Inspection of Palladio's Bridge in Bassano del Grappa, Italy, using positioning techniques by ropes

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Abstract

The old bridge across the Brenta River in Bassano del Grappa (Italy) is documented since 1209; the current bridge was built by Andrea Palladio in 1569 and it is described in a table of his treatise "The Four Books of Architecture". The structure was repaired many times because of river floods and damages caused by war, but the one that is admired today is essentially the same bridge designed by the famous architect. The structure is a 5 span truss bridge, made entirely with wooden framework. In recent years significant deformations of the deck have caused concerns about its stability. In 2014 the bridge was subjected to a thorough diagnostic campaign to assess its structural conditions. An accurate survey using laser scanning provided the precise measurement of subsidence and deformation of the current structure, which were recognized as very relevant. To carry out the consequent inspection, it was necessary to have direct access to the structural elements with positioning techniques by ropes. In this way excessive overload to the already damaged bridge and limitations to the passage on the roadway were avoided. This technique also provided an economic saving for the municipality. The direct inspection has allowed close observation of the wooden trusses in order to detect sections, construction details and reinforcing elements (plates, bolts, tie rods). The visual inspection of all structural elements has provided the preliminary survey of the state of degradation of the wood, and additional direct tests were performed by a mechanical drilling instrument (Resistograph). To complete the analysis micro-sampling and macroscopic analysis allowed the identification of the species of wood.
Keywords: timber bridge, laser-scanner, drill resistance.

WIT Transactions on The Built Environment, Vol 153, © 2015 WIT Press
www.witpress.com, ISSN 1743-3509 (on-line)
doi:10.2495/STR150621

1 Introduction

The current legislation concerning the structural assessment of Italian cultural heritage [1] 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 researches 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 an adequate knowledge of it by following these steps:

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

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 its history has been an experiment in real scale and that the cracks, distortions and states of stress in the structure will represent the results of this experiment; their measurement allows for a model as close as possible to the real behaviour of the building, and appropriate for carrying out an 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 (Foppoli and Armanasco [2]).

1.1 Description of the old bridge of Bassano

The old bridge of Bassano del Grappa (in Italy) is placed along the Brenta River that flows through the city from north to south. The structure has an overall length of 65 m and a width of 8.5 m; it is composed of 5 spans resting on two masonry abutments and on 4 piers sunk in the riverbed (Fig. 1). Each pier is made of 8 poles of equal length, arranged with equal spacing to support the deck, and six additional poles in decreasing lengths arranged both upstream and downstream to form the spurs. The poles are joined at their top by a cross beam. The deck is then supported by 8 beams arranged longitudinally to the bridge; their span length has been reduced with the interposition of cantilevers between the poles and the beams, and with the placement of other beams that act as struts, sloping close to the poles and horizontal at the centerline. The same poles are connected with wooden elements inserted between them, and opposed externally with a couple of tie rods anchored with plates in correspondence with the first and last pole. The spurs are superiorly protected by a watershed: in the upstream spur a sloping beam connects the head of the poles and is coupled with a pair of tie rods, anchored at the piles placed in the riverbed just upstream from the spur itself.

Figure 1: View of the old bridge of Bassano del Grappa from downstream.

The lower part of the poles is banded with planks with a thickness of 10 cm and width of 17 cm, set in place with a medium wheelbase of 25 cm. In the direction of their length these planks are therefore not in contact with each other, consequently performing only a limited stiffening function in their plane. In correspondence with the planks, the poles have been trimmed on both sides, reducing its width to 30 cm: the thickness of the piers is therefore 50 cm. The planks are connected to the poles by threaded bars inserted in holes drilled in correspondence with the centerline of the poles themselves.

As seen in Fig. 3 in the riverbed at the base of the poles supporting the deck, another cross beam is placed which connects the poles and is supported by wooden crosspieces supported partially by wooden piles and partially by reinforced concrete piles placed during the last consolidation works.

1.2 Structural problems and investigations carried out

The history of the bridge of Bassano tells us of the many destructions occurred either due to floods – in 1450, in 1526, in 1567, in 1748 – or because of wars – in 1511, in 1813, but also tells us of many reconstructions, and frequent maintenance.

