Non Destructive Testing and Model Validation of Corroded PC Bridge Deck Beams

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Abstract. This paper presents the preliminary results of extensive on-site experimental activities based on non-destructive diagnostic tests carried out within the BRIDGE|50 research project. This project has been established jointly by Politecnico di Milano and Politecnico di Torino with public authorities and private companies for a wide experimental campaign on a prestressed concrete (PC) viaduct dismantled after a 50-year lifetime in the context of the Torino-Ceres construction works (http://www.bridge50.org). A group of 29 PC deck beams, including 25 I-beams and 4 box beams, and 2 PC pier caps have been moved and stored in a testing site. The results of the non-destructive tests carried out on these structural elements are used for calibration and validation of both structural analysis models and corrosion deterioration models to support a proper planning of full-scale load tests on the deck beams.

Keywords: PC Deck Beams, Non Destructive Testing, Model Validation.

1 Introduction

Life-cycle methodologies have been established for long-term design, maintenance and management of infrastructure systems (Biondini & Frangopol 2016, 2019). However, the experimental validation of life-cycle criteria and tools are crucial to support their implementation in practice. The BRIDGE|50 research project has been launched with the aim of investigating the residual structural performance of a 50-year-old prestressed concrete (PC) bridge by putting in practice the current theoretical research trends with a thorough experimental campaign (Biondini et al. 2021). On-site activities include photographic mapping of the structural elements, drone surveys, non-destructive diagnostic tests, full-scale load tests up to collapse, and laboratory mechanical and chemical-physical tests. This paper presents the preliminary results of extensive on-site experimental activities based on non-destructive diagnostic tests (e.g. sclerometer and ultrasonic tests) carried out on several PC deck beams. The results of these activities can be used for calibration and validation of structural analysis models and corrosion deterioration models to support a proper planning of full-scale load tests up to collapse to be performed to the deck beams.

2 Experimental campaign

The Corso Grosseto viaduct in Turin, Italy, was a road bridge built in 1970 characterized by a double deck simply supported girder system using precast PC beams and cast-in-situ concrete slab (Savino et al. 2021). The demolition of this viaduct at the end of its service life allowed the dismantling of several structural elements (Anghileri et al. 2021). This offered an important opportunity to investigate the effects of aging and deterioration on the residual capacity of existing concrete bridges exposed to aggressive environment. In particular, 29 PC deck beams and 2 PC pier caps of the viaduct to be investigated and monitored have been moved and stored in a testing site (Fig. 1).

(a) (b)

Fig. 1. BRIDGE|50 testing site: (a) deck beams; (b) pier caps.

The experimental campaign and on-site activities include photographic mapping of the structural elements, drone surveys, non-destructive diagnostic tests (e.g. sclerometer and ultrasonic tests), full-scale load tests up to collapse, and laboratory mechanical and chemical-physical tests. Moreover, visual inspections have been conducted according to national and international standards by several groups from public authorities and private companies before the bridge dismantling (Beltrami et al. 2021). In addition, concrete coring from a bridge pier and carbonation tests, as well as dynamic identification experimental tests, have been performed (Quattrone et al. 2021).

3 Non Destructive Testing (NDT)

3.1 Tested Beams

The 50-year-old PC deck beams have total length of almost 19.20 m, characterized by I-shaped cross-section with depth of 90 cm and top concrete slab with 14 cm thickness (Fig. 2). NDTs conducted on the beams are described in the following, with emphasis on testing devices and techniques implemented in the experimental activities and by addressing basic features, functioning principles, and critical factors such as calibration procedures and accuracy limitations in operational conditions.

(a) (b)

Fig. 2. PC deck beam and top slab: (a) cross-section; (b) longitudinal view.

3.2 Experimental setup

The experimental tests are carried out by subdividing each beam in five sample portions representative of the longitudinal beam profile (Fig. 3). On the front side of the beam a small region along each testing portion is identified and the beam surface is cleaned from dust and concrete leakages segregation to properly lay the pacometer along the beam. Once detected, the steel rebars are marked on the beam surface with a chalk. This allows defining a grid of 3x3 points evenly spaced within two pairs of longitudinal and transversal rebars (Fig. 4a). On the rear side of the beam, the grids are marked exactly at the same location, checking that they do not overlap with steel bars. The marks on the rear side surface are used as ultrasound emission points, while the marks on the front side are ultrasound reception points.

