Advanced Materials Research Vols. 133-134 (2010) pp 325-330

doi:10.4028/www.scientific.net/AMR.133-134.325

The Stability of the Basilica of Maxentius in Rome

ALBUERNE Alejandra

Dept. of Building Structures. Escuela Técnica Superior de Arquitectura de Madrid, Madrid, Spain

alejandra.albuerne@gmail.com

Abstract The Basilica of Maxentius in Rome features the largest *opus caementicium* vaults known to have been constructed in the Roman Empire. The present paper presents a structural reconstruction of the building and initial stability analysis of its original geometry. The barrel vaults and groin vaults are analysed, together with the stability of the supporting and buttressing elements. This initial study yields that the original construction was stable. However, two of the three naves of the Basilica have collapsed and further study will be necessary for determining the causes of such structural failure.

Keywords: Basilica of maxentius, basilica nova, limit analysis of masonry, stability analysis, vaulted structure, opus caementicium, Roman concrete, Roman groin vaults, Roman barrel vaults

Introduction

The construction of the Basilica of Maxentius, also known as the Basilica of Constantine or Basilica Nova, was started in the year 307 AD by Roman emperor Maxentius (283-312 AD) and was later completed by emperor Constantine (272-337 AD) around year 313 AD.
The present paper presents a reconstruction of the building and a static analysis of its original structure, focusing on the large barrel vaults and groin vaults.).

Figure 1: The Basilica of Maxentius(Present state, internal view of the north nave)

Structural Reconstruction of the Basilica of Maxentius

The Basilica of Maxentius was the first *opus caementicium* (Roman concrete) vaulted basilica built in Ancient Rome. Both its barrel vaults and groin vaults were the largest known to have been constructed in the Roman Empire. It was designed according to the architectural and structural typology of the great *frigidariums* of the large baths of Rome, the Baths of Caracalla (212-216 AD) and the Baths of Diocletian (298-306 AD). The traditional basilica building type was abandoned in this case probably in an attempt to construct a fire-proof structure. The site where the Basilica of Maxentius was built had been devastated by various fires in recent decades (Amici, 2005).
The building is comprised of three naves: a central nave, higher and wider, originally covered with three groin vaults, and two side aisles covered with three barrel vaults each (Fig. 2).

Façades. The basilica was built on sloping natural ground. The pronounced level difference from the south-east corner to the north-west corner of the building reached 8m, the north-west corner being lower. This feature resulted in important structural consequences, as shall become apparent further on. The level of the internal space of the basilica was placed over the highest natural ground point, and it could be reached through the south and east façades. The main entrance was located on the south façade, looking onto the *Via Sacra*, through a portico with 4 columns at the top of a flight of stairs. The entrance through the east façade, on the contrary, accessed the inside from ground level through a low portico covered by 3 small groin vaults. The west façade was, as highlighted above, up to 8m higher than the east façade. It had no openings, but was terminated by an exedra, roofed by an *opus caementicium* semi-dome. The north façade had a second exedra in the middle section, opposite the main entrance to the building.

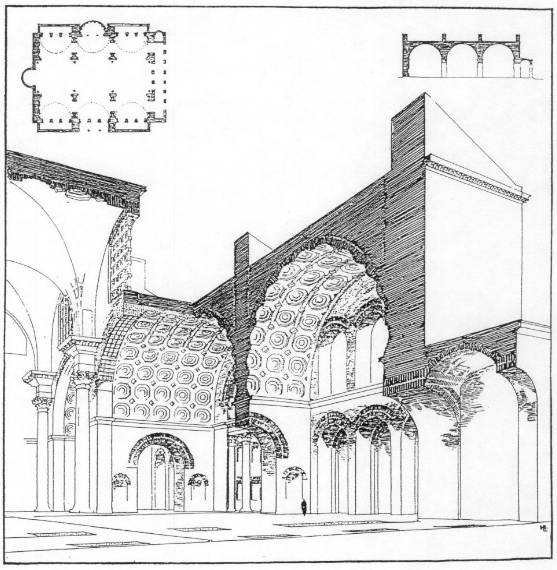

Figure 2: Basilica of Maxentius, sectioned axonometric view (Loempel, 1913)

Roofs. The side naves, as well as the portico attached to the east façade, were covered with terraced roof, while the groin vaults over the central nave were finished with a hipped roof that adapted to the shape of the internal groin vaults (see Fig. 4). These were covered by curved clay tiles.

