STRUCTURAL APPRAISAL OF A ROMAN CONCRETE VAULTED MONUMENT: THE BASILICA OF MAXENTIUS

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RUNNING HEAD: Basilica of Maxentius

ABSTRACT

The Basilica of Maxentius, the largest vaulted space built by the Romans, comprised three naves, the outer ones covered by barrel vaults and the central, highest one by cross vaults. It was built on a sloping site, resulting in a possible structural vulnerability at its taller, western end. Two naves collapsed in the Middle Ages, leaving only the barrel vaults of the north nave. We describe surveys and analyses aimed at creating an accurate record of the current state of the structure, and reconstructing and analysing the original structure. Key features include distortions of the barrel vaults around windows and rotation of the west wall due to the thrust from the adjacent vault. Thrust line analysis results in a very low safety factor for the west façade. The geometry of the collapsed cross vaults was reconstructed from the remains using solid modelling and digital photogrammetry, and thrust line analysis confirmed that it was stable under gravity loads. A survey of the foundations and earlier structures under the collapsed south-west corner revealed horizontal slip and diagonal cracking in columns and walls; this is strong evidence that the site has been subject to seismic loading which may have caused the partial collapse.

KEYWORDS

Basilica of Maxentius; Roman concrete; barrel vaults; cross vaults; earthquake loads; point cloud surveys; digital photogrammetry; limit analysis.

INTRODUCTION

The Basilica of Maxentius, also known as Basilica of Constantine or Basilica Nova, was the last of the large civil basilicas of Imperial Rome. Its construction began in 307 AD (Minoprio, 1933) under the Emperor Maxentius and ended around 313 AD, after Constantine had defeated Maxentius at the Battle of the Milvian Bridge (312 AD).

The Roman concrete structure featured three large naves. The central nave, the highest and widest of the three, was covered with three cross vaults, while the two side naves to the north and south were roofed with three barrel vaults each. The west and north sides featured apses, while entrance porticos could be found on the east and south sides (Fig. 1). The overall plan dimensions of roughly 100 x 80 m made the Basilica the largest vaulted space known to have been built by the Romans. Furthermore, both the barrel vaults, spanning 23.5 m, and cross vaults, spanning 25.3 x 20.6 m, were in themselves the largest known today in the Roman Empire (Lancaster 2005), and, for many centuries, in the world.

The building suffered a partial collapse at an unknown date in late Antiquity or early Middle Ages, widely believed to have been caused by an earthquake (Samueli Ferretti, 2005). The south and central naves were lost, leaving only the three barrel vaults of the north nave still standing. The record-breaking structure and the suspected cause of the partial collapse make this building an outstanding case study for the structural analysis of masonry vaulted buildings and their vulnerability to seismic loads.

While the building has been the subject of numerous archaeological studies, there has been only limited engineering research. Among the more recent studies, Calabresi and Fattorini (2003) conducted geotechnical investigations, concluding that all four piers supporting the north nave are founded on the same undisturbed silt layer, but provided less information about the soil structure under the south nave. Samuelli Ferreti (2005) carried out linear elastic finite element modelling of both the original and the current states of the Basilica, with the aim of obtaining the eigenvalues, namely the natural frequencies and mode shapes. The periods of the dominant sway modes in the two perpendicular directions were calculated as 0.61 s and 0.44 s. The dynamic response to an earthquake having a peak horizontal ground acceleration of 0.2g was then estimated, assuming linear elastic behaviour, using the mode superposition approach, based on the first 15 computed modes of vibration. It was concluded that the peak tensile stresses resulting from such an analysis would be sufficient to cause element failure and likely collapse of the structure. As the author acknowledges, the validity of this approach is open to question, since it takes no account of existing damage such as cracks, which are likely to dominate the response. As a result, a response calculation based on the elastic modes is unlikely to be realistic, since the dynamic response will be highly non-linear, and the mode superposition approach is not valid.

In this paper we present a series of studies aimed at: i) accurately determining the geometry of the existing structure, ii) assessing the stability of the surviving barrel vaults, iii) reconstructing the as-built geometry of the original structure, and iv) seeking insights into the cause of the partial collapse. The paper first briefly describes the structure and its history, then presents the results of surveys and photogrammetric reconstructions of the geometry, before proceeding to stability analyses using thrust line analysis and graphic statics.

A BRIEF HISTORY OF THE BASILICA OF MAXENTIUS

Construction

The construction of the Basilica of Maxentius was part of a programme of building and restoration aimed at renewing the splendour of the historic political centre of Rome around the Forum, at the turn of the 3rd and 4th centuries AD (Coarelli 1986:2). These works were initiated by the Emperor Maximian, and subsequently embraced by his son Maxentius when he succeeded his father as emperor in 306 AD (Santangeli Valenzani 2000).

The Basilica was Maxentius's most ambitious and magnificent work: a structure of monumental proportions that was to be the last of the large civil basilicas of Rome. It was built on a prominent location between the Via Sacra, one of the main arteries of the city, and the Velia Hill. Construction began around 307 AD and by the time Constantine reached power in 312 AD it is believed to have been well underway (Franklin 1924:79). The building was dedicated to Constantine and subsequently all traces of Maxentius were erased from the building. The specific use of the building remains unclear; Coarelli (1993) believes the Basilica of Maxentius hosted the seat of the judicial activity of the *praefectus urbi*, who had, from the early 4th century, the judicial responsibilities over the city.

The construction of the Basilica faced several technical challenges, of which the most significant was the large change in ground level across the site, with a drop of approximately 9m from the north-east to the south-west corner. The interior floor was situated at the higher level. As a result, the internal floor level was nearly 9m higher than the ground outside the west façade, which therefore had to be 9m taller than the east one, and had to act as a retaining wall for the fill on which the floor rested. To the present day, the taller west façade has been the weakest point of the building and has suffered numerous structural problems.

Further structural complexity arose because the Basilica was built over a large range of *horrea* (warehouses) that had suffered irreparable damage in the fire of Carinus in 283 AD and had fallen out of use (Rickman 1973). These remains were capped and used as a base for the foundations of the south nave of building, as discussed below in the *Survey of the Foundations* section, while the north nave was built on fresh and fully consolidated ground, cut into the Velia Hill.

The principal construction material of the Basilica was *Roman concrete*, an unreinforced composite material comprised of alternate layers of pozzolanic mortar and *caementa* – fist-size pieces of aggregate, mainly broken bricks or tiles and different types of stone. The material was widely used in Roman construction in regions where pozzolanic (volcanic) ashes were available. Although its method of production is different to modern concrete, the material exhibits somewhat similar mechanical properties, with relatively high compressive strength but much lower tensile strength, making it prone to cracking at quite low tensile stresses (Brune 2010).

Partial collapse and subsequent history

The Basilica suffered a collapse of two thirds of the structure (the south and central naves) at an unknown date. Doring-Williams and Albrecht (2010) studied structures that were built over the west end of the Basilica after its collapse, dating some of them to the early 6th century and hence implying that the collapse took place before then. No known written sources document the event, but it has commonly been assumed that the cause of the collapse was an earthquake.

