Metrological Validation of Non-Destructive Testing Techniques for Assessing the Condition State of Pre-Stressing Systems

STEFANO ZORZI, FRANCESCO ROSSI, DANIEL TONELLI, ALESSANDRO LOTTI and DANIELE ZONTA

ABSTRACT

The number of prestressed reinforced concrete bridges exceeding their expected lifespan is constantly increasing, leading to a growing interest by infrastructure managers and control authorities in monitoring and maintaining them. Accurate knowledge about the general degradation of bridges is necessary for effective planning and prioritization of maintenance intervention and structural monitoring. The prestressing system of a bridge is a particularly sensitive component; its condition state plays a central role in risk assessment and bridge maintenance. Non-destructive, semi-destructive, and destructive tests are recommended to evaluate the prestressing system's condition state by many guidelines. Several innovative investigation techniques are currently available on the market; however, their actual effectiveness is still debated and requires further investigation. This work aims to verify the effectiveness of the following non-destructive tests (NDTs): Digital Radiography, Ground Penetration Radar, and Reflectometric Impulse Measurement Test. These NDTs have been performed on the Alveo Vecchio viaduct, which is a decommissioned highway bridge now used as an open-air laboratory. These NDT's effectiveness is studied through correlation analyses performed by cross-referencing the NDT outcomes and the corresponding intensity levels of defects directly observed during a controlled demolition of the deck beams. This study provides significant insight into the accuracy level of non-destructive tests and is part of an extensive experimentation campaign.

INTRODUCTION

The increasing number of prestressed concrete (PC) bridges that have exceeded their expected lifespan concerns infrastructure managers and control authorities. Accurate monitoring and condition state assessment of the prestressing system of bridges are necessary to control their safety [1].

Nondestructive tests (NDTs) are commonly used to investigate defects in prestressing systems of post-tensioned PC bridges. However, the scientific literature still lacks a metrological validation of the actual accuracy of the most used NDTs.

Stefano Zorzi, University of Trento, via Mesiano 77, Trento, Italy
Francesco Rossi, University of Strathclyde, 75 Montrose Street, Glasgow, Scotland, UK
Daniel Tonelli, University of Trento, via Mesiano 77, Trento, Italy
Alessandro Lotti, University of Trento, via Mesiano 77, Trento, Italy
Daniele Zonta, University of Trento, via Mesiano 77, Trento, Italy

In this paper, we perform a metrological validation of Digital Radiography (DR), Ground Penetration Radar (GPR), and Reflectometric Impulse Measurement Test (RIMT) [2] by studying their effectiveness in recognizing defects in the prestressing system of a PC bridge's girders [3]. In particular, we discuss the effectiveness of DR in investigating the presence of grouting voids into the ducts and the integrity of steel strands and whether GPR can also detect any defects in prestressing cables besides identifying their position along the girders [4].

We performed these NDTs on the Alveo Vecchio Viaduct, a decommissioned prestressed concrete bridge now used as an open-air laboratory. Specifically, we tested four girders of the viaduct, and then we performed their autopsy. We demolished them, we extracted their prestressing system, opened the metallic ducts, and directly observed the defects of the ducts, grout, and strands along the prestressing cables. We compared the NDT outcomes with the defects directly observed during the autopsy we quantified the effectiveness of the NDTs based on a correlation analysis. Specifically, we used Contingency Tables and specific metrics for measuring the degree of association of the variables involved [5].

CASE STUDY

The Alveo Vecchio viaduct is a decommissioned post-tensioned PC structure located on the A16 highway in Italy. It was opening to traffic in 1968 and consisted of two structurally independent decks, each characterized by three 32.5 m-long supported spans with four PC girders and five reinforced concrete cross-girders. The prestressing system consists of 14 post-tensioned parabolic cables per girder. Each cable includes 12 steel strands with a diameter of 7 mm. In 2005, the bridge was hit by a landslide which caused the displacement of one pier and the collapse of one span. It was dismissed and in 2019 it was turned into an open-air laboratory for research and testing activities.

