From Palladio to Reinforced Concrete: NDT Applied to the Old and the New Bridge of Bassano del Grappa

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Abstract

An NDT campaign was performed in 2014 to assess the structural conditions of the two bridges over the river Brenta in Bassano del Grappa, Italy. A major problem in the execution of these inspection activities was related to the access to the structures: the investigation was therefore carried out with the use of ropes as positioning and access devices: engineers and technicians were able to make the inspection and to reach the test points without restrictions for traffic and moreover with effective cost savings for the client.

The old timber bridge, designed by Andrea Palladio in 1569, was carefully analysed by laser-scanning survey that provided detailed information about its current deformation pattern. The visual inspection of all the structural members was accomplished through the assessment of the state of deterioration of the wooden trusses; direct tests on wooden elements were performed by mechanical drilling instrument, and micro-sampling and macroscopic analysis allowed the identification of the species of wood. To complete the analysis drillings, corings, video surveys and flat jack tests were performed on the masonry of the abutments.

The new bridge, a reinforced concrete structure built in 1917, was analysed to detect its current state of deterioration related with the effects of the carbonation. A detailed visual inspection was carried out; NDTs were then performed by covermeter for the assessment of the thickness of the cover and of the dimensions of the reinforcement bars, with phenolphthalein for the detection of the carbonation depth, and with ultrasonic pulse measurements to detect both the weaves velocity and the cross section homogeneity (with tomographic methods). The large amount of data collected, processed with statistical methods, and the combination of different NDT provided complete diagnostic indications.

Keywords

wooden trusses, masonry, reinforced concrete, bridge inspection, access by ropes

1. Introduction

The two bridges over the river Brenta in Bassano del Grappa, Italy are the only two crossing points of the river within the urban area. That's why both bridges are essential for the city: the old bridge for pedestrian traffic and as an important touristic attraction and the new bridge as the only vehicular link between the two river banks. Their shape is completely different (Fig. 1): the old bridge is a medieval timber structure which has still survived in its original form; the new bridge is a double arch reinforced concrete structure built at the beginning of the 20th century. Their study is particularly interesting due to the peculiarity of the deterioration problems of the two structures which require different analytical techniques and raise specific organizational problems.

One of the main operational aspects was finding the best way to access the bearing structure of the bridges to enable visual inspection and reach the test points. Access techniques by mechanical devices were not suitable in either case for different reasons. Regarding the old bridge, the weight of the required platform would have overloaded the already damaged structure, the roof of the bridge would have restricted the maneuvering arm and finally the operation would have bothered the considerable number of tourists visiting the bridge every day. Regarding the new bridge, the dimensions of the platform would have narrowed the road with the consequent restriction to the vehicular traffic while carrying out the tests.

For these reasons, rope access and positioning techniques (Fig.4) were regarded as the best options. This way, specially qualified engineers and technicians were able to work in compliance with current Italian Health & Safety legislation [2]. This technique proved to be quicker and it allowed the work at the various levels to be more easily carried out; finally, this led to significant cost savings for the client.

2. Bassano and its two bridges

Bassano del Grappa is located at the foot of the Alps, where the Brenta Valley runs onto the plain of the Veneto region, a very important position for military and commercial control of the area. The first records regarding the existence of a bridge connecting the two settlements of Bassano and Angarano (located respectively on the opposite banks of the river Brenta) are found in some chronicles and Papal bulls dated 1209-1227. Since then there is substantial archive documentation mentioning the bridge. The history of the old Bassano bridge records the bridge being destroyed either by river floods in 1450, 1526, 1567 and 1748, and wars in 1511, 1813 and 1945, but also of being reconstructed and frequently repaired.
One of the key moments in the history of the bridge was the devastating flood of 1567 which caused its destruction. The famous architect Andrea Palladio was commissioned to reconstruct the bridge. Initially he proposed a stone bridge, but was then forced to review his plan by Bassano City Council, finally rebuilding a timber bridge again. The bridge designed by Palladio is described and depicted in a plate of his famous treatise *The Four Books of Architecture* (Fig. 1), which clearly shows that what we admire today is essentially the bridge built according to the original design of the famous architect.