The more recent history of the site can be traced through the numerous drawings and engravings of the remains made from the 15th century onwards. These have been collated and summarised by Albuerne (2016); an example from the 16th century is shown in Fig. 2. After the collapse, the ground level is estimated to have been raised by around 7m, at least partially due to the presence of rubble remains of the collapsed parts. Much of the rubble remained on the ground for many centuries, as evidenced by early engravings, suggesting that no great efforts were made to restore the building or re-use the site. The earliest image showing most of the rubble cleared dates from 1629 (Mercati 1629).

From the 17th century onwards, there is more evidence of attempts to use or excavate the site. A passage was opened through the Basilica, under the remaining west vault and through the lower windows of the north façade, at a level near that of the original internal floor (Giovannoli 1619), and around 1650 a new building was constructed over and against the remains of the west façade and the collapsed south nave. In the early 19th century, major archaeological excavations were undertaken by Fea and then Nibby, the latter lowering the ground level within the Basilica and exposing the original floor. Further excavations in the 20th century lifted the floor to examine the remains of earlier buildings below, as observed by Barosso, (undated) in around 1920. Finally, at the start of the 21st century, the ground outside the west façade was taken back down to the original level of the Via Sacra, restoring the 9 m height differential at this end of the building. Due to concerns over the stability of the west façade, a steel cable restraint has been fitted. Two recent views of the north nave barrel vaults are shown in Fig. 3.

SURVEYS AND GEOMETRICAL RECONSTRUCTIONS

Several surveys were undertaken with the aims of establishing the accurate geometry of the remains, quantifying the deformations that have occurred within the structure, making an improved reconstruction of the lost cross-vaults and assessing the state of the foundations.

Geometrical surveys

Two methods were used to gather geometric data. First, a point cloud survey was carried out using a Leika Flexline TS06 5" Power Total Station. Over 43000 data points were recorded. The survey focused on specific elements and profiles of key importance, in particular: transverse profiles of the barrel vaults; out-of-plane deformations of load-bearing walls; geometry of cross vault springings; geometry of north façade; profile of damage on top west corner over western barrel vault; and the geometry of the small number of broken vault fragments still present at the site. Fig. 4 shows an isometric projection of the point cloud, the different colours denoting different positions of the total station, and Fig. 5 presents a floor plan of the whole site.

A more detailed reconstruction of specific elements was obtained using digital photogrammetry, a technique by which accurate geometrical models of an object are obtained by processing digital photographs. Photogrammetry uses stereographic principles, with the general rule that more pictures will lead to greater accuracy in the results. The basic technique is well established and has been extensively used by map makers, but has recently been extended so that accurate reproduction can be achieved without prior knowledge of the camera properties or location. A number of computer programs are available, capable of handling large sets of photos of mixed sizes and different sources; provided enough photographs of sufficient quality are employed, the resulting 3D model will only need to be scaled and oriented to fulfil the purposes of a survey.

The software 123D Catch by Autodesk was selected for use. This generates a 3D mesh and surface rendering that can be processed by graphic software such as AutoCad and Rhino. It was applied to particular areas of the Basilica where particularly detailed models were desired, including fragments of the broken vaults and the cross vault springings and buttresses. The 3D models were scaled and oriented using total station measurements as reference; a typical result, for the largest extant segment of cross-vault, known as fragment A, is shown in Fig. 6.

Survey of the foundations

After the archaeological excavations of the early 20th century, a reinforced concrete supporting structure was built under parts of the south and central naves, leaving an accessible basement where the foundations and earlier structures remain visible. A full survey of the foundations was carried out by Albuerne (2016) and some of the key findings are reported here.

The southern parts of the Basilica were built over the remains of some warehouses (*horrea piperataria*). The survey revealed that the walls of the earlier structures were incorporated in the strip foundations under the new piers. The foundations were bound together in poor Roman concrete. A horizontal surface was created at the top of the strip foundations, where a layer of *bipedales* (600 x 600 mm tile-like Roman bricks) was introduced. The piers rested on these layers of *bipedales*, to which they were not mechanically connected.

Within these underlying structures, evidence was found that the structure had previously experienced large lateral loads. These included diagonal cracking and substantial inclination of some Roman concrete walls. One of the most striking examples is shown in Fig. 7, which shows a wall originally part of the *horrea piperataria* that has undergone lateral deformation at a series of slip planes. It is known that Romans used layers of *bipedales* every 1–1.5m within walls (Choisy 1873), to act as bonding courses connecting together opposite brick facings. These layers gave a very smooth horizontal surface with a much lower frictional resistance than the concrete core, leading to the observed deformation. From this and other observed foundation damage, it appears likely that the site was subjected to a significant horizontal seismic loading, with its strongest component parallel to the longitudinal axis of the Basilica.

STABILITY ANALYSES OF THE SURVIVING STRUCTURE

The survey of the surviving barrel vaults revealed two key features requiring further study: a distortion of the vaults' profile from the ideal semi-circular form, particularly adjacent to the north façade of the building; and an outwards lean of the west wall, together with loss of material at its top. These are both considered in detail below. Lastly, we analyse the effect of changes in ground level over the life of the structure.

To analyse the stability of vaults, we use the method of thrust line analysis (Heyman, 1995). An arch or vault is stable if any one of the numerous thrust lines equilibrating the applied loads can be shown to lie within the structure's profile. Limiting cases in which the thrust line touches the edge of the structure at sufficient points to form a collapse mechanism correspond to the minimum or maximum thrust for which the arch is stable, the minimum thrust generally being the case of most practical interest.

Distortion of vault shape

All three surviving barrel vaults show a deviation from the ideal semi-circular shape, as can be seen in Fig. 8. This is most extreme adjacent to the north façade, with cross-sections further to the south becoming closer to circular in form. Rather than being the result of deformations under load, we believe this to be an accommodation of a construction error. There is evidence that the northern wall was constructed before the vaults; the brick arches around the windows in the northern wall are partly hidden on the inside by the vaults (Albrecht 2009). It appears that the windows in the top row were positioned either too high or too far apart, so that they did not fit within the intended semi-circular profile of the vault (see

Fig. 8). Therefore the geometry of the vault had to be altered in order not to obstruct the windows.

Stability analyses were performed for both the actual and idealised geometries of the eastern vault. As with other large Roman concrete structures, it is known that aggregates were chosen so as to reduce densities in the upper parts of the vaults. Here the unit weight is taken as 13.5 kN/m^3 in the vaults, 17 kN/m^3 in the upper parts of the walls and 22 kN/m^3 at the base. These values are best estimates based on the properties of material samples obtained from the Basilica (Samueli Ferreti 2005) and studies of other Imperial Roman concrete structures (see for example De Fine Licht 1968). The thrust lines and force polygons for the two cases are shown in Fig. 9. It can be seen that the minimum thrust line touches the intrados very close to the region around the windows, where the profile deviates most from the circular form. The resulting alteration of the thrust line results in a change in the minimum thrust from 300 kN/m length of wall for the circular case to 335 kN/m for the deformed vault, an increase of 12%. This is a significant change, although the resultant thrust still lies well within the structure at the base, so that the eastern vault is not at risk of imminent collapse.

