Experimental tests for mechanical characterization of prestressed concrete bridge deck beams

Life-Cycle of Structures and Infrastructure Systems – Biondini & Frangopol (Eds)

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ABSTRACT: This paper presents the preliminary results of extensive experimental activities for mechanical characterization of 50-year-old prestressed concrete bridge deck beams within the BRIDGE|50 research project (http://www.bridge50.org). The experimental campaign includes non-destructive diagnostic tests (e.g. sclerometer and ultrasonic tests) carried out on several prestressed concrete deck beams and laboratory mechanical tests on concrete cores extracted from both precast beam and cast-in-situ slab. The results of these activities have been used for calibration and validation of structural analysis models and to support a proper planning of full-scale load tests up to collapse to be performed on the deck beams.

1 INTRODUCTION

Aging and deterioration processes, combined with poor durability and lack of maintenance and repair activities, may drastically affect in time the load bearing capacity reducing the structural lifetime of bridges. This is nowadays an urgent problem in many countries, including Italy, since there is a large number of bridges built over the past 50 years that are approaching the end of the service life and a significant percentage of them are in a state of moderate to severe deterioration (Malerba 2014, ASCE 2021). The amount of maintenance and repair activities necessary to restore or increase the structural capacity and functionality of deteriorated bridges is huge and represents a relevant obstacle to infrastructure facilities management for owners and public authorities. This critical situation is made more evident by recent bridge and viaduct collapse events that have occurred with alarming frequency. It is therefore of paramount importance to establish effective life-cycle criteria, methods, and tools for bridge assessment, maintenance and management under uncertainty (Biondini and Frangopol 2016, 2019).

Despite significant developments accomplished in the last decades, life-cycle approaches still need to be consolidated by robust validation and accurate calibration and gathering new information and data from existing bridges and experimental tests is key to this purpose. BRIDGE|50 is a research project established jointly by Politecnico di Milano and Politecnico di Torino as part of a research agreement with public authorities and private companies to collect data from inspection activities and experimental tests on deteriorated bridge components and investigate the residual structural performance of existing bridges. This project includes a wide experimental campaign on a set of 29 Prestressed Concrete (PC) deck beams (25 PC I-beams and 4 PC box beams) with top Reinforced Concrete (RC) slab and 2 PC pier caps stored in a testing site after the dismantling of a viaduct in service for about 50 years (Biondini et al. 2021a, 2021b, 2022, Savino et al. 2022). The on-site activities include non-destructive diagnostic tests, full-scale load tests up to collapse, and concrete samples collected for laboratory tests. This paper presents the preliminary results of the non-destructive tests and laboratory tests for mechanical characterization of the PC bridge deck beams. The results of these activities have been used for calibration and validation of structural analysis models

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(Anghileri and Biondini 2022) and to support a proper planning of full-scale load tests up to collapse to be performed on the PC deck beams (Tondolo et al. 2022).

2 PRELIMINARY ON-SITE INVESTIGATION

The experimental campaign of the research project started with a series of preliminary activities conducted on-site before the dismantling of the viaduct. These activities included visual inspections of the bridge components. Visual inspections have been conducted according to national and international standards with the participation of public authorities and private managing bodies. The large and diversified amount of data gathered through these activities has been elaborated according to inspection models typically used in practice (Beltrami et al. 2021).

Concrete coring from a bridge pier and carbonation tests have been conducted to investigate the aging and deterioration effects. Concrete split cores have been extracted from a bridge pier and carbonation depth has been assessed using a phenolphthalein solution as an indicator of the location of the depassivation front. A dynamic tests campaign has been also carried out on the bridge decks to characterize the dynamic behavior of the decks under service condition. Dynamic measurements have been acquired by using instrumented hammer and free-falling mass devices. The collected data have been analyzed in order to extract the principal modal components. The comparison of these results with those provided by full-scale experimental tests conducted in the testing site have been used to investigate the effectiveness of dynamic identification procedures in the assessment of damaged bridges. A detailed description of this activity and a critical appraisal of the results are reported in Quattrone et al. (2021) and Sabia et al. (2021, 2022).