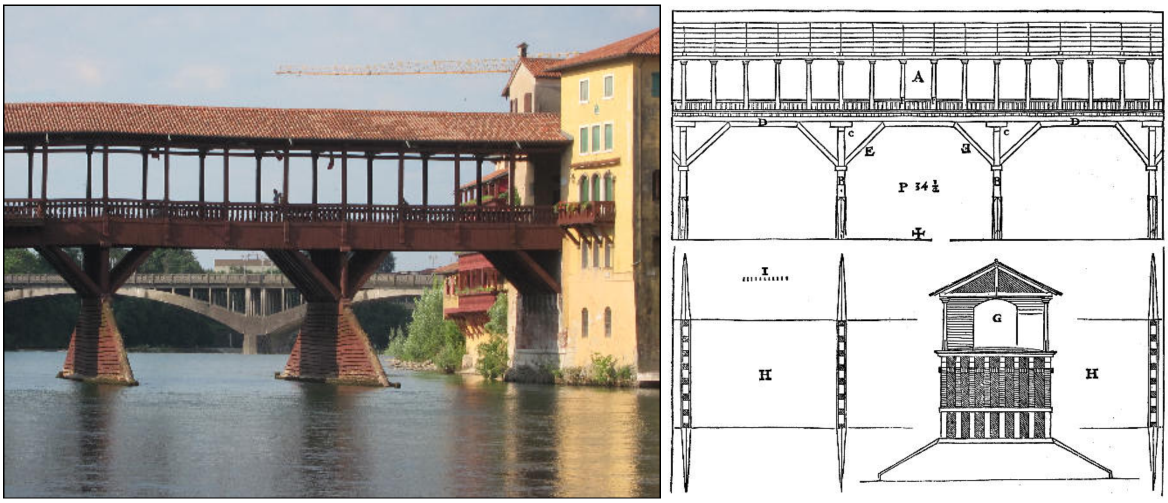

Figure 1: The two bridges of Bassano; plate from [3] Book III Ch. IX depicting the Bassano bridge

After an intense debate which developed at the end of the 19th century, the new bridge of Bassano del Grappa was built essentially for military purposes during WWI, when the city was the zone behind the alpine frontline. During WWII the new bridge was shelled several times and completely destroyed and was rebuilt in 1948 in a very similar form to the original (in the same period also the old bridge was partially destroyed for strategic reasons).

3. The Old Bridge (Alpini Bridge)

The Alpini bridge, entirely made of timber, is 65m long and 8.5m wide and consists of 5 spans resting on two masonry abutments and on 4 piers sunk into the river bed. Each pier consists of 8 poles of equal length, arranged equally spaced to support the deck, and 6 additional poles in decreasing lengths located either upstream and downstream to form the spurs. The deck is then supported by 8 beams placed longitudinally to the bridge with a 100-110cm spacing. Their span has been reduced by inserting cantilevers between the poles and the beams, and by laying other beams acting as struts sloping on the piers and horizontal to the centre line.

Despite several maintenance and refurbishing interventions during this century, in the last few years the bridge has shown significant signs of settlement, as clearly indicated by pier and roadway deformations, causing concerns regarding the structural safety of the bridge and suggesting the need to carry out a detailed assessment of its condition.

3.1 Surveys and Result Processing

A general survey of the structure was carried out by laser-scanning technique, 3D scans were obtained using a HDS7000 Leica Geosystems scanner which, by measuring the travel time of laser pulses, allows the determination of a 10^6 dot/s space cloud with +/- 1mm accuracy within a 1m-50m range. By correlating and georeferencing the single scans to describe the object in its details and complexity a single point cloud sample was generated (Fig. 2). Restitution and vectorization were then performed by Autocad applications, allowing dividing or skimming of the whole point cloud according to the sections chosen for vectorization. This operation was essential in order to manage the sample more easily.

