The Knowledge of a Three Arched Stone Bridge in the Alpine Region Based on the Comparison between Historical Analysis and Diagnostic Data

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Introduction

Ganda Bridge at Morbegno is located in the north of Italy, across the Adda river, about 15 km upstream from the Como Lake, in the very heart of the Alpine Chain. The original bridge was built during the Renaissance by the famous architect Johanne Antonio Amadeo, chief engineer of the Duke of Milan. However, during its lifetime the bridge was damaged by numerous river floods and war episodes, until in 1772 it was so badly damaged by a river flood complete reconstruction was necessary. At Ambrosiana Library in Milan many documents are filed dealing with this work of reconstruction, allowing a detailed knowledge of the design specification of a bridge construction work dated during the late XVIII century.

Recently a careful inspection was carried out on the bridge with the purpose of assessing its structural conditions. The geometric survey, that allowed also the detection of crack and deformation pattern, was done through laser-scanner. Operation by rope access and positioning furthermore allowed the execution of a close visual analysis of the state of conservation of the structures. The diagnostic on site tests were then performed both by Non Destructive Test and Slightly Destructive Test methods.

It was therefore possible to acquire a great deal of information about geometry, materials and construction techniques; which were then matched with historical data, thus pointing out similarities and differences between the original design specifications and the current bridge, both in geometry and construction.

Historical summary

In the XIV and XV centuries, the Valtellina area made up the Northern border of the Milan duchy and despite being protected by the Alps on one side, was very vulnerable to attack. In 1486/1487 the Grigioni (allied with the Swiss confederates that lived in the area currently named Canton Graubünden) invaded a large part of the duchy reaching the northern shores of Lake Como. The invaders quickly withdrew but it was a clear indication of how vulnerable the area was.

Ludovico il Moro, that at the time was governing on behalf of his nephew Gian Galeazzo Sforza (and in 1994 became Duke of Milan) began a renewal programme of Valtellina's fortifications (Scaramellini, 1981) building the walls of Chiavenna and Tirano, the defensive wall of Serravalle and the Piattamala castle. Bridges and streets damaged during the invasion were then repaired. The most urgent repairs were carried out on the valley roads in Desco and Sassella and on the bridge over the Masino creek;

furthermore it raised the necessity to build a bridge connecting Morbegno with the road along the right bank of the Adda river, not far from Traona (Fig. 1).

Bridge construction

From historical documents, it is clear that right up to the final decades of the XV century, there was no bridge spanning the Adda river between Morbegno and Traona; yet in 1477 the two banks were connected only by a wooden walkway (Grigioni, 1981).

The first records of bridge building arrive in 1489 due to a dispute between the inhabitants of Morbegno and Traona concerning where the bridge should be built. In the same year, the visit to Morbegno of the master architect Johanne Antonio Amadeo (note 1) is recorded who should give indications concerning how and where to build. Due to continued local resistance, Duke Ludovico il Moro sent also the ducal engineer Stefano Bascapè, known as "Buratto" to Morbegno, to agree on a final project. He confirmed the position located by Amadeo. Work began, very slowly, so much so that by 1497 the exact location for the bridge was put back under discussion, showing just how little had been achieved. Once more Johanne Antonio Hamadeo reviewed the project and once more confirmed the bridge's original position.

Fig. 1 *Ganda bridge in its natural setting*

In the year 1499 we have the first indication of the bridge being used, so that year we can consider the construction completed.

In 1566, the bridge was destroyed by a flood, rebuilt two years later and reinforced in 1597. The 7th August 1620 it was again damaged during a battle between the inhabitants of Valtellina and Grigioni, that occurred during the 30 years war.

XVIII century reconstruction.

In 1772, another flood almost completely destroyed the bridge. In 1775. The Morbegno and Traona council decided to rebuild it opening a tender for the project: the master builder Antonio Nolfi from Como was selected.

