NDT PROTOCOLS FOR THE DIAGNOSTICS AND MAINTENANCE OF EARLY REINFORCED CONCRETE STRUCTURES: A CASE STUDY

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Abstract: The research work presented is focused on the diagnostic and rehabilitation of historical structures in reinforced concrete, and has been carried out within a scientific collaboration program with the Railway Company "Ferrovie Appulo Lucane", aimed at monitoring the maintenance state of their architectural and infrastructural patrimony. In particular, the case of the Viaduct of Corso Italia in Bari is illustrated.
The objectives of the research are the detailed characterization of the structure through the application of a complete protocol of diagnostic, and the elaboration of correlation curves on the base of experimental data. In the future, this will allow the control of the actual structural conditions on the basis of only non destructive testing, in a short time and with reduced cost and intrusion in the structure. After a detailed survey of the deterioration, a program of ND testing has been carried out:
- Chemical and physical characterization of the concrete mixture;
- Appraisal of the corrosion level for reinforcement bars;
- Appraisal of *in situ* properties and homogeneity for the concrete (by means of rebound hammer and ultrasonic testing, extraction of samples in order to provide the correlation curves).
- By processing the data correlation curves have been obtained that will be used, in the future, the monitoring of the structure by only using ND investigations and reducing length, cost and invasiveness of inspections.

Introduction: The Viaduct of Corso Italia in Bari, built in 1915, was one of the first realizations in Europe of a superelevated railway using the RC technology (fig. 1). Together with other buildings of to the same period property of the FAL Railway, it represents a significant historical example showing the high technological and formal level achieved in the field of concrete construction at the beginning of XIX century (for a more detailed description, see [1-3]).
The routine maintenance and inspection programs have revealed an excellent level of accuracy with respect to the design and execution of the work. In a technical sense, the quality and performance of this construction are to be considered completely satisfactory: it represents an exemplary case study and a tangible evidence of the successful technological implementation. Indeed, the research work presented was inspired by the fact that, during nearly 100 years of operation, the concrete showed a very good performance and durability. Within a scientific agreement with the railway company, a comprehensive characterization of the structure has been accomplished, by applying a complete protocol of ND Diagnostics.

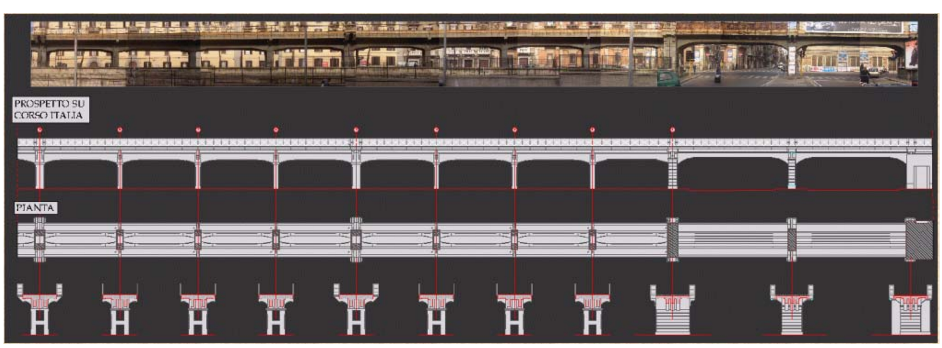

Figure 1. Views and drawings of the Railway Viaduct in Bari.

After a detailed survey of the actual conditions of the structure, a program of non destructive and quasi-non destructive tests has been planned, aimed at: the chemical/physical characterization of the concrete; the assessment of rebars' corrosion (potential mapping); appraisal of the quality and homogeneity of the reinforced concrete (ultrasonic measures and rebound hammer tests, extraction of cylindrical concrete samples). An important aspect of the research work has involved the validation of ND methods for R.C. (ultrasonic and sclerometric methods) thanks to the elaboration of correlation curves on the basis of the actual strength measured on the extracted samples. The aim is to design an effective protocol for the monitoring and the future maintenance of the structure, able to provide a rapid and reliable appraisal of the conditions of the materials (functional to the safety assessment), making use of the data recovered through ND tests.

