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Influence of spatial correlation of core strength measurements on the assessment of in situ concrete strength

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ABSTRACT

Many countries are experiencing an increasing need of checking the safety of existing structures. The assessment of structural capacity of RC structures strictly depends on the in situ compressive strength of concrete. The evaluation of this property is typically carried out by means of destructive tests on concrete cores taken from the structure. The experimental data is then interpreted using a relevant code to obtain a design strength value according to the required percentile and confidence. In this paper the principal international standards that deal with the statistical interpretation of data from concrete core tests are presented. Since it is reasonable to assume that concrete strength is a realization of a random field, the assumption of statistical independence of core test data is questioned. An extension of the classical theory of tolerance limits in the case of normally distributed correlated samples is thus proposed. Finally, application examples of this methodology are provided to illustrate some important implications of the spatial correlation of core test values on concrete strength estimations.

1. Introduction

In the last decades many countries have experienced an increasing need of assessing the performances of old buildings and infrastructures. The evaluation of existing structures is becoming a prominent priority in many countries where strong earthquakes are frequent and where a great share of the built heritage dates back to just after the World War II, when no code prescriptions were available to protect the structures against the seismic action. An accurate evaluation of the existing structures may allow to plan and execute strengthening interventions to reduce causalities in case of earthquakes and to guarantee the functionality of strategic structures, such as hospitals, when such extreme events occur.

The need of assessing existing structural systems may also be due to their aging and degradation. As an example, in the United States the various Departments of Transportation have the duty of periodically checking the conditions of existing bridges. In case of necessity an evaluation of the residual load bearing capacity has to be performed either to post the bridge for load or to plan and execute a repair or strengthening intervention. The most recent data contained in the National Bridge Inventory Database suggest that about 10% of existing bridges in the United States are structurally deficient. It is thus clear how the evaluation of the safety of existing bridges is a task that is as important and critical as guaranteeing the safety of new ones.

Finally, in countries were an old built heritage is available, the need of both preserving and reusing the traditional constructions leads to the necessity of assessing the structural capacity against new load conditions.

The result of all these different needs is that several countries have developed codes specifically aimed at providing tools and guidelines for the assessment of existing structures. As an example, in Europe prescriptions for performing this kind of evaluations have been given in the Eurocode 8 [1], specifically to address the problem of checking the safety of old buildings against earthquake-induced actions. In the United States, the American Concrete Institute released the ACI 562-16 [2] with the intention of providing minimal guidelines for the evaluation, repair and strengthening of existing RC structures. Similar indications have been released by AASHTO with the Manual for Bridge Evaluation [3] to give instructions specifically aimed at evaluating and rating the structural conditions of existing bridges.

Any kind of in-depth structural evaluation must take into consideration the properties of structural materials. Compressive strength of concrete is surely one of the prominent factors which affects the overall safety of a RC structure. Any assessment begins with a survey of the structural system and of the existing docu-

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mentation, which may contain information also on the materials that had been used for the construction. However oftentimes these documents have been lost or may be unreliable, so that an experimental evaluation of the material properties is almost always required.

The assessment of in situ concrete compressive strength is typically performed extracting concrete cores from the structure and then by testing them in compression testing machines. This type of evaluation can be integrated by the use of non-destructive techniques, like SonReb tests, which however always require a proper calibration with destructive data to provide meaningful information and are particularly sensitive to external factors such as concrete carbonation [4,5] and water content.

Many uncertainties are involved in the evaluation of in situ concrete core strength results and thus statistical tools are needed to interpret test data. This need is even more relevant for old RC structures and infrastructures built before the eighties, for which is known that the quality of the material and workmanship were far below the actual practice [6]. A brief review of some of the possible statistical methods for the evaluation of experimental data has been given by Indelicato [7].

Several standards have been published to give details on how a correct assessment of in situ strength of concrete should be performed. Nevertheless, these codes adopt different ways of interpreting the core strength test results, and some of them are even scarcely justified. It is however clear that the approach chosen for the evaluation of concrete strength from test data can significantly influence the estimations of the safety levels of existing structures [8]. Furthermore, all existing standards implicitly assume that the measured core strength values are independent one to each other, even though it is reasonable to think that in situ concrete strength is actually a realization of a random field with a certain correlation function.

