Horst Barow

Roads and Bridges of the Roman Empire
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As a civil engineer with leading German construction companies, Horst Barow has built highways and bridges in many parts of the world. He was aware of the importance infrastructure has for the development of a region, and he knew how important efficient administration is to achieve public works. During vacations he and his wife liked to visit the Mediterranean countries, and they were amazed by the vestiges of the Roman Empire, not the least of them being roads and bridges. In many cases they still carry modern traffic after 2000 years. They wondered, how much will remain of today's constructions after two millennia?

Thus Barow decided to make the study of Roman roads and bridges his special interest, and through many years he systematically collected material and surveyed bridges on the spot. Having retired, he studied history, with emphasis on the Roman period. His untimely death in 2010 left his wife with a great work in progress, and it is thanks to her efforts that this book has been realized.

Friedrich Ragette, an architect who taught history of architecture and engineering for many years, was entrusted with editing the material and translating it from German into English.

The book covers all aspects of road and bridge construction in the Roman Empire, from commissioning, planning and design to contracting and execution. Technical details include surveying, materials, tools, and implements. The Roman road network is shown with Latin place names; principles and types of construction are explained. The core of the work deals with bridge construction: design criteria, structural systems, foundations and abutments are dealt with in detail. Particular attractive are five dozens of case studies, presenting individual bridges, which were reviewed by the author on site. Countless illustrations, mostly in color, enliven the book. Bibliography and glossary complete the work.

Horst Barow studied civil engineering at the Technische Hochschule Braunschweig from 1950 to 1954. In 1961 he became director of the Bremen branch of Strabag Bau-AG. In 1970/71 he was the project manager of the construction of the nuclear power plants in Biblis and Brunsbüttel for Hochtief AG, and in 1972/73 he built a steel mill in Brazil for the same firm. From 1973 until his retirement in 1985 he had leading positions in Strabag Bau-AG in Cologne, in the last five years as a member of the board of managing directors with responsibility for the activities in foreign countries. From 1986 to 1991 he studied history of the antiquity at the University of Bonn. Friedrich Ragette spent about 30 years teaching and practicing in the Middle East. The past couple of years he was professor of architecture at the American University of Sharjah. His publications includes Traditional Domestic Architecture of the Arab Region (Edition Axel Menges, 2006).
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Roads and Bridges of the Roman Empire

Edition Axel Menges
### Foreword

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During a journey through Spain I noticed on a road near Mérida the sign «TRANSPORTES ESPECIALES». Following it, I found an old stone bridge with two semicircular arches. Apparently, the highway administration deemed the modern reinforced concrete bridge not strong enough for very heavy vehicles and rather trusted the solidity of Roman arch construction, built 2000 years ago. This rather accidental discovery sparked my decision to study Roman bridge building in depth. Based upon more than 30-years civil engineering experience, having been involved in the construction of numerous roads and concrete bridges, I increasingly realized, what technical masterworks the Roman engineers achieved in the space of seven centuries. However, we need no bridge when there is no road, so I decided to study the Roman highways as well. I also realized from my own working experience, that I would not have been able to build a single road or bridge without a functioning government to commission it, or without a highly developed construction industry to build it. Therefore, I decided to organize my study from the top down, beginning with the Roman political and administrative background, the available technology and material means, before entering into medias res. I was fortunate to visit many of the ancient sites, and I consider the case studies of bridges, each with many personal illustrations and observations, an important part of this study.

Horst Barow

1. Introduction

«But the greatest of the physical monuments, which occupied the best energies of Roman surveyors, planners, engineers, labourers, masons and slaves for centuries and made possible the growth and administration of the largest empire the world had hitherto known, was neither a mighty building nor a statue but a thing both ponderous physical and entirely horizontal and thus, at least from a distance, rather hard to see: certainly invisible, and very hard to imagine, as a whole. This was the enormous road system without which the Roman Empire could not have existed. Estimates of its size vary a good deal, depending on how many secondary and tertiary roads are figured in. But it was certainly not less than 60,000 kilometres and possibly as much as 100,000 or even 120,000, including its many bridges thrown over foaming rivers, culverts above swamps and tunnels hewn through mountainous rock. It was a stupendous feat of surveying, planning and labour, and all done without earth-moving machines, graders or explosives – just hard-tod and muscle.»

Robert Hughes, 2011

While there are many studies of Roman fortifications, palaces, towns, temples, theatres, baths and aqueducts, the number of publications about Roman road and bridge construction is limited. There are works on individual aspects of this vast field, but they hardly go beyond general data on the time of construction, their location and characteristics. Until recently (O’Connor, Cambridge, 1993) there is hardly a systematic work on the subject in the English language. This is astonishing, since up till our time the Romans must be considered the foremost builders of roads and bridges in history.

Until recently, the study of engineering in antiquity has been neglected by historians. Politics were regarded the central theme of historical research (White, 1986). This derives from the fact, that archaeology itself only slowly emancipated from the grip of classical philology. Only since the middle of the 19th-century archaeology became a science in its own right and no more served the purpose of being a mere auxiliary tool of the historians. Only since the middle of the 20th century begins the study of antique engineering. Up till then individual engineers studied particular inventions or achievements, including Roman bridges (H. Schneider, 1992). Antiquity did not divide engineering into several branches, as we do today; antique engineers were all-rounders (White, 1960). In antiquity the art of building (architectura) encompassed building construction, mechanical and military engineering (polonostics). Thus De Architectura by Vitruvius includes chapters on machinery, clocks, catapults or even astronomy, besides the major part on building construction.

