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CHARACTERISATION OF DIFFERENT MATERIALS AND CONSTRUCTIVE TECHNIQUES OF HERITAGE BRIDGES IN THE NORTHERN ITALY

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ABSTRACT

European historic bridges are made with a wide range of different materials (from masonry to wooden trusses to R.C. structures) and they present differently shaped structural elements (foundation poles, piers, shoulders, deck). If we also consider the differences in conservation and decay of the mechanical characteristic of the materials, it is possible to have an idea of the complexity of the definition of the parameters required for the static and seismic safety assessment of such structures.

Italian structural codes for the assessment and reduction of seismic hazard of cultural heritage state the knowledge of an historical construction to be the fundamental pre-requisite to obtain a reliable assessment of the structural condition of the construction. Accordingly they define a specific “path of knowledge” aimed at the identification of relevant geometric and structural information. This allows a level of knowledge to be reached that is suitable for implementing a structural model necessary to perform the structural analysis and to classify the bridge in compliance with the load categories defined by the codes themselves. As well as this, the model can also be validated and calibrated through the diagnostic data collected.

Some case histories will be presented dealing with execution of Non Destructive Testing performed on heritage bridges located in the Northern Italy: the wooden trussed Alpini bridge at Bassano, designed by Andrea Palladio and the three arched stone masonry Ganda bridge at Morbegno, designed by Johanne Antonio Amadeo. Furthermore, the analyses were performed by operating with positioning techniques by ropes, that in these cases proved to be an efficient and cost effective methodology.

1. INTRODUCTION

1.1. Path of knowledge

The current Italian code concerning the seismic assessment of cultural heritage buildings (D.P.C.M. 09/02/2011) outlines a path of knowledge that can be pursued with different levels of detail depending on the care with which relief and inspection operations, historical research and experimental investigations are carried out. This path is aimed at the definition of an interpretative model of the structure which allows for both a qualitative assessment and a quantitative analysis.

To completely identify a building, it is, therefore, necessary to achieve adequate knowledge of it through the following steps:

- geometric survey of the building, completed with its cracking and deformation pattern;
- interpretation of the historical evolution of the construction;
- identification of the building and of its structural details;
- evaluation of the mechanical properties of materials and their decay;

- evaluation of the geotechnical issues;
- monitoring.

The process outlined highlights the fact that knowledge coming from the activities of survey and diagnosis cannot be separated from the right understanding of the historical evolution of the structure: we can consider that the history has been an experiment in real scale and that cracks, distortions and states of stress in the structure represent the results of this experiment; their measurement allows for a model as close as possible to the real behaviour of the building to be created which will be appropriate for carrying out the assessment of the current safety level. The experimental analysis is therefore a powerful tool, complementing the empirical observations and making more objective considerations of the structural evolution of the construction. It also allows for the validation of the numerical model during its implementation which includes checking the results during the analysis (Armanasco & Foppoli, 2014).

1.2. Short description of the bridges

The path of knowledge will be exemplified in the following paper dealing with the case history of two bridges of outstanding cultural value, placed in the Northern Italy within the Alpine Chain; Alpini bridge at Bassano del Grappa (VI) and Ganda bridge at Morbegno (SO). They are different due to period of construction and structural and material conformation, but they exemplify a common path aimed at reaching a correct understanding of their characteristics.

The old bridge of Bassano del Grappa (in Italy) is placed along the Brenta River that flows through the city. The structure has an overall length of 65 m and a width of 8.5 m; it is composed of five spans resting on two masonry abutments and on four piers sunk in the riverbed (Fig. 1). The piers are made of 8 poles of equal length to support the deck and six additional poles in decreasing lengths arranged both upstream and downstream to form the spurs. The deck is supported by eight beams arranged longitudinally to the bridge; the whole structure is made with wooden trusses

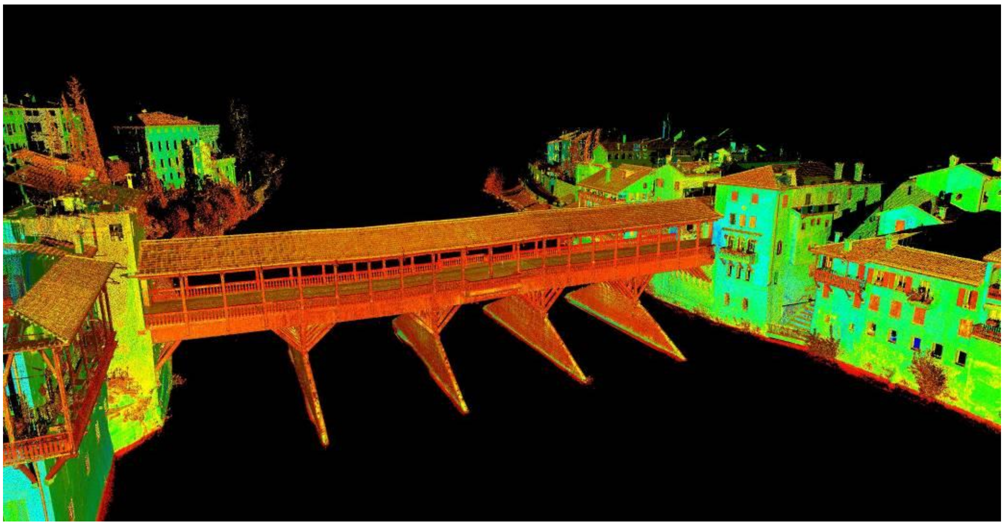

Fig. 1: shot of points-cloud carried from laser-scanner survey of the old bridge of Bassano

The Ganda bridge is placed upon the Adda River, not far from its entering in the Como Lake; it has an overall length of 57 m and a width of 6,20 m and is composed of 3 arches entirely made with squared stone masonry (Fig. 4).