One of the consequences of the assumption of independence of sample test values is that codes e.g. ACI 214.4R [9] suggest to choose core locations at random. In presence of spatial correlation however more rational sampling schemes should be developed to optimally extract cores so to maximize the amount of information on the field. With regard to this problem, recent researches [10,11] are promoting the use of NDT data to select in a more rational and representative way the sampling locations, rather than haphazardly choosing them.

This work is thus aimed at providing a consistent statistical framework, within the statistical theory of tolerance limits, to investigate the influence of spatial correlation of core test values on the confidence of in situ concrete strength assessment. In detail the objective has been the generalization of the tolerance factor method of the ACI 214.4R code to make it applicable to any correlation function. The advantage of this latter compared to other literature approaches currently in use is that it is statistically well-supported and tunable, as the user can select the desired confidence level in the estimates.

This basic framework might be used for the definition of more accurate assessment procedures which are able to take into account the levels of correlation of the material strength measurements. The proposed approach does not consider epistemic uncertainties, which may turn out to be not-negligible [12], but focuses its efforts in the reduction of the effects of aleatory uncertainty in the estimates due to the spatial correlation of strength measurements.

2. Current approaches

In this section the most relevant standards that deal with the assessment of in situ strength of concrete using cores are presented. The ACI 562-14 [2] is one of the most widely recognized codes for the assessment of existing structures. Its prescriptions on the evaluation of core test results are directly derived from the ACI 214-4R [9] that will be presented in the following section. For what it concerns European standards, the EN 13791:2007 is the main document that deals with the assessment of in situ concretes, even though Eurocode 8 [1] gives different prescriptions for what concerns the seismic evaluation of existing structures.

2.1. ACI 214-4R

The ACI 214-4R is a set of guidelines for the extraction of cores and interpretation of the compression test results. This document suggests two different approaches for the estimation of an equivalent in situ strength value to be used for the evaluation of the structural capacity of an existing structure.

Given a set of n core test data x_i with $i = 1 \dots n$, the ACI 214-4R suggests to correct these values to account for their different testing conditions (core diameter, length to diameter ratio, moisture content, damage due to drilling, etc.) multiplying the results by strength correction factors provided by the code itself. Since these factors have been empirically obtained by statistical interpretation of experimental results, they are subjected to a certain statistical variability [13], which must be accounted for in performing the evaluations. This is accomplished taking into consideration the standard deviation s_a of these correction coefficients, which is given by the code itself.

After having homogenized the test values, the interpretation of the results can be carried out following two approaches. The first one is termed the *tolerance factor method*, as it is based on the statistical theory of tolerance regions. Following this approach the estimation $f_{p,est}$ of a given pth percentile f_p of the in situ concrete strength distribution with a desired confidence level is obtained as:

$$f_{p,est} = \bar{x}_s - k s_s \tag{1}$$

where $\bar{x}_s$ is the mean value of the corrected test results, s_s is their standard deviation and k is a coefficient that depends on the desired confidence $1-\alpha$ (where α is the chosen probability of overestimating the given percentile) and on the number of samples n, under the hypotheses of independent and normally distributed samples. This coefficient can be evaluated [14] as:

$$k = k(n, p, \alpha) = t^{-1}_{n-1,1-\alpha}(z_{1-p}\sqrt{n})/\sqrt{n} \tag{2}$$

where $t^{-1}_{n-1,1-\alpha}(x)$ is the inverse non-central t distribution with $n-1$ degrees of freedom evaluated in $1-\alpha$ and with non-centrality parameter x. The term z_x represents the inverse cumulative distribution function of a standard normal distribution evaluated in x.

If the variability due to the uncertainty in the strength correction factors is accounted for, the following expression should be used:

$$f_{p,est} = \bar{x}_s - \sqrt{(k s_s)^2 + (Z s_a)^2} \tag{3}$$

where Z is a coefficient provided in the code as a function of the desired confidence level.

Alongside this approach, the ACI 214.4R defines an *alternate method* that is mainly based on the research of Bartlett and MacGregor [15]. These Authors stated that the tolerance factor approach may be too conservative mostly for two reasons. First of all, in their opinion the measured core test values overestimate the actual variability of the in-place concrete strength [16], furthermore they believe that this approach is too precise for the requirements of actual design practice.

As a consequence, the alternate method is less conservative. It is aimed at estimating the 10% percentile of concrete strength and it