While technical progress was very slow during the Stone Age and even in the river civilizations of Egypt and Mesopotamia, the Greeks and Romans introduced important changes in construction technology. New implements and methods by application of newly discovered mechanical laws, allowed a much more effective use of human or animal power. However, the many competing city states of Greece were not able to engage much in public works such as roads or bridges.

It was Roman determination to conquer and develop, what they considered, inferior populations. The strategic mind of the Roman recognized that efficient communication over land and sea was the foundation of empire building. Their genius for organization brought with it effective administration, superior engineering and faultless execution of the works. It is in this order of importance that I shall organize this study, from the top down.
Three elements are necessary for a road to be built: A commissioner to order it, engineers to plan and design it and contractors to build it.

2. Historical sources

Pliny the Elder (AD 23–79) prepared an encyclopedic *silvae historicae naturales*, collected from Greek and Roman specialists in art, geography, medicine, zoology, botany and mineralogy. Pliny Caecilius Secundus (the Younger), being curator alae Tiberis at Aquileia (administrator of the River Tiber, its embankments and of the city drains) had to deal with building problems. As governor of Illyria he reported to Emperor Trajan many technical construction problems.

Pappos, a Greek mathematician from Alexandria prepared around AD 300 a compilation of mechanical details for lifts and cranes, the windlass and reel, pulleys, worm gears and gear shifts. Apollodorus of Damascus was “imperial architect” under Emperors Trajan and Hadrian (92-117 AD). Prokopius mentions that he wrote a report about the bridge over the Danube near Turnu Severin in the Iron Gate in Romania, which he built in AD 194-215.

Prokopius of Kaisareia prepared around AD 560 by order of Emperor Justinian a book about buildings: *de aedificiis*. It includes the great bridge near Adapazari in northwest Anatolia.

Also Anthimos of Thrais and Isidoros of Milet, who built the Hagia Sophia (532-537), have written technical reports, now lost. Most likely he knew Heron’s work *Mechanica*. Roman road and bridge construction did not receive much attention, one of the earliest writings of Tacitus (AD 55–116), Sueter (AD 75–150) and Cassius Dio (AD 150–235) showed how impressed they were by the outstanding engineering achievements. Cassius Dio gives as an example the 700 m long road tunnel at Naples. Pliny writes in his biographies of great Greek and Roman personalities under Gaius Gracchus: “He was most diligent in road construction, considering pleasing design as much as technical quality. The roads stretch through the countryside in straight lines, low parts being filled, high parts being hollowed out, all without a break, engineering being understood, giving the whole a uniform and beautiful aspect. Each section was marked by milestones.”

Even in poetry we find an extraordinary source on road construction. The collection of poems by Publius Papinius Statius (silvae fasc.3) from the 1st c. BC includes detailed technical descriptions. In silvae i, 2, 5 he reproaches in praise of Emperor Domitian: “Here nature yielded, defeated by the builder and docilely accommodated hitherto unknown service. However, as far as bridges are concerned, it is astonishing how little impact they made on antique writers. In the year AD 371 the eminent scientist and poet Magnus Ausonius describes in his poem *Mosella* (Stuttgart, 2000) the beauty of the Mosel region, its towns, castles, palaces, villas and baths surrounded by vineyards – but he does not mention any of the many, beautiful bridges spanning the river. In modern times began the scientific study of antique technology, as a whole or as selected topics. Roman road and bridge construction did not receive much attention, one of the earliest exchanges of letters between Trajan and C. Pliny the Younger, governor of Bithynia, is a good example of the detailed involvement of the emperor (C. Plin. Secund., Letters to Emperor Trajan). In letter 39 Pliny asks the emperor to send an expert to examine construction defects in a theatre in Nicomedia (today Izmit in Turkey) and in baths under construction in Claudopolis (today Bolu in Turkey). The emperor rejects the request, arguing: “You can’t lack architects. There is no province, which hasn’t experts and talented people (perpetus et ingeniósos homines).” In letter 41 he reports on the canal construction and asks for the provision of a leveling specialist and a hydraulic engineer.

The Roman emperors had a staff of technical advisors. On his extended voyages through the empire, Hadrian took a team of specialists (fabrici), surgeons (perpendiculari) and civil engineers (fnitius Caecilius Secundus) on projects and facilitate their progress.

The roads were usually named after their commissioner, either a high official, a successful general or the emperor himself. Some of them considered it an honor to pay for “their” road or bridge, which could be rewarded by the right to add a triumphal arch, to mint commemorative coins, or to place stelai and memorial plates.

Many mile stones and bridges carried inscriptions upon which state was erected, restitut. On the Ponte di Nona a report about the bridge over the Moselle reads: “Lucius Fabricius, son of Marcus, being in charge of road (and bridge) construction, commissioned and accepted this bridge.”

In letter 42 Marcus Lollius, son of Marcus, and Quintus Lepidus, son of Marcus, received the works as consuls upon the Senate’s decree “Marcus Lollius and Quintus Lepidus, sons of Marcus, and Marcus, received the works as consuls upon the Senate’s decree.”

In letter 43 the consul have repaired the Via Flaminia and the bridges of Rimini (Augustus, Res gestae, Monum. Ancr. 20). However, soon after the poet Martial (K, 57) of the 1st c. AD complains: Nihil est titulus nec quae Flaminianum secant salutaris (Nothing is more derelict than the potheros of the Via Flaminia).