In the following chapters we will outline the construction events of the two artefacts, we will describe the diagnostic activities performed and we will define the achieved Level of Knowledge. It will be possible also to highlight some interesting historical link between the so different two bridges.

2. INTERPRETATION OF HISTORICAL EVOLUTION

2.1. The old bridge of Bassano

The first information concerning the existence of a bridge in Bassano came from documents of the beginning of XIII c. In the medieval period, Bassano was involved in many urban improvements, due to the enlargements of its walls; numerous maintenance or reconstruction works of the bridge are documented in this period. Documents confirming the deterioration of the structure are frequent and, following the collapse caused by a flood in 1450, reconstruction works were undertaken and lasted three years. The following events tell us about much destruction due both to floods and to wars. The most relevant fact was in 1524 with the construction of a stone bridge; despite high expectations, also it fell during a flood two years after its completion, and so the bridge was rebuilt in 1531 using a timber structure (Foppoli, 2015).

This bridge was again destroyed by a flood in 1567. The reconstruction project was then commissioned to Andrea Palladio, the famous Venetian architect ,who at first proposed the construction of a stone bridge, but was later forced to review the project, as requested by the Municipality of Bassano, and to build a timber bridge once more. The bridge designed by Palladio is represented and described in a table (Fig. 2) of his famous treatise "The Four Books of Architecture" (Palladio, 1570).

During the XVII century, the execution of periodic routine maintenance works is documented; major maintenance works were carried out on the occasion of the flood of 1707, and then again in 1748, when the bridge was swept away and then reconstructed by architect Bartolomeo Ferracina in compliance, as far as possible, with the original design of Palladio. During the Napoleonic Wars of 1809-1813, the bridge was burned again for strategic purposes and it was rebuilt only eight years after. The structure suffered other damage during the recurring floods of the XIX century.

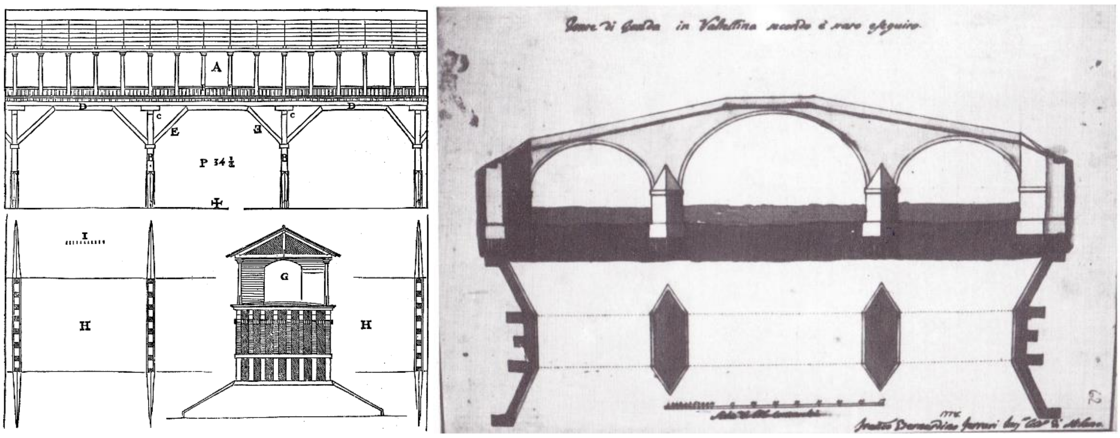

Fig. 2 table from Palladio "Four books of architecture" book III chapter. IX that represents the bridge of Bassano; table with the survey of Ganda bridge attached to the final estimation of the works (1778)

During the first World War it was bombed directly from the close Alpine front on the Grappa Mountain and it was damaged. During the second World War, it was sabotaged by the partisans and partially destroyed. At the end of the war, the bridge was once again repaired and inaugurated in 1948.

The last destructive flood took place in 1966, when the bridge was seriously damaged curving downstream because of the load of the water and again requiring important repair work.

The inspections carried out in 1990 highlighted again the poor conservation status at the bottom of the poles and the tendency to undermine the foundations. An urgent intervention was made in consolidating the foundations and drilling, for each pier, four couples of reinforced concrete poles on the top, on which four wooden crosspieces were supported to sustain the transversal beam at the base of the wooden poles. The wooden trusses were consolidated maintaining the existing elements, eliminating the decayed parts and restoring sections with casts of conglomerate resin mixed with quartz sands. At the end of the intervention, the pavement was reconstructed with stone slabs in compliance with historical information believed to be accurate.

2.2. The Ganda bridge

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.

The first records of bridge building date back to 1489 due to a dispute between the inhabitants of the two towns concerning the place where the bridge should be built. In the same year, the visit to Morbegno of the master architect Johanne Antonio Amadeo, one of the main architects of Lombardy renaissance, is recorded, who should give indications concerning how and where to build. 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. 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, which occurred during the 30 year war.

