The Roman Ashlar Groin Vault at Grotta dei Massacci

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Abstract

Some authors have downplayed the importance of complex vaulted systems in ashlar in Roman architecture. This has led them to seek the origins of Early Modern stonecutting in Christian Syria or Languedocian Romanesque. However, some examples in many regions of the Empire, including Lazio, argue for the existence of advanced stonecutting techniques in the Roman world. In this paper, we will study an interesting example of these structures, the Grotta dei Massacci in Osteria Nuova, now in the municipality of Frasso Sabino. Starting with a precise survey carried out by 3D laser scanning and automated photogrammetry, we will put forward some hypotheses about its measurement system, proportion, stonecutting technique and the hoisting systems used in its execution.

Keywords Roman architecture · Measure · Stonecutting · Stereotomy · Proportion · Hoisting

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Introduction

Are There Complex Vaulting Systems in Ashlar in the Roman World?

Research on horizontal structure systems in Roman architecture has focused on two well-known paradigms: on the one hand, the wooden, linear, partially triangulated structures used in temples; on the other hand, concrete vaults built using lime and pozzolana concrete. Vaults built in ashlar, although predating the pozzolana concrete technique, have received comparatively little attention (see Adam 2011: 205–210, as an exception). This state of affairs has influenced studies about Medieval stonecutting and Early Modern stereotomy. When dealing with the hypotheses about the origin of modern stereotomy, Jean-Marie Pérouse de Montclos (2001: 181) mentioned examples from Antiquity near the city of Rome, Southern France, Syria and Armenia, forgetting the rest of Italy, even including Lazio, Spain, Palestine and Anatolia. Sakarovitch (1998: 105–107) considered Christian Syria no less than the birthplace of learned architecture in ashlar.

Detailed study of Roman vaulting in ashlar may offer interesting data about this partially neglected technique. However, the catalogue of Roman ashlar vaults is not uniform: there are spiral vaults in the Mausoleum of Hadrian, groin vaults in Pergamon and the lower chamber of the Mausoleum of Theodoric, hemispherical vaults and arches opened in curved walls in the Mausoleum of Ummidia Quadratilla in Cassino (see Piccinin and Natividad 2020). This suggests that progress in this area will be made by means of specific case studies rather than over-arching generalisations. In this present paper, we will analyse the measurement system, proportion, stereotomy and execution of a structure known as Grotta dei Massacci in Osteria Nuova, a locality in the municipality of Frasso Sabino, in Lazio.

The Grotta dei Massacci

The Grotta dei Massacci is a tomb located in Osteria Nuova, a village in the municipality of Frasso Sabino (Rieti) in Lazio. It is placed at a crossroads of the via Mirtense and the ancient via Salaria, an important commercial road which connected Rome with the Adriatic coast and was used to bring salt to the capital. The area between Osteria Nuova and Monte Calvo is known as Piano dei Massacci, from the ancient funerary monuments set along the Salaria, known as Massacci. The Grotta is close to the area known as Vicus Novus in Itinerarium Antonini and Mansio ad Novas in Tabula Peutingeriana; the contemporary name Osteria Nuova derives from these ancient denominations. Since this area is located 33 miles from the capital—then about a day's journey from Rome—it had all the necessary services for travellers (Masciangelo 1992: 26; Matracchi et al. 2014: 117–120). Cato, Varro, Horace, Vespasian, and Titus, among others, moved to this area or built houses there.

According to some researchers, a residential building found near the Grotta, dated between the first and second century CE, may have been owned by the Laberii family. After the marriage between Laberia Crispina and Caio Bruttius Praesentes, a soldier and consul of the roman Senate in 121 and 139 CE, the villa then was probably owned by the gens Bruttii Praesentes. Taking into account their wealth and power, the Grotta may also have belonged to this family (Matracchi et al. 2014: 120; Alvino 2019; Masciangelo 2019; Coarelli 2019).

In 1712 the family Sforza Cesarini, lords of Frasso Sabino, decided to incorporate the ancient tomb in a new building (Matracchi et al. 2014: 121). This building was used as a mechanical workshop in the 1980s, despite its having been declared a National Monument in 1916. As a result, the access corridor was damaged during an attempt to enlarge it. Also, the floor of the burial chamber has been pierced with holes to dispose of water and other floods, while iron hooks have been placed in the walls.

According to Matracchi et al. (2014: 126; see also Coarelli 2019) some archaeological fragments show that the tomb is built on a square basement; a cylindrical tholobate stood on its centre. Inside the tholobate, a straight corridor lead to a burial chamber placed in the centre of the tholobate; both the corridor and the chamber are now set inside the eighteenth-century building and its later additions (Fig. 1). The burial chamber is shaped as a Greek cross (Fig. 2), with a central square and short arms, covered by a groin vault resulting from the intersection of two semicircular barrel vaults (Fig. 3). The walls of the burial chamber are naked; no cornice marks the top of the arm walls and the impost of the vault or the separation between the rectangular and semicircular sections of the walls at the end of the arms. Both the walls of the corridor and the burial chamber are constructed in very large ashlars of local travertine; the groin vault also uses large voussoirs (Figs. 4, 5, 6, 7).

With regard to construction techniques, the Grotta is often linked to other two important buildings of the first and second centuries: the Mausoleum of Hadrian (Rome) and the Mausoleum of Ummidia Quadratilla (Cassino): this fits well with the connection to the gens Bruttii Praesentes, thus presumably setting its origin between the first and second centuries CE (Masciangelo 1992: 39–40; Coarelli 2019: 20–21). In particular, Giuseppe Lugli (1957: 351, 358) dates the structure to the first century CE, like the Mausoleum of Ummidia Quadratilla.

Methodology

In this paper, we will endeavour to measure the tomb as exactly as practically possible. Then, we will draw conclusions from this survey about the units of measure used in its conception and execution; the proportion schemes employed in the design, if any; its stereotomy, that is, the stonecutting methods used during execution; and other factors connected with execution, in particular the weight of the largest stones, as well as the hoisting equipment that may have been used during execution.

To start with, we surveyed the building using both laser scanning and automated photogrammetry. We have used a Leica BLK 360 scanner, which furnishes a point cloud covering the larger part of a sphere. These points have been processed with the software CloudCompare and imported into Rhinoceros 6.1, also using the plugin Veesus Arena4D and some Rhino.Python plugins