Results: In order to obtain the data needed for the safety assessment of any existing structural, it is necessary to perform a diagnostic investigation, following a systematic sequential procedure [4-6].
In the presented case study, specifically, the diagnostic process has been organized acording to the following logic and temporal sequence:
Preliminary knowledge and analysis. Retrieval of existing data and documents (drawings, technical reports, structural details, testing and inspection certificates, maintenance or intervention documents, diagnostic reports, code practice and constructive traditions of the time); historical data (information about the construction, the events occurred); survey of materials; geometrical and photographical survey (with a particular attention to the structural details).
In order to obtain the data needed for the safety assessment of any existing structural, it is necessary to perform a diagnostic investigation, following a systematic sequential procedure that is usually called the "investigation protocol" [4-6].
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historical data (information about the construction, the events occurred); survey of materials; geometrical and photographical survey (with a particular attention to the structural details).
2. *Actual conditions – visual inspection, survey of instabilities and degradation*. Survey of cracking patterns (extension, length and depth); conditions of the concrete (deterioration, rebar covers); conditions of the steel bars (corrosion).
3. Design and time scheduling of in situ investigation program. Destructive tests: extraction of cylindrical concrete samples in the beams connecting the couplet columns. Chemical tests: determination of carbonation depth and chloride content in the samples. ND tests: rebound hammer measures and determination of the ultrasonic waves velocity in the same points were samples were extracted; potential mapping for a typical bay.
4. On site execution of the tests
5. Data processing and results discussion.
With regard to the investigation protocol, it is now described in more detail the application of points 3-5. For the other phases, the interested reader is addressed to [3].
Design and time scheduling of in situ investigation program. In this phase, some preliminary inspections have been carried out in order to preview the structural conditions, identify the structural elements and perform all the needed preliminary routine operations. This inspection has pointed out a widespread deterioration of the materials in all the bays. In many points, the spalling of the concrete and a significant corrosion of the reinforcement, often resulting in the complete expulsion of the rebar covering (especially in the beams) has been noticed (fig. 2).

Figure 2. Visual inspection: conditions of the materials.

On the basis of this results, a proper experimental investigation programme has been organized.
a. Mechanical characterization of the concrete on the extracted samples.
b. Determination of the carbonation depth in the extracted samples.
c. Execution of rebound hammer and ultrasonic measurements in specific points of the structure and determination of the correlation curves (fig. 3).
d. Potential mapping of a whole bay of the bridge (including columns and beams – fig. 4).
After identifying the structural elements to be investigated (both columns and beams), they have been compared to the original design prescriptions: the position, amount, distribution of the steel reinforcements and consistency of concrete cover has been checked with a magnetometric inspection. This operation is also necessary in order to circumscribe the areas more suitable for the extraction of samples, and also for the sclerometric and ultrasonic investigation (it is in fact well known that the presence of bars can distort the results of such tests). Once the exact locations for the tests has been chosen (fig. 3), they have been properly prepared, removing the plaster and polishing the surfaces.

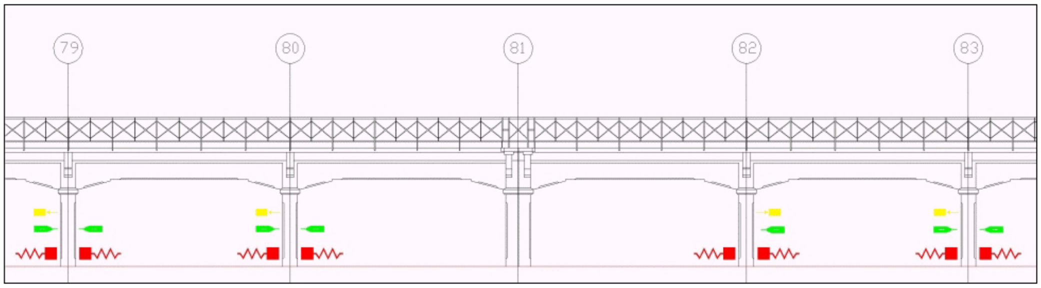


Figure 3. Location of the inspection points for the rebound hammer and ultrasonic measures and for the extraction of samples.