Foundations. The various archaeological surveys carried out at the Basilica of Maxentius (Minoprio, A 1925; Barosso, M 1940; Calabresi, G 2005) agree that the building rests partially on remains of earlier buildings which were part of Nero's market. The south and central nave of the basilica were built over these remains, while the north nave was constructed directly on natural ground, on new purpose-built foundations. Foundations under the walls are strip foundations constructed in Roman concrete, most likely tamped down.

Walls. The supporting structure of the Basilica is comprised of thick *opus caementicium* walls built inside external layers of brick or *opus latericium*. Together with the façades, the main walls of the building are those supporting the 6 powerful barrel vaults over the side aisles.

Vaults. The central nave has a span of 25.50m approx. and was covered by three adjacent groin vaults with an approximately square layout. None of these vaults are still standing. Only small sections of the corner springings remain in place, and a few pieces of the vault can be found on the floor at the site. The original decoration of these vaults can be appreciated from the remains: regularly distributed large octagonal cofferings with smaller square cofferings filling the space (Minoprio,1889). Eight enormous decorative Corinthian columns, now removed, originally stood under the springing of the groin vaults.

Each side nave was covered by three barrel vaults. These vaults had a span of approx. 23.2m, a width of 17.5m, and a height of 24.5m from the original inside level of basilica. The three vaults over the north nave are still standing and in good condition. They, too, are decorated with large octagonal and small square cofferings.

Static Analysis of the Basilica of Maxentius

Limit Analysis of *Opus Caementicium* as Masonry Jacques Heyman (1995) validated the traditional analysis of masonry structures by setting it within the frame of plastic theory structural analysis. Three hypotheses are applied in this analysis: zero tension strength, infinite compression strength and impossible sliding failure. These lead to the conclusion that the only possible failure is through loss of stability by the formation of hinges in the structure. According to the fundamental Safe Theorem of plastic theory, if it is possible to find a distribution of internal stresses that is in equilibrium with the external loads and nowhere violates the strength conditions of the material, the structure is safe. Applied to masonry structures considering the above hypotheses, this theorem translates as "if it is possible to find a thrust line for the given loads that is contained within the section of the structure throughout, the structure is safe".

Opus caementicium is a type of masonry. The three hypotheses given can be applied:

1. Zero tension strength. In *opus caementicium*, the strong mortar provides the massive elements with a degree of coherence that makes them seem monolithic. This hypothesis could therefore appear to be too conservative in this case. However, the existence of layers of *caementa* unevenly adhered to the mortar and the uncertainty about the internal state of the material –(as it is not possible to know its internal composition throughout the structure)– make this hypothesis reasonable. Cracks can open easily in the structure, and are in fact a means of the very rigid structures to adapt to deformations. Furthermore, once a crack forms, it will remain as a weak, zero-tension point.
2. Infinite compression strength. Compressive strength for *opus caementicium* can reach 30MPa. Working stresses are usually well below 10% of this value, in the range between 0.5 and 1.0MPa.
3. Sliding failure is impossible. The internal friction coefficient of the material is very large, and, in fact, failure by sliding has not been observed in vaulted Roman concrete constructions.

Static Structural Scheme The extraordinary challenge in the design and construction of the Basilica of Maxentius lied on its large scale. The structural scheme is the following (see Fig. 3.a):

- Barrel vaults rest on thick walls and exert thrust in the east-west direction. This thrust is counterbalanced at the internal supports, but needs to be withstood by the east and west façades.
- Groin vaults rest on their four corners and exert thrust both in a diagonal direction. The north-south component of this thrust is carried by the thick walls that support the barrel vaults in the side naves. The east-west component is again counterbalanced at the intermediate supports, where the thrust of two vaults counteract each other, but needs to be supported by both the east and west façades.