The research activities performed in this open-air laboratory have been carried out thanks to a research agreement between the Italian Ministry of Infrastructure and Transport, Autostrade per l'Italia SpA – the main Italian highway operator, and the University of Trento. This agreement aims to develop inspection protocols, metrologically validate NDT methods, and test monitoring systems' effectiveness in assessing the safety and performance of existing highway bridges.

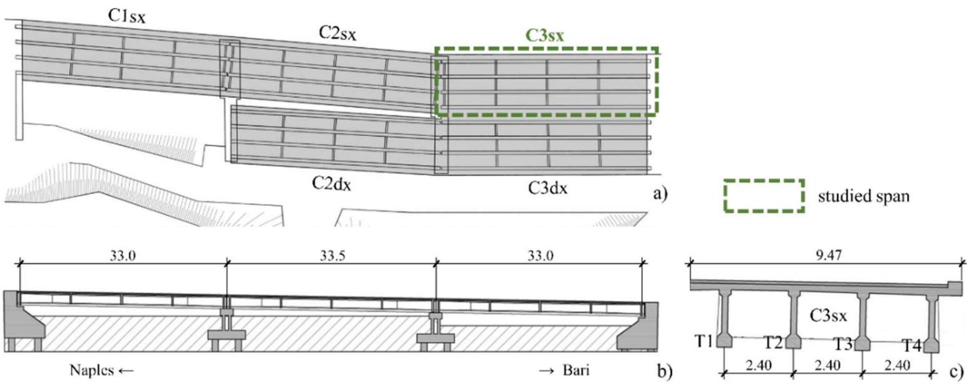

Figure 1. Top view (a), lateral view (b), and cross-section (c) of the Alveo Vecchio viaduct. All measurements are expressed in meters.

METHOD

This study aims to perform a metrological validation of DR, GPR, and RIMT by studying the effectiveness of these NDT methods in recognizing defects in the prestressing system of PC bridge' girders. To achieve this objective, firstly, we performed the NDTs on the span C3sx of the Alveo Vecchio Viaduct; then, we performed an autopsy of the prestressing system to identify the actual defect of the cables; eventually, we performed a correlation analysis using the observed defects as ground truth for the estimation of the NDTs' effectiveness.

We focused on the following NDTs: Digital Radiography (DR), Ground Penetration Radar (GPR), and Reflectometric Impulse Measurement Test (RIMT). Regarding prestressing cable defects, during the autopsy, we investigated the grade of grout fracturing (G.F), the percentage of grouting voids (G.V), and the corrosion of steel strands (S.C). Specialized practitioners and university labs performed the NDTs.

To quantify the NDTs effectiveness, we studied the correlation between the NDT outcomes and the defects observed during the autopsy. We discretized each cable into 10 cm-long segments and assigned them the NDT outcomes and the observed defects discretized in classes according to intensity scales. In this way, we organized the experimentation results into ordered vectors obtaining the ordinal variables for the correlation analysis. Ordinal variables are categorical variables whose classes have a specific logical order despite not providing a mathematically meaningful numerical quantity [5]. Table I reports the classes of the NDT outcomes' ordinal variables, defined in ascending order of intensity. It should be pointed out that DR classes consider 3 levels of defect: no presence of voids, partial injected grout lacks, and prevalence of injected grout lacks. Moreover, RIMT tests should identify two types of defects: voids in the injected grout (RIMT.V) and corrosion along the steel strands (RIMT.C). These tests consider 5 classes of intensity. Instead, GPR consider 3 classes of intensity of amplitude.

Table II reports the classes of the cables' defects' ordinal variables. We investigated two types of defects in the injected grout: we defined a scale with 5 classes for G.F and a scale with 6 classes for G.V. On the other hand, we counted how many strands were affected by corrosion among the 12 of them composing the cable; we defined the intensity scale with 13 classes, from 0/12 – no strands with corrosion – to 12/12 – all strands with corrosion. Figure 2 shows how the classes of the injected grout defects and the classes of the corrosion defect of steel strands are defined.