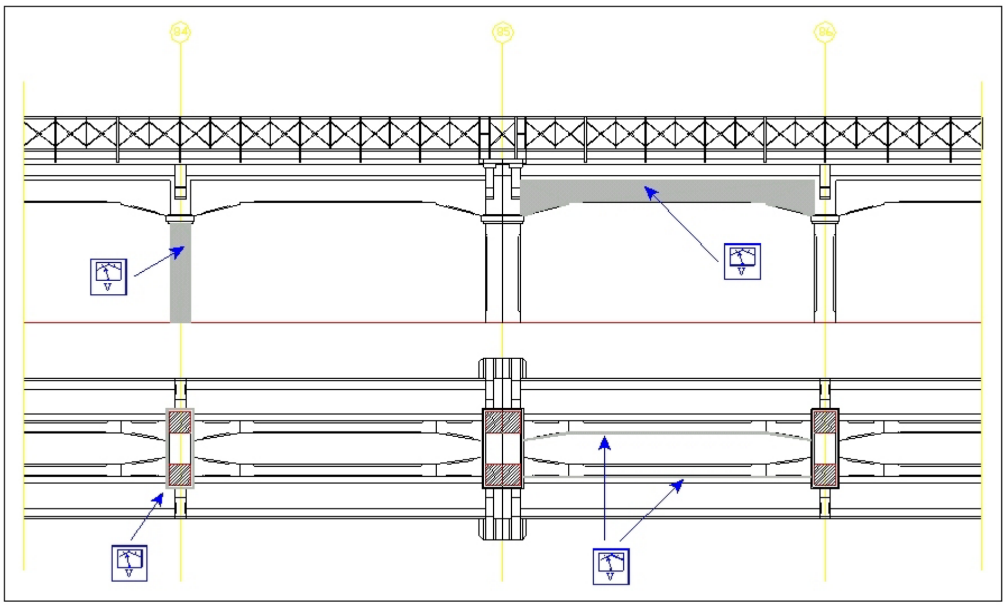


Figure 4. The structural elements on which the potential mapping has been performed.

The programmed ND investigations allows an appraisal of the structural conditions both from a mechanical and chemical point of view. Sclerometric and ultrasonic methods are suitable for assessing the homogeneity of the concrete and have a reference value for the mechanical ultimate strength.
With regard to the carbonation depth, on the other side, is useful for estimating the physical conditions of the concrete, its interaction with the surrounding environment and, hence, the protection level of the embedded reinforcements. Potential mapping, are employed in order to identify those steel bars that are endangered by corrosion phenomena, without uncovering the entire steel net. At last, compressive tests over the extracted samples have provided the compressive strength, and thus the experimental database on which obtaining "ad hoc" correlation curves relating ND measures to the actual on site resistance.

Discussion: With regard to the assessment of the structural conditions, the results provided by the potential mapping have confirmed the preliminary visual observations, but at the same time have allowed to circumscribe the problem. In fact, the progression of the corrosion, that is boosted by the high carbonation depth (in all the examined points, this has exceeded the covering- Tab.1), is particularly evident for the reinforcement of the main beams (fig. 5), while is almost negligible for the columns. Probably, this is due to the to the different exposure of the structural elements.

Unlike the plank, in fact, the columns are well protected from the meteoric water, and its humidity conditions make the corrosion velocity quite zero.