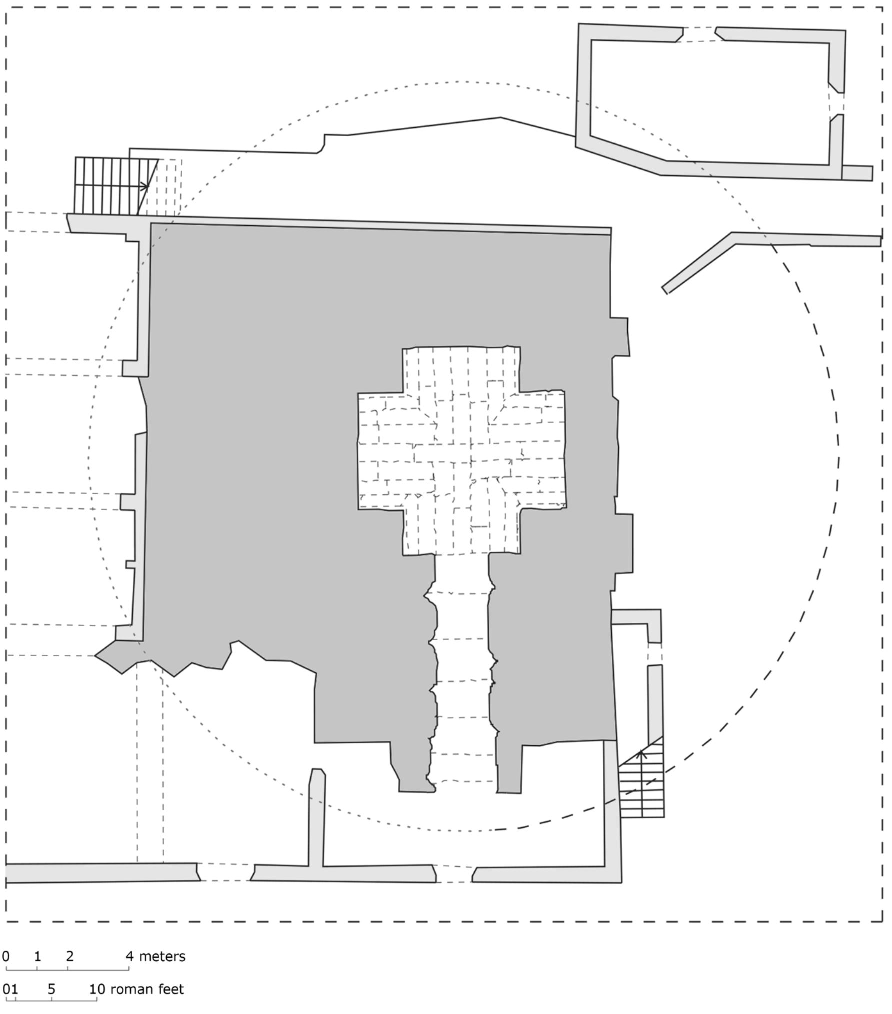

Fig. 1 Grotta dei Massacci. Plan including remains of the square basement and the circular tholobate, after Matracchi et al. (2014)

for cloud management. We have taken 257 photographs with a Nikon D800E camera and 24 mm f/1.4 and a 50 mm f/1.4 lenses, which have been processed with the program Metashape Professional in order to generate a different point cloud. Although both point clouds are nearly identical, the point cloud gathered with the laser scanner has been used to get precise measurements, while the photogrammetric one has been used to provide visual representations.

The laser scanner offers a precision in the range of 6 mm; moreover, execution tolerances make precision below 1 cm meaningless. Thus, we will present all linear dimensions and ratios with two decimal figures, except when there is a specific reason to do otherwise. In contrast, for volumes and weights, which are

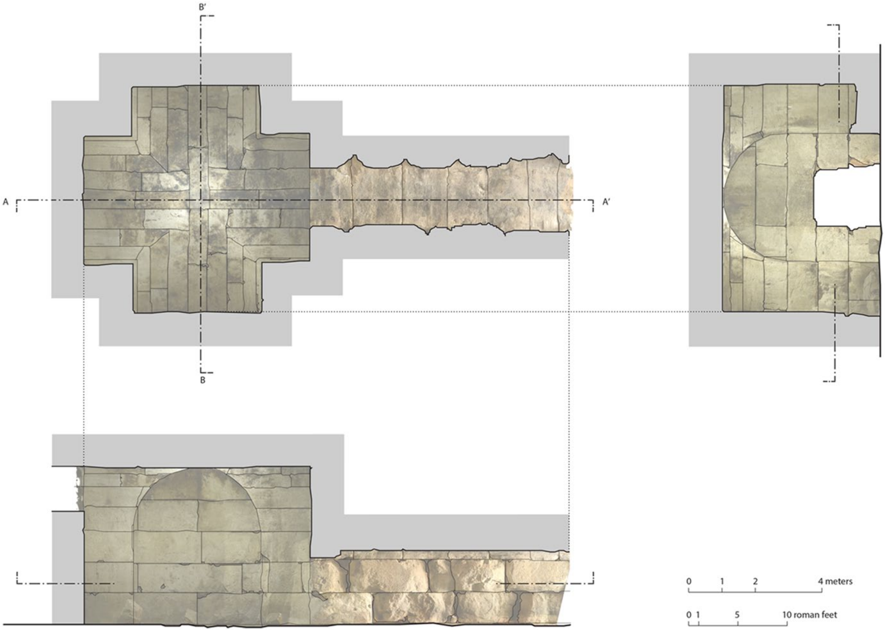

Fig. 2 Grotta dei Masacci. Plan, transversal section, and longitudinal section

Fig. 3 Grotta dei Masacci. Groin vault in the inner chamber

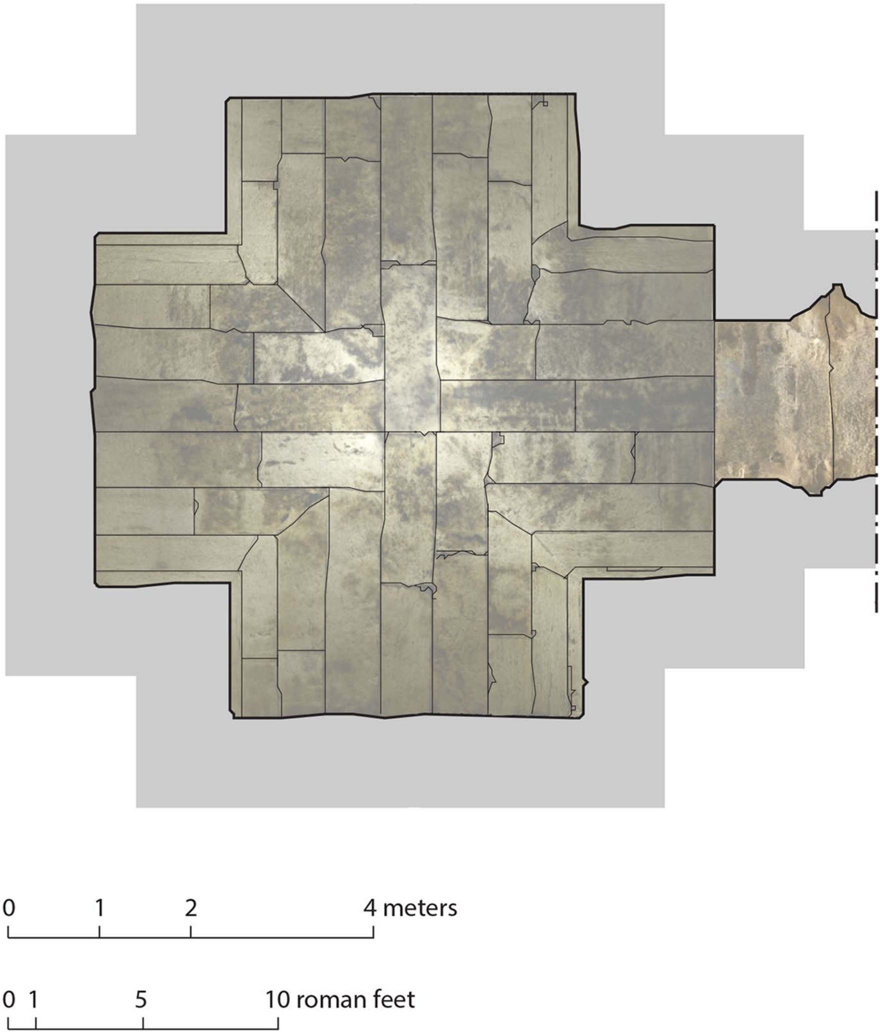

Fig. 4 Inner chamber of the Grotta dei Masacci. Ceiling plan

computed as the product of three linear dimensions, we will use three decimal figures.