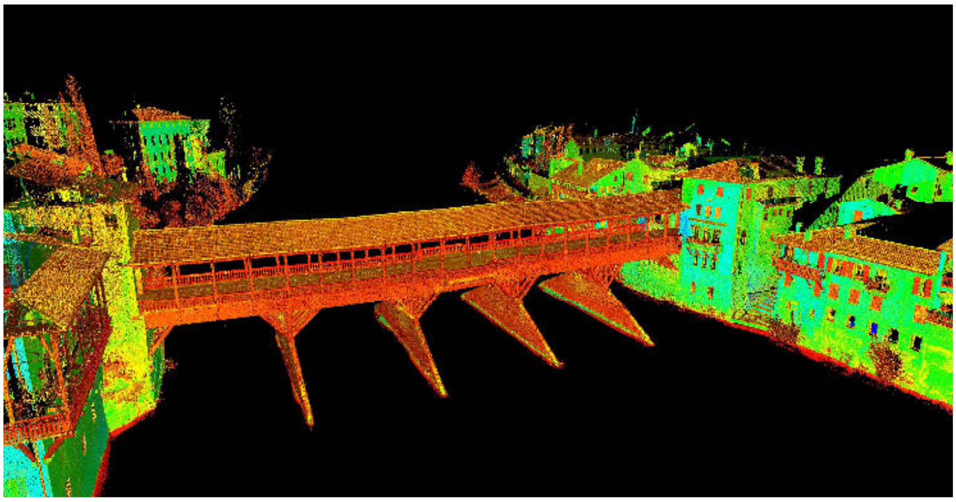

Figure 2: Image of the point cloud obtained by laser-scanner

Geometric irregularities found in both deck and piers have allowed the vertical overall deformations to be traced. Deformations of the existing paving are visually clear and it is reasonable to think that they developed after the last refurbishment in 1992. Their measurement has allowed an estimation of the current deformation pattern at the extrados of the deck, which can also be confirmed by the way the piers planks have deflected. In this case too, it is reasonable to assume that originally (in 1990-1991) the planks were laid with horizontal level, and the detected geometric irregularities are therefore indications of absolute settlement of the piers after this date. In fact, the sets of measurements converge, providing a reasonable estimate of the absolute settlement of the structure, with maximum displacements of 35-41cm at the extrados of the 2nd pier.

The surveys carried out have altogether highlighted how extremely significant the deformations of the structure are, especially those which have developed in the last few years. The following diagnostic campaign allowed a further investigation into the causes of such deformations, making an accurate assessment of the degree of deterioration of the structural members. Given the extent of the settlement and in order to monitor its evolution, further laser-scanning surveys of the roadway were then periodically repeated.

3.2 Analysis on Timber Structures

The inspection by rope access and positioning techniques allowed a close visual examination of the structural members, particularly in critical areas. Where signs of abnormalities were identified such as cracks, fissures, dry rot, wood-boring insect bore-dust and torsions, manual tools (hammer and punch) were used alongside visual investigation. This way, it was possible to establish those areas needing further instrumental analysis with the aim to quantify and position any potential areas of internal decay of the timber elements within the structure. Samples for laboratory analysis were collected from the most significant areas of the structure in order to identify wood species and strengthening materials used.