Despite several successive interventions which occurred in this century, in recent years the bridge showed significant signs of settlement made evident by the deformation of the piers and by the loss of flatness of the pavement, which caused apprehension about the structural safety of the bridge. In 2014, the Bassano municipality therefore decided to conduct the survey and a thorough inspection of the state of conservation of the structure and timber thereof, and to evaluate the assessment of the structural safety of the bridge.

One of the preliminary operating problems was to define the way of access to the supporting structure of the bridge, in order to carry out the direct inspection. Ordinary techniques of access by mechanical equipment were not appropriate because of the weight of any platform, (which would be an overload on the already damaged structure), and because of the restriction to the manoeuvring arm due to the presence of the roof of the bridge. Moreover, the municipality didn't want to carry out operations which caused significant trouble to the flow of tourists who visit the bridge daily. For these reasons, the operative choice was to work with access and positioning techniques by ropes: in this way engineers and technicians were able to work in accordance with the current Italian legislation on safety at work [3].

This operative technique proved to be expeditious and allowed easy operability for works performed at various levels of the structure, also providing a significant economic savings for the municipality.

2 Interpretation of the historical evolution

2.1 Story of the bridge

The first information concerning the existence of a bridge in Bassano came from documents of the years 1209–1227: the bridge connected the two settlements of Bassano and Angarano, situated on the opposite banks of the Brenta River and had definitely a strategic and commercial importance because of the position of Bassano at the foot of the Alps, where the Brenta valley flows into the Venetian plain.

In the medieval period, Bassano was continually involved in the struggles between Vicenza, Padua and Milan, until in 1404, when the town entered in the sphere of Venetian influence. Numerous maintenance or reconstruction works of the bridge are documented in the first half of the XV century. Documents confirming the deterioration of the structure are frequent, and following the collapse caused by a flood in 1450, a reconstruction campaign was undertaken and lasted three years (Sbordone and Pilati [5]).

However, already in 1493 the bridge was damaged again; the new refurbishment of the bridge was finished in 1498. In 1511 the French and imperial troops burned the bridge; in 1524 the construction of a stone bridge began but, despite expectations, it fell during a flood two years after its completion, and so it was rebuilt using a timber structure in 1531 (Berti [6]).

This bridge was again destroyed by a flood in 1567. The reconstruction project was commissioned to Andrea Palladio, 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 again a timber bridge. The bridge designed by Palladio is represented and described in a table (Fig. 2) of his famous treatise "The Four Books of Architecture", Book III, Chap. IX.

During the XVII century documentation exists of the execution of periodic routine maintenance works; 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. The rebuilt structure was frequently subjected to subsequent maintenance works, until, during the Napoleonic Wars of 1809–1813, it was

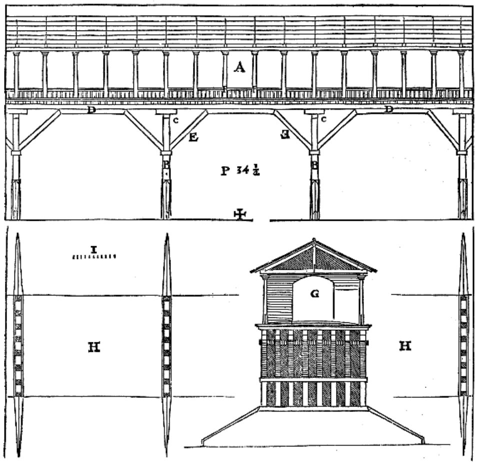

Figure 2: Table from Palladio [4] that represents the bridge of Bassano.

burned again for strategic purposes: the bridge was rebuilt only eight years after. The structure suffered other damages during the recurring floods of the XIX century.

The old bridge of Bassano was significant even in war events of World War I when Bassano was the immediate backline of the Alpine front on the Grappa Mountain and the bridge itself was damaged. During World War II a bombing destroyed the new bridge that was placed a few hundred meters downstream along the Brenta River and the old bridge was even sabotaged by the partisans, and partially destroyed. At the end of the war, the bridge was once again repaired and reinaugurated in 1948.