Records show that the project foresaw the demolishing of the two old piers, the reinforcement of the foundations with iron nailed oak poles and the construction of three new arches at least three arm's lengths wider than the previous structure, thus creating a bridge 113 arms in length and 9 arms in width (note 2).

In 1776 however, Francesco Bernardino Ferrari, an engineer expert in hydraulic questions coming from Milan, was called to "analyze the stability and solidity of the foundations laid by Nolfi". Doubts were raised owing to Nolfi's decision to place the new piers onto the old foundations rather than create entirely new foundations, as had been originally foreseen. Ferrari evaluated the right column as structurally sound but not the left one, built over the old foundation; he was particularly concerned about the absence of oak poles used in setting up the base. His suggestion was therefore, to demolish the bridge and rebuild it according to his specific proposal about the placing of the poles.

After that, work was halted and Ferrari was nominated site director. By October 1776 the new "Chapters for the factory of the bridge" (meaning constructive specifications) were ready with an extra appendix in November that was necessary to set up a seal system allowing work below water level to eliminate the old foundations and embed completely new ones. The end of October 1778 represents the successful conclusion of works for Ferrari, with, however, two anomalies. Firstly the lateral arches were wider than expected in order to narrow the central arch and increase stability. The second being the lowering of the columns and abutments and raising the central arch making the slope of the bridge less acute. A technical drawing of the bridge was also attached to the final documentation (Fig. 2).

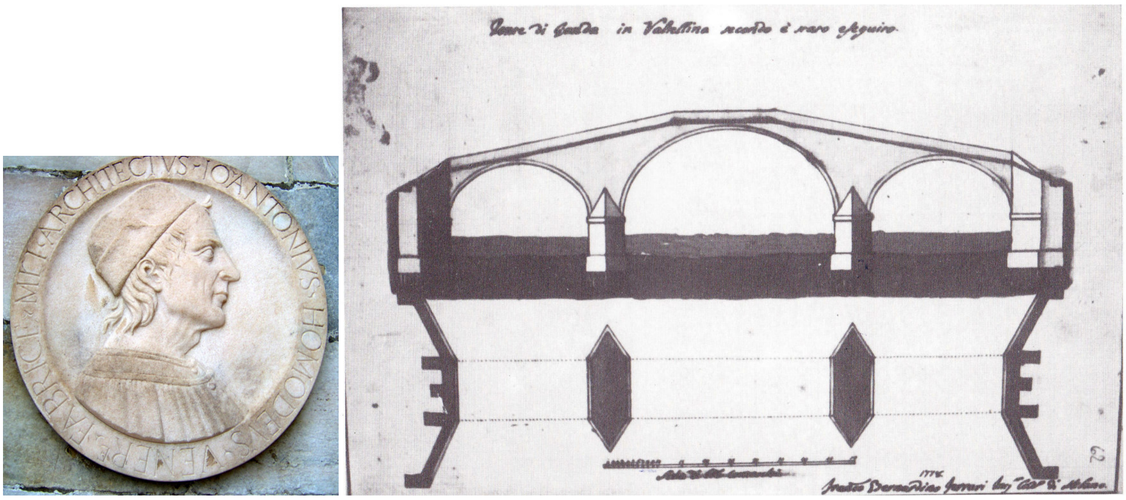

Fig. 2 portrait of J.A. Amadeo on one of the spires of the Milan cathedral (XV-XVI century); sketch of Ganda bridge at the end of the works (1778)

"Chapters" for the construction

The history of the reconstruction of the Ganda bridge is an exemplary case as the Ambrosiana library in Milan, in the Ferrari collection, contains all the historical documentation, henceforth be referred to as the "Chapters" (Grigioni 1980). These documents are of great precision in terms of measurements and technical description and allow the comparison between that defined in the "Chapters" and effective work carried out. Due to space limitations, in this paper there is no reference to the construction of the seal system, described in the appendix of the "Chapters".