Measure and Proportion

Measure

Dimensions were measured taking the laser-scanner survey as a basis, since this process is more direct than the photogrammetric survey. However, this

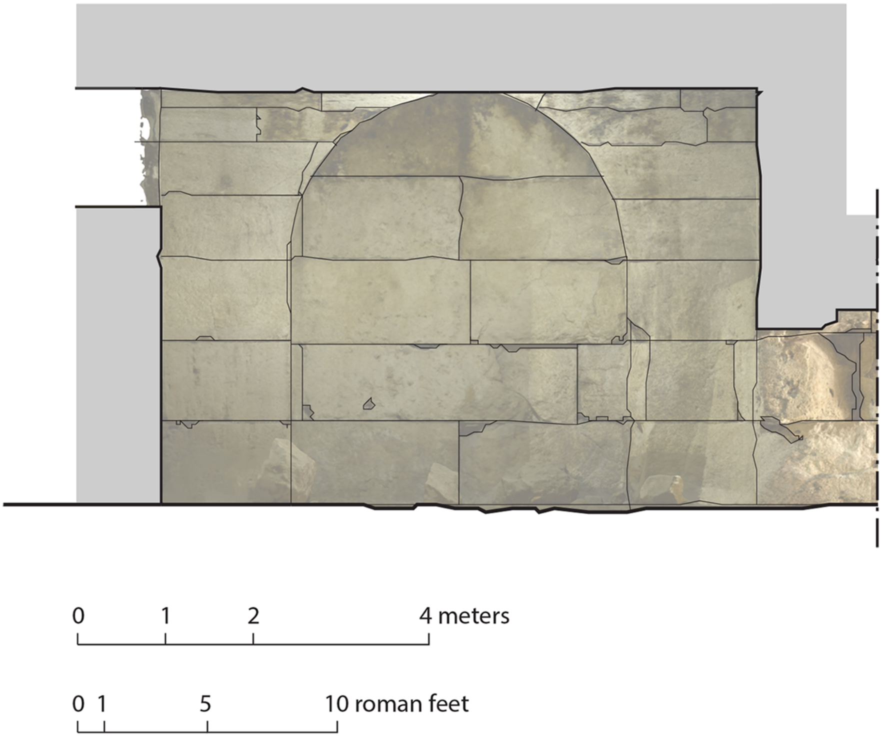

Fig. 5 Inner chamber of the Grotta dei Masacci. Longitudinal section

operation is not as automatic as we might think. First, the scanner uses a carpet-bombing technique and does not allow the direct location of key points, such as the intersections of two walls and the floor. Second, the surfaces of the walls and vaults are not exactly planar or cylindrical, as a result of execution tolerances, mechanical deformation, physical degradation, and human intervention. Third, there are several instances of each of the basic dimensions, for example the length of the arms of the Greek cross. Fourth, in the actual state of laser scanning technology and point cloud management, it is not easy to take measures directly from the 3D model; in fact, it is easier and more precise to take measurements from scaled orthophotographs obtained from the point cloud.

Taking all this into account, we have prepared Table 1, which shows the average measures and standard deviations of a number of samples of four key dimensions: (a) size of the central square, that is, distances between the vertical arrises at the intersections of the lateral sides of the arms of the Greek cross; (b) depth of the arms of the Greek cross; (c) height of the courses in the walls; and (d) rise of the groin vault from its impost to its apex. The first conclusion is that standard deviations are relatively low, ranging from 1 to 4 cm; the largest value corresponds to the vault rise. This attests to the precision of the execution of the structure, much above mediaeval standards and comparable with the best practices of the Early Modern period and even with usual standards in industrial constructions (Fig. 8).

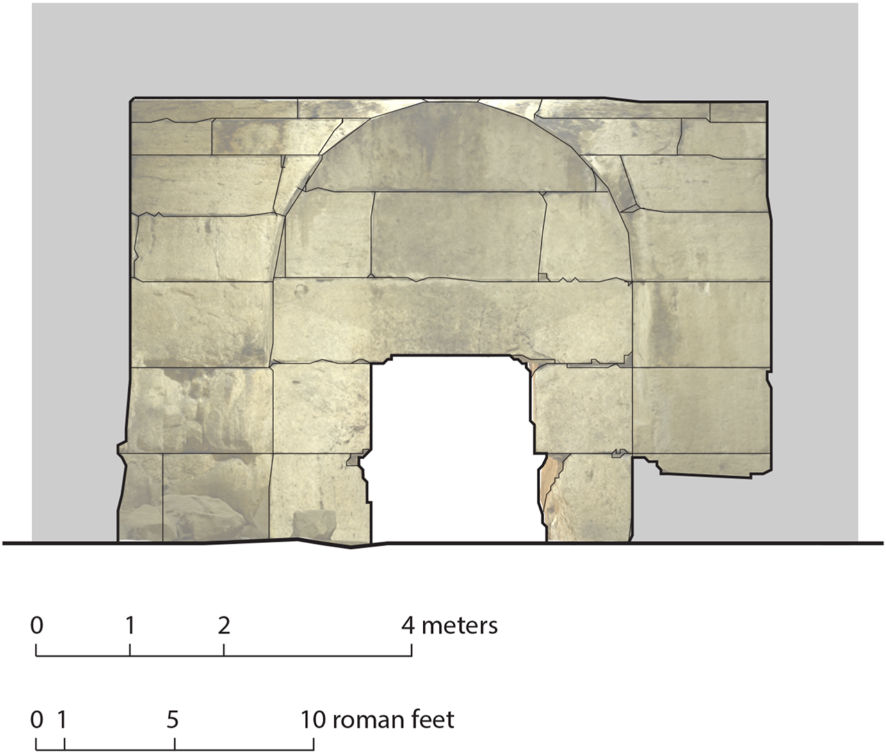

Fig. 6 Inner chamber of the Grotta dei Masacci. Transversal section

As a next step, we have converted these dimensions to the standard Roman foot of 29.6 cm (Adam 2011: 43). The results, shown in Table 1, suggest that the builders may have started with measures of 13 feet for the central square and 5 feet for the depth of the arms of the Greek cross (see Fig. 8). The section of the vault is almost exactly semicircular; thus, its theoretical rise should equal half the side of the central square, that is, 6.5 feet.

Table 1 also shows the differences between the actual measurements and the theoretical measurements in Roman feet, which range from 1 to 4 cm, and thus are similar to standard deviations and can be explained by execution tolerances. The largest differences appear in the length of the end walls of the Greek cross arms and the rise of the vault.

As for the height of the three courses in the walls, individual measures range between 0.93 and 0.94 m, close to 3 feet and 2 inches. However, the inch was not in wide use in Roman Italy, where the digit was preferred (Adam 2011: 43); the theoretical height of the course equals 3 feet, 2 digits and 2/3 of a digit. This suggests that the builders started from a "project" dimension of 9 ½ feet, that is, 9 feet and 8 digits, for the total height of the wall and then divided it into three equal parts to get the course height of 3 feet and 8/3 digits.

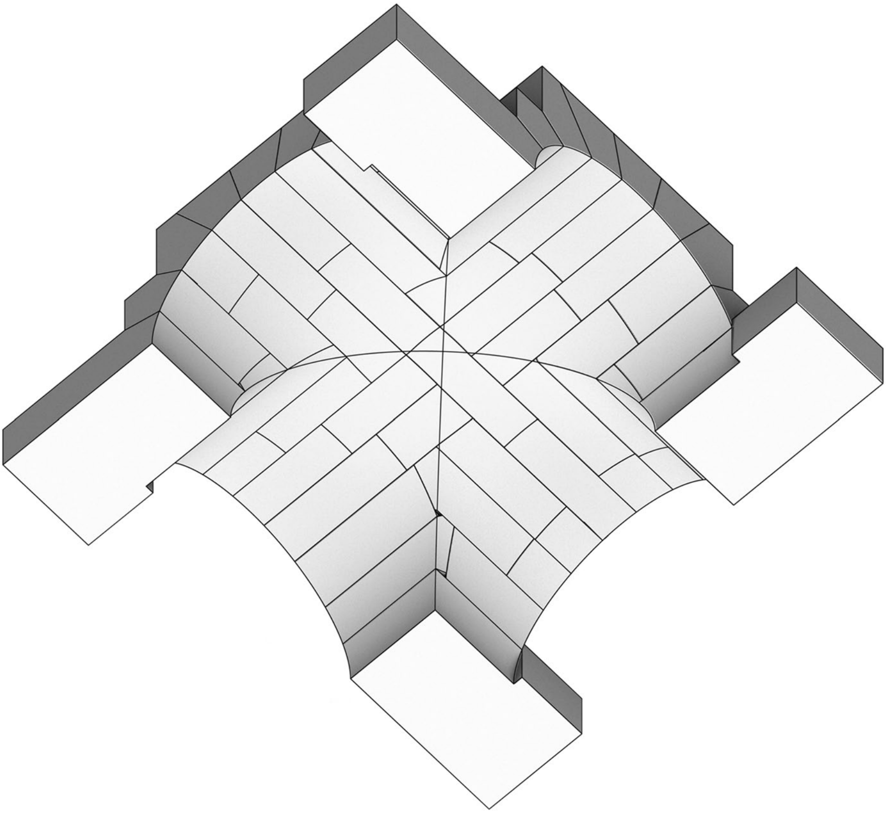

Fig. 7 Vault at the inner chamber of Grotta dei Massacci. Axonometry

Proportion

Table 2 shows the most significant ratios between the basic dimensions, namely the enclosing square of the whole ensemble, including the central square and twice the depth of the arms of the Greek cross; the height of the walls from the floor to the vault impost; and the total height of the internal space of the chamber, from the floor to the vault apex. It includes both the averages of actual measurements and the "theoretical" dimensions in Roman feet.