Comparisons across different structures can be aided by putting these results into non-dimensional form. Taking the minimum arch thickness at the crown, the ratio of thickness to radius is 0.27. Assuming the idealised geometry, the minimum thrust is 17.7% of the vault self-weight, whereas using the actual geometry increases this ratio to 19.4%. These figures can be compared with those of Block et al. (2006) for a semi-circular arch with thickness to radius ratio 0.18, for which the minimum thrust was 16% of the self-weight. However, the cases are not directly comparable since Block et al. considered stability only of an arch in isolation, whereas for the Basilica the influence of the supporting walls below the semi-circular vaults is significant.

Deformation of west wall and north-west barrel vault

Fig. 10 shows the current profile of the barrel vaults of the north nave measured near the central nave, compared to an ideal original profile assuming vertical walls and perfectly semi-circular vaults. It can be seen that the structure leans significantly at the west end, the magnitude of the lean reducing to a negligible level at the east end. The magnitude of the west wall rotation is around 0.8°, or a maximum lateral displacement of around 300 to 400 mm. This deformation is largest next to the central nave and reduces as we measure along the remaining length of the west wall towards the north façade. The wall has experienced a combination of out-of-plane rotation about a horizontal axis and about a vertical axis. The latter is explained by the restraining effect of the north façade, as large forces may be generated at the interface between the two orthogonal walls (Casapulla & Argiento 2016). Additionally, the partial collapse has caused the loss of a substantial mass of material from the top corner of the structure; this mass would have added to the vertical load component in the wall, helping to stabilise it under gravity loading.

The Basilica of Maxentius was built on sloping natural ground, the highest point of which was the north-east corner, and the lowest, the south-west. The height difference between these points was close to 9 m. The height of the walls is a crucial factor for the stability of the structure, hence the western vaults were the most critical in the building. Although the Romans constructed the western external wall thicker than the eastern one (5.0 m vs. 4.5 m), the difference was found not to be enough to provide both ends with the same degree of stability and the western vaults resulted in weaker elements. Further action was taken on the western vaults as construction progressed, introducing additional buttressing elements (Amici 2005): a buttress that rested on the adjacent Temple of Peace, a further buttress, and an external staircase. The substantial damage present in the north-west vault and the deformations of the remains of the west wall south of the apse are a clear proof that the final design did in fact have a weak spot at this end.

The deformations of the north-west vault can be explained very accurately by a simple mechanism which is consistent with a thrust line analysis. The thrust line and resultant kinematic analysis of the mechanical deformation of the vault in the present day are shown in Fig. 11, where the observed lateral sway has been correlated to the consequent displacements of the vault. Both walls are leaning towards the west, but by different amounts. The thrust line analysis has been performed at the cross-section where the most material has been lost from the top corner. The amount of missing material becomes smaller into the vault, and the additional restraint provided by the connection to the north will also increase the stability. Therefore, the stability safety factor resulting from the analysis will increase at these locations, with the thrust line lying further inside the cross section at the base of the wall. (The influence of the missing material can be seen in Fig. 12, introduced and discussed in the next section).

It is interesting to compare the thrust line in the west vault (Fig 11) with that shown earlier for the east vault (Fig 9). It can be seen that the lost material in the west vault is almost entirely at the top of the left-hand wall, and not above the vault itself. Therefore the two thrust lines within the vaults are similar, and the most obvious difference is between the thrust lines in the walls. For the west vault, the reduction in vertical load due to the lost material causes the thrust line to lie close to the edge of the cross-section at the base of the wall. For the east vault, although the wall is thinner, the thrust line lies further from its edge, due to the greater vertical loaded coming from the top of the wall and an additional vault above.

Stability through the ages

It has already been mentioned that the ground level both inside and outside the Basilica has undergone a series of changes through the life of the structure. A series of analyses was performed to assess the impact of these changes on the structural stability, focusing on the west vault. These are summarised in Fig. 12. Besides gravity loads, in cases a) and d) lateral soil pressures were included to account for the effect of differing ground levels either side of the west wall. A lateral earth pressure coefficient $K_0 = 0.5$ was assumed.

As can be seen in Fig. 12, these show that the original structure possessed a good level of stability, the minimum thrust line lying well inside the structure at the base of the west wall. The loss of material at the top of the structure during the partial collapse had a negative effect which was offset by the raise in ground level.

The subsequent excavations, first inside the building and more recently outside the west wall, have a clear justification in archaeological terms, enabling us to learn more about the building's history and returning it closer to its original state. However, they have had a negative impact on the safety of the structure, reducing its geometric factor of safety and necessitating the installation of the intrusive steel tie system visible in Fig. 3.

ANALYSIS OF THE COLLAPSED CROSS VAULTS

While the general form of the original structure is well-known, uncertainty persists over the exact configuration of the cross vaults over the central nave. In this section we use the survey results to estimate the structural form at a more detailed level than has previously been attempted, and hence to gain insights into the structural behaviour.

Reconstructing the cross vaults

The plan of the cross vaults has been inferred from the floor plan of the Basilica presented in Fig. 5, in particular the footprint of the barrel vaults' supporting walls, in conjunction with the north side springings. This implies a series of three cross vaults, rectangular in plan, with a proportion of about 4:5 between the sides, the longitudinal (east-west) direction having the larger span of length 25.3m.

The form of the cross-vault was inferred from the 3D photogrammetric model of fragment A. This was positioned within the reconstructed vault using the surface decoration as a guide. The decoration pattern was projected onto the intrados of a 3D reconstruction of a cross vault, and fragment A was oriented to match it. This yields a slope of the extrados of just under 25°, which can be extrapolated to the rest of the roof. The resulting minimum thickness of the vault is approximately 1.70m, that is, 1/15 of the largest vaulted span. A general view of the reconstructed geometry and the position of fragment A are shown in Fig. 13, and dimensions are indicated on Fig. 14. A further check was carried out by checking the alignment of the vault with the roof buttresses over the north nave, giving good agreement (Albuerne et al. 2012).

Stability analysis

Limit analysis has been applied to assess the structural behaviour of the cross vaults under static loads. Graphic statics, and in particular the slicing technique, first introduced by Poleni (1748) and more recently described by Heyman (1995), has been applied to the western vault, dividing it into two sets of arches perpendicular to the longitudinal and transverse directions respectively (see Figs. 14). Two different densities of material have been assumed: a unit weight of 17.0 kN/m^3 in the lower part of the structure, and a lighter 13.5 kN/m^3 at the top (levels shown on Fig. 14) - consistent with values used earlier for the barrel vaults, and based on the studies of De Fine Licht (1968) and Samuelli Ferretti (2005). The resulting horizontal thrust along the diagonal is 3.08 MN.

Results are shown in Fig. 15, for the most critical slice (having the largest angle of embrace) and for the resolved thrust in a vault diagonal. There no stability issues with the arch slices. Of particular interest are the resolved components of this diagonal thrust in the directions parallel and perpendicular to the west façade (Fig. 15). The parallel component is 1.95 MN and the perpendicular component is 2.39 MN. The latter force is the one which would tend to destabilise the west wall, which has already been shown to be a vulnerable element of the structure.