Foundation structures as described in the "Chapters"

The bridge will be formed of three clearly distinct arches of 27 - 45 - 27 arms (*13.63 – 22.72 – 13.63 m*) and two columns of 7 arms (*3.53 m*) for a total length of 113 arms (*57.06 m*).

All construction will be carried out using cut stone blocks except for buttresses and infilling of the arches where irregular and river stone can be used. Mortar shall be made of lime and sand of the best quality.

Foundations shall be wider than columns with excavations arriving at 4 1/2 arms depth (*2.27 m*). Poles shall be inserted at the base of the excavations with 5 arms long (2.53 m) iron nailed oak poles tipped with 4 branch elements (Fig. 3) placed at 1/2 arm distance (*25 cm*) from each other. The poles will be sunk into the foundations in such a way that their heads will be just above the level of excavation.

Then, foundations will be raised to the level of the heads using bitumen made with lime and fresh mortar and above this will be laid stone blocks squared on the top and sides, all of the same thickness and perfectly laid down (Fig. 3).

Above this layer squared stone blocks, 5 face slabs of 9 ounce (*38 cm*), laid head to shoulder will be bound with iron ties made sound with lead. Foundation will be built up uniformly, layer by layer, including water breaks.

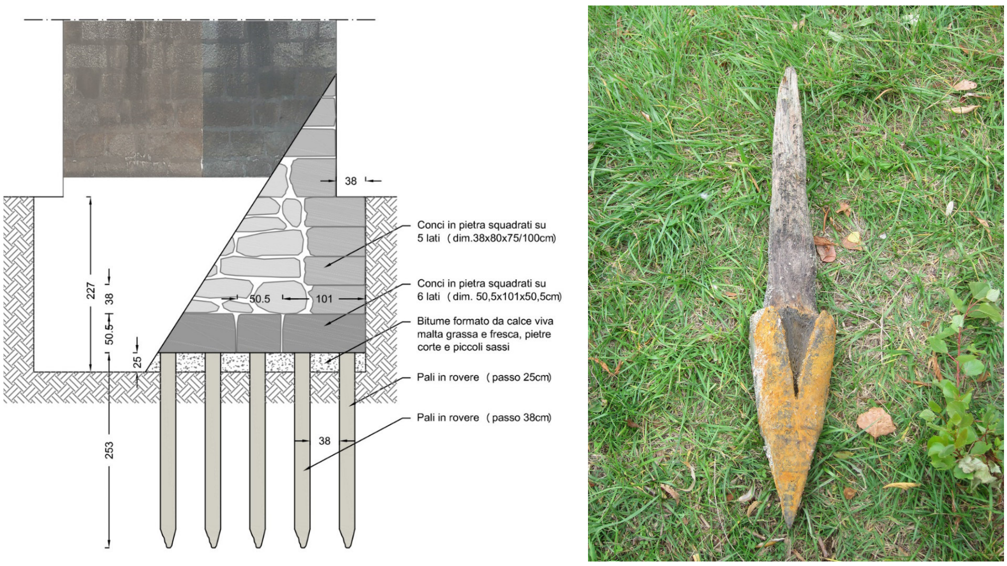

Fig. 3 foundation construction in compliance with the "Chapters"; nailed poles recovered at Bassano bridge site (XVI-XVIII century)

Elevation structures as described in the "Chapters"

Piles will be 10 arms length (*5.05 m*) with two water breaks of 5 arms and 9 ounces (*2.90 m*), for a total length of 21 1/2 arms (*10.86 m*) (note 3). The width of the piles will be 7 arms (*3.54 m*) and their height 10 1/2 arms (*5.30 m)*. Above this height, water breaks will form a pyramid.

The abutments will be as long and high as the piles and have three back buttresses. The abutments and spurs will rise above the arch level to create the vaults. Bridge parapets will be proportioned to needs.