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The Romans had a particular genius in determining the routing of roads. Over all they followed strategic considerations, but locally they chose the best position of a road, be it in the valley, along a hillside or on a plateau. They avoided snowed in northern slopes, flooding zones and swamps. On the other hand, they did not avoid major obstacles, if they felt it worthwhile. The Via Appia features 10 m high buttressing walls around Ariccia; near Terracina a 40 m high rock projection was removed. In the Aostra valley there are cuttings, which retained milestones and a triumphant arch out of solid material.

They also straightened out existing republican roads, such as at the Ponte di Nona on the Via Praestina (RE XX, Sp. 243). The low single arch bridge was replaced by a much higher bridge of seven arches.

There are a few tunnels for carriage ways, such as the 700 m tunnel crypta Neapolitana near Naples. Sienese describes in a letter the problems of the “rush hour.” “Nothing is darker than the torch light, we can’t distinguish the shadow and if there would be more light, it would be extinguished by the dust.” (letter to Lucilus Off.

At Fiesole near Pesaro the Via Flaminia has a 40 m tunnel cut out of lime stone, which is still in use.

2. Building roads and bridges for an empire

2.1. Historical sources

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2.2. Commissioning and maintenance

In Italy consuls were mostly responsible for road construction, while in the provinces praetors and censors were elected. According to Pekary (1968) consuls were not eligible as public road builders, since they did not have the lus publicans, which gave the right to appropriate private property.

Since Augustus the emperor was the supreme building authority. There was an imperial planning office heading large projects, to be approved by the emperor, who had an advisory committee of specialists.
In the mountains considerable grades had to be accommodated. The Romans preferred to cover great differences in levels by steep but short ramps, instead of maintaining a winding road with uniform slope. At the Maláka Pass to Switzerland ropes and winches were used to pull carriages up. When travelling to Gaul, the Romans preferred the straightforward but 1850 m high Mont Genève pass, to the ever winding road along the Mediterranean.

In antiquity the term architect had a much wider meaning than today. It derives from the Greek architekton = chief and builder and meant chief- or master builder. At this time it included engineering in general, specifically civil engineering. The term engineer derives from ingenium, something ingenious, clever. He works on the basis of applied sciences, to make something work, while the architect’s work should satisfy the requirements for utility, solidity and beauty. The external image of the architect’s profession not always matched Roman reality. For instance, an ingenium could be assembled on site. Exposed surfaces and decorations were finished on the erected structure.

2.3.3. Formation of architects and engineers

Our best Roman source on building matters are the Ten Books on Architecture (De Architectura) by Vitruvius Pollio. He was born in 89 BC and received profound training as an architect—in today’s sense equal to an engineer’s formation. He served as sage in the armies of Caesar and Augustus. Vitruvius was a man of practice. During his retirement he wrote the classical work on Roman construction. In ten sections he discusses the architect’s formation, his training, properties of materials, the design of temples, markets, basilicas, theatres and private dwellings, as well as the preparation of time and (isa, the decoration of buildings, and even hydraulic and mechanical engineering, surveying, siege technology and astrology.

Vitruvius tried to depict Greek and Italic-Roman architecture as variants of one whole. He praises the buildings of the late Republic and criticizes contemporary innovations such as vaulting, brick or multi-floor construction.

Unfortunately he was too early to cover the use of concrete (opus caementicium), the revolutionary and dominating construction technique of imperial times. Roman concrete attained strengths of today’s product. Neither does he treat large span construction by means of vaulting with vousoirs, thus ignoring a technique basic for bridge building. Briefly he mentions the use of buttressing arches or arches as substructure for buildings. It is difficult to tell, why he does not at all mention the construction of bridges, although there were already outstanding examples during his time. Nonetheless his treatise is of great value for this study, as it covers materials and the preparation of mortars, foundations, hydraulic works and methods of drainage.

How did the Roman architect/engineer document and communicate his plans? Vitruvius tells us (I, 1, 4) that ground plans, elevations and perspectives, including dimensioning, were part of the building trade. Large buildings were often defined by a model. Unfortunately, the drawings which had been part of his de architectura have been lost. The Roman architects used papyrus, parchment or wax tablets to draw on, but none of this survived. The tomb of Titus Statilius Aper, inventor of the aqueduct, shows the deceased with a parchment roll and a bundle of wax tablets, plus a quiver with styluses. (Grewe, 1985)

Design drawings were made on parchment, while the wax tablets served for sketches or notes. Usually, working dimensions were laid out on top of foundations, floor slabs, screeds or timber platforms at full scale, to guide the workmen. The exact preparation of stones, such as for arches or vaulting, required detailed plans and measurements. Especially the wedge like shapes for vaulting needed to be defined by jigs and templates. Usually, only the bottom surface was finished. While arches were laid out like this, to be assembled on site. Exposed surfaces and decorations were finished on the erected structure.