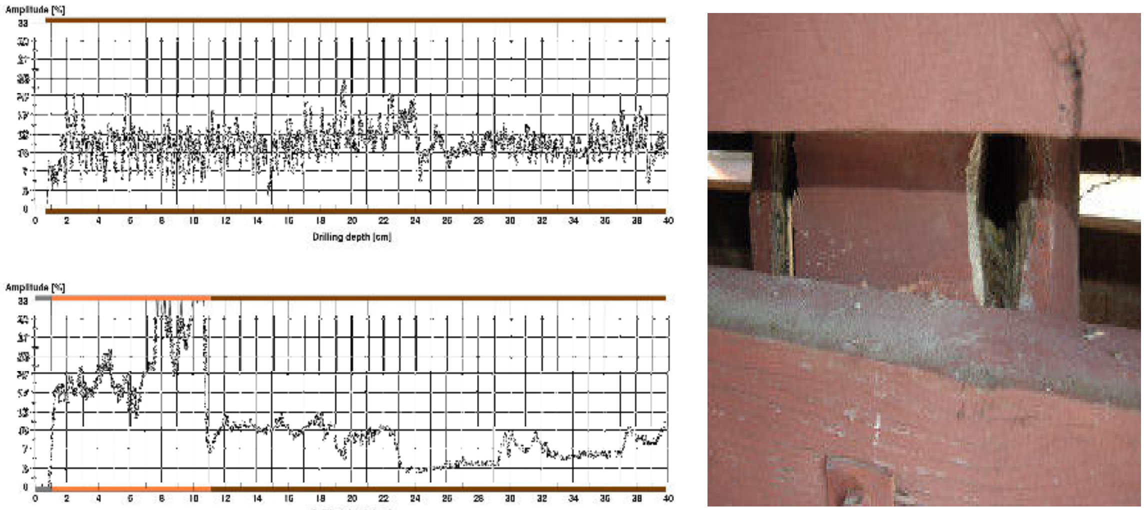

Figure 3: Drilling diagrams; decay on the wood-resin interface

Visual inspection was key to accurate identification of the various strengthening works already carried out in the past (metal supports and timber board supports, resin with sand casts), but also to assess the level of timber decay and, in some cases, the poor effectiveness of the strengthening interventions which caused further deterioration (Fig. 3). Resistograph tests [4] provided significantly different diagrams for the timber located well above the seasonal variations of the river level and the timber directly subjected to wet and dry cycles (Fig. 3). In the latter case, it is not possible to identify with certainty the variations in density between summer and spring timber areas, indicating a significant morphological variation of the timber itself. To identify the wooden samples macroscopic examination was performed using dichotomous keys existing in literature, which identified the wood species of the struts (larix decidua) and of the pile constantly immersed in water (quercus petraea) according to the traditional use in the Veneto region.

3.3 Analysis on Masonry Abutments

The other key element in the structural assessment of the bridge was its abutments which on the surface appear to be made partly of bricks and partly of stone blocks. Their geometrical characteristics and composition and the masonry stress state and mechanical characteristics were assessed. Core samplings, surveyed with additional video-inspections and single and double flat jack tests were performed. In this case too, rope access and positioning techniques proved to be the only way to operate (Fig. 4).

The investigations carried out showed that the upper part of the two abutments was constructed with a masonry of thin thickness from 60 to 75 cm and backfilled with various size blocks of stone and a great amount of mortar. The lower part was built in brickwork masonry from 90 to 120cm thick, more compact on the side towards Bassano, backing on chaotic texture stone masonry, made by stones essentially taken from the river Brenta (crystalline rocks); the back of the abutment towards Angarano is made of limestone masonry of a different lithological nature.

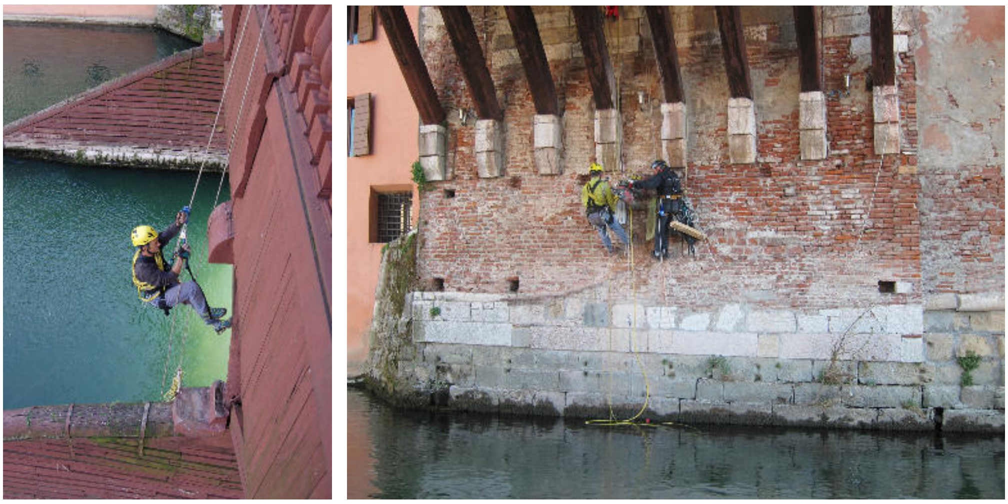

Figure 4: Rope access and positioning for inspections and tests

Finally, flat jack tests allowed the determination of mechanical characteristics of the brickwork masonry, obtaining overall low stress levels [5] and high deformation modulus values [6]; the compressive strength of masonry is over 3.6 MPa.