This analysis has shown that the vault was safe under self-weight loading, since stability only requires that a thrust line can be found that lies within the structure. However, it represents only one of many possible solutions for this indeterminate system. In practice, since the vaults are monolithic and feature a modest amount of cohesion, it might be expected that, while they are uncracked, they would span predominantly in the shorter span (north-south) direction. This would be desirable, since the north and south naves would have provided a stiffer restraint in the transverse direction than exists in the longitudinal direction (Albuerne 2010). The simple system of cutting planes could be optimised by finding less conservative load paths that exploit the existence of a shorter span in the north-south direction, where buttressing is stronger thanks to the piers supporting the barrel vaults of the north and south naves and the buttresses sitting on top of them to pick up the thrust of the cross vaults.

CONCLUSIONS

The Basilica of Maxentius was one of the great Roman construction achievements. Its cross vaults and barrel vaults were each the largest of their type known to have been built by the Romans. Key structural issues included a large drop in ground level across the site and the construction of such a large building over earlier remains; these are thought to have resulted in the south nave and the west wall being the most vulnerable parts of the structure.

The building suffered a partial collapse at an unknown date in the Middle Ages, possibly as early as the 6th century. The south nave and the cross-vaulted central nave were lost, leaving only the three barrel vaults of the north nave. These enormous vaults remain one of the most impressive sites of Ancient Rome.

This project has created an accurate record of the geometry of the Basilica of Maxentius in its current state. Two key features were identified and investigated in detail. First, it was found that the barrel vaults are severely distorted from their ideal circular shape, particularly adjacent to the north façade. We suggest that this distortion was introduced during construction, to accommodate an error in window positioning. The deformations have a local impact on the thrust generated by the barrels, which increases by over 10%. Second, the height of the west façade, together with the loss of some material from the top corner of the west vault, have contributed to a rotation of the west wall, resulting in a significant outward lean yielding a very low safety factor of the west façade.

The geometry of the collapsed cross vaults has been reconstructed from the remains, in particular the springings and a broken fragment, which have been modelled in 3D using the technique of digital photogrammetry. This has enabled a reconstruction of the roof profile, slope and thickness, believed to be the most accurate available. A thrust line analysis of the reconstructed cross vault using a conservative slicing approach has confirmed that the vault was stable under gravity loads.

A survey of the foundations and earlier remains under the collapsed south-west corner of the Basilica revealed evidence of horizontal slip and diagonal cracking in columns and walls, strongly implying that the site has been subject to severe seismic loading which may have triggered the failure. Further investigations of the remaining foundations of the collapsed south nave of the Basilica could help in the characterization of the structural failure of the nave, shedding more light on the cause of partial collapse.

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LIST OF FIGURES

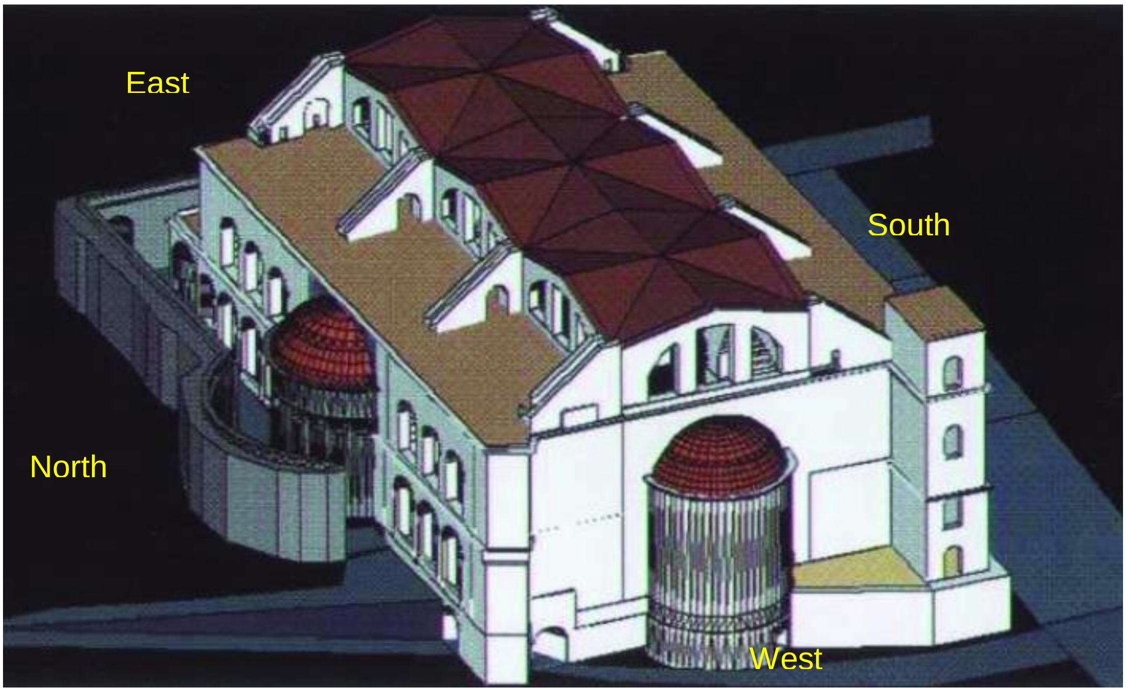

Fig. 1. Reconstruction of the idealised geometry of the Basilica of Maxentius in the 4th century, seen from the north-west (Amici 2005). The west and north apses are visible, as are the flat roofs over the side aisles and the four-way pitched roof over the cross vaults of the central nave.

Fig. 2. Engraving of the Basilica of Maxentius (Giovanni Battista Cavalieri, 1569)

a)

b)

Fig. 3. North nave: a) view of the interior, from the south, and b) exterior, from the north