With two exceptions, neither of these ratios correspond to (a) simple numerical ratios, (b) the ratio of the diagonal and the side of the square, mentioned by Vitruvius and known as *diagon* in some modern publications, or (c) the Golden Ratio. An obvious exception is the ratio between the rise of the vault and the side of the central square. Since the span of the vault equals the side of the square and its section is semicircular, the ratio between the side of the square, that is, the span of the vault, and rise of the vault equals in theory 2.00. In practice, it amounts to 2.01, with a very tight execution tolerance of 0.5%.

Table 1 Dimensions

Dimension	Measure (m)	Measure (feet)	Standard sample deviation (m)	Standard sample deviation (%)	Rounded measure (feet)	Deviation (m)	Deviation (%)
Central square, average	3.80	12.85	0.03	0.72	13	−0.04	−1.15
Greek cross arms, end wall, average	3.79	12.80	0.02	0.65	13	−0.06	−1.51
Greek cross arms. depth, average	1.46	4.94	0.03	2.14	5	−0.02	−1.22
First course height, average	0.93	3.13	0.02	2.08	3.16	−0.01	−1.11
Second course height, average	0.93	3.14	0.02	1.67	3.16	−0.01	−0.71
Third course height, average	0.93	3.14	0.01	0.69	3.16	−0.01	−0.71
Total height of walls from floor to vault impost, average	2.78	9.40	NA	NA	9.5	−0.03	−1.05
Vault rise. average	1.89	6.38	0.04	2.38	6.5	−0.04	−1.85
Total height from floor to vault apex	4.67				16.00		
Diagonal of the enclosing square					32.53		
Side of the square inscribed in a circle of diameter 32					22.63		

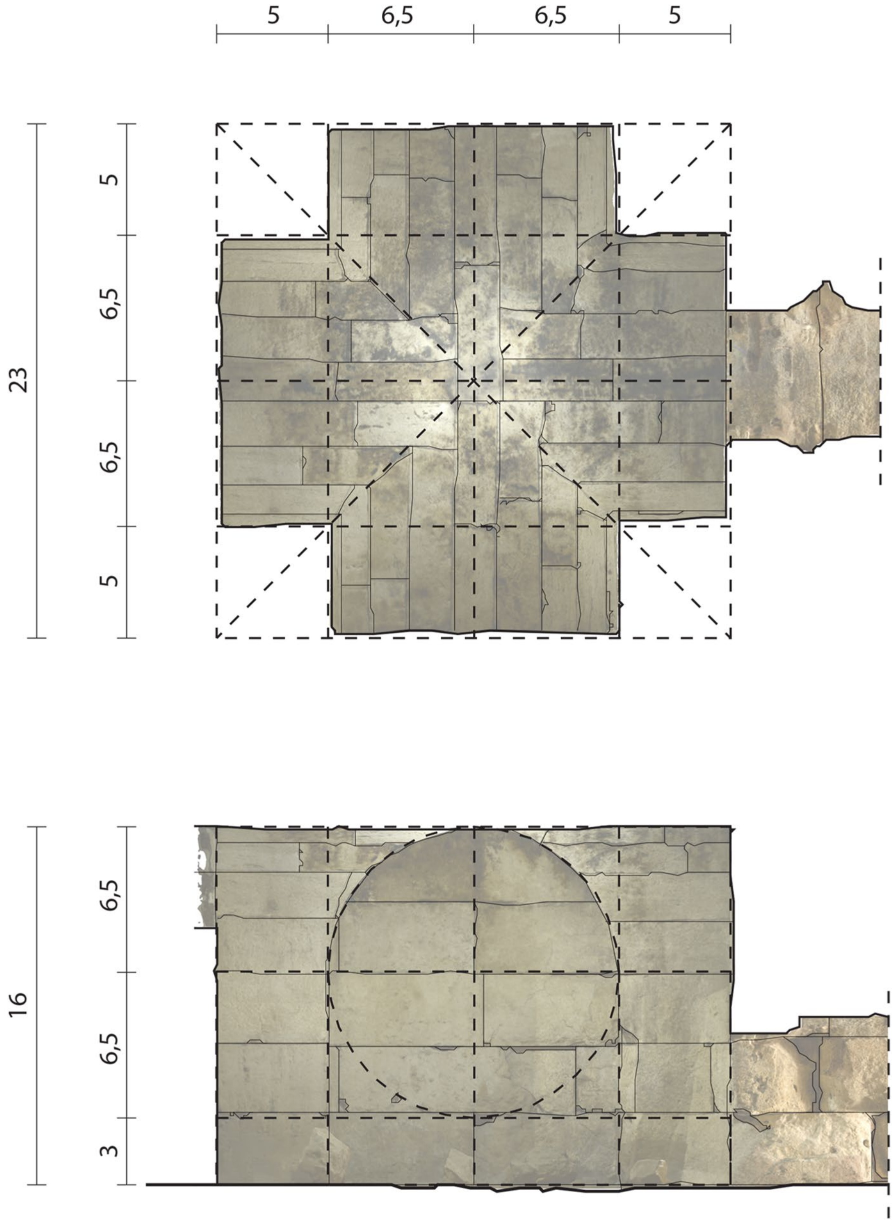

Fig. 8 Vault in the inner chamber of Grotta dei Masacci. Scheme of the basic dimensions, rounded to Roman feet

The other exception demands careful consideration. The ratio between the enclosing square and the height from the floor to the apex of the intrados of the vault amounts to 1.44, both in practice and in theory. This is near to the *diagon* or ratio between the diagonal and the side of a square. However, the ratio between the

Table 2 Proportions

Ratio	Ratio according to actual dimension	Ratio according to rounded measures
Central square/Greek cross arms	2.602	2.600
Enclosing square/central square	1.769	1.769
Enclosing square/Greek cross arms	4.602	4.600
Central square/total height of walls to impost	1.367	1.368
Central square/vault rise	2.014	2.000
Total height from floor to vault apex/central square	1.228	1.231
Enclosing square/total height of walls to impost	2.418	2.421
Enclosing square/total height from floor to apex	1.440	1.438

averages of the actual measurements of the side of the enclosing square and the total height from floor to apex, expressed with four decimal places, amounts to 1.4403, while the ratio between the theoretical dimensions of the enclosing square, 23 feet, and the total height, 16 feet, amounts to 1.4375; of course, the *diagon* equals 1.4142. In other words, the ratio 23/16 is closer to the geometry of the ensemble than the *diagon* and other explanations involving the Egyptian triangle and the Golden Ratio put forward by Salvatore Liberti (2019: 72–73).

Stereotomy

L-Shaped Versus Staggered Voussoirs in Roman Groin Vaults

The well-known groin vault at the lower chamber of the Mausoleum of Theodoric in Ravenna (Fig. 9) is built from two intersecting cylinders, with four intrados surfaces in total. These surfaces are divided into courses by bed joints; the intrados joints, that is, the apparent edges of the bed joints, are horizontal generatrices of the cylinders. The intersections between the two cylinders are surbased ellipses placed on vertical planes passing through the diagonal of the area. In some cases, voussoirs crossing these planes are V-shaped, with a fair length for both arms of the V, as in Early Modern solutions (see, for example, de la Rue 1728: 44–46, pl. 24). Also, side joints are generally orthogonal to the axes, although there are many exceptions, which may be the result of the breaking of voussoirs, either at execution or later on, and subsequent repairs.