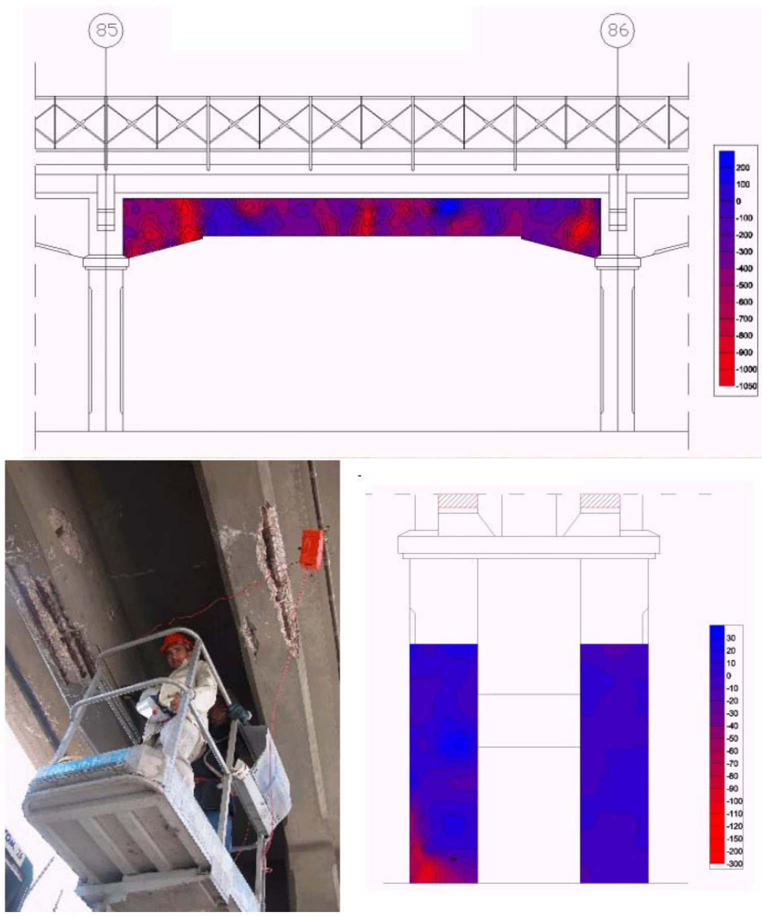


Figure 5. Potential mapping over a main beam and a column.

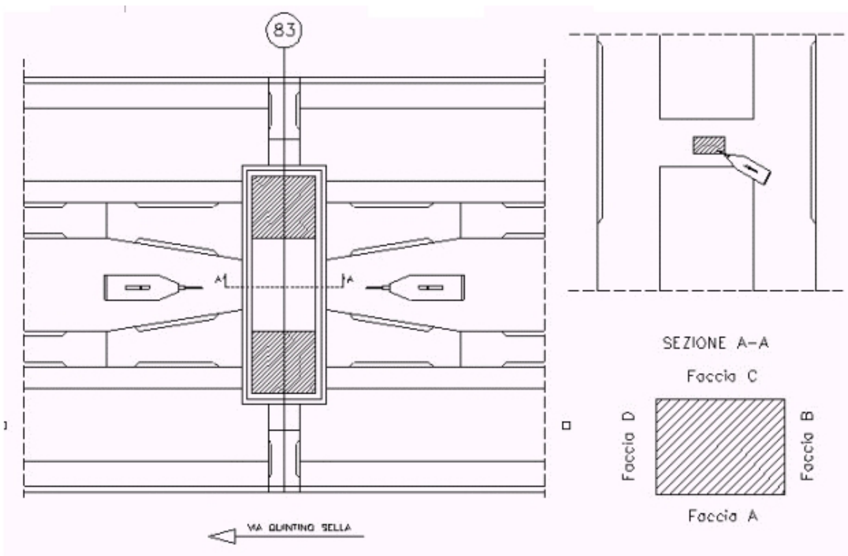
Sample	Concrete appearance	Carbonation depth	Distribution
C1	Slightly porous; large aggregate size	>45 mm	Uniform
C2	Slightly porous; large aggregate size	>50 mm	Uniform
C3	Slightly porous; large aggregate size	>50 mm	Non Uniform
CN1	Slightly porous; large aggregate size	>45 mm	Uniform
CN2	Slightly porous; large aggregate size	>40 mm	Uniform
CN3	Slightly porous; large aggregate size	>50 mm	Uniform

Table 1. Carbonation depth for the extracted samples.