Arches will be made of well chiselled and smoothed stone. The central arch will have span of 45 arms and a raise of 15 arms (*22.72 m – 7.58 m*), the lateral arches will have span of 27 arms and a raise of 10 arms (*13.63 m – 5.05 m*). In the Chapters the ratio raise/span equals 1/3 for the central arch and 1/2,7 for the lateral arches.

It is interesting to compare these dimensions with the ones which can be found in Palladio, 1570. In the book III chapter. XIIII a plan for "another bridge of my invention" is shown. The bridge is not well identified but, due to its dimensions, it can be hypothesized it refers to the first design for a stone bridge in Bassano; this bridge was later built with wooden frame as shown in book III chapter IX. It is significant to note that this bridge has a central arch span very similar to the Ganda bridge (21.31 m vs. 22.72 m), albeit with an almost double width. The ratio raise/span used in the Palladian arch is 1/3: 20/60 feet for the central arch and 16/48 feet for the lateral ones (note 4), the same as foreseen by Ferrari in his "Chapters".

It is also useful to note that Palladian pile width is 12 feet, that means 1/5 central arch span and 1/4 smaller arches; Palladio declared to have "changed and increased ordinary measures" of the piles "in order that they resist river flow strength as well as debris flowing down the river". Ganda bridge piles were designed with smaller width, 7 arms equal to 1/6.4 of central arch daylight and 1/2.8 of smaller arches (which in this case are very narrow). Clearly Ferrari believed that in the case of the Adda river it was not necessary to conform to the criteria carried out by Palladio for the Brenta river.

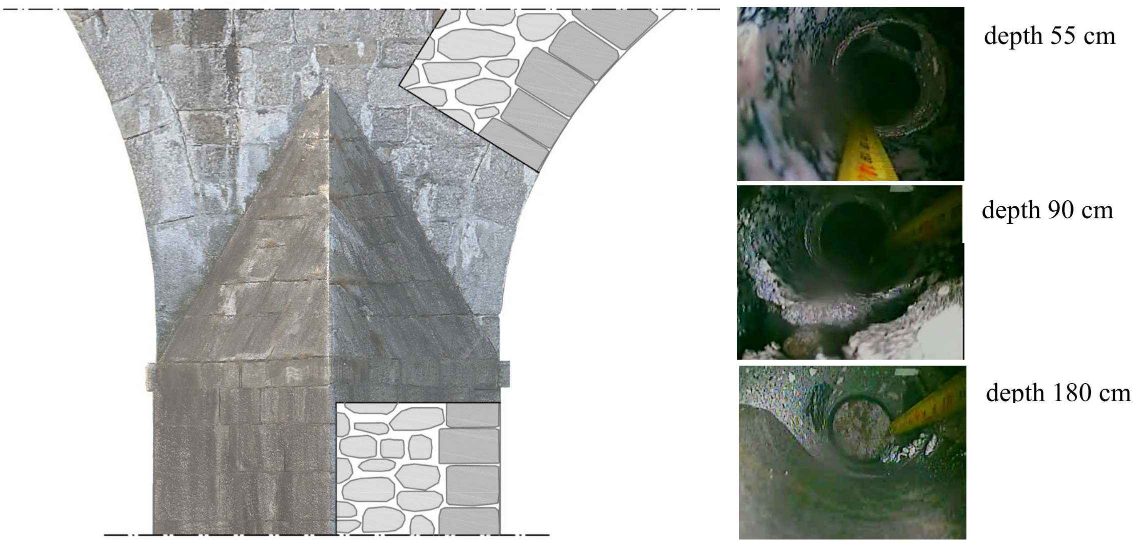

Fig. 4 a pile as shown in the Chapters; images coming from coring holes inspected with endoscopic video camera

At the end of his description Palladio specifies that external arch moulding must be 1/17 span for the central arch and 1/14 for lateral arches, larger than that specified for the Ganda bridge. In this case it has to be observed that on Ganda bridge, the voussoirs are equal to the thickness of the arch, while Palladio's structures saw external moulding probably not corresponding to structural thickness because it has merely decorative function.