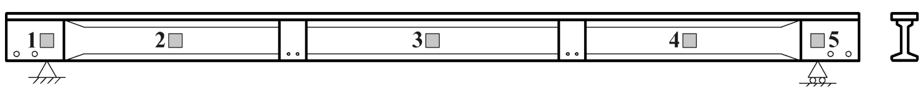


Fig. 3. Beam profile and five NDT sample zones.

3.3 Ultrasonic Tests

Pacometer and Ultrasonic Device. The pacometer allows detecting in a non-destructive way the location and the orientation of the steel reinforcing bars. The device principle is based on magnetic induction. It consists in a probe generating a magnetic field couple with a controller, measuring the power dissipated by the metallic object as result of the magnetic induction from the probe. The device detects the direction of maximum electromagnetic absorption associated with the bar profile, allowing the pacometer to localize the reinforcement location and estimate the concrete cover.

(a) (b)

Fig. 4. (a) 3x3 measurement grid points; (b) use of pacometer for longitudinal bar detection.

Fig. 4b shows the device in use. First, the concrete beam surface should be as clear and smooth as possible to let the probe slide in order to detect steel reinforcement. If magnetic elements are detected, the controller emits an acoustic signal and the detected rod location is visualized in real time via a digital display. The device can be considered quite accurate in identifying steel reinforcement position. However, the measured concrete cover is generally not accurate, especially for non-homogeneous concrete.

The pulse velocity method is an alternative method for in-site concrete strength assessment. This technique is based on the measurement of the propagation velocity of compressive mechanical waves along a solid medium. Each wave type propagates with a characteristic velocity based on dynamic equilibrium that depends on elastic mechanical properties and material density (Malhotra & Carino 2003). The compressive wave velocity V in elastic homogeneous solid media can be evaluated as follows:

$$V = \sqrt{\frac{(1-\nu)E_d}{(1+\nu)(1-2\nu)\,\rho}} \tag{1}$$

where E_d is the dynamic Young's modulus (static Young's modulus $E = E_d/1.062$) of the investigated media, ρ is the material density, and ν is the Poisson's ratio. Compared with the rebound method, the ultrasonic pulse velocity method is truly non-destructive because it does not damage the tested specimen. The method can also be used to detect internal cracking and other defects as well as damage in concrete such as environmental deterioration due to aggressive chemicals inadequate concrete cast.

Ultrasonic Tests. The test must be performed by two operators. At one side, an operator places firmly on the marked point the ultrasound emission sensor which sends the impulse. At the opposite side, the other operator places firmly on the marked point the ultrasound reception sensor. It is noted that the measurements at supports (sample zones 1 and 5 in Fig. 3) might be characterized by a lower accuracy with respect to the measurements over the web in the inner regions (sample zones 2, 3, and 4). This is presumably due to both larger irregularities in the material volume when larger distances are covered by the ultrasound waves and interaction with denser reinforcement pattern.

3.4 Rebound Tests

Rebound hammer. This device allows estimating the material strength of structural elements based on a low-cost technique. The basic principle of the rebound method is associated with the correlation between material surface hardness and its residual strength. A rebound hammer (i.e. sclerometer) is composed by a sliding mass coupled with a spring within the instrument. The mass is in contact with a swinging rod used to strike the material surface. The rebound distance of the mass is converted by a graduated scale into the rebound number S. The hammer is associated to a correlation curve, calibrated by the device manufacturer using standard specimens, in order to convert rebound numbers into the estimated concrete strength. The rebound method may provide a good estimate only of concrete cover strength. Even though concrete carbonation has a detrimental effect on reinforcement durability, it generally increases the concrete strength. Therefore, the results of rebound tests may overestimate concrete strength. For this reason, results of hammer blows are generally coupled with ultrasonic tests (i.e. SONREB method) leading to more accurate estimate of the actual material properties.

Rebound tests. The rebound test is carried out after the ultrasonic test, because the hammer blows leave small marks on the beam that may affect surface roughness. Fig. 5 shows the test in progress.

Fig. 5. Rebound hammer test.