With regard to the mechanical parameter of the concrete, the rebound hammer test has revealed a certain unhomogeneity. In fact, it can be noticed (see table in fig. 6), that in the investigated elements the rebound index varies in a quite large interval (44-56). This can be ascribed to two main reasons:

- the granulometry of the concrete includes aggregates of relevant size (even 6-8 cm), and particularly tough (they are silicious materials coming from northern Puglia, as it was learned by examining the documents retrieved in the Porcheddu Archive -Torino).
- the presence of a thick carbonated concrete layer (sometimes even 5 cm deep).

The recorded rebound index was very variable with the examined element, and therefore we have decided not to use them to the strength of the extracted samples.



REBOUND INDEX	
FACE D	FACE B
52	50
49	49
49	48
48	46
48	46
48	44
46	44
46	44
44	44
42	44
AVERAGE INDEX	
47,2	45,9
Ir	
46.55	

Figure 6. Location of the rebound hammer measures and corresponding indexes for some investigated elements.

With regard to the ultrasonic measures, a greater homogeneity has been observed (Tab. 2). The measurement of the ultrasonic waves propagation velocity has been performed on site and on the concrete samples as well, and the two data sets have turned out to be comparable. It can be therefore be deduced that the extraction has not induced a significant disturb, and the samples can considered as actually representative of the on site concrete.

In order to estimate the compressive strength for existing structures, it is absolutely necessary to refer to destructive compressive tests performed on samples extracted from the structure, even if their number will necessarily be scarce. In these cases, ND techniques or destructive tests alone are not able to perform a reliable appraisal of the mechanical features needed within a safety assessment. In order to avoid this drawback and obtain a reliable indirect ND measurement method, correlation curves are used, relating indirect indexes such as the ultrasonic propagation velocity within the concrete to the compressive strength experimentally determined on samples.

Table 2. *Transmission times and velocities for the propagation of ultrasonic waves in some of the investigated elements..*

	Dimensions	Direction of transmission	Time	Velocity
	cmxcm	cm	s	**M/s**
E78 – Trasversal	63x48	63	196	3214
E79 – Traversal	63x46	63	161	3913
E80 – Vertical left	60x58	60	191	3141
E82 – Vertical rigth	63x58	63	194	3247
E83 – Trasversal	62x47	62	193	3212

The results of the ultrasonic tests have been correlated to the experimental compressive strength of the samples extracted in the same points. Such a correlation can be obtained through a statistic elaboration of experimental data, by applying the minimum square method in order to identify the best interpolating function [9]. As previously pointed out, this procedure has been applied only

for the ultrasonic measurements, since the rebound indexes have been judged as scarcely reliable because of the granulometry and the relevant carbonation detected.
In particular, in order to determine the mentioned correlation curve between the ultrasonic velocities and the compressive strength of the samples, we have used a logarithmic regression:

$$R = A \times B^{V}$$

where:

R : concrete strength;

A,B: constant coefficients, to be determined from the experimental data;

V: velocity measure.

The regression curve obtained for the ultrasonic velocities is reported in fig. 6. This curve, even if obtained on the basis of a quite reduced number of experimental data, represents a very useful tool for the investigation. In fact, it will allow an easy systematic time monitoring of the decay of the mechanical concrete properties thanks to the measure of the ultrasonic propagation velocity alone, and therefore with no disturbance at all on the structure, that is in a full service and, moreover, is characterized by an architectural and historical relevance.