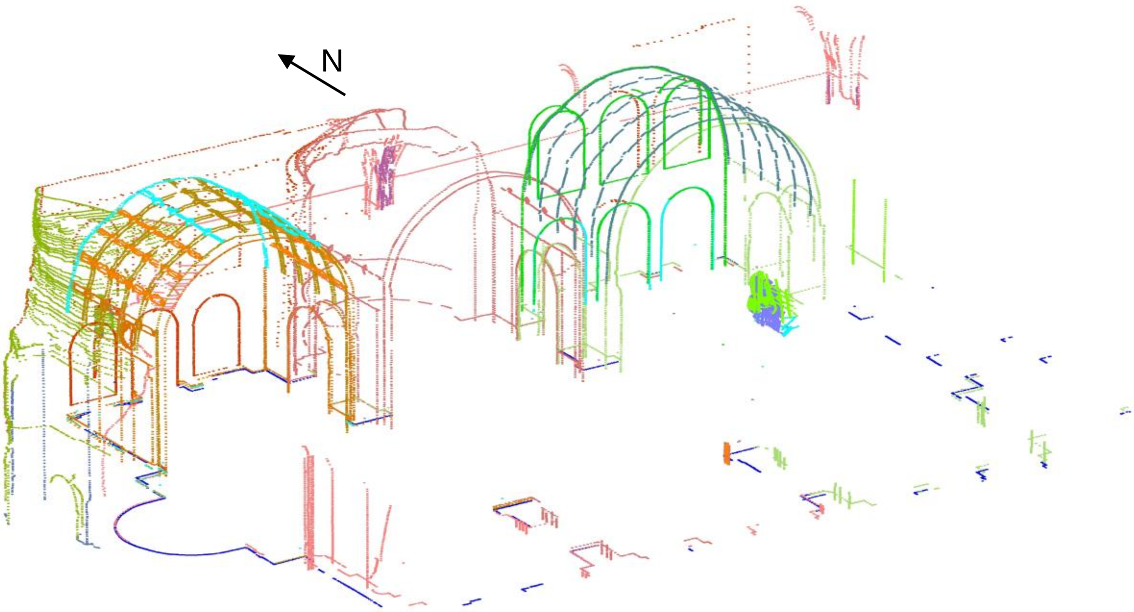

Fig. 4. Point cloud survey viewed from the south-west

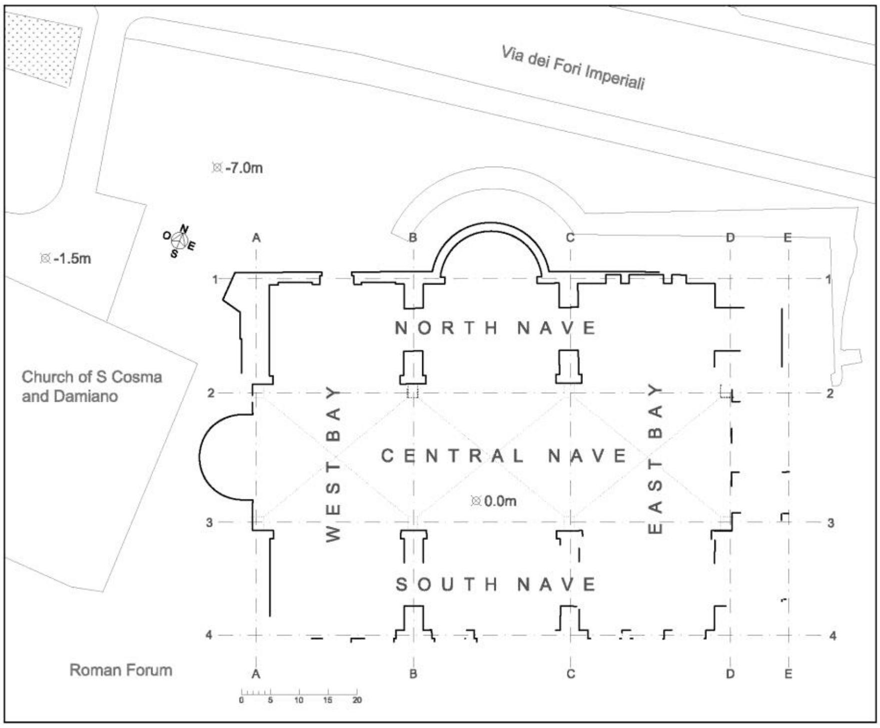

Fig. 5. Floor plan obtained from total station survey

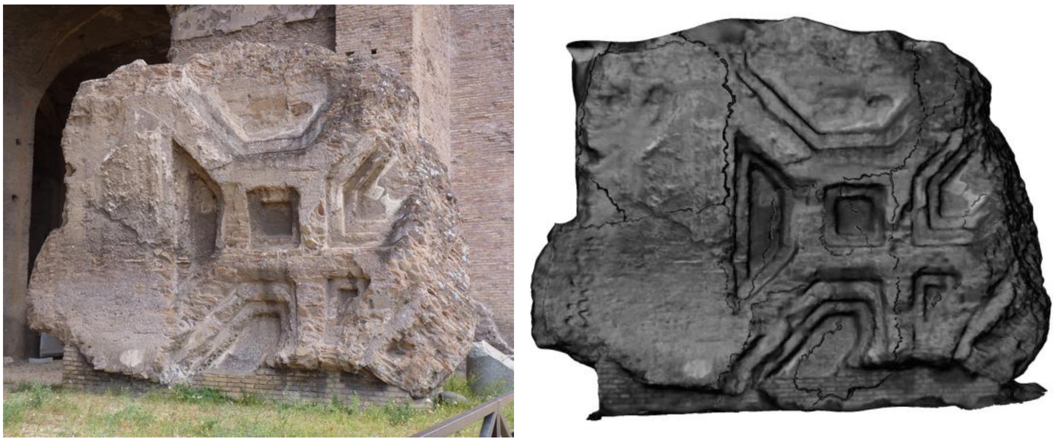

Fig. 6. Photo of vault fragment A, and 3D model created by digital photogrammetry

Fig. 7. Remaining wall of the *horrea piperataria* showing lateral slip at *bipedale* layers