4. The New Bridge (Victory Bridge)

The Victory Bridge is 300m downstream of the old bridge. It is 175m long and 12.5m wide; with the addition of pavements, 1.25m wide either side of the road, it reaches an overall width of 15m. The structure consists of 2 large arches, with a 64m, span supported on lateral abutments and on a central pile sunk into the riverbed. Each arch consists of 6 R.C. arches of variable height (Fig. 5), from 55 to 60cm wide and with a spacing from 170 to 180cm, interconnected by a lower slab. The pillars emerging from the arches support the upper slab which forms the roadway.

4.1 Assessment of Reinforced Concrete Structures

Inspections of structures of the central pile were also in this case conducted by rope positioning techniques, with access from the deck.

A great number of instrumental inspections of structural members were conducted (Tab. 1), so that this would allow for later statistical data processing. The right-hand side arch, where the deterioration appeared more relevant due to large water infiltration, underwent a greater number of tests.

The visual test (VT) enabled to assess the state of the R.C. structures and to define the areas clearly deteriorated and those which are beginning to deteriorate and need further diagnostic analysis. The detailed inspection allowed to identify elements previously refurbished or repaired and enabled a close observation of structural members, particularly in critical areas (i.e. structural joints and around drainpipes). Moreover, major cracking and deterioration phenomena were identified such as gravel pockets, exposure of reinforcing bars, concrete spalling. Where signs of abnormalities were identified, alongside visual inspection manual tools (hammer and punch) were used to locate the extent of the deterioration and to define the state of conservation.

Figure 5: Downstream arches seen from left-hand side abutment; substantial concrete loss of mass

The survey of the reinforcements of the R. C. structures was conducted by electromagnetic covermeter (EL) according with standard [7]; this enabled the accurate and quick location of the reinforcement bars in concrete and their orientation as well as the measurement of the cover thickness and the estimate of the bar size. It was used a magnetometer type Elcometer 331 consisting of a central unit connected via a cable to a standard research probe, fitted with a special keyboard and sound and light indicators.

Tests aimed to the determination of the carbonation depth in concrete (PC) were carried out in compliance with standard [8] by using a drill to take samples of sand, collected in a transparent test tube. The measure of the carbonation depth was taken using a 1% solution of phenolphthalein ethanol, which turns pink when in contact with materials with pH higher than 9.2 and remains colourless with lower pH values.

Tests to determine the rebound number (SC) were conducted in accordance with standard [9] using a Schmidt N-9 standard hammer. However, the high carbonation level found in the structures made the results unreliable and these tests were therefore not extended to all the structures.

Table 1: Number and location of tests

Member	EL	PC	SC	UT	TS
Left-hand side arch	28	32	-	29	2
Right-hand side arch	53	60	15	60	
Total	**81**	**92**	**15**	**89**	**2**

EL = electromagnetic analysis; PC = carbonation depth; SC = rebound number;
UT = ultrasonic pulse velocity measurements; TS = sonic tomography

Ultrasonic pulse velocity measurements (UT) were conducted according with standard [10] using a pulse generator, two transducers, an amplifier and an electronic timing counter. Measurements were obtained through direct transmission by positioning the ultrasonic wave transmitter on one side and the receiver on the opposite side of the concrete structure to be analyzed. Acoustic coupling between transducers and concrete surface was obtained using plasticine. Tests were carried out by repeating the measurements 6 times in adjacent areas and calculating the result as the average of the 6 measurements.

On a couple of structural sections a series of sonic measurements through direct transmission was conducted with the transducers positioned according to a prearranged grid. Sonic pulse velocity, rather than ultrasonic, was used as the measuring path length did not allow to acquire ultrasonic pulses (having lower energy) with sufficient definition. These measurements were then processed obtaining 2D color maps, called tomograms, that plot the variation of P wave velocity field on cross structural section (TS).

4.2 Deterioration of Reinforced Concrete Structures

The bridge has three transverse expansion joints which are the preferred way for water leakages as the drainage system for meteoric water is not adequate; this causes relevant deterioration of many structural members.

Both lower and upper slabs are also crossed by an evident casting joint which runs along the centre line of the whole bridge. Next to the joint, the central joists are cracked and partially show surface reinforcements and concretions which indicates water leakages. General observation of structural members suggests that the reinforcement bars were laid without rebar spacers.