TABLE I. CLASSES OF NDT OUTCOMES

ID	*Description*	*Intensity scale*
RIMT.V	Reflectometric Impulse Measurement Test for injection voids identification	0-1, 1-2, 2-3, 3-4, 4-5
RIMT.C	Reflectometric Impulse Measurement Test for strands corrosion identification	0-1, 1-2, 2-3, 3-4, 4-5
RD	Digital Radiography	0, 1, 2
GPR	Ground Penetration Radar	0, 1, 2

TABLE II. CLASSES OF CABLES' DEFECTS

ID	***Description***	***Intensity scale***
G.F	grade of grout fracturing	1, 2, 3, 4, 5
G.V	percentage of grouting voids	=0%, <25%, <50%, <5%, <100%, =100%
S.C	corrosion of steel strands	0/12, 1/12, 2/12, …, 12/12

To test the correlation between the NDTs outcomes and the intensity classes of defects, we considered Contingency Tables (CTs) – also known as cross-tabulations or two-way tables [5]. CTs are a statistical tool used to analyze the relationship between two categorical variables, often used in social science, medical research, and economic research. In this work, CTs involve the ordinal variables defined in Table I (NDTs outcomes) and Table II (cable defects). Given two ordinal variables, a CTs reports the frequencies of occurrence of each combination of their classes. The rows and columns of the CTs represent the classes of the two variables under study. Since we are operating with ordinal variables, the row indices and column indices follow the logical order of the classes of the variables. The frequency of occurrence of each combination of classes is reported in the CTs' corresponding cells.

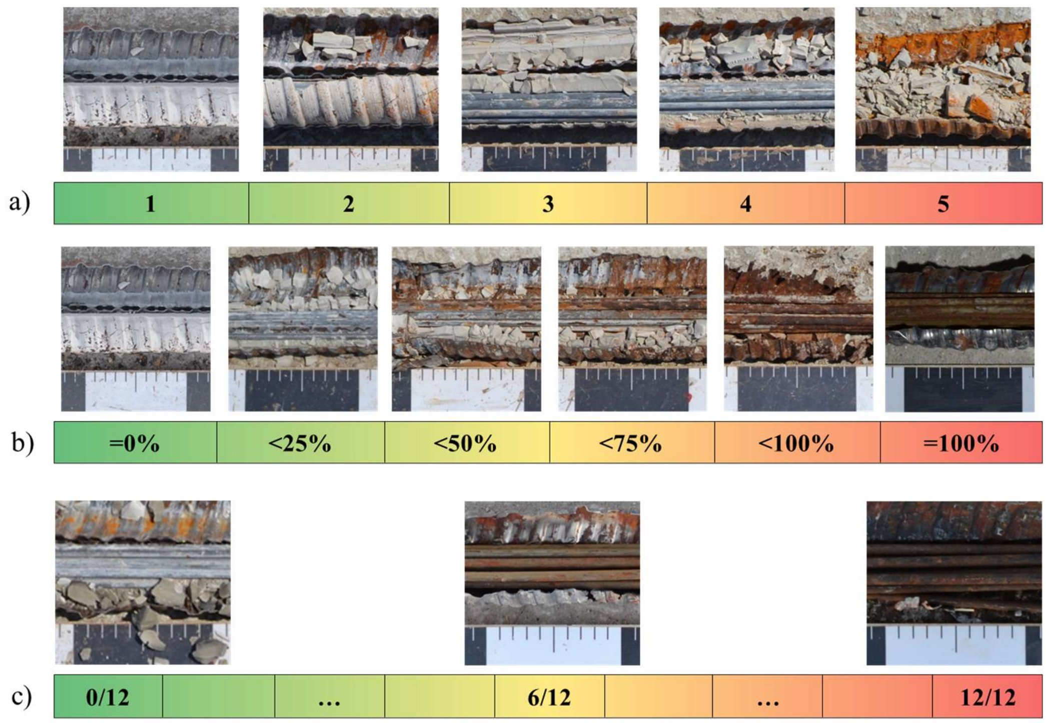

Figure 2. Defects classes of the injected grout and of the steel strands.
a) grade of grout fracturing – G.F; b) percentage of grouting voids – G.V,
c) corrosion of steel strands – S.C.

