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Assessment of concrete strength combining direct and NDT measures via Bayesian inference

Renato Giannini [a], Lorena Sguerri [a], Fabrizio Paolacci [b,*], Silvia Alessandri [b]

[a] Department of Architecture, University Roma Tre, Rome, Italy
[b] Department of Engineering, University Roma Tre, Rome, Italy

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ABSTRACT

Assessment of existing reinforced concrete structure entails a series of steps, among which the evaluation of the mechanical properties of concrete can be considered a corner-stone. To this end, direct compression tests on cores extracted directly from a structure provide the most reliable estimation of the strength. Unfortunately, the number of cores usually accepted is often limited because the method is expensive and invasive.

For this reason, non-destructive (ND) methods are mostly used, whose results are usually calibrated using a limited number of destructive tests, to provide some preliminary information about the homogeneity of the investigated concrete and possibly to suggest zones where to extract other cores.

In addition, non-destructive tests may be used to enlarge the database for the estimation of concrete strength. The main drawback in using this approach is that a correlation formula between the in situ measures and concrete strength is required. In many cases, such formula cannot be easily generalized and must be restricted every time based on pairs of indirect and direct measures of strength. Moreover, the use of different experimental techniques (destructive and non-destructive) provides information with different reliability, and the results are thus difficult to combine. For these reasons, in this paper, a technique based on Bayesian inference is proposed to combine in a rational manner the results of direct and indirect measures, providing the probabilistic distribution of the concrete strength and some significant properties such as the median and characteristic value.

In this paper, the proposed methodology is developed by considering the ultrasonic pulse velocity (UPV) technique, one of the most popular non-destructive methods employed for the evaluation of concrete strength, although it may be easily extended to other types of in situ measures. To validate the proposed method, two real cases, for which experimental data are available, are analyzed and discussed.

1. Introduction

In many European countries, particularly in Italy, most of the reinforced concrete constructions date back to the reconstruction after the Second World War. After fifteen years, the concrete of these structures began to show significant aging phenomena, often due to the poor quality of concrete caused in turn by a limited knowledge of concrete mix design and a limited number of quality control checks.

In addition, in Italy, the seismic regulations at that time were inadequate given that only a limited portion of territory was classified as seismic and the codes were based on the allowable stress approach, which required a check against a horizontal force equal to 7% and 10% of the construction weight for the second and first seismic category, respectively.

Currently, almost the entire Italian territory is considered seismically hazardous: thus, most of the modern and historic constructions have been designed based on a code, which, only partially accounted for the seismic action, and in some cases not at all. Therefore, the assessment of the real strength in existing structures, in particular against earthquakes, can be considered a problem with a high social and economic impact, whose importance in the future will certainly increase, given the aging effect of materials.

Even though tools for the assessment of structural resistance are the same both for existing and new constructions, the evaluation of these latter deserve particular attention for specific problems relevant to geometrical (e.g. placement of reinforcement in

* Corresponding author. Address: via Vito Voltrra 62, 00146 Rome, Italy. Tel.: +39 0657336418.

E-mail address: fabrizio.paolacci@uniroma3.it (F. Paolacci).

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Nomenclature

a, b	coefficients of the r–v regression function
g	degrees of freedom of the t-distribution
n	total number of UPV measures
n_c, n'_c	number of cores extracted from the structure
n_i	dimension of the sample $\mathbf{v}_i$
n_v	number of the UPV measures used for the evaluation of the prior distribution of r
r	compressive concrete strength (logarithm)
$\mathbf{r}_c$	vector containing the measured compressive concrete strength (logarithm)
$\bar{r}_c, \bar{r}'_c$	sample mean of the compressive concrete strength (logarithm)
f_c	compressive strength of concrete
t_0	reference value of t over which the hypothesis of homogeneity is refused
S^2	sample variance of differences from the means of UPV of two homogeneous zones
s_{rc}, s'_{rc}	sample standard deviation of the compressive concrete strength (logarithm)
s_{rv}	sample covariance from UPV measures and compressive strength of cores (logarithm) used for calibrating the r–v regression function
s_{v_i}	standard deviation of the data in sample $\mathbf{v}_i$
s_v	sample standard deviation of the UPV measures (logarithm) used for the evaluation of the prior distribution of r
s_z	sample standard deviation of z
V	UPV measures
v	logarithms of the UPV measures
$\mathbf{v}_i$	vector containing the UPV measures (logarithms) concerning the homogeneous zone i
$\bar{v}$	sample mean of the UPV measures (logarithm) used for the evaluation of the prior distribution of r
$\bar{v}_c$	sample mean of the UPV measures (logarithm) used for calibrating the r–v regression function
$\bar{v}_i$	mean of the sample $\mathbf{v}_i$
z	difference of the logarithmic strength of cores r and the term bv of the regression.
$\bar{z}$	sample mean of z
α	accepted value of probability for type I error
ε	error of the regression function
Δv	$\bar{v} - \bar{v}_c$
μ	mean value of a random variable
ρ_{rv}	correlation coefficient between r and v
σ	standard deviation of a random variable