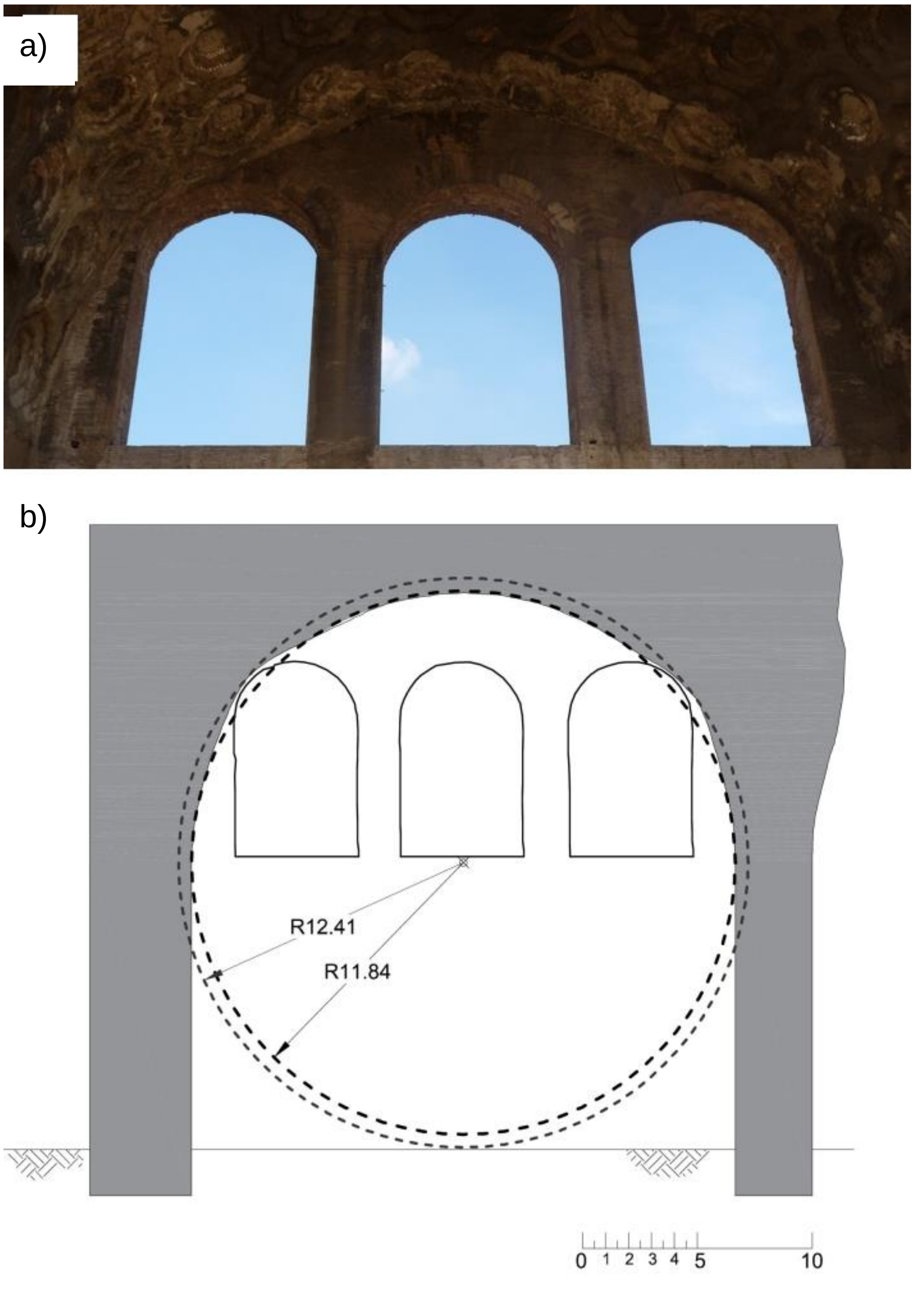

Fig. 8. a) Distortion of east barrel vault around windows on north façade, b) surveyed profile compared to ideal circular profile; the outer circle indicates the maximum radial discrepancy from the intended vault radius (inner circle)

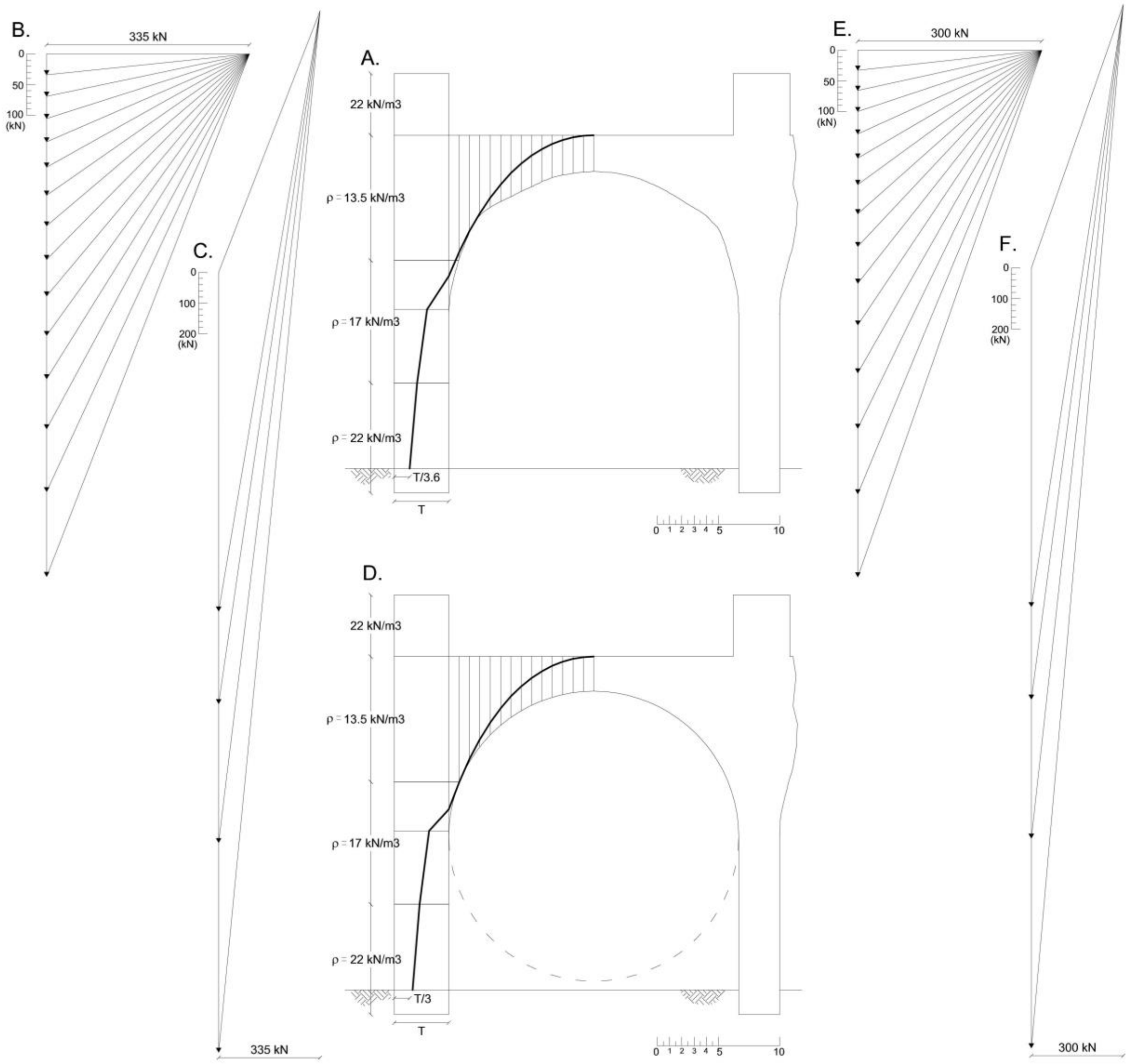

Fig. 9. Thrust line analyses of east barrel vault. Diagrams A-C use the actual vault profile. A: thrust line; B: polygon of forces for vault; C: polygon of forces for buttress. Diagrams D-F show the corresponding results for the ideal circular profile.

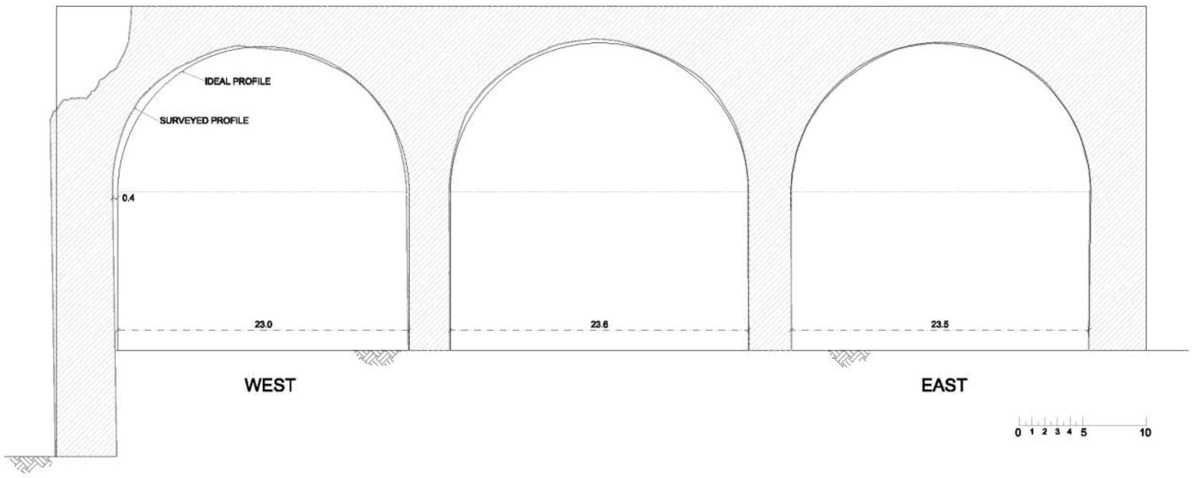

Fig. 10. Comparison of ideal original and current as-surveyed cross-sections of north nave

