Construction techniques of Roman vaults and opus caementicium: The cases of Lupo and St. Gregory's Bridges

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ABSTRACT: In this paper the revolution induced by the use of the opus caementicium on the Roman construction techniques of buildings and vaults, especially during the imperial age, is outlined. Although this new technique reminds that adopted in the proto-Mediterranean period, the revival proposed by the Romans is quite different thanks to the use of pozzolana mortar and intelligent structural solutions to guarantee a mechanical behaviour mainly in compression. Three bridges are analyzed where the opus caementicium is used: in the first two cases for restoration works, and in the last as a consolidate technique for building new arch bridges.

1 INTRODUCTION

Roman vaults made using stone and lime mortar concrete - opus caementicium – consist of full masonry from the intrados to the higher floor, and the caementa - the rubble used for the voussoirs, generally pieces of stone the size of a mason's fist - are arranged in strictly horizontal courses. If we analyse broken vaults, the stones are arranged as though the caementa had been placed dry and then covered by layers of viscous mortar so that distances between them remained constant; distribution is uniform also on the intrados surface, where the cast came into contact with the boards used for the centring. Roman concrete was laid in a series of horizontal casts, as can be seen by the traces left by the carbonatation surfaces, which corresponded to a mason's day's work.

The result is an artificial type of concrete rock, so that Roman vaults can be seen as inert monoliths supported on walls; this comparison is appropriate for vaults that have a thickness comparable with the area they span, such as barrel vaults of the Colosseum. One wonders whether this comparison is still appropriate for structures of larger span as the aqueducts arches, or domes as the Pantheon and the Domus Aurea (Conti et al. 2009).

Gustavo Giovannoni was the first to equate the vault in opus caementicium to the false vaults of Mediterranean proto-history: "The system of concretion used to build a vault in horizontal layers, like an artificial monolith, is much removed in conception from the constructive technique of wedges of cut stone, and would appear to be more similar to the Mycenae pseudo-vault of shelf-like projecting horizontal stones placed one on top of the other". Stability in the so-called false-vaults is guaranteed by the great thickness of the walls and the regularity of the construction. The stones forming the intrados are held in place by the stones above and those at the side: each stone embedded in others, without mortar, held in place by the weight and thickness. It is common opinion that these types of construction only apparently behave like a vault, since they were built in horizontal courses and generally without the aid of centring.

The technique described above is very similar to that of Roman vaults in opus caementicium, but with one difference: the absence of mortar. In fact, it is precisely pozzolana mortar, used in the casting phase and characterized by a certain degree of tensile strength after it has dried, which transforms the various horizontal courses of caementa into a sort of pseudo-continuum, made in thin layers like plywood and therefore possessing cohesion – thanks to the adherence between mortar and stones - and moderately resistant to tensile stress in any direction. The Romans therefore invented an "artificial" concrete material to cover an "artificially" defined area by means of a monolithic structure.

What is sure is that the switch from a radial arrangement of the elements used in the construction of arches and vaults to the horizontal layout typical of the caementa in opus caementicium is in line with the principle of economy and industrialization of the constructive process: the advantage of using stone chips (caementa) instead of bricks, and the need to arrange it in a regular manner to ensure homogenous mechanical behavior in all directions, meant that that construction had to be in layers, the thickness of which depended on the working day. Opus caementicium therefore revolutionized construction and also restoration techniques (see the case of the Lupo Bridge here discussed), ensuring rapid work and on site savings; separate layers are piled horizontally in a way that is very similar to that adopted in the construction techniques of the proto-Mediterranean period, when projecting pseudo-vaults were made to cover small areas. Giovannoni's observation then, rightly hits on the similarity between the opus caementicium technique of the Romans and the proto-Mediterranean pseudo-vaults of Mycenae, although the revival of the older technique by the Romans was used in typologies characterized by different structural behavior.