In 1772, another flood almost completely destroyed the bridge, three years later the reconstruction works began and in 1776 Francesco Bernardino Ferrari, an engineer expert in hydraulic questions coming from Milan, was entrusted with its reconstruction.

Fig. 3 pictures of Bassano bridge during the flood of November 1966 and Ganda bridge during the flood of July 1987

The history of the reconstruction of the Ganda bridge is an interesting case history case as the "Ferrari book collection", preserved at the Ambrosiana library in Milan, contains the documents drafted for its reconstruction called “Chapter for the construction of the bridge”, henceforth be referred to as the “Chapters”. These documents are of great precision in terms of technical description and allow the comparison with the current status of the bridge, that reflects the effective work carried out (Foppoli, 2017). The construction of the bridge lasted until 1778; in the library, a drawing is also filed attached to the final estimation of the works representing the "as built" of the bridge.

After that, many floods occurred and the bridge was subject to further improvement works, the last one after “Valtellina” flood of 1987, when the foundations were consolidated.

3. SURVEY AND DIAGNOSTIC

3.1. Geometrical survey

The choice of laser scanner technology for the execution of the geometric survey was suggested by several concomitant considerations:

- high precision, appropriate to the result required;
- high acquisition speed which made the survey expedient;
- collection of a series of redundant data, usable, however, for subsequent structural evaluation.

Three-dimensional scans were performed through HDS 7000 (Leica) scanner. By measuring the distance time of the laser pulses, this scanner is able to determine a spatial cloud of 106 dots/s with an accuracy of +/- 1mm in a range from 1to 50m.

Each scan was correlated and geo-referenced to describe the object in its detail and in its complexity, creating a sole points-cloud model (Fig. 1-4).

Afterwards, the phases of restitution and vectorialization were performed by Autocad applications which allowed dividing and skimming the whole points-cloud on the basis of the chosen sections, managing the model with greater agility.

3.2. Survey of materials, construction and conservation status

The survey has been integrated through direct measurements to determine the dimension of some structural elements which, because of their position, could not be identified in the points-cloud and to detect the construction details necessary for the structural identification of the bridges. The inspection was carried out with access and positioning techniques through ropes: so specifically qualified engineers and technicians worked in compliance with current Italian Health & Safety code (D.Lgs. n. 81/2008). This technique proved to be effectual and cost effective, in addition to being the only one applicable in these cases due to the impossibility of access to the bridge through Movable Work Platforms.

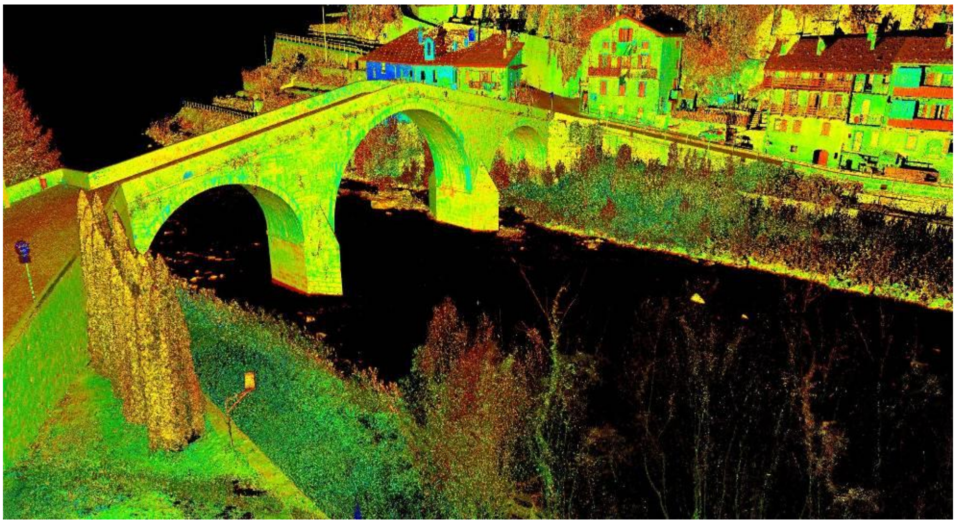

Fig. 4 shot of points-cloud carried from laser scanner survey of Ganda Bridge

To analyse the construction techniques and materials, structural stratigraphic analysis was carried out through continuous coring; video endoscopy was used in bore holes to further improve data collection and to identify internal cavities or discontinuities. Using ultrasound tomography (pulse echo technology) the data was then improved through the analysis of elastic waves, allowing the location of eventual cracks, cavities and other deformations (Fig. 5). 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, meaning pulses will be entirely returned.

3.3. Mechanical characteristics of masonry structures

The brick solid unit masonry of Bassano bridge abutments was characterised to determine in situ compressive stress through single flat jack test in compliance with ASTM C 1197-09 and to measure the in situ masonry deformability proprieties through double flat jack test in compliance with ASTM C 1196-09.

3.4. Conservation status of wooden beams

The inspection carried out with access and positioning techniques by ropes has allowed the close-up view of the structural elements, particularly at the critical points. It is important to note that all structural timbers of the Bassano Bridge are covered with a thick layer of coating that made difficult the detailed observation of the surfaces and even the bare identification of the resin reinforcement casts.

Where signs of deterioration such as cracks, fissures, torsions, wood rot and holes of xylophages insects were found, the visual investigation, performed in compliance with UNI 11119:2004, was integrated through the use of manual tools (awl and hammer). In this way, it was possible to outline the area to be subjected to a more accurate instrumental analysis, carried out by Resistograph (Piazza & Del Senno, 2001), in order to locate and quantify regions of internal decay on timber elements (Fig. 5).