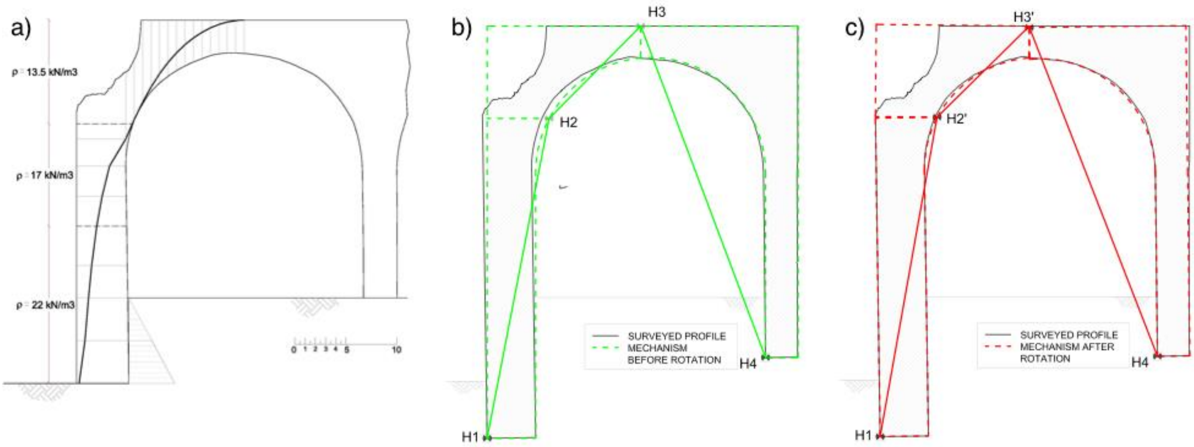

Fig. 11. Analysis of west barrel vault: a) Thrust line, b) Mechanism before rotation, c) Rotated mechanism

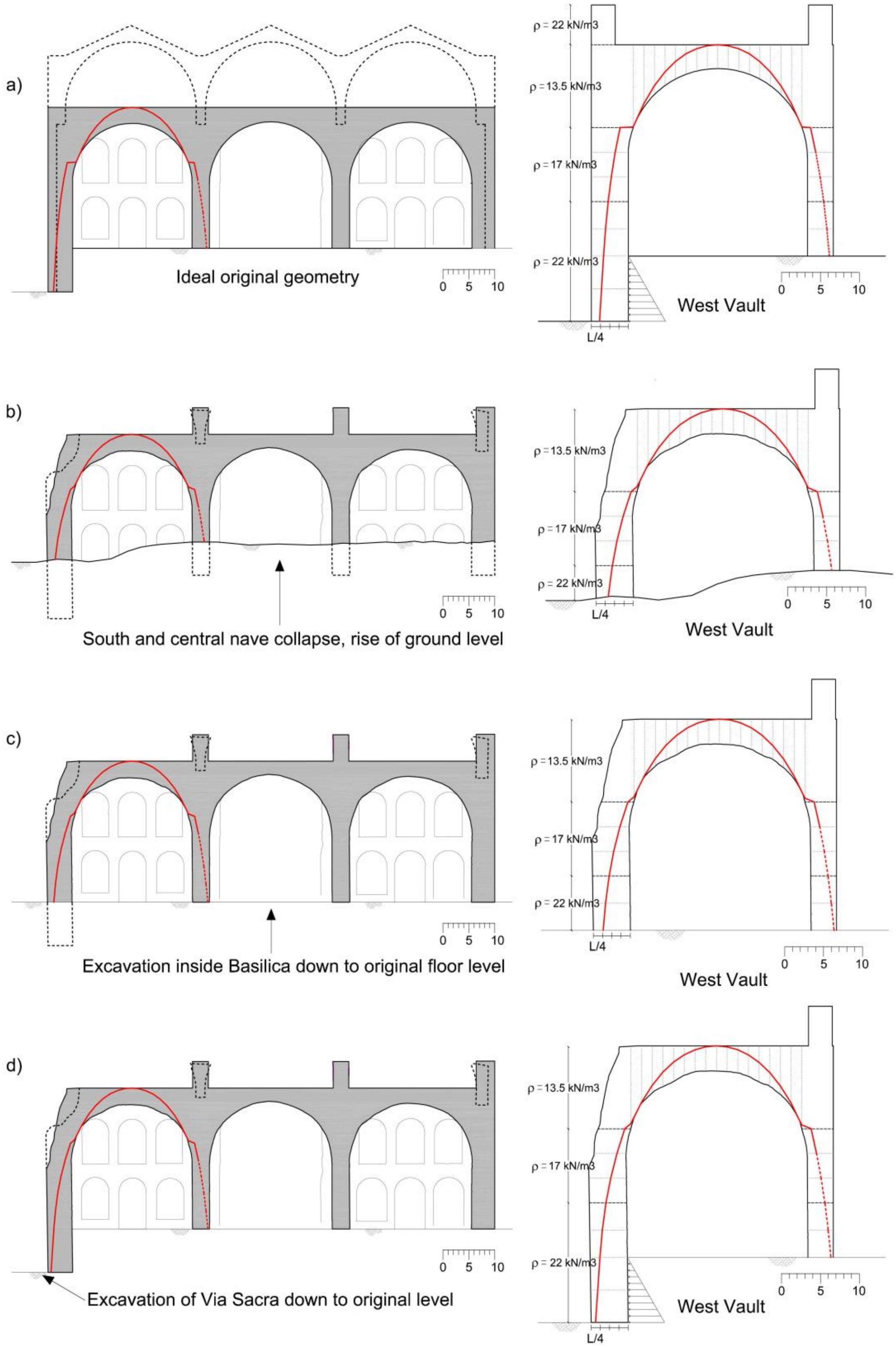

Fig. 12. Influence of changes in ground level on thrust line in west vault: a) Original structure, 313 AD, b) After collapse, pre-1450, c) After first excavation, c. 1820, d) After recent excavation, c. 2000.