Pillar stirrups are occasionally irregular and look systematically more exposed on the corners, which are generally rounded off. Beams and joists at the intrados show extensive exposure of stirrups and sometimes of longitudinal bars as well. Consequently, there are some cases of considerable surfacing, oxidation and sizeable concrete spalling (Fig. 5).

Furthermore, pillars alongside the central pile of the bridge show clear decay patterns, especially at the bottom, possibly due to mechanical effect. Some of the shorter pillars symmetrically show shear cracks at the beam-pillar junction and, in one single case, an edge crack due to horizontal forces is evident.

4.3 *Statistical Data Processing*

Based on the peculiarity of the measurements and on the methods used to obtain it, statistical processing of the acquired data was possible and convenient. Acquired data, taken as samples, were sorted into classes in relation to their values; these classes have been graphically represented both by a histogram plotting on the primary axis the frequency percentage, and by a curve plotting on the secondary axis the cumulative percentage (Fig. 6).
On the basis of the percentage and standard deviation values, the probability density function which refers to the sample quantity was estimated; it represents the probability distribution of an infinite series of measurements. The analyzed variable is shown on the horizontal axis and the probability density function on the vertical axis (Fig. 6). Normal distribution (Gaussian) and gamma distribution were used, the former for symmetrical, the latter for asymmetrical variable samples with regard to the mean value.
From the probability density distribution, the order *k* percentile was identified (that is the value of the variable with *k* probability of nor being overtaken).
The survey of the reinforcement of RC structural members (EL) highlighted how cover values are extremely variable within various members and also along the longitudinal length of a single structural member, as the reinforcements were probably positioned without rebar spacers. The irregularity of the positioning of the longitudinal bars and of the distance between stirrups also indicates that the reinforcement cages were not adequately tied.

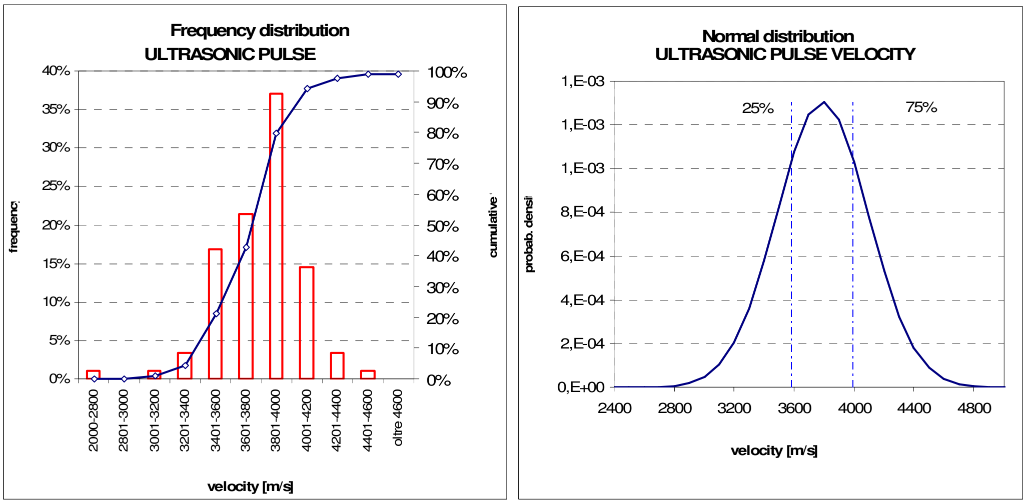

Figure 6: Frequency distribution and normal distribution of ultrasonic pulse propagation velocity

Instrumental analysis used to determine the reinforcement cover enabled us to draw the following general conclusions:

- the large arches shows a very thick concrete cover at the extrados, where the reinforcement steel is located, the cover of the stirrups is more superficial on the sides;
- the reinforcement steel of the pillars, as it can be visually observed, is very superficial at the

rounded off corners, with zero concrete cover in places, while the minimum cover value on the sides is on average 11mm;

- the reinforcement steel of beams and joists, similarly to that of the pillars, appears very superficial at the rounded off corners, the average value of the concrete cover is 16mm for the beam stirrups and 11mm for the joist stirrups.