In the "Chapters" a thickness at keystone of 15 ounces (*63 cm*) is recommended, as is the thickness of the voussoirs. Arches will be constructed of natural stone, of 15 ounce

(*63 cm*) size and reinforced with 17 iron bars as long as the width of the bridge. Infill will be in masonry, raising the abutments and buttresses using squared cut stone connecting the crown of the vaults to the height of the wings.

In the “Chapters” there are further references to the building of parapets with half egg decoration, but these are not relevant for the present discussion.

Surveys and inspection

Operative methods

Geometric survey of the structure was carried out with laser scanner enabling the quick and precise results required and the collection of sufficient data for the successive structural analysis as well.

The HDS 7000 (Leica Geosystems) scanner was used for 3-dimensional scanning which enables the creation of point cloud models at 1 million dots per second at an accuracy of +/- 1mm at a range of 1m-50m. Single scans were correlated and fully geo-referenced to describe the complexity of the structure in a single point cloud model (fig 5). Using the Cyclone programme (Leica) the geo-referenced calculation makes use of both topographic target points and surface super imposing guaranteeing a correct correlation across scans. Autocad was then used to vector the following phases creating a skimmed point cloud model depending on the sections chosen – an essential operation to manage the vectored model with sufficient agility.

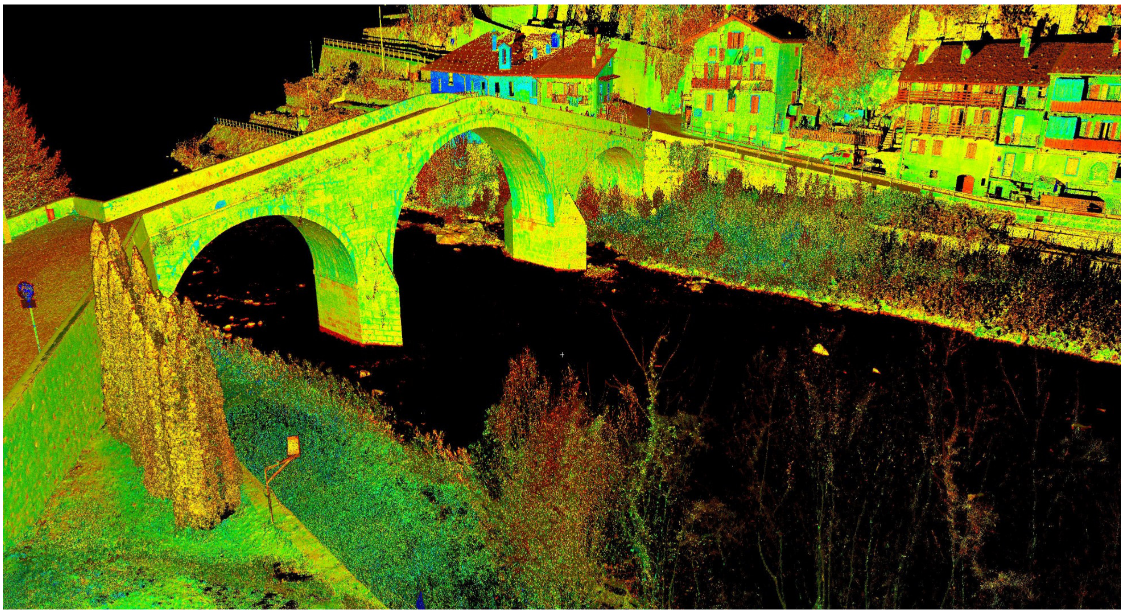

Fig. 5 point cloud model coming from laser-scanner survey of the bridge

Cracking and deformation conditions were analyzed through direct surface inspection: for this purpose access and positioning methods by ropes were chosen as the best and safest procedure (Fig. 7); this choice also proved to be the fastest way to gather relevant structural and conservation data.