2.3.5. Measuring units

The basic Roman unit of measurement for building was the foot (pes). Many subdivisions were in use. J.P. Adams (1984) gives the following details:

- digitus = 1/16 foot = 1.848 cm
- palmus = 1/4 foot = 3.792 cm
- pes = 1 foot = 29.570 cm
- palmipes = 1 1/4 foot = 35.990 cm
- cubitus = 1 1/2 foot = 44.305 cm
- gradus = 2 1/2 foot = 73.955 cm
- palmum = 5 foot = 147.900 cm
- decempeda = 10 foot = 2,957 m
- mille passus = 5000 foot = 1478.500 m

Further measures in use were the peritica, the third of one decempeda = 98,566 cm. There were calibration boards, such as one in Tribulis (Algeria), indicating the Roman foot and other yardsticks. (Sieve, 1982)

2.3.5.2. Layout, measuring and leveling implements

Square wooden or bronze squares were employed to produce a right angle—the horizontal layout of a site. The architect’s staff was used with a rope, knotted at 3, 4 and 5 feet. Water levels allowed control of horizontality.
The Roman surveyors were variably called agrimensores, metatores, mensores or libratores (levels). For linear measurements they used a pole or waxed ropes with markings. For leveling and determination of ground angles they used the chorobates, the groma and the dioptra. Grewe remarks, that the method of leveling hardly changed since antiquity. It all depends upon accurate horizontal sightings, for which served the chorobates.

Next to the common water level (libra aquaria) the chorobate was the most important tool for establishing alignments and levels. It consisted of a wooden frame with a horizontal 20 ft straight edge, fitted with a water level. At the ends were plumb bobs to check verticality. A groove served as sight line. It had a notch and bead sight to establish distant levels. Vitruvius writes on this matter: "First comes the method of taking the level. Leveling is done either with dioptrae, or with water levels, or with chorobates. It is done with greater accuracy by means of chorobates, because dioptrae and levels are deceptive. The chorobate is a straightedge about twenty feet long. At the extremities it has legs, made exactly alike and jointed on perpendicularly to the extremities of the straightedge and also to crosspieces fastened by tenons, connecting the straightedge and the legs. These crosspieces have vertical lines drawn upon them and there are plumb lines hanging from the straight edge over each of the lines. When the straightedge is in position and the plumb lines strike both the lines alike and at the same time, they show that the instrument stands level. ... But if the wind interposes and constant motion prevents any definite indication by lines, then have a groove on the upper side, five feet long, one digit wide and a digit and a half deep, for the water to flow over."

8. Reconstruction of leveling tools by Cesare Cesariano (Como, 1521).
9. Taking levels by two-way sighting.
and pour water into it. If the water comes up uniformly to the rims of the groove, it will be known that the instrument is level. When the level is thus found by means of chorobates, the amount of fall will also be known.

They were especially used for the construction of water mains and aqueducts. For instance, the 50 km water supply of Nîmes across the Pont du Gard had a continuous gradient of 34 cm per km, an excellent achievement. Since the drawings of Vitruvius are lost, there have been several attempts to reconstruct the chorobates.

The groma served for measuring angles. On a stand or tripod a revolving cross of coordinates was fitted with plumb lines. Sightings across the plumb lines allowed the marking of angles. The marking of a right angle was done by sightings across the two sets of plumb lines.

The diopter (dioptra) was similar to our transit. Already Hero of Alexandria (1st c. AD) described this precision instrument, which allows to establish horizontal and vertical angles. An integrated water level of communicating vessels assured the horizontal rotation of a sighting device. An example of the perfect execution of leveling is the water supply of Samos at the time of Polycrates (535–522 BC). An 825 m long tunnel had to be cut through a mountain. To speed up the work one proceeded from both ends. Meeting in the middle, the two teams were only 1 m off vertically.

12. Reconstruction of a groma found in Pompeii.
15. Model of a first century groma at the Saalburg, Germany (Kretschmar, 1983).
16. Roman surveyor with a groma (Kretschmar, 1983).
17. Tombstone of the mensor Lucius Aebutius Faustus from Ivrea (Italy) (Greve, 1985).
18. Reconstruction of a dioptra according to the description by Hero of Alexandria (White, 1986).
19. Auxiliary attachment to Hero’s dioptra on the basis of communicating vessels. Two vertical tubes connected by an internal channel indicated horizontality (Neuburger, 1987).
2.3.6. Materials and their use

2.3.6.1. Building materials and their procurement

The fabric of roads and bridges consisted mainly of stone, concrete (opus caementitium) and burnt brick. In addition, bronze, lead and wood were used as connectors and temporary shuttering. Quay walls gave us clues about the extraction and quality of materials, transport problems, the number of workers and the duration of construction. Another source are the remains in place, or reused parts of masonry in other buildings. Modern material testing methods also offer new knowledge. Later we shall return again to materials.

While for small, private projects the material was furnished by the local builder, the procurement of materials for large, public projects was very early on managed by the government. Since imperial times the state was the dominant client in construction and most quarries – especially for marble – as well as brickyards and mines became government property.

Stone

The most important building material was stone. Vitruvius discusses at length the necessary properties of stone for building (8, chap. 7), revealing the ancients’ notion of the components of materials.