The Resistograph is a drill testing instrument that inserts a thin needle in wood and measures the drilling resistance. The electronic control of the engine ensures a constant speed of the needle, which can be adapted to the specific characteristics of density of the wood to be examined. The drilling resistance is concentrated on the tip of the needle because its diameter is twice the thickness of the stem.

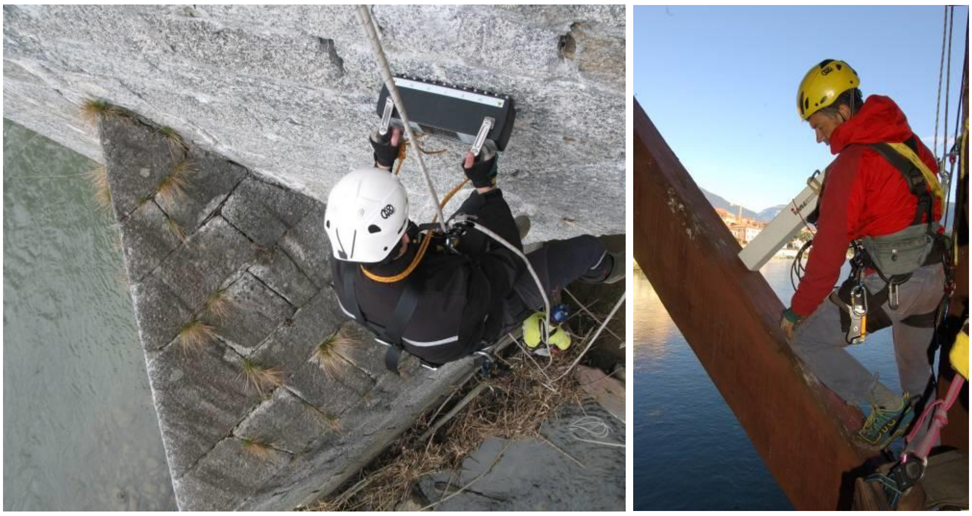

Fig. 5 ultrasonic tomography on masonry and execution of measurement of drill resistance on wood both performed by ropes access techniques

The Resistograph profile allows density variation measurements (Rinn, 1993): the wood that is decomposed, or in the process of decomposition due to decay, is highlighted by specific density profiles which are also early indicators of:

- presence of wood-decay fungus;
- presence of damages due to xylophages insects;
- splits, slipping fibre, annular ring shakes, hollow areas.

In order to characterize the wood species, some samples were collected using a Pressler auger, they were then subjected to laboratory analysis aimed at identifying the wooden species and the consolidation materials.

4. RESULTS OF THE PERFORMED ANALYSIS

In the following chapter some considerations that exemplify the goals of the research and the quality of the results that were possible to reach through the analysis performed will be summarised with specific reference to each one of the analysed bridges.

4.1. Foundation structures (of Ganda bridge)

The "Chapters" clearly states how the foundations of the piles had to be made (Fig. 6): at the base of the excavations iron nailed oak poles tipped with 4 branch elements had to be inserted. The foundations had to be raised to the level of the heads of the poles using bitumen made with lime and fresh mortar and above this stone blocks had to be laid, squared on the top and sides, all of the same thickness and perfectly laid down. Above this layer, stone blocks squared on 5 faces were placed head to shoulder and they were bound with iron ties made sound with lead. Foundations had to be built up uniformly, layer by layer, including the spurs. This conformation is described also in the detailed dimensions.

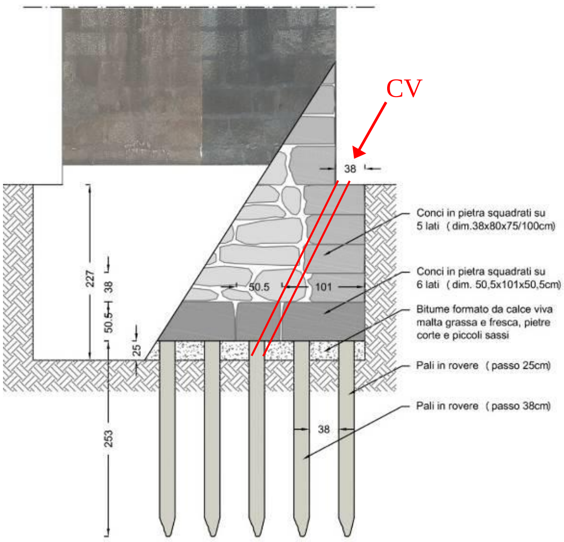

Fig. 6 foundation construction in compliance with the "Chapters";
sample of nailed poles recovered at Bassano bridge site (XVI-XVIII century)

The actual foundation asset greatly differs 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". On the left column, where corings were carried out, in agreement with the diagnostic results, masonry is haphazard and not following guidelines: mortar of bad quality was used with stones and lumps of brick. Abundant water leaked from the bore hole showing the great amount of cavities that allow water filtration inside the structure. While reaching through coring the maximum depth possible (as indicated in the "Chapters") 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.

4.2. Piers (of Ganda bridge)

The "Chapters" prescribes that the construction had to be made with stones squared with chisels, except in the buttresses and infilling of the arches where it was possible to place irregular stones of sufficient thickness taken from river bed, with good mortar made of lime and sand of the best quality.