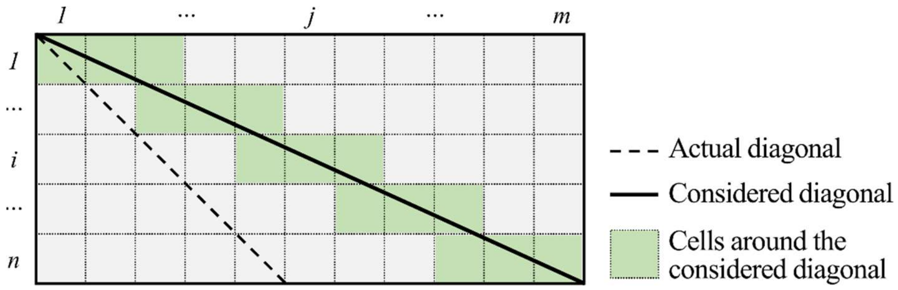

Figure 3. Difference between actual and considered diagonals in CTs.

The distribution of the frequencies of occurrence in the CTs allows us to qualitatively verify the effectiveness of NTDs in detecting the presence and the intensity of cable defects. Indeed, when the NDT outcomes are not associated with a defect, the relative CT is approximately uniformly distributed with respect to the columns because the NDT outcomes do not depend on the intensity of such defect. In contrast, the relative CT is approximately diagonal when the NDT outcomes are strongly associated with a defect. Since CT is generally non-square, we do not refer to the actual diagonal of the table (the elements with equal row and column index) but to the ideal diagonal obtained by drawing a line that collimates the first and the last elements, as shown in Figure 3.

In the scientific literature, several metrics measure the degree of association between two ordinal variables, i.e., the measure of their correlation. We exploit the following correlation indices: the Pearson Correlation Coefficient (PearsCC) [5], the Spearman Correlation Coefficient (SpearCC) [5], the Polychoric Correlation Coefficient (PolyCC) [6], the Goodman-Kruskal Gamma (GKγ) [7], and the Stuart-Kendall Tau-c (SKτ) [8]. They are expressed by a real number varying from -1 to 1 and are subject to the same interpretation shown in Figure 4.

Specifically, a correlation coefficient equal to 1 identifies a perfect and direct association between the variables, while a correlation coefficient equal to -1 identifies a perfect and inverse association. In contrast, a correlation coefficient equal to 0 identifies the complete lack of association between the variables. In all other cases, a correlation (direct or inverse, depending on the sign) exists but is not perfect.

RESULTS

In this Section, we present the results of the correlation analyses. We performed the correlation analyses by comparing pairs of NDTs outcomes and intensity levels of cable defects. The results are expressed in terms of CTs and the correlation indices mentioned above.

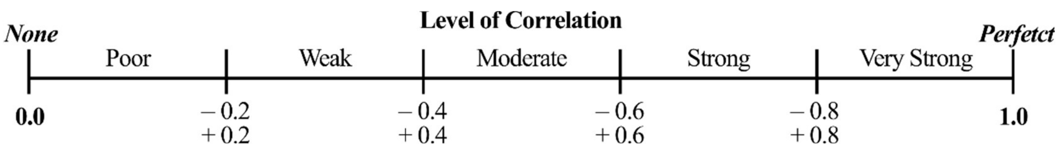

Figure 4. Interpretation of correlation metrics [9].

We also considered Conditional Probability Tables (CPTs) to report the absolute frequency of occurrence of association between NDT outcomes and defects intensity. CPTs represent a discrete representation of the conditional probability distribution of the NDT outcomes given the intensity level of defects. Differently from CTs, CPTs relate the frequency of occurrence of each pair to the number of occurrences of its intensity level.

Concerning the defects of the injected grout, we focused on the NDT outcomes with code DR, RIMT.V, and GPR. The correlation analysis results are reported in Tables III, IV, and V. These tables show the elements of the CTs and the CPTs, the latter in brackets. They also report the values of the correlation indices.