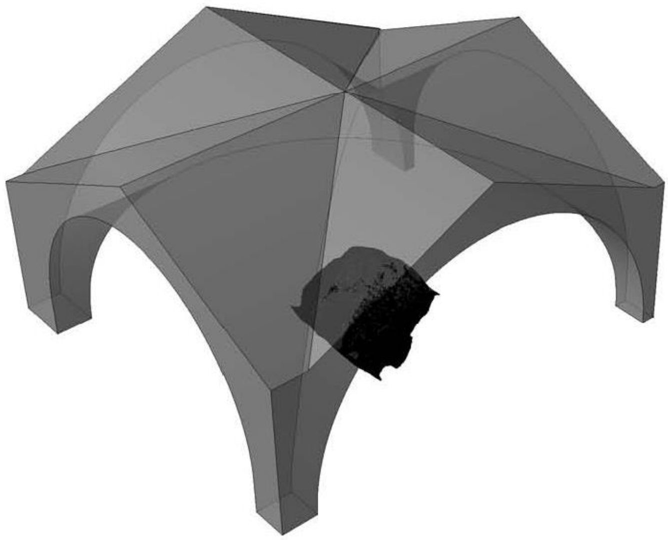

Fig. 13. Reconstruction of cross vault showing original position of fragment A

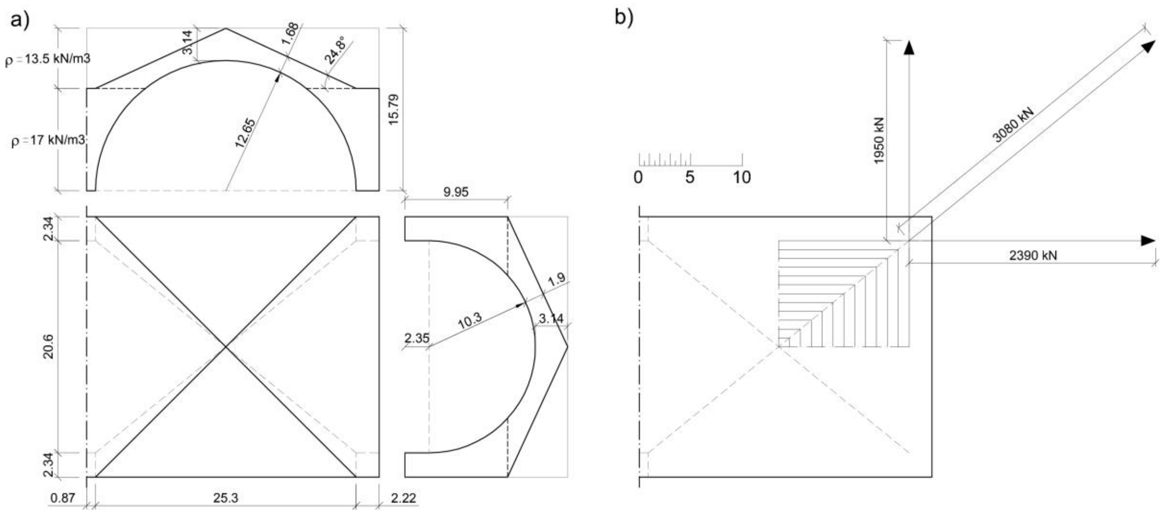

Fig. 14. Thrust line analysis of cross vault by the slicing method. a) Geometry, including density profile, b) Slicing strategy

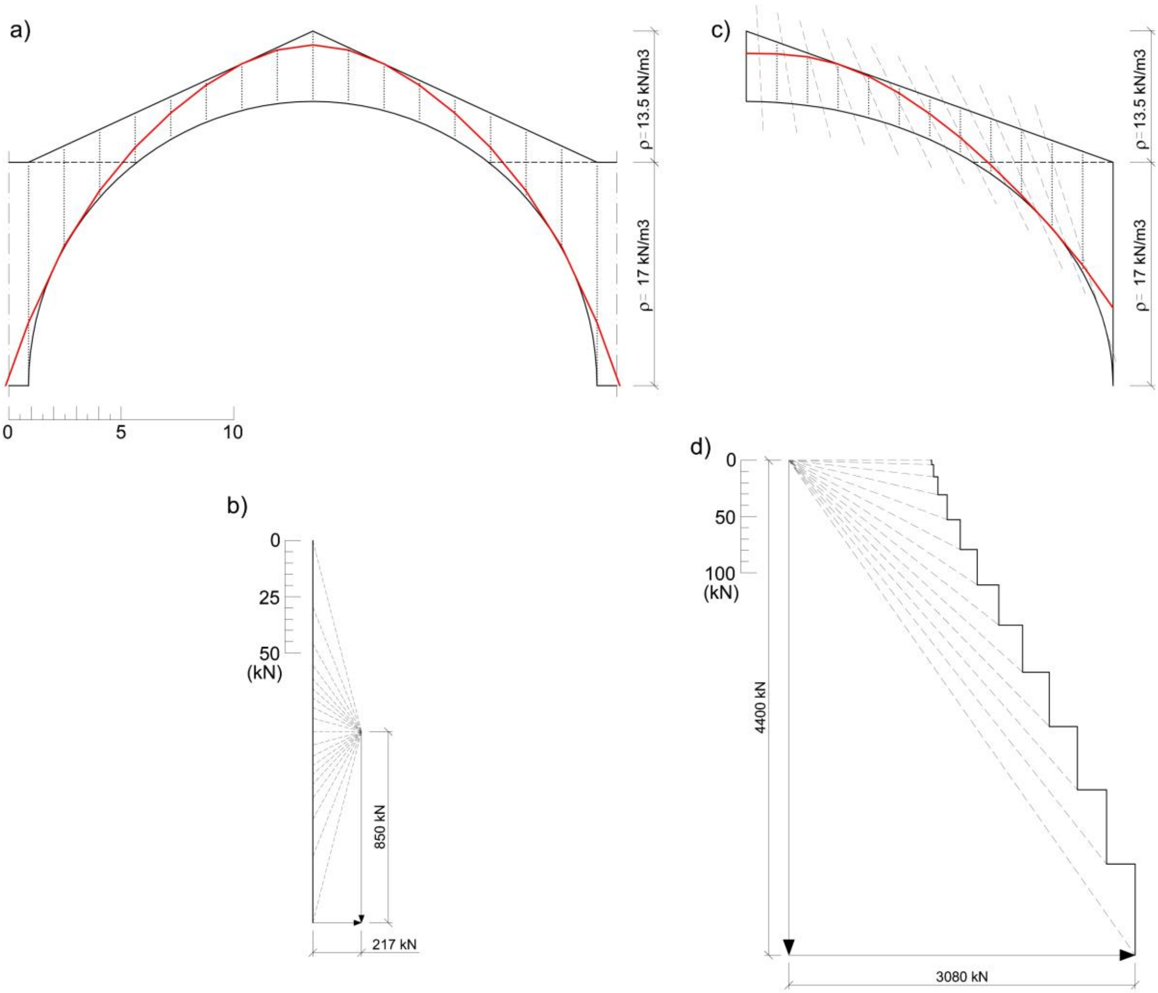

Fig. 15. Results of thrust line analysis of cross vault, a) Thrust line in most critical slice, b) the force polygon, c) Thrust line along vault diagonal, d) force polygon for diagonal.