1. Next comes the consideration of stone quarries from which dimension stone and supplies of rubble to be used in building are taken and brought together. The stone in quarries is found to be of different and unlike qualities. In some it is soft: for example, in the environs of the city at the foot of the Capitoline, the Palatine, the Esquilin, and near the Alban Hills; in others, it is hard, as at Tivoli, at Arnimium, or Mt. Soracte, and in quarries of this sort; in still others it is hard, as in lava. Some are of different and unlike qualities. In some it is soft: for example, in the environs of the city at the foot of the Capitoline, the Palatine, the Esquilin, and near the Alban Hills; in others, it is hard, as at Tivoli, at Arnimium, or Mt. Soracte, and in quarries of this sort; in still others it is hard, as in lava. Some are of different and unlike qualities. 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In the absence of natural stratification, horizontal and vertical grooves were cut, or series of holes drilled, according to the size of a block, and the block split off with iron wedges driven in. Sometimes dry wedges of wood were inserted between iron plates. By watering, the swelling force of the wood split off the block. Sawing stone was a kind of grinding procedure, moving a metal blade back and forth along a groove, with very hard, watered sand in between. The ancient Egyptians accomplished astonishing things with such a primitive method. Ausonius (about AD 370) describes in his poem »Mosella« some flour mills along a tributary of the Mosel River, which drove marble cutting saws. And Gregor of Nyssa (4th c. AD) claims in a description of quarries in Cappadocia that stone is being cut with iron and water. How to change the rotary movement of a mill into a linear, horizontal action was already discussed by Heron of Alexandria in the 1st c. AD and should have been known to the Romans. For bridge construction the weight of individual blocks hardly exceeded seven to eight tons. Larger blocks required for architectural parts, such as column shafts, lintels, cornices had to be excavated all around and finally split off along the bottom. The biggest blocks quarried in this fashion are found in Baalbek (Roman Syria now Lebanon). They form the famous Trilithon, three blocks of stone as the middle layer of the podium enclosure for the Temple of Jupiter. Each block measures 20 by 4.6 by 4 m and weighs close to 800 tons. They are perfectly placed on top of the blocks below, without any mortar joint. Nobody has come up with a convincing explanation of how the blocks were put into position. Another block has been readied in the quarry, weighing close to 1000 tons.

Ideally, the building site was lower than the quarry, offering the opportunity to bring the blocks down on ramps, either on rollers or sleighs. Otherwise special roads were built to allow transportation on carts or carriage. There were cabalarias, heavy oxen carts taking loads up to 500 kg, lighter four-wheeler called rada (300 kg loads), vereda taking 100 kg and the two-wheeled biruta, mainly for passengers. Very big pieces were encased in wheel shaped timber constructions and rolled along, pulled by oxen. Vitruvius (I, 2, 11-13) writes of »rowing machines« for columns and architraves.
5.6.3. Evolution of arches

The inclined positioning of beams produces a false arch. If we lean two beams against each other without fixing them at the bottom and put a load upon them, the beams will be pushed apart. Following the diagram of forces the load will be split up into horizontal and vertical components. The horizontal push can be absorbed by buttressing or a tie rod (as introduced by Italian Renaissance builders).

It seems, true arches have been known by the Assyrians and Babylonians since 3500 BC. In Ur a king’s tomb dating from the 4th c. BC has been excavated, featuring a gate and vaulting with semicircular brick arches. In Egypt true arches have been employed since the 3rd millennium BC, and the Greeks did so in classical times, but in all these cases such construction was limited to subterranean work, to ensure sufficient buttressing.

An Etruscan bridge with stone voussoirs near Viterbo indicates, that they were the Romans’ teachers, as in so many other things (Lugli, 1957). Examples are the Ponte della Rocca near Bleda (Etruria) or the Ponte della Badia at Vulci.

After the subjugation of the Etruscans by the Romans, their high standard of living and their skills were played down by their new masters.

Seneca (Epist., 90, 32) writes, that Democritus of Abdera (c. 460 BC) was the inventor of true vaulting. Most likely, the fame of Democritus as universal scientist prompted this view.

5.6.4. True-arch construction

The height of corbelled structures had a practical limit of 5 m, anything beyond became too bulky. The problem was to find a technique, which would fully exploit the superior compressive strength of stone. The solution was the use of wedge-shaped stones, arranged in a curved fashion. It imposed two new requirements: Sufficient timber for the temporary shuttering and solid buttressing to resist the sideways push of the arch. The everlasting horizontal thrust of an arch is well expressed in the Arab saying: “An arch never sleeps.”

103. The wedge stone solution.


105. Semicircular arch of a tomb at Lydai in Caria (Turkey), about to fail due to lack of buttressing. Only friction is keeping the three central voussoirs in place.

106. Flow of forces in arches and rule-of-thumb dimensioning. (Schlussstein = keystone, Stützlinie = pressure line, Kämpfer = impost, Spannweite Sahne = span).

A true arch consists of wedge shaped stones, called voussoirs, which are arranged in a semicircle with radial joints. By their radial arrangement the voussoirs brace each other and keep them in suspension. The number of voussoirs should be uneven, to provide for the last stone at the top, which is aptly called keystone and completes the arch. Vertical loads are deflected along the curvature of the arch, starting horizontally at the top. The resulting push must be arrested by the weight of the spandrels and abutments. A single arch usually has the width of a beam and is a linear support. If we place many arches side by side we receive a tunnel-like structure, called a vault. The Roman engineers employed both methods to perfection.

Heyman (1969) devised a formula to determine the minimal height of voussoirs for a given span of a bridge under its dead load. The values differ for various segments of a circle:

<table>
<thead>
<tr>
<th>Segment</th>
<th>H / R</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semicircle 180°</td>
<td>H / R = 0.1060</td>
</tr>
<tr>
<td>Circle segment 160°</td>
<td>H / R = 0.0680</td>
</tr>
<tr>
<td>Circle segment 140°</td>
<td>H / R = 0.0410</td>
</tr>
</tbody>
</table>

We can see that a reduction of the segmental opening diminishes the voussoir height or allows a larger span. The values presuppose a perfect circular arch shape. Deviations caused by sagging abutments, poor fit of the voussoirs, imperfect condition of the falsework, may require an increase of voussoir height by up to 25%. It is also assumed that the superstructure of spandrel and abutment walls will add to the strength of the masonry, as would a core of concrete.