3 PC BRIDGE DECK BEAMS

The dismantling of the viaduct at the end of its service life allowed the opportunity to investigate the residual capacity of several PC elements. In particular, 29 PC deck beams and 2 PC pier caps of the viaduct have been moved and stored in a testing site. The preliminary activities of the experimental campaign started with the study of the I-shaped PC bridge deck shown in Figure 1. The beams are characterized by a total length of about 19.40 m and made of a precast PC beam with top cast-in-place RC slab.

Figure 1. PC bridge deck beams stored at the testing site.

The I-shaped bridge deck beams are reinforced with twenty 7-wire prestressing strands with straight longitudinal profile. The nominal diameter of the steel strands is 12.7 mm (effective area 99 mm^2). The initial prestressing stress, net of instantaneous and estimated long-term losses reported in the technical design documentation is σ_{pd}=836 MPa. However, based on the results of full-scale load tests and diagnostic activities aimed at evaluating the residual prestressing, the actual prestressing level after a lifetime of 50 years resulted significantly lower with respect to the design value, with a prestressing stress level σ_p=614 MPa estimated to best fit the experimental results of full-scale load tests (Anghileri 2022).

4 NON-DESTRUCTIVE TESTING

Rebound hammer tests and ultrasonic tests have been conducted on several PC bridge deck beams to characterize the concrete mechanical characteristics. The tests have been carried out by subdividing the beams in five sample portions representative of the longitudinal beam profile. Longitudinal steel bars and stirrups are detected by means of pacometer and marked on the beam surface. This allowed to define a grid of 3×3 points on both the rear and front side used for sclerometer and ultrasound emission and reception points.

Ultrasonic tests have been conducted to measure the propagation velocity of compressive mechanical waves along the beam. This method can allow to detect internal cracking and other defects as well as damage in concrete such as environmental deterioration due to aggressive chemicals and inadequate concrete cast. It is worth noting that the outcomes at beam lateral regions might be characterized by a lower accuracy with respect to the measurements over the beam web in the inner regions due to both larger irregularities in the material volume when larger distances are covered by the ultrasound waves and interaction with denser reinforcement pattern.

The ultrasonic test measures the time required by the ultrasonic waves to cross the beam depth which is converted to concrete elastic modulus assuming concrete density ρ=25 kN/m^3 and Poisson ratio ν =0.2, as reported in the design technical documentation. Figure 2 shows mean and standard deviation values of concrete elastic modulus E measured in correspondence of the support lateral regions and over the beam web regions for 11 PC I-shaped beams.

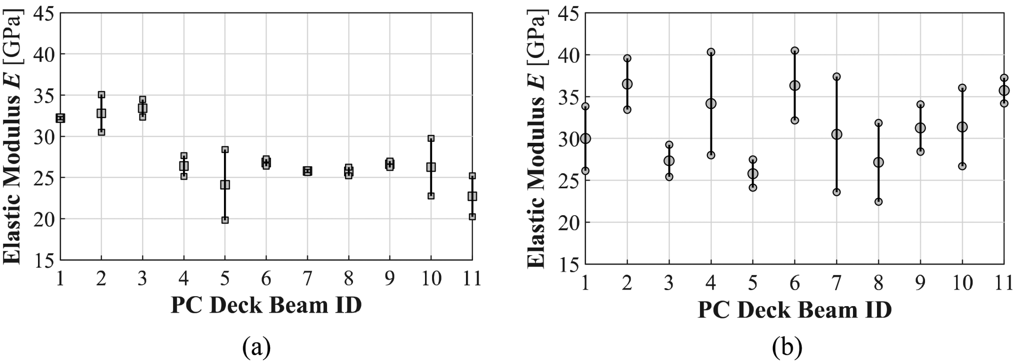

Figure 2. Mean and standard deviation values of elastic modulus E for 11 beams: (a) support regions, and (b) beam web regions.