As mentioned above, the basilica is constructed on sloping natural ground, with a difference in the foundation level between the east and the west façade of 6.0 to 8.0m, so that the west façade is an average of 7.0m higher than the east. This has a very relevant structural effect –the west façade is the most critical point for the stability of the structure of the Basilica of Maxentius. The Romans were aware of this fact and incorporated extra stability aids on the outside of the wall, such as buttressing against the *Templum Pacis*.

The analysis presented in this paper focuses on the stability of the critical vaults under static loading, that is, the west barrel vault of the north nave and the west groin vault of the central nave.

Barrel Vaults Barrel vaults can be analysed by studying a single slice, considered as a simple semi-circular arch. The minimum thrust line will be drawn. This is to be tangent to the extrados of the arch at the keystone (mid-point), as, due to symmetry, it is to be horizontal at that point. A three-joint arch forms as the thrust line touches the intrados of the arch on a point near the springing of the arch (Fig. 3.c). This is not a mechanism: a mechanism will only form when the thrust line touches the extrados of the abutments on its way down to the ground. If this does not occur, the vault is stable.

The geometry adopted for the analysis was obtained from the floor plan by Siedler, Hemmleb and Sacher (2002), scale 1/25, and from the measurements given by Ferretti (2005). This is shown in Fig. 3.c. The span of the vaults is 23.2m approx., the height is around 24.5m above the internal ground level of the basilica.

The coffering found on the intrados surface of the vault, together with its decorative purpose, serves a structural function as it reduces the weight of the vault. The volume suppressed by each coffering is $2.24m^3$, that is, $0.32m^3/m^2$ over the internal surface of the vault. This is equivalent to 18% of the weight at the keystone and 4% at the haunches.

The only weight considered in the analysis will be the massive self-weight of the structure, the rest of the surface loads (live, wind, snow…) being insignificant in comparison. It is well known that the Romans varied the density of the concrete in accordance to the location in the structure, using lighter concrete for the upper parts. This technique was used in the Basilica of Maxentius, as can be determined from the densities of the samples discussed by Giavarini (2005). Giavarini, however, only provides densities for the material in the vaults, and not for the supporting walls or upper buttresses. These densities have been assumed based on comparison with other contemporary buildings. The concrete densities used in the analysis (Fig. 3.b) were:

- light: top third of the vault (16.5m upwards): $\rho = 13.50kN/m^3$
- medium-weight: intermediate section of structure (7.0 to 16.5m): $\rho = 17.00kN/m^3$
- dense: low section of walls and buttress over wall (below 7.0m): $\rho = 22.00kN/m^3$

