condizione, sarebbe insufficiente a rompere il pilastro» (Benvenuto 1981, 301-2)

33. Si può valutare la forza trasversale massima, quella per la quale il blocco ribalta, cioè la forza che produce un momento ribaltante uguale al momento stabilizzante ... questa sembra dipendere solo dallo spessore e non dall'altezza, ma se il blocco è appoggiato sul suolo senza un vincolo rispetto al moto orizzontale esso può scivolare prima di ribaltare. ... si osserva cha al crescere dell'altezza il blocco resiste a forze crescenti, fino ad un limite oltre al quale la forza resistente rimane costante. Tale limite è quello che fa passare dal meccanismo di collasso per scivolamento a quello per ribaltamento, e si raggiunge quando L'altezza è tale da rendere la forza di scivolamento uguale a quella di ribaltamento. (Giuffré [1991] 1999, 12-3)
34. La più importante delle azioni esterne che il muro è chiamato a sopportare, oltre al peso proprio, è quella che tende a ribaltarlo, direttamente ortogonalmente al suo piano. (Giuffré [1991] 1999, 13)
35. Il muro in concrezione prevede, a interessi di tre piedi (circa 90cm) lungo lo sviluppo verticale, strati orizzontali di bipedaliche attraversano tutto lo spessore e per tutta la lunghezza. Si osservi che da una parte la nuova concezione muraria realizza, senza necessità di alternanze tra ortostati e diatoni, un muro ad un unico spessore d'un sol pezzo, e dall'altra, mediante i ricorsi di bipedale, predisposti gli spigoli orizzontali attorno a cui si possono realizzare, all'occorrenza, i cinematismi che abbiamo individuati nei muri in pietra squadrata. Vi sono molte importanti ragioni tecnologiche per giustificare la presenza dei ricorsi di bipedali nel muro in concrezione, ma se poi si riflette sulla consapevolezza, intrinseca nella tecnologia dell'opus quadratum, che una buona resistenza ai pesi (carichi verticali) si ottiene con superfici di appoggio orizzontali, si attribuisce agli orizzontamenti di bipedali una funzione statica di regolarizzazione del vincolo di appoggio. Finalmente, come si è detto, la presenza di orizzontamenti consente il cinematismo del muro oscillante sulla base. (Giuffré [1991] 1999, 22-4)
36. *For more informations about the earthquakes that preceded the eruption of 79 AD see: Fröhlich, Jacobelli (1995, 219); Guidobuoni (1989, 765).*
37. *La motivazione più calzante sembra però essere quella che parte dalla considerazione che la disposizione a 45 gradi dei blocchetti fa si che ogni "allettamento" dovuto al ritiro della malta, in fase di presa, viene agevolmente assecondato e compensato da piccoli, graduali spostamenti verticali della struttura, favoriti dalla stessa forza peso, che ricompattano la muratura, prima dell'indurimento, senza la formazione di lesioni verticali. Più semplicemente si potrebbe dire che la disposizione per diagonali a 45 gradi genera un effetto di precompressione orizzontale della struttura che previene la formazione di lesioni verticali in fase di presa ed indurimento. (Manieri Elia 2003, 11)*
38. Se il muro è caricato con una forza inclinata avviene che la forza trasmessa da un blocco a quello sottostante lungo la superficie di contatto orizzontale potrebbe essere inclinata, e posizionata, in modo tale da no essere più contenuta nella base del blocco che la riceve. Per questo l'equilibrio sarebbe impossibile ma in realtà esso può appoggiarsi al blocco adiacente nella direzione della forza, e ricevere una reazione orizzontale sufficiente a rispettare l'equilibrio. Il blocco che lo sostiene sarà a sua volta caricato dalla reazione corrispondente: l'equilibrio di quest'ultimo è possibile se il risultante delle forze che riceve, sia da quello sovrastante, che da quello adiacente, è interno alla sua base di appoggio e inclinato non più di quanto il coefficiente di attrito non consenta. (Giuffré [1991] 1999, 7-8)

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