The masonry of the right pier has the external layer made with squared stones (mainly "serizzo" and "ghiandone" – types of local stone) taken out from quarries placed not far from the construction site; the infilling is made of compact masonry, made with stones with lower dimensions, 20-40 cm (Fig. 7), probably picked up from the river bed, and mortar with good quality and adhesion characteristics.

Coring allowed detecting half the thickness of the pier (that means the whole thickness of the same because it can be considered symmetric). The good texture detected enables to suppose that the masonry also in this case was built in compliance with the "Chapters", that is with uniform horizontal layers, built for the whole section including the spurs of the bridge. Only the cusps above the spurs seem not to be properly connected to the masonry body. The surveys performed also led to acquiring information on the abutments, that were constructed with similar care.

4.3. Geometry of the arches (of Ganda bridge)

The "Chapters" prescribes that arches have to be made of well chiselled and smoothed stone. The central arch with span of 22.72 m and raise of 7.58 m, the lateral arches will have span of 13.63 m and raise of 5.05 m. This means that the ratio raise/span equals 1/3 for the central arch and 1/2,7 for the lateral arches (the metrical units used in the "Chapters" is "Como arm", whose length is equal to 0,505 m and "ounce" whose length is equal to 1/12 "arm" = 0,042 m.

It is interesting to compare these dimensions with the ones which can be found in the “Four books of architecture” (Palladio, 1570), that carry us back to the Bassano bridge: in book III chapter. XIIII, the table of “another bridge of my invention” is shown. This bridge is not well identified but, due to its dimensions, it can be hypothesized it refers to the first plan for a stone bridge in Bassano, as referred to in the previous chapter. 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 (in this case the metrical unit used is the "Vicenza foot" that equals 35,5 cm), the same as foreseen by Ferrari in his “Chapters”.

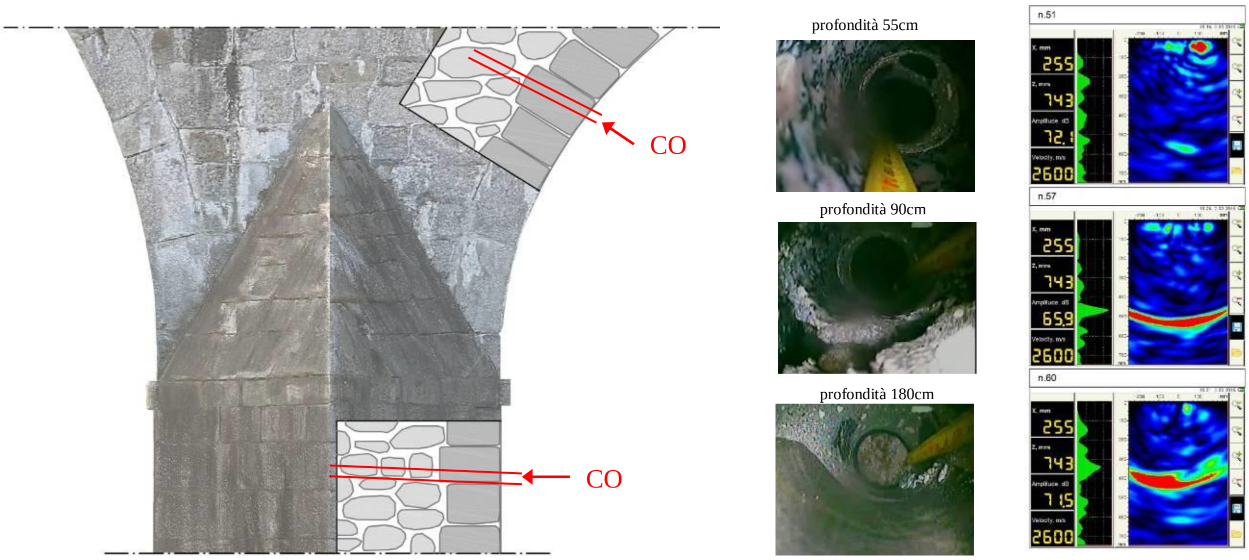

Fig. 7 a pile as prescribed in the "Chapters"; images coming from coring holes inspected with endoscopic video camera and tomographies on the outer stone layer

Current dimensions of Ganda bridge are highly similar to those specified in the "Chapters", excepting the differences already 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 having in mind 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 "old" 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 structures.

Current structural calculations show the 1/3 ratio, as defined in the “Chapters”, as the most efficient still reproducing the original project specifications; the stability of 1/2.48 arch requires the structural contribution of pile infilling material.

At the end of his description of the stone "bridge of my invention" 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 the Ganda Bridge, the voussoirs are equal to the thickness of the arch, while Palladio’s structures saw external moulding probably with a mainly decorative function and not corresponding to structural thickness.

In the “Chapters”, a thickness at keystone of 63 cm is recommended, as it is the thickness of the voussoirs; arches had to be constructed of natural stone and reinforced with 17 iron bars as long as the width of the bridge. Infill had to be made with masonry, raising the abutments and buttresses using squared cut stone connecting the crown of the vaults to the height of the wings.

For the current bridge arch masonry is made of stone blocks that, for the voussoirs, have a uniform thickness of 55/60 cm (less than the dimension requested on the project specifications). Surveys show 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 are of different origin (including metamorphic) and smaller size (20-30 cm). This complies with the "Chapters" description that states that “in the infilling of arches irregular and river stone may be used, as long as they are of sufficient size".