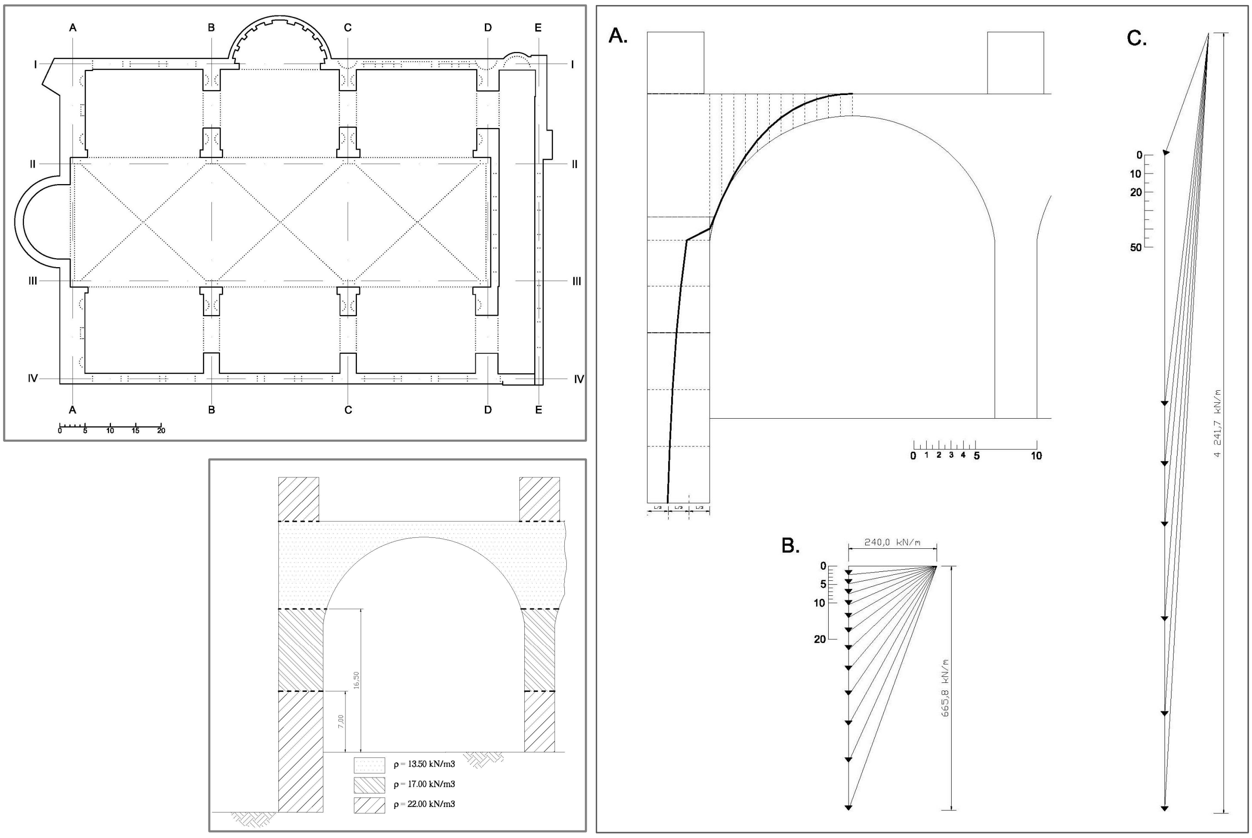

Figure 3: (a) Floor plan of the Basilica of Maxentius; (b) adopted opus caementicum densities in barrel vaults; (c) static analysis of the west barrel vault of the north nave

A simple section excluding additional buttressing elements was analysed, ignoring the reduction of weight introduced by the coffering. The analysis can be seen in Fig. 3.c.

Vertical planes are used for dividing the vault in imaginary 'vousoirs'. Horizontal planes were chosen for the walls. The thrust line touches the intrados of the vault some 17.70m above the internal floor level of the basilica, less than 1m from the springing. The horizontal thrust is calculated to be approx. 240kN/m along the length of the wall. The thrust line continues down the wall and remains within it, falling just outside the middle third of the wall at the base. The vault design is, therefore, stable.

An approximate way to introduce the weight reduction of the coffering in the analysis would be to simply reduce the thrust by the same percentage that the load is reduced overall. This is worked out to be a 10% reduction, and the thrust line would finally lie in the middle third of the external wall.

Groin Vaults The structural progress introduced by groin vaults meant that the loads generated by the vault could be concentrated in 4 points instead of being spread along a linear element. The analysis of these vaults can be done using the *slicing technique* originally described by Frézier in his 1737 stereotomy treatise, used later by Poleni in 1748 (Huerta, 2004) and more recently by Heyman (1995). In this method, each of the 4 quarters of the vault is considered to be comprised of elemental parallel arches, working independently from each other. The thrust generated by these arches is channelled along the diagonals of the groin vault, and driven towards the supporting elements in the corners. A vault with double symmetry will exert the same thrust on its four corners.

The three groin vaults of the Basilica of Maxentius collapsed at an unknown time. The only remains are two springings and some fragments that have been preserved on the site. This information, together with the similarity to the *frigidarium* of the Baths of Diocletian (the still-standing Santa Maria degli Angeli) have allowed architects and art historians in the past to reconstruct the vaults. The geometry used in this analysis (Fig. 4.b) has been worked out from the floor plan and the remaining springings. All three vaults are considered to be equal.