However, this is not the most frequent solution for Roman groin vaults in ashlar. Generally speaking, in the vaults at a tomb and the Gymnasium in Pergamon (Choisy 1899: I, 518–519; Adam 2011: 205–207), the quadrifrons arch in Cáparra (Inglese and Pizzo 2015) and in the Grotta dei Massacci, the voussoir in one of the cylinders—let us call it A—invades the adjoining cylinder B. Cylinder A adapts its end to the curvature of cylinder B, but it does not include a long arm in order to generate a V-shaped voussoir. Usually, this scheme is reversed in the next course: the last voussoir of cylinder B invades cylinder A and adapts to its curvature. The

Fig. 9 Groin vault in the lower chamber of the Mausoleum of Theodoric in Ravenna

advantage of this solution is that the whole vault can be built starting with ordinary barrel vault voussoirs, just with a small cut at the end in order to adapt its intrados to the curvature of the other cylinder, avoiding loss of stone and the risk of cracks; we will see in "Some Hypotheses About the Dressing of the Voussoirs for the Grotta dei Massacci Vault" the particular application of this scheme to each course of the Grotta dei Massacci vault.

Orientation of Bed and Side Joints in the Grotta dei Massacci

Matracchi et al. (2014: 124) suggested that the bed joints in the first course of the Grotta dei Massacci vault were horizontal and wondered whether the second course follows the same pattern. However, our survey points in another direction. Laser scanning does not depend on existing light, in contrast with photogrammetry, since it projects its own light in the form of laser pulses. Thus, our survey (Fig. 10) has shown that all joints, up to the extent they are visible from the station point of the scanner, are set radially, as a sheaf of planes passing through the axis of each cylinder, and thus the only horizontal joints are those at the springing of the vault.

Another interesting issue is posed by the orientation of the side joints, that is, those that divide each course into voussoirs. Most of these joints are set on planes orthogonal to the axes of each cylindrical portion, except the ones placed in the vicinity of the diagonals of the area, which are arranged in different orientations. Some are set at the diagonals, others almost orthogonal to the intrados joints, others clearly deviate from orthogonality. This layout may seem haphazard at first sight.

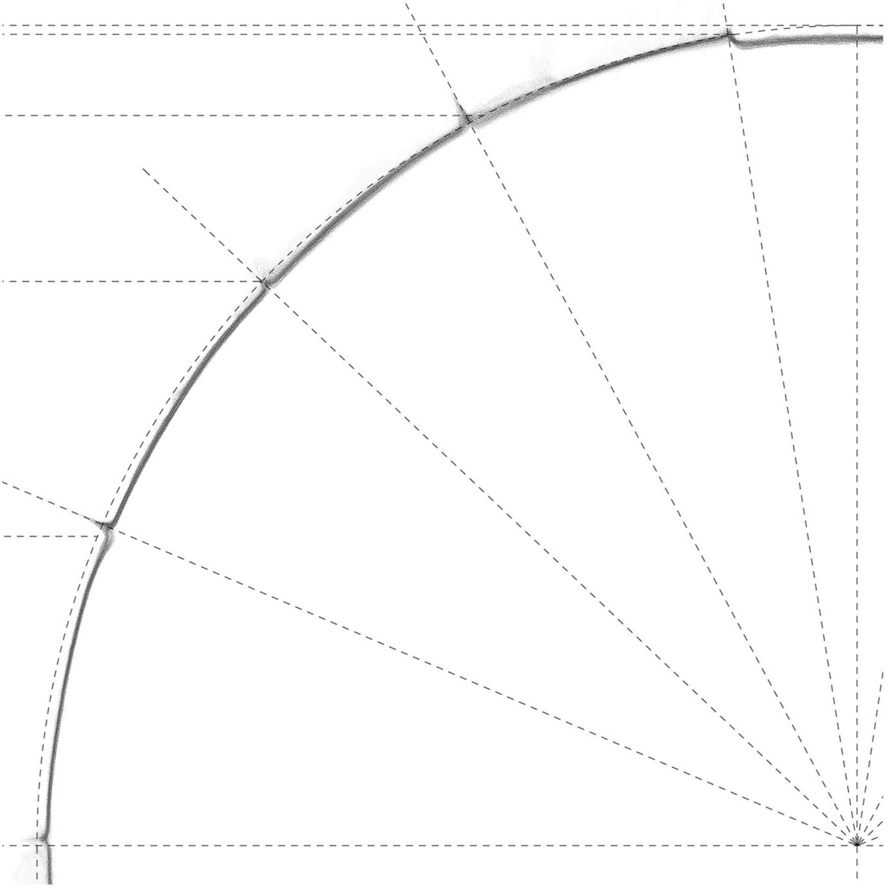

Fig. 10 Point cloud representing the cross section of half a barrel vault in the Grotta dei Massacci

However, it solves efficiently the problem of breaking joints between a course and the next one, as we will see in the next section.

Some Hypotheses About the Dressing of the Voussoirs for the Grotta dei Massacci Vault

Broadly speaking, three different approaches to the formal control of the voussoirs are used. In order of increasing difficulty, the simplest is the one for the first course; the intermediate one is that for the fourth and fifth courses; and the most complex one is the one for the second and third courses.

In each corner of the vault, the first course is solved with a single, large stone which includes a portion of the wall at the end of the arms of the Greek cross, in order to tie the barrel vault and the wall (Fig. 11). Masons should take off four wedges from the starting block. The lower ones should have a curved profile, with

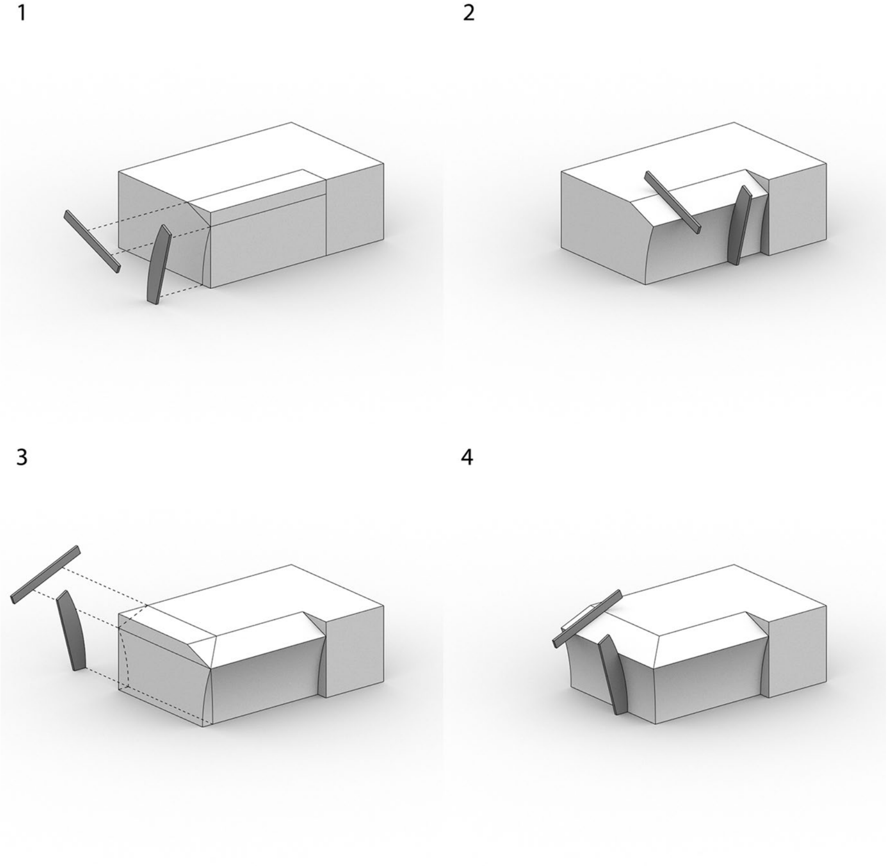

Fig. 11 Vault at the Grotta dei Massacci. Dressing scheme of a voussoir in the first course

their radius corresponding to half the side of the central square, that is, 6 ½ Roman feet. Next, the bed joints should be slanted and orthogonal to this curve. Renaissance masons used the arch square for this operation, but as far as we know, there is no evidence of the use of this tool in Roman times (see Adam 2011: 42–44 for other geometrical instruments). However, at least a templet, that is, a ruler with a curved edge, is needed to dress a simple barrel vault voussoir. The masons may have used a templet, placing it on the face of the cuboid block opposite the wall in order to score the curved profile of the barrel vault, as well as a straightedge to score a line representing the bed joint over the springer. Then they may have carved the intrados of the vault until reaching the end wall, controlling the operation with a square and a straightedge. In the next step, they may have dressed the bed joint over the springer using a straightedge. Once this process was finished, they may have repeated it starting from a face of the cuboid block orthogonal to the end wall, in order to materialise the intrados and the bed joint of the barrel vault whose generatrices are parallel to the end wall; the elliptical groin would arise automatically as the intersection of both cylinders.