The measurements of about 100 bridges gave a mean value of H / R = 0.2150. The smallest values were found at the Eski Kühlt Bridge in eastern Turkey = 0.0351 and St. Martin Bridge in Italy with 0.0382.

5.6.5. True-arch construction

The height of corbelled structures had a practical limit of 5 m, anything beyond became too bulky. The problem was to find a technique, which would fully exploit the superior compressive strength of stone. The solution was the use of wedge-shaped stones, arranged in a curved fashion. It imposed two new requirements: Sufficient timber for the temporary shuttering and solid buttressing to resist the sideways push of the arch. The everlasting horizontal thrust of an arch is well expressed in the Arab saying: “An arch never sleeps.”

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165. Semicircular arch of a tomb at Lydai in Caria (Turkey), about to fail due to lack of buttressing. Only friction is keeping the three central voussoirs in place.

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The measurements of about 100 bridges gave a mean value of H / R = 0.2150. The smallest values were found at the Eski Kühlt Bridge in eastern Turkey = 0.0351 and St. Martin Bridge in Italy with 0.0382.
The listing of bridges by date of construction reveals a steady reduction of Heyman’s value due to increasing experience of the builders:

<table>
<thead>
<tr>
<th>Period of construction</th>
<th>Number of bridges</th>
<th>Ratio H / R</th>
</tr>
</thead>
<tbody>
<tr>
<td>2nd c. BC</td>
<td>8</td>
<td>0.3690</td>
</tr>
<tr>
<td>1st c. BC</td>
<td>41</td>
<td>0.2010</td>
</tr>
<tr>
<td>1st c. AD</td>
<td>16</td>
<td>0.2030</td>
</tr>
<tr>
<td>2nd to 6th c. AD</td>
<td>29</td>
<td>0.1850</td>
</tr>
</tbody>
</table>

The ratios H / R for individual bridges are given with the Case Studies:

Structurally a vault consists of parallel arches, having tie stones to link with each other for improved cohesion. Often individual vaulted sections were built in succession, repeatedly using the same shuttering by shifting it. Critical sections of masonry were reinforced with iron clamps set in lead against corrosion.
IM 1. Milvius Pons
River: Tiber, road: Via Flaminia, location: Rome. Length: 150 m, width: 7.5 m, height: 15 m, spans: 9 + 18 + 18 + 9 m, material: tuff, travertine, gabino, ratio of voussoirs to radius: 1.2/9 m = 0.133, pier width: 7.5 m. Built under Flaminius (?), time of construction: 3rd c. BC. Visited: July 1992.
The Via Flaminia, built in 220 BC by Censor Gaius Flaminius was the most important northward road. The road was described by Ashby and Fell (1921), its bridges by Balance (1951) and Blake (1947). It has the greatest number of bridges of Roman roads.
Milvius Pons, also called Ponte Molle, is situated in northern Rome. It is known through the victory of Constantine I over Maxentius on 28 December 312 AD, an event connected with the adoption of the cross by Christian iconography (in hoc signo vinces). This part of the Via Flaminia was begun in 220 BC, and the bridge is first mentioned by Livy in 207 BC. In 174 BC it is recorded as a timber bridge on stone piers, in 142 the timber was replaced by stone arches. Around 109 BC the Censor Aemilius Scaurus ordered repairs or even reconstruction. In 27 BC Augustus commissioned maintenance works for the Via Flaminia, excluding Milvius Pons and Minucius Pons, which must have been in good condition. To commemorate the works a triumphal arch was built in the middle of the bridge.
Today’s condition stems from a restoration by Pope Pius VII in 1805. In 1849, when the defenses of Rome, Garibaldi had one arch destroyed. It was rebuilt within a year. Today the bridge serves for pedestrians only, but in World War II heavy tanks rolled over it.
Nowadays the northern abutment is hidden, also the seventh arch of the north ramp. The square 7.50 m piers, cutwaters and floodways are original and consist of a tuff core faced with travertine. Arches 1 to 6 seen from north were variably restored, arch 1 having a brick vaulting, 2 and 3 gabino vaults with facing travertine voussoirs 60 x 120 cm. The fourth arch consists of two layers of travertine, topped by brickwork. Arches five and six are entirely built with brick. Gabino is a volcanic rock quarried at the ancient town of Gabii.