The vaults have a rectangular layout of 24.80 x 23.04m, in the transverse and longitudinal directions respectively. The rise of the vault is given by the largest span. The diagonal lines of a perfect intersection between two barrel vaults of different span would not be contained in a plane. However, a simplification likely to have been used in Roman construction was applied: the lines of intersection are indeed considered to be in a plane, and the surface of the smaller barrel vault is not regular and adapts to this imposed line of intersection.

The hipped roof was formed by the extrados of the concrete vaults. It has been estimated to have a slope of 23º and a minimum thickness of 1.80m (Ferretti, 2005). This leads to a thickness at the crown of 3.0m and approx. 3.7m at the haunches. The material densities adopted are shown in Fig. 4.a.

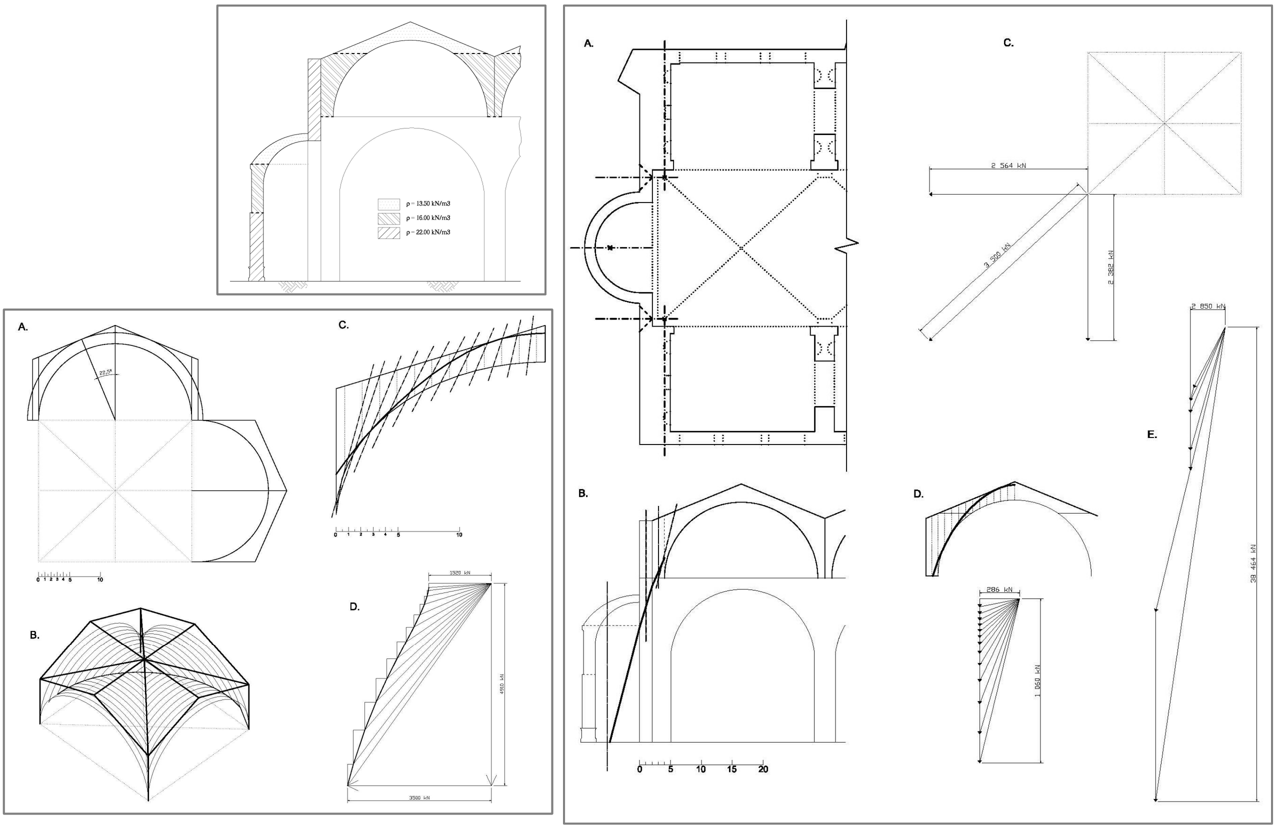

Figure 4: (a) Estimated opus caementicium densities; (b) geometry and static analysis of groin vault; (c) Static analysis of buttressing elements in west façade

The fact that the vault is not square means that the resultant of the thrust along the diagonal is not parallel to the diagonal, but the horizontal components of the two concurrent arches do not balance out. In this case, however, the deviation is small and was neglected for simplicity of the calculation.