2.2 Interventions over the last 50 years

The last destructive flood took place in 1966, when the bridge was seriously damaged curving downstream because of the thrust of the water and again requiring important works of repair. It was reinforced by anchoring it to four large diameter piles, made immediately upstream of each spur. Subsequently, in the years 1980–1983, important works of maintenance were again performed.

The inspections carried out in 1990, however, highlighted again the bad conservation status at the bottom of the poles and their tendency to undermine the foundations. The decay of the timber of many structural elements, made even more precarious the general structural condition.

An urgent intervention was made in consolidating the foundations and drilling for each pier four couples of reinforced concrete piles, with a reinforced concrete capital on the top, on which 4 wooden crosspieces were supported to sustain the transversal beam at the base of the poles (Fig. 3).

The wooden structure was consolidated maintaining the existing elements, eliminating the decayed parts and restoring sections with casts of conglomerate resin mixed with quartz sands.

Figure 3: Cross beam at the base of the poles during the last restoration works.

The timber was finally impregnated with products against woodworm and coloured with linseed oil with oxides that provide a covering pigmentation. At the end of the intervention the pavement was reconstructed with stone slabs in accordance with the available historical information.

3 Geometrical survey and structural identification

3.1 Laser-scanner survey and relief of construction details

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 number of redundant data, usable for subsequent structural evaluation.

For the execution of the three-dimensional scans, the scanner HDS 7000 (Leica) was used. By measuring the distance time of the laser pulses, this scanner is able to determine a spatial cloud of 106 points per second with an accuracy of +/- 1 mm and a range from 1 m to 50 m.

Overall, 20 scans near the bridge were performed, as well as 10 scans from points outside the bridge, along the river banks. To allow the execution of the intrados scans of the bridge's spans, the positioning of the instrument was carried out using a specially designed extendable arm. Each scan was correlated and geo-referenced to describe the object in its details and in its complexity, creating a single model of point clouds (Fig. 4) with the use of the program Cyclone (Leica). For geo-referencing calculation, this program makes use of both topographic targets and the analysis of superposition surfaces, thus ensuring a more accurate correlation of the various scanning.

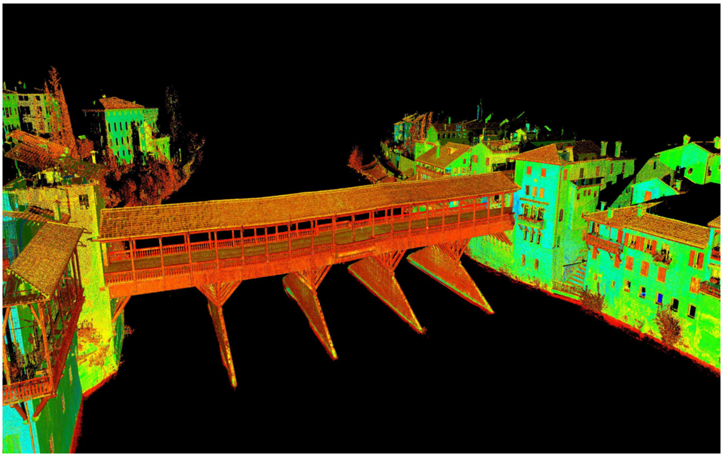

Figure 4: The point cloud obtained by laser-scanner survey.

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

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 point cloud. The detection of the details through direct measurement was necessary for the partial identification of the structural behaviour. Furthermore, the details of the connections were surveyed between the various timber elements as well as the details of the reinforcements made with metallic elements such as brackets, plates and cramps. The stratigraphy of the pavement was finally reconstructed in correspondence with two inspections made in the pavement of the roadway.

3.2 Deformation pattern gathered from geometrical survey

Relevant information was returned in vectorial form making plans, elevations and sections of the structure. The data obtained by the point cloud, however, can also provide significant diagnostic data on the basis of observation and comparison of the cracking and deformation pattern of structural elements.

The true potential of laser-scanner survey lies in the great redundancy of information acquired: geometrical measurements, (for example, leanings, inflexions, deformations), can thus be extracted and correlated in the next phase of data analysis without the need to have a prior definition of the variables to detect, but selecting them subsequently, and even better, choosing them in progress on the basis of the available indications.