Differences between the Chapters description and current condition

Current dimensions are highly similar to those specified in the Chapters, excepting the differences reported by Ferrari at the end of his works: the widened side arches (current dimensions 14.28-21.55-14.26 m) and the lowered columns (current dimension 3.91 m). This changes the ratio raise/span, increasing the acuteness of the arches with a current ratio of 1/2.48 for the central arch and 1/2.63 for the lateral arches.

One must ask why this geometric difference from the Chapters came about (especially thinking that the final project was in compliance with the state of art as proved by the comparison with Palladio's book). Ferrari declared the changes, narrowing the central arch, were necessary to increase stability and reduce crossing difficulty, even though the original project specifications foresaw the central arch at least three arms wider than the previous structure. It can be noted that using these dimensions, the bridge could be built on the same foundations as before, possibly even using part of the previous structure. Current structural calculations show the 1/3 ratio, as defined in the “Chapters”, as the most efficient; the stability of 1/2.48 arch requires the structural contribution of pile infilling material, thus still reproducing the original project.

A further difference can be seen in the arch and piers width that is 12 arms rather than 10 as requested by the “Chapters” (*6.19m vs 5.05 m*), probably with the goal of widening the bridge deck. Finally the thickness of the voussoirs is lower as the blocks are slimmer than those specified in the “Chapters”.

Stone lythology and signs carved by stonecutters

The type of stone used is uniform, 90% magmatic, typical of the Val Masino area. There is also a small quantity of brown metamorphic stone, gneiss and even some grey and lighter colour stone, changing in grain and texture.

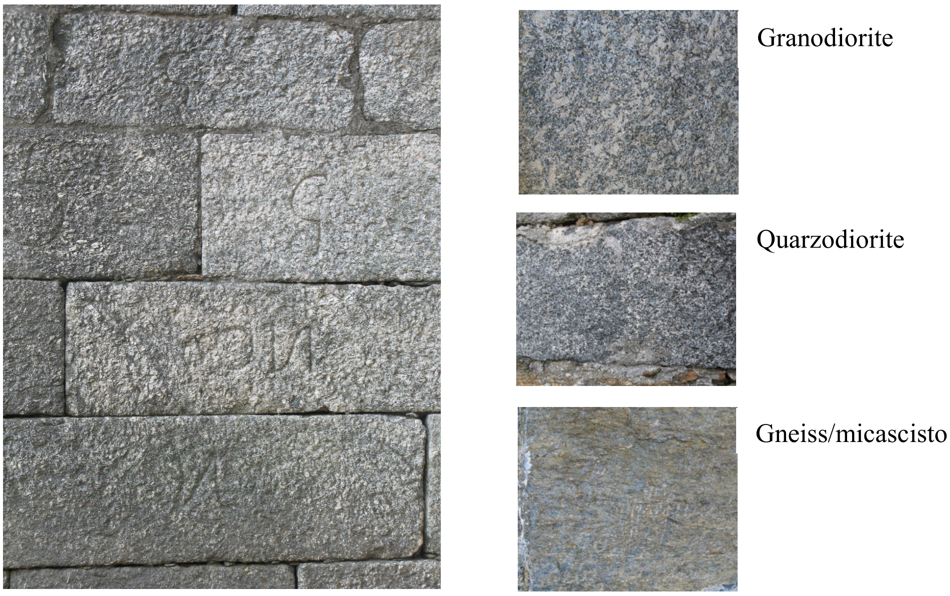

Fig. 6 signs left by the stonecutters during construction

From close up, many signs left by the stonecutters during construction can be seen (Fig. 6). The symbols, probably marks made by stonecutters, are grouped together principally in 3 groups, Z, Ç and NO. There is no order to the symbols suggesting no particular assembly hierarchy. Stones were laid with great care while external mortar, due to the limited thickness of the joints, is eroded or absent, while the erosion not reach serious depth inside the structure.