The minimum thrust at each of the four corners was calculated to approx. 3500kN. This thrust was decomposed in two forces, one parallel to the façade with a value of 2565kN, and one perpendicular to it, of magnitude 2380kN. The vertical reaction corresponding to the weight of the vault was added to the latter and the stability of the wall was assessed for the resulting force.

The west façade wall, despite being the thickest in the building, is not enough on itself to support this weight, and indeed requires extra buttressing. This extra support was given by the Romans introducing additional elements such as the apse, at the critical point where the thrust of the groin vaults is applied. Taking into consideration the section of the wall with the apse, the thrust of the vault is then withstood (Fig. 4.c). According to these results, the initial design of the Basilica was stable.

Conclusions

The static analysis of the Basilica of Maxentius described in this paper yields that the original design of the structure was stable. However, the middle and south naves have collapsed. According to pictorical evidence, there is no doubt that the collapse took place before the 15th century. Most of the literature agrees that the collapse was caused by an earthquake, but there is no evidence to prove this. Further work will be required to clarify the causes of the collapse of the building. This work will focus on a more in-depth study of the structural behaviour of the groin vaults, and the interaction between structure and foundations. This study will also include seismic analysis.

References

[1] Amici, C M (2005). “From project to monument,” in “*The Basilica of Maxentius. The Monument, its Materials, Construction, and Stability*.” Giavarini, C (ed.) (2005). Rome, Italy: “L’Erma” di Bretschneider: Università di Roma “La Sapienza”. CISTeC.

[2] Barosso, M (1940). “Le construzioni sottostanti la Basilica Massenziana e la Velia,” in *Atti del V Congresso Nazionale di Studi Romani, vol. 2*. Rome, Italy: Istituto di Studi Romani Editore.

[3] Choisy, A (1873). “*L’art de bâtir chez les Romains*.” Paris, France: Librairie générale de l’architecture et des travauz publics Ducher et Cie. Spanish translation (1999) “*El arte de construir en Roma*.” Madrid, Spain: Instituto Juan de Herrera.

[4] Durm, J (1885). “*Handbuch der Architektur: Die baukunst der Etrusker; Die Baukunst der Römer.”* Darmstadt, Germany: Bergsträsser.

[5] Ferretti, A S (2005). “The structures of the Basilica,” in “*The Basilica of Maxentius. The Monument, its Materials, Construction, and Stability*.” Giavarini, C (ed.) (2005). Rome, Italy: “L’Erma” di Bretschneider: Università di Roma “La Sapienza”. CISTeC.

[6] Giavarini, C (2005). “Materials” in *“The Basilica of Maxentius. The Monument, its Materials, Construction, and Stability*.” Giavarini, C (ed.) (2005). Rome, Italy: “L’Erma” di Bretschneider: Università di Roma “La Sapienza”. CISTeC.

[7] Heyman, J (1995). “*The Stone Skeleton*.” Cambridge, United Kingdom: Cambridge University Press.

[8] Huerta, S (2004). “*Arcos, bóvedas y cúpulas. Geometría y equilibrio en el cálculo tradicional de estructuras de fábrica*.” Madrid, Spain: Instituto Juan de Herrera.

[9] Loempel, H (1913). “*Die monumentale Tonne in der Architektur.*” Munich, Germany: K. Hof und Universitätsdrückerei Dr. C. Wolf und Sohn.

[10] Minoprio, A (1932). “A restoration of the Basilica of Constantine, Rome.” *Papers of the British School at Rome 12*: 1-25.

[11] Siedler, G, Hemmleb, M, and Sacher, G (2002). “Documentation of the Basilica of Maxentius in Rome: methods for providing foundations for monument research.” in *International archives of photogrammetry, remote sensing and spatial information sciences.* London, Canada: Natural Resources Canada.