TABLE III. CT AND CPT OF GROUTING VOIDS (G.V) AND DIGITAL RADIOGRAPHY (DR)

Digital Radiography (DR)	Percentage of grouting voids (G.V) =0%	<25%	<50%	<75%	<100%	=100%	
0	117 (0.386)	39 (0.167)	25 (0.253)	5 (0.119)	8 (0.080)	10 (0.068)	**204**
1	122 (0.403)	97 (0.416)	30 (0.303)	7 (0.167)	12 (0.120)	7 (0.048)	**275**
2	64 (0.211)	97 (0.416)	44 (0.444)	30 (0.714)	80 (0.800)	130 (0.884)	**445**
	303	**233**	**99**	**42**	**100**	**147**	**924**

PearsCC = 0.452; SpearCC = 0.474; PolyCC = 0.565; GKγ = 0.570; SKτ = 0.431;

TABLE IV. CT AND CPT OF GROUTING VOIDS (G.V) AND RIMT (RIMT.V)

Reflectometric Test - Voids (RIMT.V)	Percentage of grouting voids (G.V) =0%	<25%	<50%	<75%	<100%	=100%	
0-1	1398 (0.536)	1447 (0.544)	200 (0.370)	58 (0.254)	47 (0.156)	22 (0.129)	**3172**
1-2	402 (0.154)	348 (0.131)	113 (0.209)	42 (0.184)	56 (0.185)	21 (0.123)	**982**
2-3	768 (0.295)	807 (0.303)	227 (0.420)	128 (0.561)	199 (0.659)	128 (0.749)	**2257**
3-4	39 (0.015)	57 (0.021)	1 (0.002)	0 (0.000)	0 (0.000)	0 (0.000)	**97**
4-5	0 (0.000)	0 (0.000)	0 (0.000)	0 (0.000)	0 (0.000)	0 (0.000)	**0**
	2607	**2659**	**541**	**228**	**302**	**171**	**6508**

PearsCC = 0.258; SpearCC = 0.237; PolyCC = 0.315; GKγ = 0.329; SKτ = 0.179;

TABLE V. CT AND CPT OF GROUTING VOIDS (G.V) AND GPR

Ground Penetration Radar (GPR)	Percentage of grouting voids (G.V) =0%	<25%	<50%	<75%	<100%	=100%	
0	568 (0.706)	317 (0.749)	60 (0.732)	8 (0.471)	36 (0.522)	86 (0.662)	**1075**
1	175 (0.218)	73 (0.173)	15 (0.183)	5 (0.294)	12 (0.174)	20 (0.154)	**300**
2	61 (0.076)	33 (0.078)	7 (0.085)	4 (0.235)	21 (0.304)	24 (0.185)	**150**
	804	**423**	**82**	**17**	**69**	**130**	**1525**

PearsCC = 0.113; SpearCC = 0.049; PolyCC = 0.096; GKγ = 0.080; SKτ = 0.035;

Note that only the correlation indices we obtained for DR (Digital Radiography) suggest a moderate correlation (from 0.4 to 0.6 – see Figure 4) with respect to the percentage of grouting voids. In contrast, the correlation indices we obtained for the other tests suggest a poor correlation for GPR and a poor/weak correlation for RIMT.

We repeated the same procedure for the other two defects: grade of grout fracturing (G.F) and corrosion of steel strands (S.C). Regarding G.F, we obtained similar results. Regarding S.C, we focus only on the correlation analyses for GPR and RIMT.C. The results suggest no clear association between the defect S.C and the considered NDTs. Indeed, the correlation indices suggest a poor correlation for GPR and a poor/weak correlation for RIMT.

Table VI summarizes correlation indices for all the combinations of NDT outcomes and defects observed in prestressing cables.

TABLE VI. CORRELATION COEFFICIENTS RESULTING FROM CONTINGENCY TABLES

	RIMT.V	**RIMT.C**	**DR**	**GPR**
G.F	PearsCC = 0.109	PearsCC = 0.174	PearsCC = 0.414	PearsCC = 0.059
	SpearCC = 0.101	SpearCC = 0.170	SpearCC = 0.415	SpearCC = 0.013
	PolyCC = 0.116	PolyCC = 0.213	PolyCC = 0.484	PolyCC = 0.044
	GKγ = 0.129	GKγ = 0.220	GKγ = 0.481	GKγ = 0.017
	SK = 0.079	SKτ = 0.131	SKτ = 0.384	SKτ = 0.009
G.V	PearsCC = 0.216	PearsCC = 0.258	PearsCC = 0.452	PearsCC = 0.113
	SpearCC = 0.167	SpearCC = 0.237	SpearCC = 0.474	SpearCC = 0.049
	PolyCC = 0.216	PolyCC = 0.315	PolyCC = 0.565	PolyCC = 0.096
	GKγ = 0.228	GKγ = 0.329	GKγ = 0.570	GKγ = 0.080
	SK = 0.127	SKτ = 0.179	SKτ = 0.431	SKτ = 0.035
S.C	PearsCC = 0.114	PearsCC = 0.141	PearsCC = 0.129	PearsCC = 0.013
	SpearCC = 0.154	SpearCC = 0.177	SpearCC = 0.162	SpearCC = 0.035
	PolyCC = 0.168	PolyCC = 0.225	PolyCC = 0.164	PolyCC = 0.059
	GKγ = 0.189	GKγ = 0.220	GKγ = 0.180	GKγ = 0.059
	SK = 0.120	SKτ = 0.138	SKτ = 0.146	SKτ = 0.025