The results show a quite large variability at the same sample zones, particularly for the elastic modulus over the beam web. This effect might be attributed to differences in local concrete composition and/or deterioration state. The overall sample mean x and sample coefficient of variation (CoV) of the concrete elastic modulus E are 29.89 GPa and 0.17, respectively. Moreover, assuming a Student's t-distribution for the standard variate associated to concrete elastic modulus sample mean x, the two-sided 95% and 99% confidence interval are (x± 1.54 GPa) and (x± 1.95 GPa), respectively. These statistical confidence intervals can provide a quantitative measure of accuracy of point estimates of the sample mean (Ang and Tang 2007). Also, considering the total set of samples n=55, Figure 3 shows the results of the χ^2 and Kolmogorov-Smirnov (K-S) statistical tests conducted to estimate the validity of probability distribution models associated to the considered random variable and discriminate the relative goodness-of-fit among assumed distribution models. The χ^2 test compares the empirical probability mass function and the theoretical probability density functions by assuming normal and lognormal distributions. The K-S test compares the experimental cumulative frequency with a lognormal cumulative distribution function. Both statistical tests are passed with a significance level of 5%.

The rebound hammer test is used to estimate the compressive concrete strength based on the correlation between material surface hardness and residual strength. In fact, the sclerometer includes a sliding mass coupled with a spring. 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, which is then converted into the estimated concrete strength through a correlation curve calibrated by the device manufacturer using standard specimens.

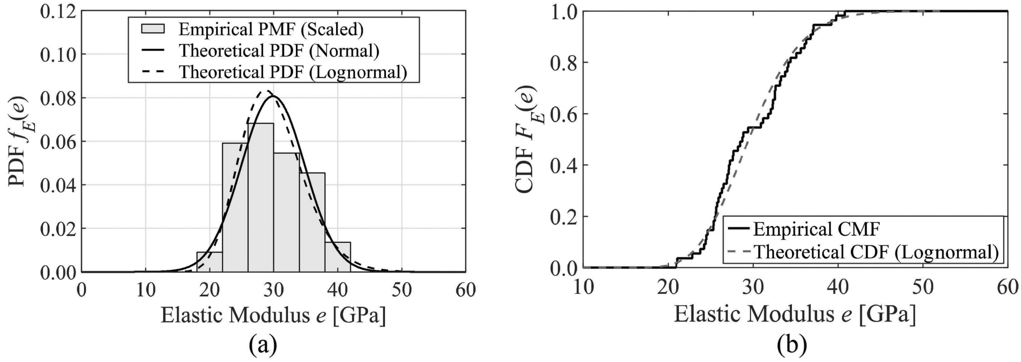

Figure 3. Concrete elastic modulus E distributions: (a) $\chi 2$ and (b) Kolmogorov-Smirnov statistical tests.

The rebound test is carried out after the ultrasonic test because the hammer blows may leave small marks on the beam that may affect the concrete surface roughness. The sclerometer test has been applied to three PC bridge deck beams collected in the testing site for a total of 15 sampling points. The rebound number S is converted into concrete compression strength. The overall sample mean and CoV of compressive concrete strength f_{cm} are 48.25 MPa and 0.20, respectively. The rebound hammer method generally provides a good estimate only of concrete cover strength. Even though concrete carbonation may lead to steel reinforcement corrosion, it generally increases the concrete strength. Therefore, the results of rebound tests may overestimate concrete strength. A more accurate estimate of the concrete strength has been evaluated based on SonReb method, with mean value f_{cm}=31.88 MPa and CoV=0.25. A detailed description of this activity is reported in Anghileri et al. (2021).

5 LABORATORY MECHANICAL TESTS

Laboratory mechanical tests have been performed on several concrete cores extracted from the PC bridge deck beams (Figure 4) after full-scale load tests have been performed. The concrete strength has been evaluated with uni-axial compressive tests on cylindrical samples characterized by aspect ratio 1:1 or 1:2 (Figure 5) and different diameter values (i.e., ∅75, ∅100, and ∅150 mm). The results showed a small variability between the samples extracted from three PC deck beams. Considering a set of n=17 samples, the overall sample mean and CoV of the concrete compressive strength f_c are 29.94 MPa and 0.15, respectively, showing a good agreement with the results of non-destructive tests processed through the SonReb method.

Figure 4. Coring of samples from PC bridge deck beams.