3.5 SONREB Method

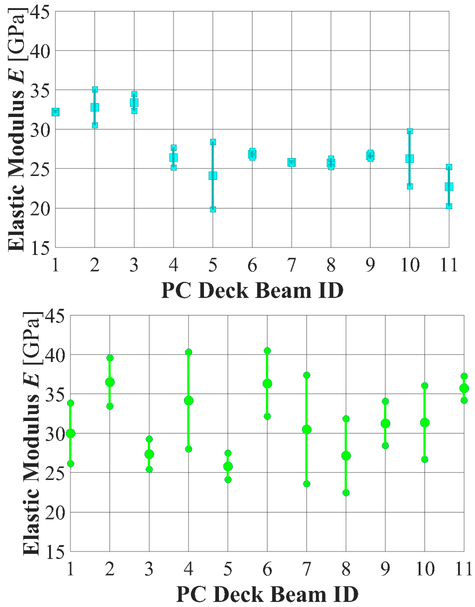
The SONic REBound method (i.e. SONREB) combines the rebound number S and the wave velocity V to provide more refined estimates of the material strength based on empirical formulations calibrated via statistical regression, as follows:

$$R_c = aS^b V^c \tag{2}$$

where R_c is the cubic compression strength of concrete [MPa], S is the rebound measure from the sclerometer test, V is the wave velocity from the ultrasonic test [m/s], and a, b, c, are calibration coefficients. Several authors proposed different coefficients based on experimental evidence (Bocca & Cianfrone 1983, Giacchetti & Lacquaniti 1980).

4 Experimental Results and Model Validation

The outcomes of ultrasonic tests represent the time required by the ultrasonic waves to cross the beam depth. The experimental results are converted into wave velocity V and dynamic and static elastic moduli are computed based on Eq. (1). Concrete density ρ and Poisson ratio ν are assumed as reported in the design project, namely ρ =25 kN/m^3 and ν=0.2. Fig. 6 shows mean and standard deviation values of static elastic modulus measured in correspondence of the support regions 1 and 5 (Fig. 6a) and over the beam web regions 2, 3, and 4 (Fig. 6b) for 11 beams.



(a) (b)

Fig. 6. Mean and standard deviation values of elastic modulus E for 11 beams: (a) support regions 1 and 5 and (b) beam web regions 2, 3, and 4.

The results show a quite large variability at the same sample zones, particularly for the elastic modulus over the beam web. This is mostly due to the differences in local concrete composition as well as deterioration state. The outcome of each test is affected by aleatory uncertainties associated with measurement errors. The overall sample mean $\bar{x}$ and sample coefficient of variation (i.e. CoV) of the static elastic modulus are 29.89 GPa and 0.17, respectively. The statistical confidence intervals provide a quantitative measure of accuracy of point estimates of descriptors, such as sample mean and sample standard deviation. Considering a Student's *t*-distribution for the standard variate associated to elastic modulus sample mean $\bar{x}$, the two-sided 95% and 99% confidence interval are ($\bar{x} \pm 1.54$ GPa) and ($\bar{x} \pm 1.95$ GPa), respectively.

Goodness-of-fit tests allow to estimate the validity of probability distribution models associated to random variables. Moreover, when different distributions appear to be plausible models, the same test may be used to discriminate the relative goodness-of-fit among assumed distribution models (Ang & Tang 2007). Considering a set of n=55 observed values of concrete elastic modulus, Fig. 7a shows the results of the χ^2 test comparing empirical probability mass function (PMF) and theoretical probability density functions (PDF) of assumed distributions. Furthermore, Fig. 7b shows the result of the Kolmogorov-Smirnov test, which compares the experimental cumulative frequency with the cumulative distribution function (CDF) of assumed theoretical distributions. Both statistical tests are passed with a significance level of 5% indicating a slightly higher accuracy on modelling the elastic modulus as a lognormal random variable.