Next in complexity are the fourth and fifth courses, where the side joints that divide both cylinders from the adjoining one are set approximately as an extension of the bed joints of the other cylinder. This suggests a relatively simple dressing process (Fig. 12), starting from a standard barrel vault voussoir; this avoids the need for using complex full-scale drawings or sophisticated instruments, although it requires the use of full formwork. Once masons have placed the voussoirs for cylinders A and B up to the third course, they would place several standard barrel vault voussoirs for the fourth course of cylinder B. The first voussoirs of this series do not need any retouching. In contrast, the last one, near the diagonal, should be adjusted in order to fit neatly with the voussoirs of cylinder A. In the next step, the mason should retouch the end of this voussoir so that it is aligned with the plane of the bed joint of the third-course voussoir for cylinder A; this operation can be carried out easily with rulers leaning on the bed joint of the third-course voussoir of cylinder A. Then, the mason should put in place the voussoirs for the fourth course

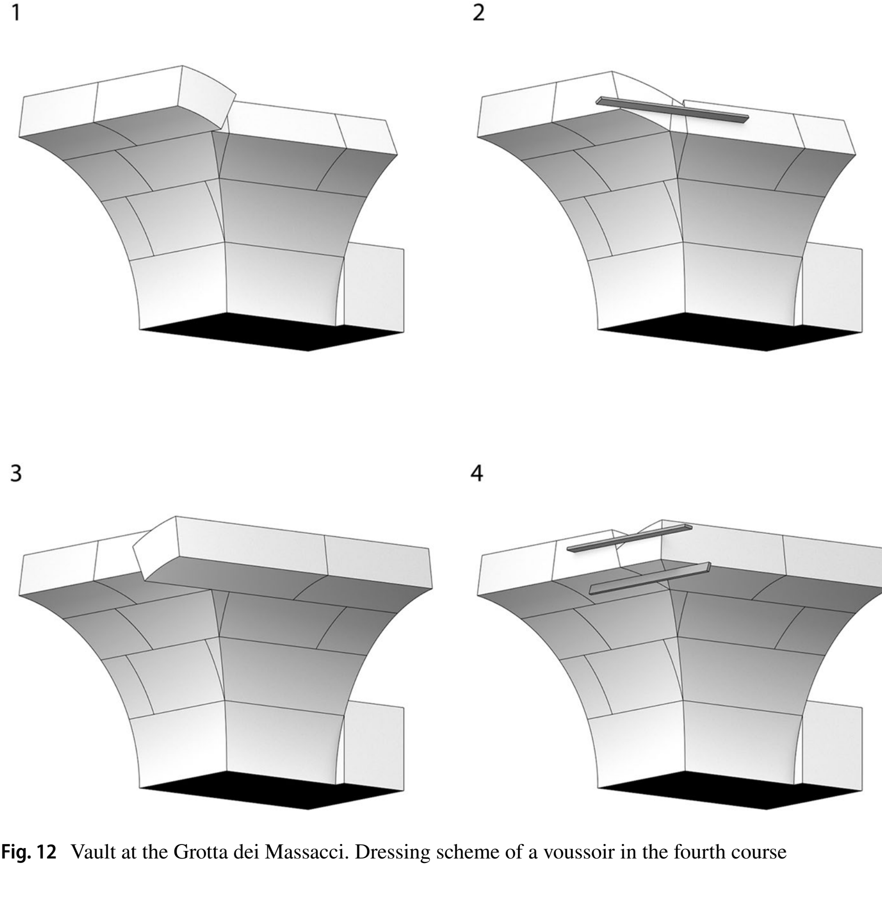

Fig. 12 Vault at the Grotta dei Massacci. Dressing scheme of a voussoir in the fourth course

of cylinder A. As before, most of this voussoirs may be left as ordinary barrel vault voussoirs, but the end voussoir, crossing the diagonal plane, should be adapted to fit the end voussoir of cylinder B. As in the preceding case, this can be done easily, controlling the operation with a ruler leaning on the bed joint of the voussoir of the fourth course in cylinder B, generating a side joint for the voussoir in cylinder A as an extension of the bed joint in cylinder B. In other words, the side joint for the fourth course of cylinder B is aligned with the bed joint for the third course in cylinder A, while the side joint for the fourth course of cylinder A is aligned with the bed joint of the fourth course for cylinder B.

All this guarantees a correct fit between the internal surfaces of the vault, both bed and side joints. However, the intrados surface for cylinder A sticks out from the surface in cylinder B, and the intersection ellipse between both cylinders is not materialised. To address this issue, masons should cut the tip of the diagonal voussoir for cylinder A in order to adjust it to the intrados surface of cylinder B. As always, this operation can be controlled by means of a ruler leaning on the intrados surface of cylinder B. It would be safer, however, to use an arch square with a straight arm leaning on the side joint of cylinder A, in addition to a curved face that would materialise a cylindrical intrados surface as an extension to the intrados of cylinder B. The problem with this last detail is that there is no evidence of the use of the arch square in the Roman world. Thus it is safer to assume that the tip of the last voussoir in cylinder A is dressed using only a square leaning on the intrados of cylinder B.

A similar procedure may have been followed for the second and third courses (Fig. 13), but in this case it requires an additional operation. In these courses, one of the joints near the groin is projected in plan as an *oblique* straight line, in contrast with the fourth and fifth courses, where this line is orthogonal to the intrados joints. The precise orientation of the bed joint cannot be ascertained, since it is hidden in the masonry; only its external edge can be seen by the naked eye or the scanner. However, we will put forward some alternative hypotheses for the orientation of this hidden joint and the dressing process of the voussoirs placed next to it. In order to implement a manageable dressing process, the joint must fulfil two conditions: first, it should be materialised by a plane passing through the intersection of the lower bed joint of the course and the groin of the vault; second, this plane can be rotated at will depending on the size of the starting block used to dress the final voussoir. Both conditions explain the fact that the joint is projected in plan as a straight line with different orientations in the second and third courses and the four arms of the Greek cross. However, once it is settled that the joint must include a portion of a vertical plane, there are two possibilities: the vertical plan may completely cut the involved voussoirs or it may cut the voussoirs only to the required extent to allow their assembly; this last hypothesis is the only one depicted in Fig. 13, since it involves less dressing effort. However, the issue cannot be settled unless the vault is disassembled, which is of course out of the scope of our research. An interesting detail are some holes or maladjustments between the voussoirs in the second and third courses (Fig. 14), *but not in the first, fourth and fifth courses*; these holes may be a result of the difficulties placed by this complex dressing process; however, they can also be the result of damage to the voussoirs during placement.