The tensile concrete strength has been evaluated through splitting tensile strength test (Figure 6). The experimental results showed a small variability between samples extracted from three PC deck

Figure 5. Uni-axial compressive strength tests on concrete samples.

beams also for the tensile concrete strength. Considering a set of n=9 samples, the overall sample mean and CoV of the concrete tensile strength f_{ct} are 3.33 MPa and 0.13, respectively.

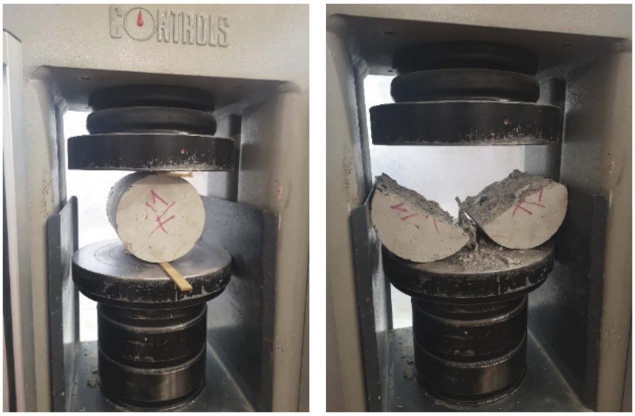

Figure 6. Splitting concrete tensile strength test.

The concrete elastic modulus has been also evaluated with uni-axial compressive strength test (Figure 7). Considering a set of n=8 samples, the overall sample mean and CoV of the concrete elastic modulus E_c are 27.22 GPa and 0.07, respectively. Moreover, the same eight samples have been used for uni-axial compressive tests to evaluate the complete stress-strain curves (Figure 8).

The level of concrete carbonation depth has been measured on the samples spraying a solution of phenolphthalein on concrete surfaces. Figure 9 shows the concrete carbonation depth assessment through a bar graph for concrete cores extracted from the support regions (rectangular cross-section) and beam web regions (I-shaped cross-section) of three PC deck beams.

Two tensile concrete strength tests have been also performed on concrete cores extracted from the top RC slab of the deck beams. Moreover, tensile tests have been conducted on samples of both prestressing strands and reinforcing bars. Table 1 and Table 2 summarize the mechanical properties of materials for both precast PC bridge deck beams and cast-in-situ RC slab, respectively, as evaluated from the complete set of information collected from available technical documentation, results of laboratory tests on samples, and results of on-site non-destructive testing.

The deck beams, particularly in the end regions, exhibit local damage due to corrosion with steel mass loss and concrete spalling. These effects can be attributed to the inadequacy of the bridge water conveyance system and use of road salts during the service life of the bridge.

Figure 7. Uni-axial concrete compressive test for elastic modulus assessment.

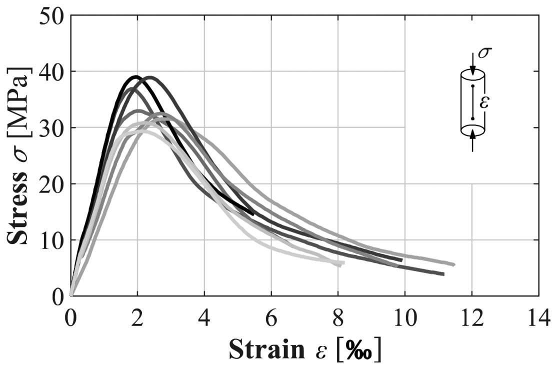

Figure 8. Uni-axial stress-strain curves of concrete in compression.

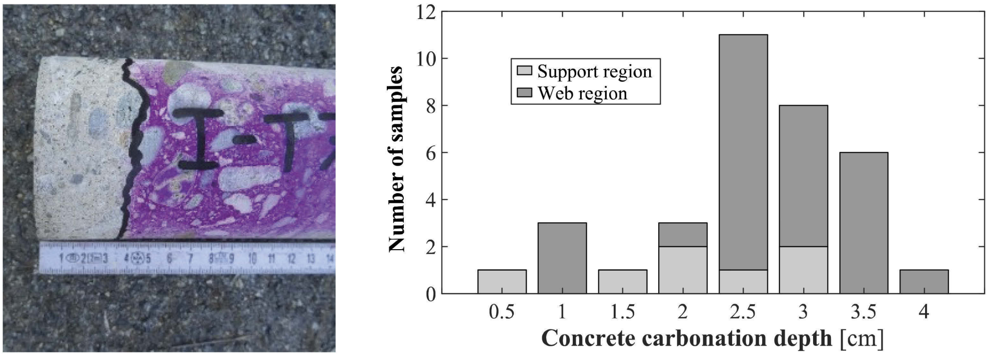

Figure 9. Concrete carbonation depth assessment.