CONCLUSION

This work aims to verify the effectiveness of Digital Radiography (DR), Ground Penetration Radar (GPR), and Reflectometric Impulse Measurement Test (RIMT) in recognizing defects in the prestressing system of prestressed concrete bridges.

We tested these NDTs on the Alveo Vecchio viaduct case study, a decommissioned prestressed concrete bridge turned into an open-air laboratory. We compared the NDT outcomes to the defects directly observed along the cables after their autopsy. The investigated defects include the percentage of voids in the injected grout, the grade of fracturing of the injected grout, and the corrosion level of the steel stands. We verified the effectiveness of the NDTs through correlation analyses based on Contingency Tables and specific correlation metrics.

The results suggest a moderate correlation between the outcomes of DR and the defects of the injected grout. In contrast, the results suggest a poor correlation between the outcomes of GPR and the defects of grout and strands and a poor/weak correlation between the outcomes of RIMT and the defects of grout and strands.

Further analyses of these data are planned. In particular, the NDTs' effectiveness will be verified using supervised machine learning techniques.

ACKNOWLEDGEMENT

This research has been supported Autostrade per l'Italia SpA, Fondazione CARITRO Cassa di Risparmio di Trento e Rovereto (grant number 2021.0224), MIUR PON RI 2014-2020 Program (Project MITIGO, ARS01_00964), ReLUIS Ponti 2021–2022 'Implementation of provisions of DM 578/2020', and DPC-ReLUIS 2022-2024 WP6 'Monitoring and satellite data'.

REFERENCES

1. M. Bonopera, K.-C. Chang, and Z.-K. Lee. 2020. "State-of-the-Art Review on Determining Prestress Losses in Prestressed Concrete Girders," Applied Sciences, vol. 10, no. 20, p. 7257.
2. S. Kashif Ur Rehman, Z. Ibrahim, S. A. Memon, and M. Jameel. 2016. "Nondestructive test methods for concrete bridges: A review," Construction and Building Materials, vol. 107, pp. 58–86.
3. R. D. Innocenzi, G. Pigliapoco, S. Carbonari, F. Gara, and L. Dezi. 2022. "Damage Detection of Post-tensioned Cables in Existing Bridges with Digital Radiography," in Proceedings of the 1st Conference of the European Association on Quality Control of Bridges and Structures.
4. M. K. Lim and H. Cao. 2013. "Combining multiple NDT methods to improve testing effectiveness," Construction and Building Materials, vol. 38, pp. 1310–1315.
5. A. Agresti. 2013. *Categorical data analysis*. Wiley series in probability and statistics, no. 792.
6. J. Choi, S. Kim, J. Chen, and S. Dannels. 2011. "A Comparison of Maximum Likelihood and Bayesian Estimation for Polychoric Correlation Using Monte Carlo Simulation," Journal of Educational and Behavioral Statistics, vol. 36, no. 4, pp. 523–549.
7. L. A. Goodman and W. H. Kruskal. 1954. "Measures of Association for Cross Classifications," Journal of the American Statistical Association, vol. 49, no. 268, p. 732.
8. A. Stuart. 1953. "The Estimation and Comparison of Strengths of Association in Contingency Tables," Biometrika, vol. 40, no. 1/2, p. 105.
9. H. Akoglu. 2018. "User's guide to correlation coefficients," Turkish Journal of Emergency Medicine, vol. 18, no. 3, pp. 91–93.