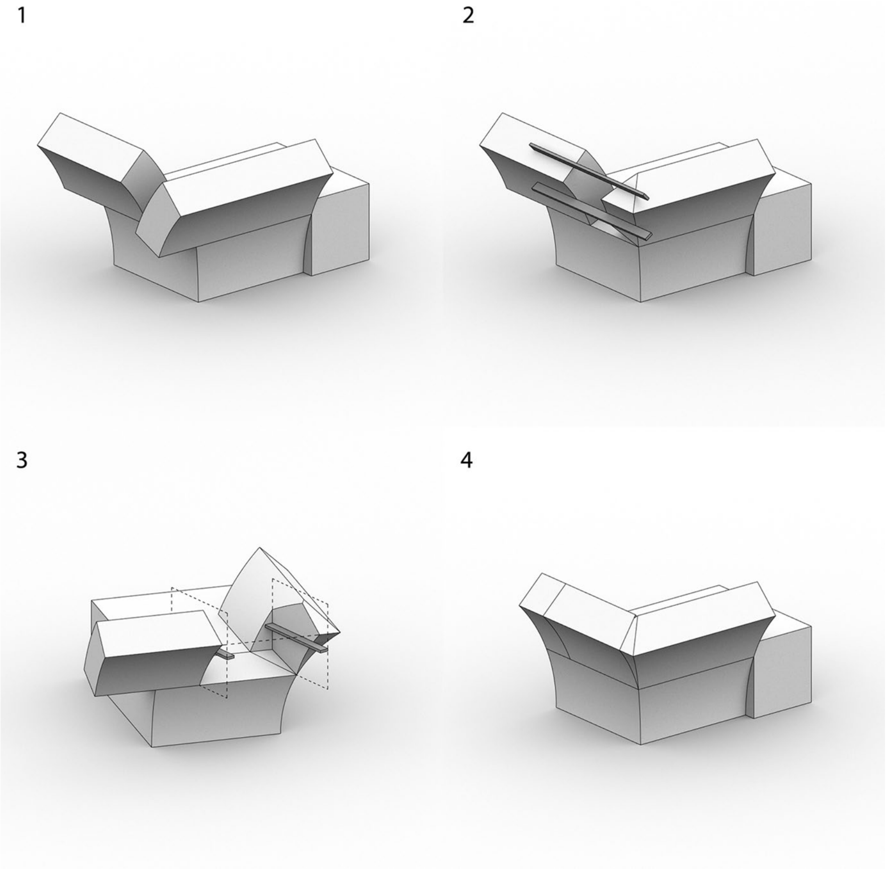

Fig. 13 Vault at the Grotta dei Massacci. Dressing scheme of a voussoir in the second course

Execution

Weight of Individual Stones

The survey of the Grotta dei Massacci gives us a good opportunity to gain insights into the hoisting devices that may have been used during its construction and, indirectly, the power and complexity of the technology used to build the vault. The first step in this inquiry is to compute the volume and weight of the individual stones (Table 3). Most of the stones in this construction cannot be measured precisely since they are covered by other materials. However, there are two locations where all three dimensions of the stones can be determined safely: the stones spanning the entrance corridor, in the shape of a monolithic surbased arch, and the lintel at the entrance.

In order to simplify our computations, we will surmise that the stone was dressed at the quarry. This will furnish a lower limit of the volume and weight of the stones,

Fig. 14 Vault at the Grotta dei Masacci. Detail of the springings

Table 3 Volume and weight of individual stones

Corridor, dressed stones	
Span (m)	2.75
Length (m)	1.35
Height (m)	0.88
Cross-section (m^2)	2.420
Volume (m^3)	3.267
Cut-off area (m^2)	0.313
Cut-off stone in the the surbased arch (m^3)	0.423
Net volume (m^3)	2.844
Weight (kp)	6542
Lintel at the entrance, dressed stones	
Length (m)	3.84
Width (m)	1.13
Height (m)	0.91
Volume (m^3)	3.949
Weight (kp)	9082

and indirectly of the power of the hoisting equipment. If the stone were dressed in the building site, as frequently done in later periods, all dimensions of the stone would have been increased in order to protect the stone during transport. This hypothesis would result in an increase in the volume and weight of the stone and the power of the lifting equipment of around 10–20%.

The largest dimension of the stone covering the corridor equals 2.75 m, including both the span of the corridor and the area where the piece rests on the walls. Its total height from the impost to the upper surface is 0.88 m, while its length in the direction of the axis of the corridor measures 1.35 m. Thus, the enclosing volume can be computed at 3.267 m^3. However, we should detract from this measure the amount of stone taken off to generate the segmental arch. The area of the cross-section of this cut-off volume amounts to 0.313 m^2; multiplying this area by the length in the direction of the axis of the corridor, 1.35 m, we get a total volume for the cut-off stone of 0.423 m^3 and a net volume of 2.844 m^3. Considering a density of 2.3 for the travertine, the total weight of the stone that must be hoisted to its final position is 6.542 metric tons. In the case of the lintel at the entrance, it features a length of 3.84 m, a height of 0.91 m and a depth of 1.13 m; this leads to a volume of 3.949 m^3 and a weight of 9.082 metric tons.

Hoisting Devices Mentioned by Vitruvius: The Machine for "Colossal Loads" and Other Variants

In Book X, Chap. II, §1–5, of his *Ten Books on Architecture*, Vitruvius describes three hoisting machines, including one capable of lifting "colossal loads". These lifting devices have been analysed thoroughly by Patrick Fleury (1993: 96–112, 129–135; see also Adam 2011: 44–53 and Martines 1999). Thus, it will be enough to include here a general description of the device for "colossal loads", together with an adaptation of Fleury's estimation of its lifting power, taking into account the particular circumstances of the Grotta dei Massacci.

The machine for "colossal loads" (Fig. 15) is based on a derrick or gin, that is, a device formed by two slanting struts joined at their tips and secured to the ground by their lower ends. Since the ensemble tends to fall forward, a number of ropes should tie the upper ends of the struts to the ground. The primary force is furnished by a capstan, that is, a vertical-axis cylinder or axle joined to the ground by its axis. Several radial handles are tied to the axle. The handles allow the workers to rotate the capstan, acting as the same time as levers, that is, multiplying the force exerted by the operators. A rope is tied to the capstan axle by one end, while the other one is fixed to a large drum attached to the struts of the derrick. The drum is also joined to another axle. The diameter of this second axle is much smaller than the one of the drum; this device again acts as a lever, providing further multiplication. A pair or ropes tied to this second axle go up to a block of three pulleys, known as a trispast. Each of the ropes coming from the axle passes through a first, fixed pulley, goes down to the second, mobile pulley, comes up to a third, fixed pulley attached to the first one and goes down again to the second pulley; the load is attached to this second pulley. However, since there are two ropes going into the block, it is easy to surmise that there are six pulleys in total: two parallel groups including three pulleys each. Thus, when the load is lifted, three sections of the rope, namely one from the first to the second pulley, one from the second to the third pulley, and one from

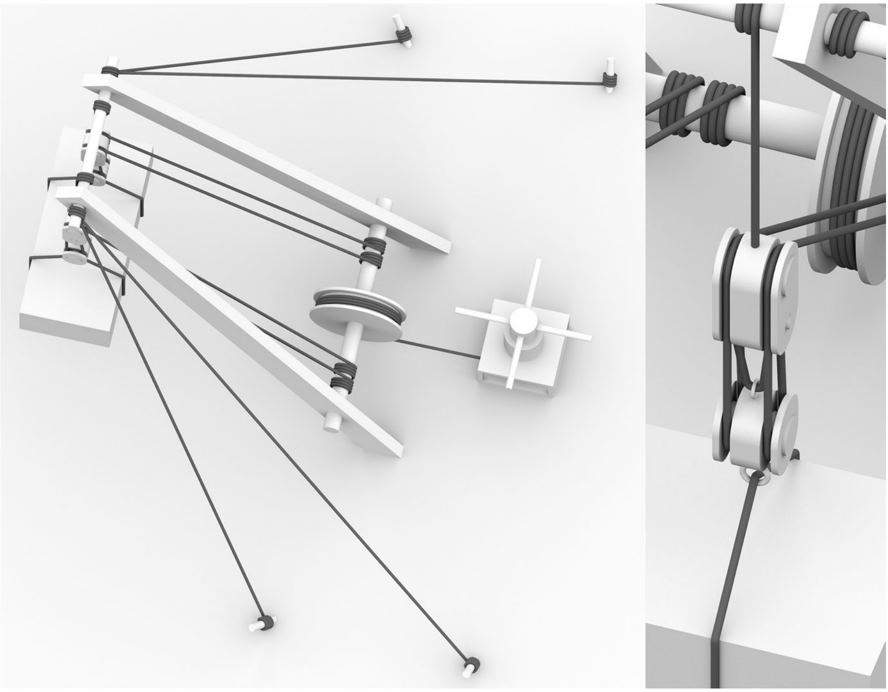

Fig. 15 Schematic reconstruction of Vitruvius' "machine for colossal loads". (Left) general bird's eye view; (right) detail of the tryspasts

the third to the second pulley are shortened. This means that the displacement of a point of the rope connecting the drum-and-axle combination with the first pulley is three times greater than the ascension of the second pulley and the load. Since the law of the conservation of energy states that the product of displacement and force must remain constant, the tryspast multiplies the force exerted by the drum-and-axle mechanism by three.