In radial jointed stone arches, thrust and weight work together to guarantee compression along the contact joints; thrust, which is essential for equilibrium, helps the material to resist compression, while the greatest amount of friction is needed only at the springing, where it can be easily provided. In the pseudo-arch, on the contrary, compression at different horizontal joints is along the vertical direction and provided only by the weight; moreover, thrust works against stability since, in the absence of mortar, a great amount of friction is needed, especially as we go further up, where great thicknesses and weights are required to prevent collapse. This is why corbelling vaults have an upper horizontal extrados of great vertical thickness, which guarantees the thrust provided by the compressive strength along the key section be balanced by friction along the horizontal layers.

In principle building a vault by means of horizontal layers would make it unstable, unless structurally intelligent measures are taken, such as using an appropriate degree of thickness and the control of thrust and flow lines produced by it (Sinopoli, 2008.).

Thanks to the opus caementicium technique it would be not necessary, in vaults and domes, for the elements to be "ideally" arranged, i.e. radially, as is typical for materials that have no tensile strength. Despite the characteristics of cohesion and adhesion guaranteed in opus caementicium by the ageing of the slaked lime and the hydraulicity of the pozzolana mortar, however, it seems that the Romans did not have much confidence in the tensile strength of the resulting structure; the constructive solutions adopted in almost all opus caementicium vaulted structures seem to indicate that the aim was to guarantee only compression, as if the material although the presence of the pozzolana mortar did not have tensile strength; the thicknesses adopted were in fact that of the proto-Mediterranean pseudo-vaults.

Roman concrete was laid in a series of horizontal casts, as can be seen by the traces left by the carbonatation surfaces, so that Roman vaults in opus caementicium can be considered as horizontally layered structures. Although the construction technique of these vaulted structures is very similar to that of proto-Mediterranean pseudo-vaults, as first suggested by Gustavo Giovannoni, the revival of the older technique by the Romans was used in typologies characterized by different geometrical features (large spans) and consequent different structural behavior. If the span to be covered is large in comparison with the springing thickness, thus, the corbelling vault is a structure that produces thrust; in this respect, the Roman constructive technique at its highest development planned - as we shall see - the insertion of "hidden" strengthening masonry bricks corresponding exactly to the structural behaviour required by the covered span; the opus caementicium can be therefore considered as an anticipation of the modern concrete.

In this paper, after a brief outline of sources and development of the opus caementicium, three arch bridges, belonging to aqueducts of different historical periods, will be analyzed. Technological and structural innovations introduced during the Roman late republican and imperial age will be discussed; this is an era during which the opus caementicium, after a long experimental phase, was widely and efficiently used also in consolidation processes of important public works as the aqueducts.

2 OPUS CAEMENTICIUM: BRIEF OUTLINE OF SOURCES AND DEVELOPMENTS

Structura ex caementis calce et harena: genus pulveris mixtum cum calce et caemento is the description of the structura caementicia given by Vitruvius in his De Architectura. The caementa are held together with mortar to form a mixture used, from the earliest days of concrete works, to build foundations or walls of cisterns or small rooms, often plastered. Roman mortar, a refinement of the most ancient building systems common throughout the Mediterranean basin at least since the 5th century B.C., which already made use of clay-based binding mixtures mixed with fillers (stones, river pebbles) and lime, was introduced into Roman building methods starting at least from the 3rd century B.C. It consisted of slaked lime and fillers such as “pozzolana” sand, gravel, and cocciopesto (crushed earthenware, tiles, and/or bricks). In fact, according to Vitruvius, the Romans had already been doing concrete work for at least three centuries (Vitruvius wrote between 40 and 32 B.C.), and had been using it in simpler buildings of late-Republican Rome for at least two. From the more modest buildings, the experimentation of techniques by the Roman builders developed various solutions and uses for concrete structures: for trench foundations with wood reinforcement, for masonry work above ground, in vaults, and for road sub-bases. The concrete structure was used both alone and as the internal core of masonry works, starting from the 3rd century B.C., with wall surfaces having different facings, using large or small elements, which take their names from the type of surfaces (opus incertum, opus reticulatum, opus latericium, opus listatum, and opus mixtum) and which, with time, joined and then replaced the opus quadratum and polygonal building techniques.