4.4. Wood (of Bassano bridge)

The inspection has allowed us to detect the details of the structural carpentry of Bassano bridge, but also to identify the strengthening techniques applied in recent years. It was also possible to observe the different procedures used in 1990 for the reconstruction of the resistant section where damaged: generally, the poles have been infilled at the centreline by positioning a grid of fibre-resin bars and then casting a conglomerate resin mixed with sand. It has been observed that in some cases this cast has not been completed. The larger cracks have been sealed with injections of resin and their surfaces have been protected with several layers of red coating, also in order to make their aspect uniform.

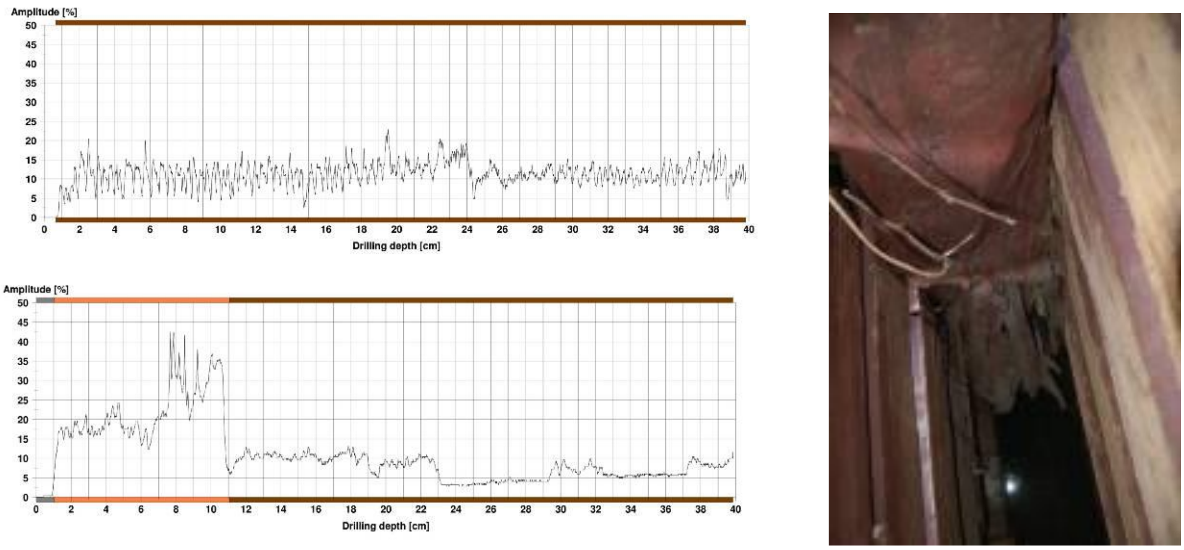

Fig. 8 drilling tests at lower and higher level of the structure,
evidence of the decay of the wooden section at the base of the poles

Almost all the wooden poles are cracked at the centreline, perhaps because of the holes drilled to insert the threaded bars connecting the planks. Systematically within these cracks, extensive decay phenomena have developed, generally connected to the growth of wood rot. It was also noted that where the past reinforcement with cast resin has been employed, detachment between the resin and the wood at contact edges has occurred. Presumably, this phenomenon is consequent to the cyclic wet-dry expansions due to changes in the water plane of river. These slots result in a preferential trend of wood rot penetration, thus causing the growth of the decay phenomena. In correspondence with the second pier it was also possible to observe the complete decay of the lower part of the poles within the planks (Fig. 8).

In order to analyze the elements for which signs of deterioration are not visible, the inspection has been integrated with instrumental techniques. Tests found significantly different values of drill resistance between the timber put in place at higher level and the one that is directly affected by variations of water level (Fig. 8).

The identification of wood samples was finally carried out using dichotomous record cards: the trusses are made of deciduous oak (presumably durmast) for the poles and coniferous wood (larix decidua) for the struts.

4.5. Differential settlements (of Bassano bridge)

In spite of the many interventions previously described that have occurred over the last century, Bassano bridge at the time of the inspection, presented signs of major settlement that caused concern for its structural safety. They were mainly highlighted by the deformations of the piers (Fig. 9) and by the out of plane of the road deck.

Relevant information taken from the laser-scanner survey was returned in vectorial form drawing plans, elevations and sections sketches of the structure. The data obtained by the point cloud, however, also provided significant diagnostic data, allowing the analysis of the cracking and deformation pattern of structural elements.

The survey carried out on Bassano Bridge thus enables us to highlight some significant deformations that, on the basis of reasonable assumptions, could be correlated to the overall failures of the structure throughout its history.

Fig. 9 the loss of horizontality of the planks of second pole shows the settlements of the poles

The geometrical irregularities detected in the deck and in the piers allow for identification of the overall deformation in the vertical direction.

The deformations of the roadway are evident to the naked eye and it is reasonable to assume that they developed after the placement of the pavement, which occurred in 1992. Their measurement gets the current outline of deformation at the extrados of the bridge's deck. Feedback can also be sought by observing the strong deflection of the planks covering the piers. In this case too, it is reasonable to assume that in 1990-1991 works the planks were put in place with a proper horizontal alignment, so their current geometrical irregularities indicate absolute settlements suffered by the structure after that date. In fact, the measures thus obtained on the deck and on the piers converge satisfactorily providing a reasonable estimate of the very relevant absolute failures of the structure, with maximum values of 35 cm for the second pier.