As an alternative, Vitruvius mentions in the same paragraph that a larger drum may be used so that men tread inside it, exerting force against several small laths. As they tread they go up, but their own weight pulls the wheel back, so they stay at the bottom of the wheel, causing the wheel and the axle to rotate; against, the force exerted by these men is multiplied in proportion to the diameters of the wheel and the axle. All this makes the capstan unnecessary.

Another essential item in the lifting equipment are the elements that tie the load to the tryspast; it is easy to understand that they should permit quick attaching and unfastening. Vitruvius mentions *forcipes*, known in English as "pincers". This instrument is formed simply by two S-shaped iron bars joined through an intermediate point. The upper ends of the S-bars are tied to the tryspast, while the lower ones are placed inside of two mortises in the lateral sides of the stones being lifted. When the hoisting device lifts the load the upper ends of the bars approach, working as a pair of scissors, so the lower ends push against the mortises. Heron of

Alexandria mentions an alternative instrument, known as a lewis. Masons should open a mortise with a dove-tailed section in the upper face of the stone. Then, they should insert into this mortise three special pieces. Two of them are dove-tailed; the masons should place them at both ends of the mortise. The third one acts simply as a fill between the other two. All three pieces have rings at their upper ends so the builders may pass a rope through all three holes to join them to the tryspast, providing thus a safer attachment.

Effective Lifting Power of the Devices Mentioned by Vitruvius

Fleury (1993: 132–135) has computed the lifting power of these devices; we will adapt his conclusions to the particular circumstances in the Grotta dei Massacci (Table 4). For the capstan-drum combination, Fleury states that a strong worker can exert a force of 15 kp during a whole day's work, but that for isolated efforts such as the hoisting of a particularly heavy stone, he can go up to 20–25 kp. However,

Table 4 Hoisting power of typical devices adapted to the Grotta dei Massacci context

Gin + capstan + wheel + trispast	
Capstan, primary force per man (kp)	15
Capstan, diameter (cm)	15
Distance from hoist axis to the point of application of the primary force (cm)	150
Number of workers	8
Gross force of the capstan (kp)	1200
Friction at the capstan	20%
Force at the outset of the capstan (kp)	960
Wheel, diameter of the axle (cm)	15
Wheel, diameter (cm)	150
Friction at the wheel	20%
Force at the outset of the wheel (kp)	7680
Multiplication at the trispast	3
Friction at the trispast	20%
Net force (kp)	18,432
Gin + treading wheel	
Treading wheel, primary force per man (kp)	60
Treading wheel, axle diameter (cm)	15
Treading wheel, inner diameter (cm)	400
Treading wheel, number of men	5
Treading wheel, friction	20%
Force at the outset of the treading wheel (kp)	6400
Multiplication at the trispast	3
Friction at the trispast	20%
Net force (kp)	15,360

this is not the case in the Grotta dei Massacci, where all stones, although maybe not as heavy as the examples we have analysed in "Weight of Individual Stones", are rather large. Thus, we will stick to the more conservative estimate of 15 kp per worker. Now, as stated by Fleury, a capstan can hold four crossing bars, giving a total of eight handles. Considering a diameter of the axle of 15 cm and 150 cm for the drum, and thus a multiplying factor of 10, this machine can exert in theory a lifting power of 1200 kp. However, we must consider the effect of friction between the rope and the surface of the capstan, which can be evaluated as 0.2, that is, 20%. Taking this into account, the effective lifting power of the capstan can be estimated at 960 kp. This equals approximately the resistance of a rope 31 mm in diameter, the one that corresponds to the grooves in a set of pulleys found at Kenchreai. Now, the force going out of the capstan is multiplied by the drum-and-axle mechanism in proportion to their respective diameters; taking into account diameters of 15 cm for the axle and 150 cm for the drum, the theoretical lifting power at the outset of the axle equals 9600 kp. However, we must take into account the resistance of the ropes: using two ropes at the outset of the axle we may compute a lifting power of 2000 kp minus friction. Now, this power is multiplied three times thanks to the tryspast; taking into account friction, it may be computed at about 4500 kp. Thus, the limiting factor is mainly the resistance of the ropes. In the working site, four ropes—and thus a set of twelve pulleys, in four parallel trispasts, may be sufficient for lifting 8000 kp, about the weight of the lintel at the entrance of the Grotta dei Massacci after dressing. However, if the lintel were to be lifted in the quarry before the final dressing stages, six ropes and six tryspasts would be necessary.

Conclusion

To start with, the groin vault at the Grotta dei Massacci, together with other examples, such as the skew Arch of Augustus in Perugia, the cylinder intersections at the Gymnasium and a tomb in Pergamon, the hemispherical vault at the tomb of Ummidia Quadratilla in Cassino, the groin vault at the lower chamber of the Mausoleum of Theodoric, the spiral ramp at the Mausoleum of Hadrian, the sail vaults at the Baths at Gerash, and other examples, prove the existence of complex vault systems in ashlar in Roman architecture. Up to this moment, these examples belong to isolated foci, as stated by Pérouse. However, looking at the map in Pérouse's own work (2001: 187), it becomes clear that Early Modern stereotomy in France focuses also in three isolated areas: Languedoc-Provence, the Loire valley and Paris. Further, we should ask ourselves if there are still other examples that have been studied only in local publications, as was the case with the Cassino and Frasso Sabino examples up to recent times.

Another interesting point is that most Italian examples are tombs and many of them, like the ones at Cassino and Frasso Sabino, were half buried, or at least surrounded by significant masses of earth. This suggests that Roman builders were aware of the thrust posed by these vaults and used them only where the thrust was compensated with retaining earth masses, or with significant masses of building materials, as in the Mausoleums of Hadrian and Theodoric.

As for measure and proportion, it is clear that the design and execution of the tomb was controlled through the use of the Roman feet. What is not clear is whether the builders used on top of this system other proportional schemes based on Egyptian triangle or the Golden Section, as suggested by Liberti, or whether the final proportions of the tomb are exclusively the result of the use of Roman feet. Further research on the metrology of Roman buildings, based on precise surveys, may shed light on these issues.

Perhaps the problems connected with the division of the vault into voussoirs are the most interesting ones posed by this vault. Our analysis has underscored the difference between the staggered voussoirs in the Grotta dei Massacci vault and the L-shaped pieces in the Mausoleum of Theodoric; it has also shown that the voussoirs of the vault *may* have been shaped by demand on their definitive position, with masons working on the formwork, using the voussoirs in other courses to shape each voussoir at the most critical point, the intersection of both cylinders. This leads to another interesting point: this stonecutting method, which starts from ordinary barrel vault voussoirs, *does not require* a preliminary tracing or the use of orthogonal projection, which seems to be absent in the Roman formal control method. Finally, the details connected with the weight of the stones and the hoisting equipment are also quite interesting; they underscore the need of specialised machines, such as the ones described in Vitruvius's Book X, to materialise construction with large ashlars and voussoirs.

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