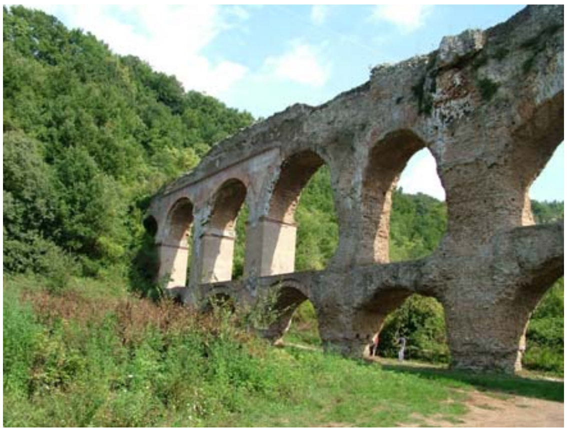

Figure 1 : The St. Gregory’s bridge: Ponte della Mola.

For the mortar, well seasoned slaked lime was used in order to permit a good level of hydration of the calcium carbonate; the fillers added into the mortar composition prevented shrinkage during setting and hardening. Generally speaking, it is possible to distinguish the crumblier mortars of the earliest periods from the more solid ones of the early Empire age and from the compact, very fine conglomerates of the mid-Empire.

Concrete works were created by pouring into ditches or formworks, or tamping successive, more or less disorderly, layers of caementa with mortar, or by laying orderly horizontal layers of finished caementa and mortar on the surface with veneers containing stones or bricks. Technically, this was different from the Greek emplektòn, which consisted of large stones arranged, like bricks, in horizontal courses longitudinally and crosswise within the wall thickness. The Roman opus caementicium technique consisted of using core veneers arranged in very closely interlocked and cohesive horizontal layers (during the Imperial period).

The first example of a concrete vault seems to be that of the porticus Aemilia on Via Marmorata (174 B.C.), created using an arched frame of wood slats. During the Republic, vaults were constructed starting from an initial arch of a thickness of about half a meter and then, on the extrados of the arch, a mixture of stone fragments and mortar was poured in horizontal layers from the sides up to the top. During the mid-Empire, the advances made in the technique brought the introduction, in place of the full wooden frame for pouring the opus caementicium, of a mesh frame on which to lay a thin curved wall of bessalis bricks and from which to start inserting bricks, set on edge and arranged following regular grids, so as to define a surface that was resistant in depth, as thick as the bessalis bricks, and solidly connected with the concrete structure and the bessalis bricks themselves, laid flat against the intrados (Hadrian’s Villa, Villa dei Sette Bassi).

Van Deman proposes, for dating Roman and late Roman concrete works, a method based on the direct observation of the mortar and the caementa, in particular of the materials, if they are heterogeneous and where there are pieces of brick or marble, in the case of late works, or of a single homogeneous quality and consisting of small quarry waste, for the mid-Empire works.

3 ANALYZED ARCH BRIDGES

3.1 Acqua Marcia aqueduct: The Lupo bridge

The Lupo bridge is connected with the Aqua Marcia passage which, at this point, runs for 115 m at a height of 30 m. The bridge has undergone various enlargement and consolidation operations. Built in 144 B.C. with two arches in opus quadratum, it was reinforced once by Agrippa with the construction of a new channel with a wall in opus reticulatum. Other reinforcement works followed, between 11 and 4 B.C., at the sides of the bridge, also in opus reticulatum; during the empire of Titus (79-81), three structures were built on the front and new buttresses were built under Hadrian (117-138). Major transformation and consolidation work was carried out on the bridge during the Severian age (193-235): the arch spans were closed with concrete creating a double row of arches. The central pillar was incorporated into a semicircular buttress on the eastern side. Lastly, eight pillars were inserted to hold the wall of the southern side. A final operation consolidated the south-eastern side of the bridge with a brick wall, created during the empire of Diocletian (284-305).