1. View from south. Brick was used for most of the repairs.

1. View from the west.

IM 2. Fabricius Pons
River: Tiber, road: urban, location: Rome. Length: 61.25 m, width: 6 m, height: 15 m, spans: 25 + 24.7 m, material: tuff, popeline, travertino, gabino, ratio of voussoirs to radius: 1.5/12.4 m = 0.121, pier width: 9.5 m. Built under L. Fabricius, time of construction: 62 BC. Visited: July 1992.
Fabricius Pons, commonly called Quattro Capi, is the only completely preserved Roman bridge in Rome. It is one of the most beautiful Roman bridges. Built at the same time as the Cestius bridge (IM 5), it connects the Tiber isle with the left bank of the river. Inscriptions identify the builder as curator viarium L. Fabricius and the date of construction. A second inscription records repairs in 21 BC by Q. Lepidus and Consul M. Lollius.
The bridge is easy to measure up since the balustrade has metal markers indicating the center of arches or piers. The pier between the two arches has a big floodway. The arches are faced with white travertine, each with 61 voussoirs of 65 x 150 cm. Vaults, piers and abutments are of gabino. Originally the bridge had a bronze railing and was embellished with statues of Hermes, giving the bridge the popular name Ponte dei Quattro Capi. Pope Innocent XI (1676–89) replaced the railing with a stone parapet and used the metal for coinage.
IM 3. Aemilius Pons, today Ponte Rotto

River: Tiber, road: urban, location: Rome, province: Rome. Height: c. 15 m, spans: 6 x up to 24 m, material: tuff, travertine, gabino, ratio of voussoir to radius: 1.2/9 m = 0.1333. Built under Lepidus and Nobilior, time of construction: 179 BC. Visited: July 1992.

It is said to be the first bridge with stone piers in Rome, appropriately named Pons Lepidus. Being commissioned by Censor M. Aemilius Lapidus the name served both origins (Jurecka 1986). In 142 BC Scipio Africanus and L. Mummius replaced the wooden spans with peperino stone arches. Augustus restored it with travertine.

In 1557 a flood destroyed the bridge, Pope Gregory XIII rebuilt it, but in 1586 the eastern part collapsed again. Later an iron suspension bridge was superposed, which was removed in 1885, together with the western arches. Today only two piers and one arch of the southern part remain, explaining today’s name »broken bridge«.


IM 4. Aelius Pons (Angels’ Bridge)

River: Tiber, road: urban, location: Rome, province: Rome. Length: 135 m, width: 10.95 m, height: 15 m, spans: 2 x 7.5 + 3 x 18 + 2 x 7.5 + 3.5 m, material: peperino/gabino concrete, travertine. Built under Hadrian, time of construction: 136 BC. Visited: July 1992.

When Emperor Hadrian built a mausoleum for himself and his family on the right bank of the Tiber, he added an access bridge with three arches of 18 m spans, called Pons Hadriani. Changes of the river necessitated the extension of the bridge to eight spans. It had a 33 m ramp on the city side and a 22 m ramp on the mausoleum side. In 1527 Pope Clement VII placed statues of Peter and Paul at the east end (paid from the bridge toll), later augmented by figures of the evangelists. Since the statues had decayed, Pope Alexander VII commissioned new Baroque statues of angels by Bernini, hence the name of the bridge.

In the course of a Tiber regulation at the end of the 19th c. the old bridge was replaced by a new one with five arches, each with a span of 18 m, which increased the flow capacity. The construction works revealed many details of the bridge’s history.

IM 10. Viadotto di valle Ariccia

River: Tiber, road: urban, location: Rome, province: Rome. Length: 68.8 m, width: 8.9 m, height: 15 m, spans: 20.2 + 25.5 + 21.4 m, material: tuff, travertine, gabino, ratio of voussoir to radius: 1.1275 m = 0.0784. Built by Lucius Cestius, time of construction: 46 BC. Visited: July 1992.

The bridge was built by the curator viarum Lucius Cestius in 46 BC while Caesar battled in Spain. Repaired in AD 102 by Antonius Pius and rebuilt after a flood in AD 370 by Valentinian I and Gratian. It was named Pons Gratiani. It had 20.2 m middle arch flanked by 5.8 m arches. During the 19th century building rage it was torn down and newly built. The middle arch was retained its original size: 347 of the previous 563 travertine blocks of the Pons Gratiani were reused. Marble from the theatre of Marcellus built under Trajan was also used. The middle arch has 59 voussoirs 68 x 100 cm, the side arches have 55 voussoirs 60 x 100 cm. The demolition revealed an intricate system of iron clamps set in lead to reinforce the masonry.

Merckel considered this to invite the penetration of water, leading to frost damage and rusting – which would be the case if the leading was not properly done.


IM 5. Cestius Pons

River: Tiber, road: urban, location: Rome, province: Rome. Length: 68.8 m, width: 8.9 m, height: 15 m, spans: 20.2 + 25.5 + 21.4 m, material: tuff, travertine, gabino, ratio of voussoir to radius: 1.1275 m = 0.0784. Built by Lucius Cestius, time of construction: 46 BC. Visited: July 1992.

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1. View of part of the causeway.
2. Detail of masonry.
F 11. Pont sur l'Ouvèze

River: Ouvèze, road: off Via Domitia, location: Vaison la Romaine, department: Vaucluse.
Length: 18 m, width: 9 m, height: 13 m, span: 16.2 m, material: granite, ratio of voussoirs to radius: 1/8.1 m = 0.1234. Built under Agrippa, time of construction: 1st c. AD. Visited: June 1991.

This single-arch bridge is fitted between the rock faces of the ravine at its narrowest point. The vault is slightly parabolic, similar to IM 04, IM 90 and IN 35. It consists of five arches connected by metal ties and starts at 3 m above water level. The structure was damaged during World War II and rebuilt in 1954. It is in full service.


F 10. Pont Julien

River: Coulon, road: Via Julia Augusta, location: 8 km west of Apt, department: Vaucluse.
Length: 115.5 m, width: 5.9 m, height: 14 m, spans: 10.5 + 16.2 + 10.5 m, material: limestone, ratio of v/r: 85/810 cm = 0.1049, 75/525 cm = 0.1428, pier width: 3.8m. Built under Augustus, time of construction: c. AD 10. Visited: June 1991.