RC construction) and mechanical aspects (e.g. assessment of mechanical properties of concrete). For poor quality and handmade concrete, as often seen in the past, this aspect is particularly critical due to the variability of strength. In fact, the concrete strength depends on several factors that may not be properly controlled during the construction process. In addition, the collapse of frame structures often results from a deficiency in the concrete strength, which strongly affects the capacity of the columns to carry vertical loads [1].

The most reliable method for the in situ measurement of concrete strength is compression testing on cores extracted from the concrete structure. Although this method is not errorless and requires the use of correction factors to account for the dimensions of the core and the method of sampling [2], in the following, the values measured by a direct compression test will be assumed to be the actual concrete strength at the measuring point. Unfortunately, this type of test is invasive and expensive, particularly for structures in service conditions. For these reasons, the number of cores extracted from the structure might be extremely limited.

To enlarge the survey field, in addition to results on cores, it is possible to use non-destructive measures. These latter methods do not alter the structure and are in general less expensive; therefore, they can be more numerous and widespread within the structure. Several non-destructive methods are available for evaluating concrete strength; however, in all cases, their reliability in estimating the concrete strength depends on the degree of correlation between the measured quantities and the concrete strength [3,4].

In this work, the ultrasonic pulse velocity method (UPV), one of the most popular non-destructive methods, will be used as it is completely non-invasive and easy to execute. Nevertheless, wave propagation into the concrete depends on several factors which can affect its velocity and consequently the estimation of compressive strength. A general regression formula requires not only the ultrasonic velocity, but the knowledge of different factors (such as the water/cement ratio and aggregate characteristics) that are often unknown, in particular for very old concretes. One possible approach consists of calibrating multivariable regression models based on indirect measures and several concrete properties (e.g. density, mix proportions, cement strength, etc.) [5], and updating the strength values using, when available, the results on cores extracted from the structure [6]. Similar considerations can be found in more recent approaches based on non-parametric methods, such as neural networks [7,8]. The conclusion is that in practice, it is not possible to obtain a unique general regression function between ultrasonic pulse velocity and concrete strength, as clearly stated by many authors [9–11], even though some codes (e.g., the European [12] or the American codes [13,14]) suggest formulas, which are often criticized [15].

A simple approach to overcome this drawback is to build a specific regression formula case by case. This approach requires that some direct and indirect tests be executed at the same points of the structure. If the concrete is supposed to be homogeneous in terms of aggregates, water/cement ratio and environmental conditions (a reasonable hypothesis if referred to a single construction), the regression function would not be affected by systematic errors.

These correlation functions can be used to obtain more information on the concrete strength by extending the non-destructive tests to a larger number of points in the structure, although these estimates are clearly less reliable than those obtained by direct compression tests. This approach entails the execution of different measurements, characterized by a different degree of accuracy: the direct ones, conventionally considered exact, and the indirect ones, affected by the inherent dispersion of the regression function. Consequently, the problem of using data with different reliability levels should be addressed.

A limited number of contributions on this subject are observed in the literature. For example, an interesting approach was suggested by Kriviak and Scanlon [16]; they adopted the Bayesian approach to update the strength, estimated by non-destructive measurements (UPV or SonReb), using compression test results on cores. However, the authors use a simplified formulation, neglecting the uncertainty of the variance of the estimated quantities.

In the present paper a similar approach is proposed, but within a more systematic framework, based on the theory of small samples, accounting for the uncertainty of the regression parameters and the distribution of strength.