General structural conservation

Rope inspection of both sides of the bridge gives a detailed analysis of cracks and deformations as well as the general state of bridge conservation. Voussoirs and external parameters maintain a good standard of masonry. The arch and buttresses show continuity with original planning; higher sections, however, are showing signals of sliding.

The archway intrados show significant signs of discontinuity between voussoirs and the vault. On the right arch this has led to a lowering of the vault compared to the front arch. Concretions are present in the intrados showing the gradual washing away of mortar in the masonry. The water breaks are positioned above lateral masonry and made of pyramid shaped blocks; they are not connected to the masonry behind and are now significantly detached from their original position. The apex and the blocks below show the absence of mortar in the joints; vegetation can be seen on the left side of the bridge between the joints.

Pile masonry appears solid; however at the base of the right pier, where heavy water flows occur, mortar has been eroded and washed away. In this area one block is so badly connected that it is now held in place only by iron bars. Joints at the base of the left column are in a bad shape, grouted with cementitious mortar. Furthermore on the upstream masonry of the left arch there is a visible crack developing along the mortar joint line (it is however the only relevant crack for the whole bridge).

Diagnostic analysis

Operative methodology

Fig. 7 inspection and ultrasonic measurements performed with positioning techniques by ropes

Structural stratigraphic analysis was carried out through continuous coring; to further improve data collection, video endoscopy was used in bore holes to identify internal cavities or discontinuity. Using ultrasound tomography (Fig. 7); the data was then improved through the analysis of elastic waves, allowing the finding of eventual cracks, cavities and other deformations (pulse echo technology). Wave frequency varies between 25 and 85kHz; shorter waves increase tomographic detail with better adaptation to material variety and thickness as well as identifying cracks filled with water.

Wave intensity will vary according to material acoustic impedance (acoustic impedance Z = density x elastic wave velocity). Air is an empty space and presents sound impedance at almost zero, that means that pulses will be entirely returned.

Foundation structures as identified by the analysis

The actual foundation asset differs greatly from that prescribed in the "Chapters". It is not clear how the right column was constructed following the declaration that it was built on a "sounding rock" and depending how big or solid this was. Three possibilities emerged: "light basis" made with the chisel or "laid down a strong foundation masonry" or "broken and hollowed out".

On the contrary, from the documents, the rebuilding of the left column foundation followed the guidelines. To confirm this, corings were carried out (fig 3). In agreement with the diagnostic results, masonry is haphazard and not following guidelines: mortar of bad quality with stones and lumps of brick was used. Abundant water leaks from the bore hole showing the great amount of holes that allow water filtration inside the structure. While reaching the maximum depth possible (as indicated in the "Chapters") through coring, it wasn't possible to recover cores from the foundation stones; conversely wooden fragments from the poles were recovered proving their use in foundation reinforcement.

Elevation structures as identified by the analysis

Arch masonry is made of stone blocks that, for the voussoirs, have a uniform thickness of 55/60 cm, while the "Chapters" indication was for 63 cm. Analysis shows that the two symmetric springs of the right arch have stone thickness of 80 and 63 cm, as the stones were cut on five faces but not on the back side, creating such variation in thickness. In this part of the structure, the infilling of the masonry is compact with good adhesion between mortar and blocks and stones of differing origin (including metamorphic) and smaller size, 20-30 cm. This rings true with Chapters descriptions that state that "in the infilling of arches irregular and river stone may be used, as long as they are of sufficient size".

The right pile, under investigation, shows the use of irregular stones but of 63 cm thickness, good mortar condition and infilling made with stones of varying lithology and size 20-40 cm. Coring allowed for direct inspection the half thickness of a pile, as the other side would be symmetrical. Results confirm the "Chapters" prescription of uniform layer construction. The abutment on the left side shows irregular blocks from 45 to 60 cm used on the external face, compact mortar and yet stones sized 20-40 cm used for the infilling.