The name of the bridge seems to derive from Caesar's dynasty the Julians. The site was carefully chosen, down or upstream no better place could be found. The bedrock was carefully prepared to receive the foundations of the piers. This way the bridge survived various floods that destroyed bridges in the vicinity, such as the Pont des Beaumettes. A 49 m long northern and a 20 m long southern ramp connect with the bridge, which rises to the top of the central arch. Large floodwater openings (1.5 x 3.1 m) pierce the spandrels. At pavement level a triangular molding projects 25 cm. A parapet made of blocks 60 x 80 x 145 cm carries a metal railing. The net road width is 4.3 m.

In the masonry of the vaulting we notice many deep holes. Most likely the stones were linked by metal anchors, which prompted metal thieves to chisel them out.


1. Elevation of the bridge.
2. The rise to the central arch, metal hunters’ damage to the vault.
3. View of the principal arch.
F 13. Pont Flavien

Length: 25.4 m, width: 6 m, height: 7.8 m, span: 13.7 m, material: limestone, ratio of voussoirs to radius: 1/7 m = 0.0142. Built under Domnius Flavius, time of construction: 12 BC. Visited: June 1991.

This small but very solid bridge received two elaborate 6.7 m high and 7.6 m wide commemorative gates, with full entablature and Corinthian pilasters. Even four crowning lions are still in place. The well-to-do builder commissioned them in his testament. The arch has exceptionally heavy voussoirs: 55 cm wide, 1 m high and 2 m deep, adding up to 1 m³ or 2.7 tons each. In 1763 the bridge was thoroughly renovated.

In contrast to the well preserved gates and stone work, the pavement has been severely worn down. Up to 65 cm pavement thickness have been lost, exposing the crest of the vault and leaving only 35 cm for the voussoirs. Contrary to the rules of statics it is perfectly stable.


F 19. Bridge at St. Gabriel

River: local, road: Via Domitia, location: St. Gabriel on D33, department: Bouches-du-Rhône.
Length: 12.25 m, width: 4.3 m, height: 4.5 m, span: 3.25 m, material: sandstone, ratio of voussoirs to radius: 50/165 cm = 0.3030. Visited: June 1991.

This modest bridge is a sample of the countless secondary structures needed for a road. Although grown over, it is in good condition. 4.5 m long wing walls reduce the road width from 6 to the 3.3 m of the bridge. The parapets consist of blocks of 50 x 50 x 200 cm with tongue and groove connections. On 7 April 1939 the structure made it into the French list of Monuments Historiques.

7 km south of Tarascon it is 100 meters from the Romanesque chapel St. Gabriel.

Ref.: Chevallier 1979, p. 211; Gazzola 1969, p. 179.
F 25. Bridge at Viviers
River: Escoutay, road: Vía Antoninus Pius, location: Viviers, department: Ardèche. Length: 107.15 m, width: 4.25 m, height: 7 m, spans: eleven of 5.5 to 13 m, material: limestone, ratio of v/r: 55/650 cm = 0.085, pier width: 1.55–4.95 m. Built under Antoninus Pius, time of construction: 2nd c. AD. Visited: June 1991.
A very wide but shallow river had to be crossed by the road running along the Rhone River. The bridge has been built with material readily available in the river bed, the voussoirs are slightly trimmed and mortar has been used in abundance. This indicates the rather late date of its original construction, block sizes are small, voussoirs 32–35 x 40–55 cm only, the parapet walls are of rough irregular stones from the river (opus incertum). Ashlar masonry was no more used during the time of Antoninus Pius. In 1767/68 the crossing was fully renovated, including reconstruction of wide arches in parabolic shape. The flow opening is 71%.
Ref.: Chevallier 1979, p. 171; Prade 1986, p. 71.

The reader is kindly referred to the extensive literature regarding this famous structure.
Ref.: Chevallier 1979, p. 171; Prade 1986, p. 71.

F 26. Pont du Gard
River: Gardon, road: local, location: Pont du Gard, department: Gard. Length: 275 m, width: 6 m height: 49 m, spans: see below, material: local limestone, ratio of voussoirs to radius: 145/960 cm = 0.151. Built under Agrippa / Claudius, time of construction: 1st c. AD. Visited: June 1991.
This world-renowned structure served as an aqueduct, supplying Nice with water from 50 km away. The first level left a 70 cm footpath on either side of the next arcade, the road has been added in 1746.
There are three tiers of arcades:
1. Lower level of 6 arches with 19–24.4 m span, 142 m long, 6.3 m wide, 22 m high.
2. Middle level of 11 arches with 15.5–19.2 m span, 242 m long, 4.5 m wide, 19.6 high.
3. Top level of 35 arches of 4.8 m span, 275 m long, 3.06 m wide, 7.4 m high.
It is the tallest Roman bridge construction, surpassing Alcántara (42 m) or Narni (30 m). No mortar was used, except for lining the 1.25 m wide and 1.8 m high water channel on top.
The reader is kindly referred to the extensive literature regarding this famous structure.
Ref.: Brogan 1953, p. 82; De Camp 1977, p. 195; Emerson and Gromort 1925, p. 25; Frontinus Ges. 1988, p. 207; Grenier 1931/4, p. 38; Nikolajev 1967, p. 38; Prade 1986, p. 179.