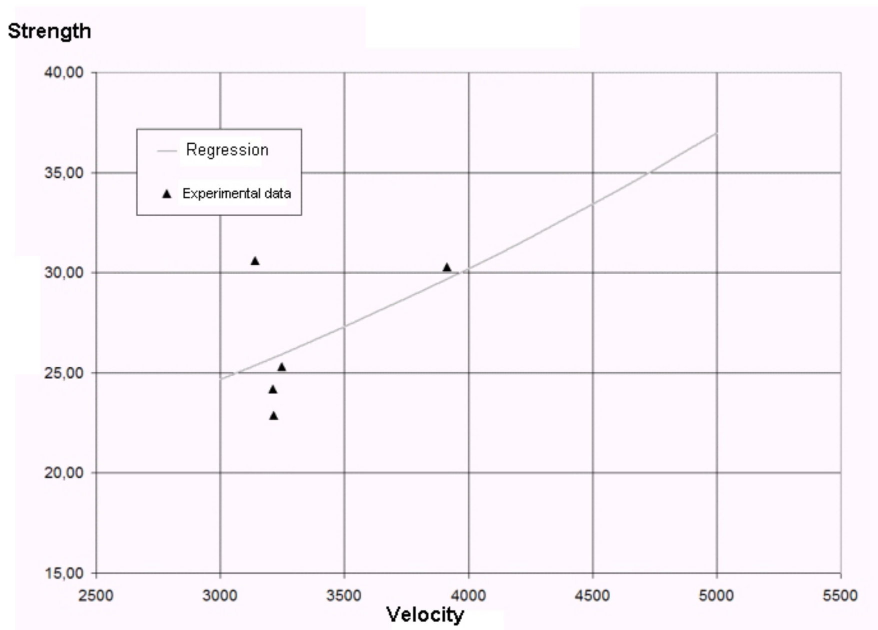


Figure 7. Correlation curve for the ultrasonic measures.

Conclusions: The objectives of the research work were: the detailed characterization of the viaduct by applying a complete diagnostic protocol; the elaboration, on the basis of the experimental data obtained, of correlation curves to be used for the monitoring of the degradation conditions on the basis of ND tests alone, reducing the time, the cost and the disturb of the investigation (all these are primary exigencies, above all in the case of public constructions). Some of the results of the research project, that is still in progress has been concisely.
The investigations have pointed out that some parts of the Viaduct actually find themselves in a severe deterioration state. In particular, the potential mapping and the determination of the carbonation profile, together with the visual inspection, show that the concrete (that was cast almost 100 years ago) no longer has a protective action on the inner reinforcement bars. As a consequence, where the humidity conditions are less favourable, the corrosion progression has severely and extensively affected the steel. Because of the different exposition, the main beams are more damaged than the columns, where the corrosion velocity is even negligible. For the

beams, therefore it is urgently needed the design and execution of an intervention able to account for the actual scenery: the carbonation has by far overcome the rebar covering depth, and the propagation of corrosion has caused a widespread damage of the external concrete layer. A traditional technique could be for instance adopted: complete removal of the carbonated concrete layer, and substitution with an alkaline mortar, specifically designed, that brings the reinforcements again in a passivation state. In order to guarantee an acceptable service life for the intervention, it is necessary, of course, to remove a relevant amount of carbonated concrete even if the mechanical strength is not compromised yet [10]. The ND tests have also revealed a certain unhomogeneity of the concrete in the different structural elements. For this reason indeed, and for the high carbonation depth, the values of the rebound indexes can not be considered reliable, and have not been used in the determination of the correlation curve. Different is the case of the ultrasonic tests. Results are definitely more reliable, and have been correlated to the experimental compressive strength through a regression curve. The obtained curve will be possibly used, in the future, for the on site control of the mechanical strength of the concrete through the execution of ND controls. Presently, the mechanical strength detected on the extracted samples are high enough, and can guarantee acceptable safety factors. Considering the importance of the construction, it is however advisable a constant and systematic monitoring.
In order to complete the assessment of the condition and safety of the viaduct, more chemical/physical investigations are being performed on the materials. In particular, a detailed granulometric identification will be performed, and diffractometric, SEM (scanning electronic microscope), EDAX and thermal analyses will be executed in order to determine the mineralogical and the petrography of the concrete, and properly design a compatible mortar mixture to be used in the interventions.

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