Seismic Hazard

Italian codes for assessment and reduction of seismic hazard of cultural heritage define the knowledge of a historical construction as the fundamental pre-requisite to obtain a reliable assessment of the seismic hazard and accordingly they define a specific "path of knowledge" aimed at the individuation of relevant geometric and structural information.

In the case of Ganda bridge, the path of knowledge allowed the obtaining of the interpretation of the historical evolution of the construction and the crack and deformation pattern; the diagnostic activities allowed furthermore to obtain the structural identification of the construction and of its details and the evaluation of the correlation between soil and foundations. Tests for the evaluation of the mechanical properties of the materials were not performed (these properties were obtained from the tables of the codes) neither were tests for the geotechnical characterisation of the soil performed (for Ganda bridge this is not a relevant aspect).

On the basis of the surveyed geometry, it was thus possible to implement a structural model suitable to perform the analysis necessary to classify Ganda bridge according to the bridge categories defined by the Italian codes. As a result, the bridge is suitable for the 3rd category loads (that means it is a pedestrian walkway); so under these conditions it was verified both for static and seismic aspects.

Verifications were satisfied with reference to the stability (a fundamental aspect) and to the friction. With regard to compressive strength, the values of masonry resistance provided by the codes do not allow to express a positive judgement. However, the tabular values are probably overly cautious with regard to the compactness and regularity of the masonry of the Ganda bridge: to assess its actual strength it shall be necessary to deepen the analysis through specific test aimed at determining the effective compressive strength.

Conclusions

The historical analysis of the 18th century documentation in the Chapters confirms an excellent relationship between the design planning and final construction. There is, however, substantial difference between the detailed foundation design in the Chapters and the current state. Coring has shown stratified mortar in a highly weakened state due to its permanence under water. Water seeping is also present in the blocks constituting the foundation. These factors preclude a positive judgement on foundations until further analysis is carried out.

Detailed analysis also showed significant discontinuity at the intrados of the arches at the line between external voussoirs and the vault; this shows up the inadequate transversal strengthening in arch masonry and the evident difference in deformability between the external voussoirs and the vault, thus underlining a problem in global structural behaviour.

Overall, the survey and analysis, correlated with historical knowledge has provided a powerful tool in full expertise concerning an historical monument leading to the structural assessment of the present status and the best possible conservation in the future.

Acknowledgments

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Notes

1. Johanne Antonio Amadeo, born in Pavia in 1447, worked from 1470 as the architect on the Colleoni chapel in Bergamo, the duomo in Milan and Cremona cathedral, the facade of S. Satiro church, Pavia cathedral (with Bramante) and the maggiore hospital in Milan, some of the most important Renaissance monuments in Lombardy.
2. 1 Como arm length is equal to 0,505 m and 1 ounce is equal to 1/12 arm = 0,042 m; in the paper metric conversions are shown in brackets.
3. 21 1/2 arms = 20 arms and 18 ounces, meaning 1 ounce = 1/12 arms
4. the unit used by Palladio was the Vicenza foot equal to 35.5 cm

Bibliography

Grigioni G., La definitiva ricostruzione settecentesca del ponte di Ganda in Valtellina, Periodico della Società Storica Comense vol. 47, 1980, pagg. 197-216

Grigioni G., Nuovi documenti per la costruzione quattrocentesca del ponte di Ganda in Valtellina, Arte Lombarda n. 60, 1981, pagg. 103-106

Palladio A., I quattro libri dell'architettura, Venezia 1570, ristampa anastatica ed. Hoepli, Milano, 1980

Rapella R., Il ponte di Ganda, in Le vie del bene, Morbegno, 1966 pagg. 2-4

Scaramellini G., L'Architetto Amadeo in Valtellina e Valchiavenna, in Addua, studi in onore di Renzo Sertoli Salis, Sondrio, 1981 pagg. 25-267