A similar consideration, although intrinsically less precise, has been carried out regarding the alignments at the intrados of the deck, measuring the differences between the supports of the load-bearing wooden beams. These measurements may be correlated to the total settlement of the bridge that has developed since its building (assuming that the beams were originally set in place with reasonable alignment). The measures thus obtained are systematically larger than the previous ones, highlighting that relevant failures have affected the bridge since its construction, but also indicating that the extent of displacement occurring after the work of 1990-1992 is certainly significant when compared to the global historical settlements.

Specific inflections of the load-bearing beams of the deck were also measured from the intrados of the beams. These measurements, carried out span by span along three alignments, have drawn attention to the fact that in some cases this local inflection assumes high values, locally up to 25 cm (1/50 of the beam span) in the middle of the second span.

The bridge has an overall downstream inflection, presumably due to the damage that it suffered during past flooding events. Horizontal deformations were measured once again on the extrados, along the joints of the pavement, and the intrados along the edge of some of the deck beams. Again in this case, relevant deformation (19-21 cm) of the second pier was recorded, larger for the beams than for the pavement for the same reasons as mentioned before.

The surveys carried out showed that the overall deformation of the structure, especially that which has developed in recent years, is extremely relevant: the causes of this deformation were identified with the correct evaluation of the state of degradation of the structural wooden elements, as already described.

4.6. Monitoring (of Bassano bridge)

The considerations taken from the survey suggested going on with the activation of structural monitoring for checking the evolution of the detected settlements. This monitoring was carried out for the first period with a periodic repetition of the laser scans, to check the measurements of some key-points placed along the alignments tracked on the pavement. Then, following the decision to remove the pavement, a number of key-points (topographic targets consisting of flat prisms) were placed on the columns of the cover; their position was monitored with reference to the position of topographic targets placed on the walls of the entry lobby of the bridge, assumed to be fixed and used as the reference for the self-centring of the instrument.

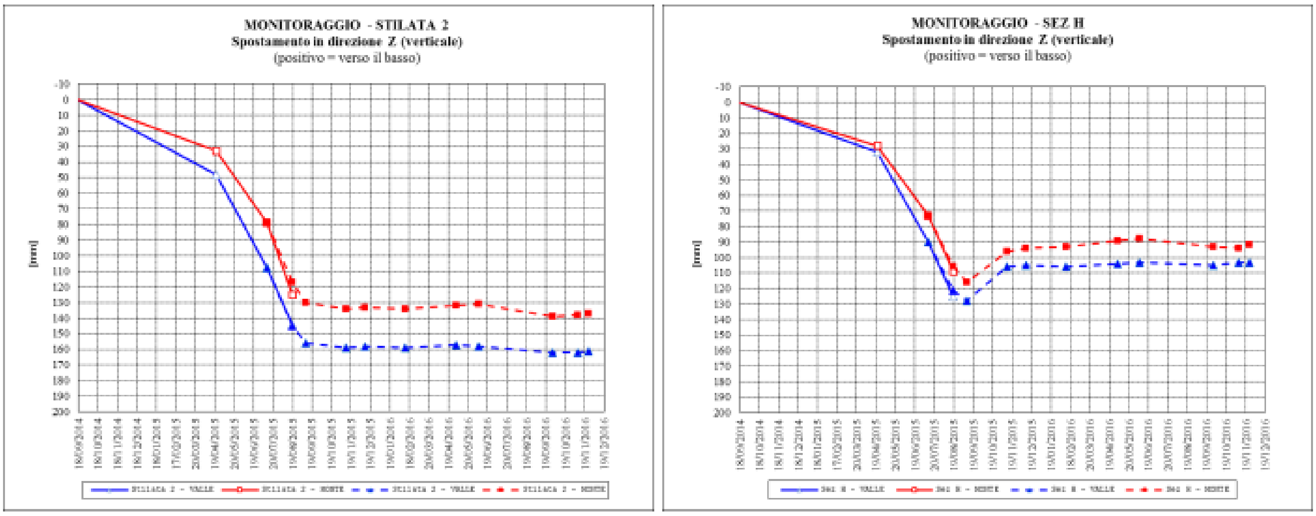

Fig. 10 monitoring diagrams

The measurements were performed though a "topographic total station" Leica TCRA 1201 with precision 1" that allows detection displacement of the target in three orthogonal directions. From the diagrams in Fig. 10, it is evident that the monitoring data immediately highlighted serious settlements: in the first period it proved to be in incremental evolution, with settlements up to 15 cm over 12 months at the second pier. This situation suggested proceeding immediately with the execution of urgent works to guarantee the safety of the bridge, starting from the removal of the heavy stone pavements on the deck.

This intervention was carried out during winter 2015 and it allowed to considerably reduce the dead load on the deck, to stop the settlements of the bridge, as confirmed from the diagrams of fig. 10: in same case, as resulting from section B, the deformations following the intervention proved to have the opposite position (upward) than the previous ones due to the elastic recovery of the deformation of the wooden beams of the deck, when lightened by the significant load of the superposed pavement.

4.7. Seismic Safety Assessment (of Ganda bridge)

As already stated, the 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 identification of relevant geometric and structural information.