The survey carried out thus enables one 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.

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 at eyesight and it is reasonable to assume that they have developed after the placement of the pavement, which occurred in 1992. Their measure allows getting the current outline of deformation at the intrados 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 the planks have been put in place with a proper horizontal alignment, so their actual geometrical irregularities indicate absolute settlements suffered by the structure after that date. In fact, the measures thus obtained converge satisfactorily providing a reasonable estimate of the absolute failures of the structure, which are very relevant, with maximum values of 35–41 cm for the 2nd pier.

A similar consideration, although intrinsically less precise, has been carried out regarding the alignments at the intrados, measuring the differences between the supports of the current beams of the deck. These measurements may be correlated to the total settlement of the bridge that 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 the fact that relevant failures have affected the bridge since its creation, but also indicating that the extent of displacement occurring after the work of 1990–1992 is absolutely significant when compared to the historical settlements.

With regard to the structure of the deck, inflections were also measured from the intrados of the current beams. These measurements, carried out span by span along three alignments, have drawn attention to the fact that in some cases the inflections assume high values, locally up to 25 cm (1/50 of the span) in the middle of the 2nd span.

The bridge has an overall downstream inflection, presumably in consequence of the damages 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. Also in this case, a relevant deformation (19–21 cm) of the 2nd 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 deformations of the structure, especially those that have developed in recent years, are extremely relevant: the subsequent diagnostic survey allowed investigating the causes of these deformations with a punctual evaluation of the state of degradation of the structural elements.

4 Mechanical properties of materials and their decay

4.1 Assessment of the conservation status of timber structures

The inspection carried out with access and positioning techniques by ropes, (Fig. 5 on the left), has allowed the close-up view of the structural elements, particularly at the critical points. It's important to note that all structural timbers of the 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.

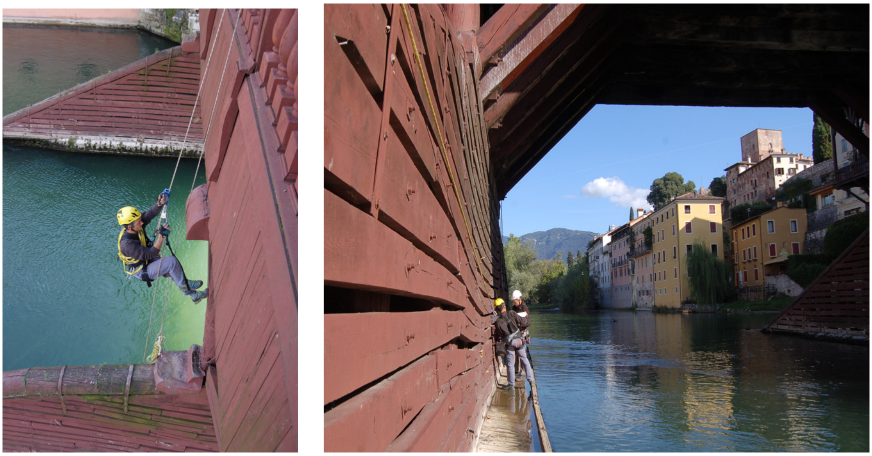

Figure 5: Inspection performed by ropes and measurement of drill resistance.

Where signs of deterioration such as cracks, fissures, torsions, wood rot and holes of xylophages insects were found, the visual investigation 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 (Rinn [7]), in order to locate and quantify regions of internal decay on timber elements (Fig. 5 on the right).

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.

The Resistograph profile (Fig. 7) plots in abscissa the depth of drilling and in ordinate the drill resistance which can be correlated, with a good approximation, to the density of the wood (Rinn [8]). The density profile produced by the instrument therefore allows measuring the density variations: the wood 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 and the strengthening materials used, some samples were also taken for laboratory analysis. The timber samples were collected using the Pressler auger, which was screwed into the trunk perpendicular to the growth rings and allowed to extract a little barrel of wood in diam. 4–5 mm; samplings of consolidating materials were taken with a chisel.