Ancient as well as more recent fractures can be distinguished looking at the part of the bridge in square blocks (Fig.2), in particular along the high middle pillar, on the arch over it and the two symmetric arches at the pillar sides. Consolidation work solutions realized in opus reticolatum at different historical periods are not discussed here; we shall analyse the restoration work in opus caementicium, realized during the Severian age. The key idea of the structural retrofitment work has been to restore the old stone bearing structure by building a buttress with semi-circular base on the oriental front (back side of Fig.2) for the central pillar, and by plugging and strengthening the empty zone under the two symmetrical stone arches, at both sides of the central pillar, by means of a system of vaulted structures in cascade obeying to the general criterion of diminishing the supported weight from the top to the bottom.

In fact, a plain arch in sesquipedales is placed dipped into the plugging in opus caementicium, below both the two symmetric stone arches, in order to support the preservation of the arch geometrical shape and to collaborate as lightening arch to the bearing function. Below the plugging, a vault with double ring nut can be observed, mainly self-bearing, and finally, below it, a vault with double ring nut of greater thickness covering a greater span is noticed (Fig.2).

The main interesting thing, on the point of view of the technological revolution, is the way how the façade arches of the vaults are realized so as the bearing structure along the directrix and the generatrices (Fig.3). Apart from the façade bricks with esthetical function, the façade arches are built in opus caementicium, but inserting regularly spaced bricks (sesquipedales) along the radial direction, so as to scan the real bearing sections along the arch, in analogy with the previous squared stone constructions.

The vaults in opus caementicium obey to the same structural criterion; in fact, according to the typical technique in progress during imperial age, instead of the continuum centering at the intrados, it seems that a mesh frame centering was used on which a thin curved layer of bessalis was placed. From the frame a regular mesh of bricks starts, each brick placed across,along the two directions orthogonal to the vault intrados surface. It seems that the Romans wanted to define ideal block boundary sections, radially placed along the generatrices and each other parallel along the directrix. Moreover, along the intrados two masonry thin arches with radial joints are dip into the opus caementicium along the generatrices, immediately placed behind the façade arches, as to guarantee the continuity of functioning between the façade arches and the vault. The constructive revolution induced by opus caementicium seems therefore to be a smart synthesis of the previous techniques, maintaining their advantages and their precepts. The awareness of the ideal bearing shape, known with the structures in squared blocks, is added to the advantage of the proto-mediterranean technique, which allows to realize structures by means of horizontal courses. The consequence is that, since the vaults were realized in analogy with corresponding structures in squared stones, transversal bearing structures are defined inside the masonry starting from the centering: in opus caementicium the voussoirs modify in blocks, whereas contact joints between voussoirs are represented by bricks. The same criterion to define into the opus caementicium through bricks the "favoured" bearing sections can be noticed along the vertical pillars sustaining the vaults, scanned at regular intervals by horizontal plans made in masonry bricks (Fig.3).

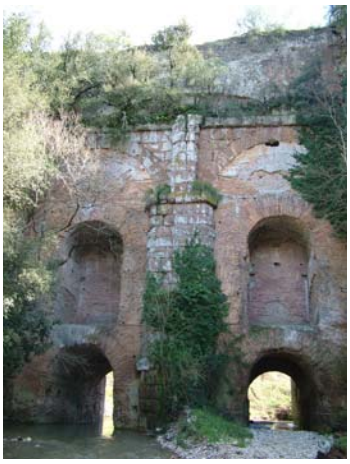

Figure 2 : The Aqua Marcia Lupo Bridge

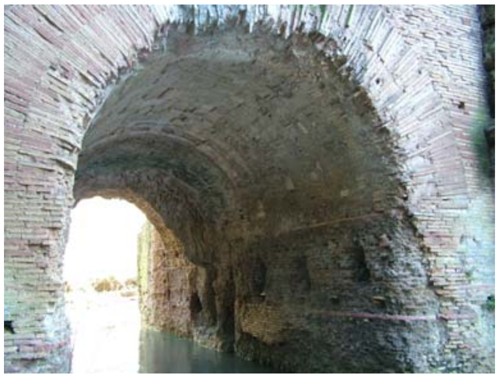

Figure 3 : The Lupo Bridge: horizontal layers, arches and intrados vault.