In the case of the Ganda bridge, the exhaustive path of knowledge provided a complete historical-critical analysis of the construction phases, the survey of crack and deformation pattern; the diagnostic activities allowed furthermore to obtain the structural identification of the construction, of its details and of its foundations. The diagnostic campaign performed took on a Factor of Confidence FC = 1.18. On the basis of the geometry surveyed, it was then possible to model the structure so as to carry out the structural analysis required both to assess the eligibility of the bridge to meet the load conditions in compliance with the codes and to assess its seismic vulnerability. The structural analysis were carried out both with the static and the seismic conditions, performing for each arch, the limit analysis (Heyman, 1966) and then the analysis of the out of plane behaviour of the macro-elements in compliance with D.P.C.M. 09/02/2011.

Limit analysis was performed with 2D models (Fig. 11), defined by limiting the arc only to the sector subtended by the span that guarantees the aforementioned ratio 1/3, so as to produce the maximum structural effectiveness of the arc itself; this is supported by the results of the tests, that show the substantial compactness and homogeneity of the arch spring on the abutments.

Macro-elements analysis was performed with a 3D model (Fig. 11) representing the global spatial structure and considering the out of plane interaction between the different structural elements; they were modelled along their baricentric line though macro-elements, using geometrical and mechanical properties provided by the structural analysis.

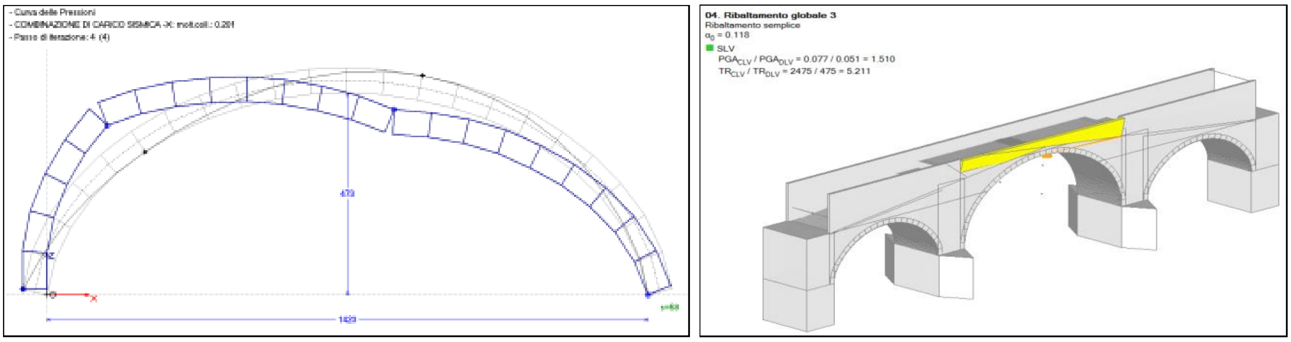

Fig. 11 2D model – kinematic analysis;
3D model – macro-element analysis ifor seismic risk factor evaluation

With these models, arcs were first analyzed recursively, evaluating each single load combination and increasing all the variable loads to determine the maximum applicable values; as a result the bridge was classed to be suitable to support the loads defined by the current technical standards (D.M. 14/01/2008) for a 3rd category bridge (a pedestrian walkway); with this classification it has been then tested both for static and for seismic conditions.

Seismic analysis of each arc was carried out using the kinematic approach to define the collapse configurations of the arcs and the seismic risk indicators associated with them; each arc was compliant with the requirements of the standard. The further verification of the collapse mechanism was carried out. This analysis highlighted the structural elements (macro-elements) sensitive to out of plane structural behaviour: each significant local collapse mechanism was examined, and also in this condition the results assessed the adequacy of the bridge.

It has to be noted that, while the analysis are positive if referred to the stability (fundamental element) and to the friction, the compression strength values used for the masonry do not reach a good index. However these values were taken from the tables of the codes, that proved to be highly conservative (Foppoli, 2016) especially if referred to regular and compact texture masonry like that of the Ganda Bridge. In this case, it is therefore advisable to deepen the level of analysis through specific tests to determine the effective strength of the masonry; subsequently to reformulate the evaluation in a more precise way on the basis of the data thus obtained.

5. CONCLUSIONS

The approach to the analysis of the structural problems and deficiencies of the two analyzed bridges was possible through the path of knowledge prescribed by Italian legislation. Since the bridges analyzed are historical, and therefore made with techniques not completely known, it was necessary to combine the proper technique activities with the study of the historical evolution of the constructions, an operation which proved to be essential in reaching a proper understanding of the artefacts.

Diagnostic investigation has then allowed the global analysis of the structures (geometry, crack patterns, deformation and settlements) and the analysis of each single structural element (pile, shoulder, deck). In the paper, diagnostic investigation techniques have been exemplified which are useful for characterizing different materials: the wood of the poles and of the deck, the brickwork of the shoulders and the stone masonry of the piles and of the arches. They have proved to be essential tools in order to identify the structural problems of the two analyzed bridges. Data obtained from the surveys and from the diagnosis has also led to an overall evaluation, in order to define the safety level of the bridges both in the static and in the seismic field.

Furthermore, the monitoring carried out has proved to be an essential activity for the safety of the bridge as it led to immediate and urgent interventions when the structure gave clear signals of differential settlement development at a progressively increasing speed. The diagnostic operations were performed through positioning techniques with ropes, that in these cases have proved to be efficient and cost effective methodologies as well as the only applicable because of the serious problems of stability suffered by the structures and of the impossibility of access to the bridges through Movable Work Platforms.

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