4.2 Data from the inspection of timber structures

The inspection has allowed us to detect the details of the structural carpentry, but also to identify the strengthening techniques applied in the recent past. In particular we have identified the following consolidation methods:

- some of the poles that support the deck were consolidated by coupling them with two structural steel profiles C300, thickness 10 mm, connected to each other with threaded rods diam.18 mm;
- some of the poles of the spurs were consolidated by coupling them with two wooden planks, section 10x30 cm, connected to each other by steel brackets.

It was also possible to observe the different procedures used for the reconstruction of the resistant section where damaged: generally the pole has been emptied at the centerline 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.

Almost all the elements are cracked at the centerline, 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 formation of wood rot. It was also noted that where the past reinforcement with casted resin has been employed, separation and detachment between the resin and the wood at points of contact has occurred. Presumably, this phenomena is consequent to the cyclic wet-dry expansions due to changes in the level of river. These slots result in a preferential way of wood rot penetration, thus causing the incremental increase of the decay phenomena (Fig. 6 on the left). In correspondence of the 2nd pier it was also possible to photograph within the planks and therefore observe the complete decay of the lower part of the poles, (Fig. 6 on the right).

The close inspection allowed mapping and analysis of degradation phenomena, which have been rendered by photographic documentation and in synoptic tables that document the photo references, the geometry and the mapping of the strengthening interventions carried out in the past.

In order to analyze the elements for which plain 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 (Fig. 7 on the left above), and the one that is directly affected by variations of water level (Fig. 7 on the left below).

The identification of wood samples (Fig. 7 on the right) was finally carried out using dichotomous record cards allowing for the identification of the timber used in the structure, among coniferous wood (*larix decidua*) with which the struts are made, and deciduous oak (presumably durmast) with which poles are made.

Figure 6: Decay phenomena at the contact between wood and resin casts and at the base of some poles.

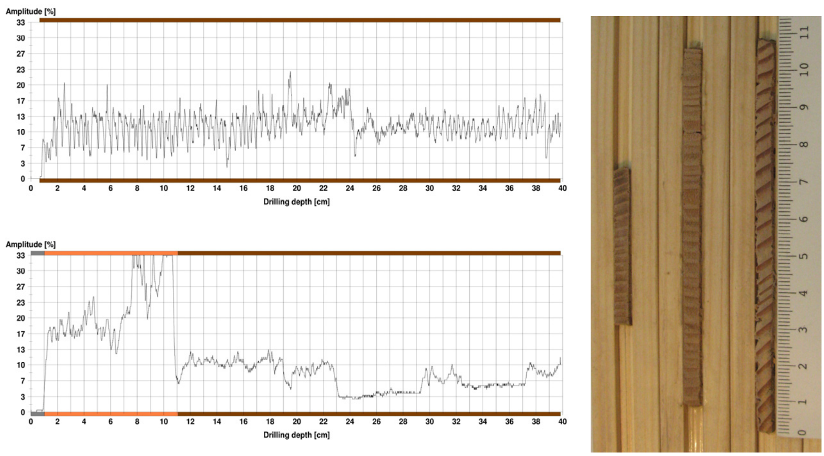

Figure 7: Drilling tests at lower and higher level of the structure, macroscopic observation of the section of wood samples.

5 Conclusions

The survey carried out allowed characterizing the conditions of deformation and the state of preservation of the old timber bridge of Bassano del Grappa. For the execution of this investigation, the availability of engineers and technicians that were able to perform the inspection using access and positioning techniques by ropes has been essential.

The survey with the laser-scanner technique has provided the measurements of current (relevant) settlements of the structure: it was possible to estimate the historical and the actual deformations, as well as to assess their effects. The thorough inspection, then, allowed for obtainment of evidence of documentary information regarding the structural identification, the observation of the building details of the structure in its original conception, and the recent interventions (with their positive and negative effects). It also allowed for the acquisition of accurate information about the state of the overall degradation.

Acknowledgements

The author would like to thank the Bassano Municipality, especially the Municipal Technical Department for the pictures and information provided for the present paper and professor Claudio Modena from Padova University for having suggested the present inspection activity.

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