3.2 Aqua Marcia aqueduct: The St. Peter's bridge

The S. Pietro bridge enabled the Aqua Marcia water to cross the Mola di San Gregorio ditch with a span of 16 m. Built in the 2nd century B.C. of square blocks of limestone, still visible in the intrados of the vault and at the abutments, it was clad during the empire of Titus (79-81) with a revetment of opus mixtum which, in turn, was covered by a brick veneer in the 3rd century. The bridge has a slanted intrados and large protruding structures at the base which date from the last enlargement and consolidation phase. Also in the 3rd century, the central and side arches were rebuilt, but with smaller openings than before (Fig.4).

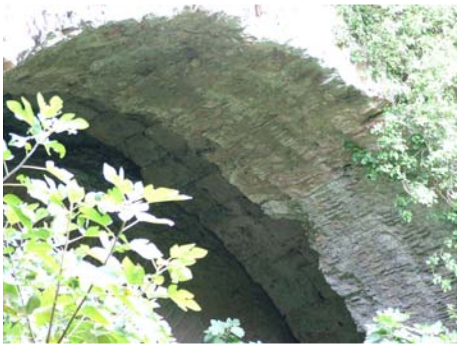

Figure 4 : Strengthening work of St. Peter's bridge: multi-ring arch framework in opus caementicium. See also, in the middle between the new arches, the old stone arch in square blocks

With reference to the last retrofitting work of the bridge (third century), it is possible to notice that the construction techniques utilized for the arcades of the multi-ring arch are different: symmetrically at both sides of the ancient stone bridge, the internal ring is realized in masonry bricks placed radially, whereas the two external rings are realized with mixed technique. In fact, at springing arches are made of bricks placed continuously and radially, while going on from them towards the haunches and the key, they are made of *opus caementicium* regularly spaced by radial bricks - the same technique of the Lupo's bridge, here with a space between bricks quite reduced (Fig.5). It is therefore meaningful to notice also the erosion of the arcades at springing, as well as if the retrofitting intervention had strengthened the ancient stone bridge making the thrust line to move to the extrados, with unhelpful masonry pushed out consequently (Fig. 5).

Figure 5 : St. Peter's bridge: the springing erosion.

3.3 Opus caementicium and new constructions: the St. Gregory's "della Mola" bridge

The construction of the bridge dates back to the age of Hadrian (117-138) and was judged necessary to shorten the course of the Anio vetus. It originally consisted of 22 double arches for a length of 155.5 m. In 1965 two central arches collapsed, and in 1982 other ones, ruined, were demolished. The entire structure of the bridge is built in opus caementicium with brick veneer; the masonry work and vaulted systems date from the phase of the best development of the construction type, when research and experience gained down through the previous centuries produced their best results.

The construction techniques utilized show as the first tests experienced at the Lupo's and St. Peter's bridges are almost consolidated. Looking at the actual external surfaces of the arcades, deteriorated by atmospherical agents and the negligence of institutions, it is possible to notice the presence of hidden arches built with retaining function and distributed inside the bridge and in depth, dip into the mortar. We refer to the thin full masonry arches well visible at the arcades intrados and to the bricks which scan in depth the axis line of the façade arches, often double, next to each other and radially placed at regular intervals, starting from the springing to the haunches until the key.

Again, as in the previous cases, the new idea is to insert the stone arch inside the concrete: the sesquipedales work as radial joints of the arch where the voussoirs are made of opus caementicium. The Romans thus reinvent revolutionizing the available techniques: the key idea is the invention of new solutions based on new techniques by synthesis and analogy with the ancient ones.

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