The frequency distribution diagram of concrete carbonation depth (PC) shows a rather uniform distribution of values within a 21 to 60 mm wide interval. All members inspected have a deep carbonated layer, in fact only in 7 measurements carbonation was less than 10 mm deep. There is more carbonation in the joists, reaching an average depth of 56 mm; in inspected beams, pillars and large arches carbonation is lower, but anyway significant, reaching maximum values respectively of 43, 37 and 28mm.

Since the most relevant carbonation effect is to expose the reinforcement bars to oxidation, carbonation analysis have to be compared with the cover depth to evaluate any damaging effects.

As clearly shown in the typical pattern of some of the analyzed structural members (Fig.7), in several cases at present, the concrete carbonation front has advanced beyond the stirrups cover depth: consequently the rebar lies in an environment which allows their corrosion. The resulting increase of volume causes cracks to open and cover to detach. This consideration can be statistically substantiated by comparing the frequency distribution of both stirrups cover and carbonation depth (Fig.7). Their comparison shows that the carbonation depth detected in the analyzed structures represents a significant factor in rebar deterioration.

The same can be underlined observing the longitudinal bar cover, highlighting how these bars also suffer from the same relevant oxidation problem.

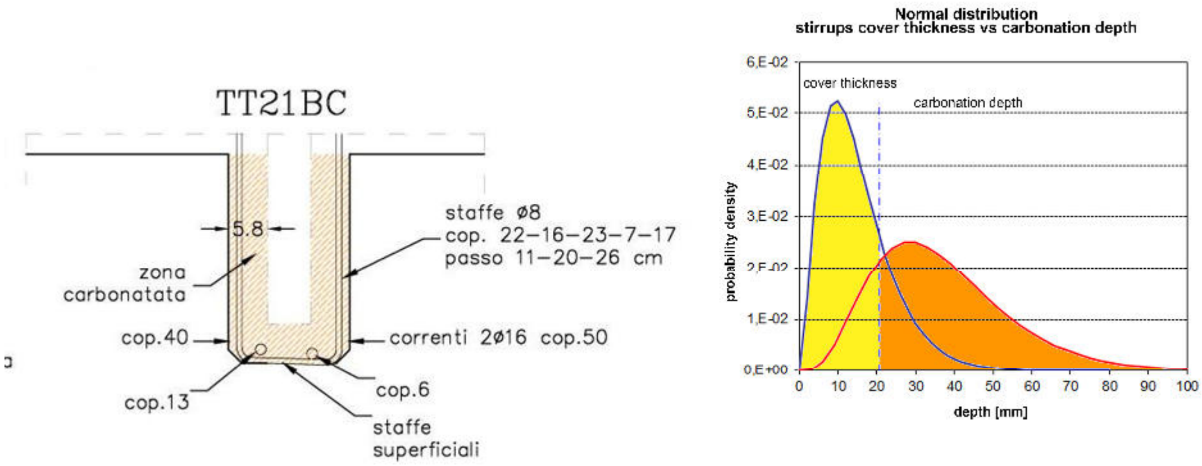

Figure 7 Sketch of carbonation in some structural members; normal distribution cover vs carbonation depth

Measurements of ultrasonic pulses velocity (UT) provide values resulting rather homogeneous within the same typology of structural members, with the average speed values for arch, beams and joists respectively of 4051m/s, 3659m/s, 3508m/s. Topographies of some arch (TS) were performed by measuring sonic pulse velocity and were used to evaluate the section homogeneity. They show a significant dispersion of velocity values within each section, confirming the rather poor concrete compaction during casting already highlighted by the dispersion of carbonation values.

5. Conclusions

The method of inspection and assessment by rope access and positioning techniques, in the case of the two bridges of Bassano, was successful and cost-effective as well as being the only suitable way to proceed under the circumstances.
In this paper it has been highlighted how it was possible to analyze either the wooden poles sunk into the river bed or the masonry abutments of the old bridge and the RC structural members of the new bridge.
The survey techniques used have allowed an accurate evaluation of the deterioration of both structures, which was relevant for the old timber bridge, as it might be expected. However, the deterioration was most unexpectedly significant also for the "new" reinforced concrete bridge. This highlights how construction characteristics are likely to limit the life span of the structures, especially of those built immediately after WWII, with no attention to cover, rebar tie and compaction during casting, and therefore the monitoring of their conditions is essential.

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