However, based on visual inspections of the tested beams in the failure regions after the full-scale load tests, no significance corrosion of the prestressing strands has been observed. This indicates a relatively good attention during the construction phase of the precast PC beams.

The results of visual inspection activities, non-destructive and destructive tests, and laboratory tests have been also used for validation and calibration of structural modeling for non-linear analysis (Anghileri and Biondini 2021, 2022, Anghileri 2022) and a proper plan of the full-scale load tests (Tondolo et. al 2022, Savino et. al 2023).

Table 1. Nominal material characteristics of precast PC bridge deck beam.

Material characteristic	Value
Compressive concrete strength, f_c	-29.94 MPa
Tensile concrete strength, f_{ct}	3.33 MPa
Concrete elastic modulus, E_c	27.22 GPa
Steel bar yielding strength, f_{sy}	450 MPa
Steel bar ultimate strength, f_{su}	540 MPa
Steel bar elastic modulus, E_s	200 GPa
Steel strand yielding strength, f_{py}	1486 MPa
Steel strand ultimate strength, f_{pu}	1722 MPa
Steel strand elastic modulus, E_p	195 GPa

Table 2. Nominal material characteristics of cast-in-situ RC slab.

Material characteristic	Value
Compressive concrete strength, f_c	-26.00 MPa
Tensile concrete strength, f_{ct}	2.35 MPa
Concrete elastic modulus, E_c	27.00 GPa
Steel bar yielding strength, f_{sy}	450 MPa
Steel bar ultimate strength, f_{su}	540 MPa
Steel bar elastic modulus, E_s	200 GPa

6 CONCLUSIONS

Experimental activities based on non-destructive and laboratory tests carried out on concrete samples extracted from several 50-year-old PC bridge decks beams with cast-in-situ RC slab have been presented. Non destructive diagnostics included rebound hammer tests, ultrasonic tests, pacometer tests, sclerometric tests, and ultrasonic tests. The results of the non-destructive tests have been elaborated based on confidence intervals and statistical tests. The mechanical properties of materials have been estimated based on laboratory tests on concrete cores and samples of prestressing strands and reinforcing bars. For concrete, the results of laboratory tests show good agreement with the results of non-destructive tests processed through the SonReb method. Furthermore, concrete carbonation has been measured with higher carbonation depths in the web regions of the PC deck beams. For prestressing strands, no significance corrosion has been found based on visual inspections of the tested beams in the failure regions after the full-scale load tests.

The results of these experimental tests will be continuously updated based on the ongoing activities of the BRIDGE|50 research project and 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.

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REFERENCES

Ang, A. H.-S., Tang, W. H. 2007. *Probability concepts in engineering: Emphasis on applications to civil and environmental engineering*. Vol. 1, Wiley.

Anghileri, M. 2022. *Life-cycle structural performance of RC/PC bridges: computational modeling and experimental validation*. PhD thesis. Politecnico di Milano.

Anghileri, M., Biondini, F. 2021. Nonlinear structural analysis of PC bridge deck beams. *1st Conference of the European Association on Quality Control of Bridges and Structures* (EUROSTRUCT 2021), August 29 – September 1, 2021, Padua, Italy.

Anghileri, M., Biondini, F. 2022. Formulation and experimental validation of nonlinear finite element analysis of PC bridge deck beams. *11th International Conference on Bridge Maintenance, Safety and Management* (IABMAS 2022), July 11 –15, 2022, Barcelona, Spain.