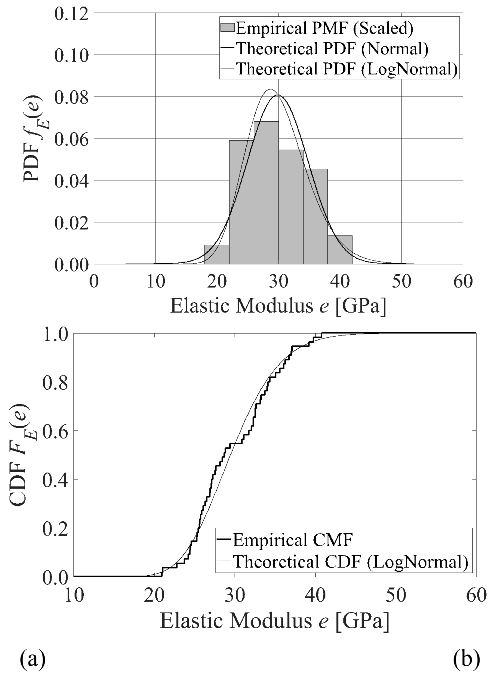
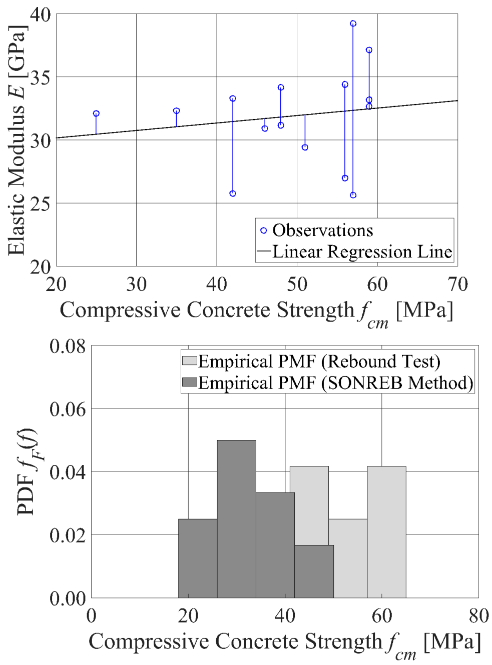


Fig. 7. Concrete elastic modulus distributions: (a) χ^2 and (b) K-S statistical tests.

The rebound number S from the rebound hammer test is converted into concrete compression strength. The overall sample mean and CoV of concrete strength f_{cm} are 49.33 MPa and 0.20, respectively. Fig. 8a shows the scattergram and the corresponding linear regression line of concrete elastic modulus E and concrete strength f_{cm}. A more accurate estimate of concrete strength f_{cm} based on SONREB method is provided in Fig. 8b after calibration of coefficients a, b, and c, based on Giacchetti & Lacquaniti (1980).



(a) (b)

Fig. 8. Experimental results: (a) scattergram and linear regression of concrete strength vs elastic modulus; (b) updating of concrete strength based on the SONREB method.

5 Conclusions

The preliminary results of on-site experimental activities based on non-destructive diagnostic tests carried out within the BRIDGE|50 research project have been presented. NDT devices have been described focusing on functioning principles and critical aspects such as necessary calibration procedures and accuracy limitations in operational conditions. The experimental results obtained for several PC deck beams have been presented and discussed through confidence intervals, statistical tests, and linear regression analysis. The results show a quite large variability of the concrete elastic modulus for different PC beams, as well as along each single beam due to the differences in local concrete composition and deterioration state. Furthermore, concrete strength exhibits significant dispersion based on sample zones and NDT methods (rebound or SONREB method). The results of these NDTs carried will be used for calibration and validation of structural analysis models and corrosion deterioration models to support a proper planning and interpretation of full-scale load tests to be performed on the deck beams within the ongoing BRIDGE|50 research project. This project is expected to advance life-cycle design of bridges and to improve safety, maintenance, and management of existing infrastructure systems.

Acknowledgments

BRIDGE|50 is a research project based on a research agreement among universities, public authorities, and private companies. Members of the Management Committee: S.C.R. Piemonte (President); Politecnico di Milano (Scientific Coordinator); Politecnico di Torino (Scientific Responsible of the Experimental Activities); Lombardi Engineering (Secretary); Piedmont Region; City of Turin; Metropolitan City of Turin; TNE Torino Nuova Economia; ATI Itinera & C.M.B.; ATI Despe & Perino Piero; Quaranta Group. BRIDGE|50 website: http://www.bridge50.org

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