Anghileri, M., Savino, P., Capacci, L., Bianchi, S., Rosati, G., Tondolo, F., and Biondini, F. 2021. Non-destructive testing and model validation of corroded PC bridge deck beams. *First Conference of the European Association on Quality Control of Bridges and Structures* (EUROSTRUCT 2021), August 29 – September 1, 2021, Padua, Italy.

ASCE 2021. *Report card for America's infrastructure*. America Society of Civil Engineers, Reston, USA.

Beltrami, C., Bianchi, S., Cervio, M., Anghileri, M., Felicetti, R., Quattrone, A., Chiara, M., Salza, B., and Masala, D. 2021. Bridge visual inspections: Experience of local authorities and the case study of the Corso Grosseto viaduct. *Tenth International Conference on Bridge Maintenance, Safety and Management* (IABMAS 2020), June 28-July 2, 2020 (postponed to April 11-15, 2021), Sapporo, Japan.

Biondini, F., Frangopol, D. M. 2016. Life-cycle performance of deteriorating structural systems under uncertainty: Review. *Journal of Structural Engineering*, American Society of Civil Engineers, 142 (9), F4016001.

Biondini, F., Frangopol, D. M., (Eds.) 2019. *Life-cycle design, assessment, and maintenance of structures and infrastructure systems*. American Society of Civil Engineers, Reston, USA.

Biondini, F., Manto, S., Beltrami, C., Tondolo, F., Chiara, M., Salza, B., Tizzani, M., Chiaia, B., Lencioni, A., Panseri, L., and Quaranta, L. 2021a. BRIDGE| 50 research project: Residual structural performance of a 50-year-old bridge. *Tenth International Conference on Bridge Maintenance, Safety and Management* (IABMAS 2020), June 28-July 2, 2020 (postponed to April 11-15, 2021), Sapporo, Japan.

Biondini, F., Tondolo, F., Manto, S., Beltrami, C., Chiara, M., Salza, B., Tizzani, M., Chiaia, B., Lencioni, A., Panseri, L., and Quaranta, L. 2021b. Residual Structural Performance of Existing PC Bridges: Recent Advances of the BRIDGE|50 Research Project. *First Conference of the European Association on Quality Control of Bridges and Structures* (EUROSTRUCT 2021), August 29 – September 1, 2021, Padua, Italy.

Malerba, P. G. 2014. Inspecting and repairing old bridges: Experiences and lessons. *Structure and Infrastructure Engineering*, Taylor & Francis, 10 (4), 443–470.

Quattrone, A., Sabia, D., Tondolo, F., Capacci, L., Lencioni, A., and Legramandi, C. 2021. Dynamic tests and modal identification of Corso Grosseto viaduct decks before the dismounting. *Tenth International Conference on Bridge Maintenance, Safety and Management* (IABMAS 2020), June 28-July 2, 2020 (postponed to April 11-15, 2021), Sapporo, Japan.

Sabia, D., Quattrone, A., Tondolo, F., and Savino, P. 2021. Dynamic identification of damaged PC bridge beams. *First Conference of the European Association on Quality Control of Bridges and Structures* (EUROSTRUCT 2021), August 29 – September 1, 2021, Padua, Italy.

Sabia, D., Quattrone, A., Tondolo, F., and Savino, P. 2022. Experimental evaluation of the effect of controlled damages on the dynamic response of PC bridge beams. *11th International Conference on Bridge Maintenance, Safety and Management* (IABMAS 2022), July 11 –15, 2022, Barcelona, Spain.

Savino, P., Tondolo, F., Sabia, D., Quattrone, A., Biondini, F., Rosati, G., Anghileri, M., Chiaia, B. 2023. Large-scale experimental static testing on 50-year-old prestressed concrete bridge girders, *Applied Sciences*, MDPI, 13(2), 2023, 1–22.

Tondolo, F., Sabia, D., Chiaia, B., Quattrone, A., Savino, P., Biondini, F., Rosati, G., and Anghileri, M. 2022. Full-scale testing and analysis of 50-year old prestressed concrete bridge girders. *11th International Conference on Bridge Maintenance, Safety and Management* (IABMAS 2022), July 11 –15, 2022, Barcelona, Spain.