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Influence of concrete strength estimation on the structural safety assessment of existing structures

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HIGHLIGHTS

- Monte Carlo simulations are used to evaluate concrete strength estimation methods.
- Estimation performance can be coupled to structural reliability quantification.
- Characteristics of estimation errors are calculated using numerical statistical methods.
- Performance of estimations should be considered when performing safety evaluations.
- The results serve as guidance for choosing estimation methods and number of samples.

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ABSTRACT

In case of existing concrete structures, the estimation of the characteristic strength values from limited data is a difficult, but important task. There are currently different commonly used estimation methods available, among which the classical coverage method, a Bayesian procedure with vague prior distributions (as mentioned in EN 1990) and the method described in EN 13791. There exists however currently no comprehensive framework in order to quantify the influence of these concrete strength estimation methods on the safety assessment of existing structures. In order to analyse this effect, a previously developed semi-probabilistic partial factor approach for the evaluation of existing structures is considered herein, namely the Adjusted Partial Factor Method. The influence of the different concrete strength estimation methods on the safety level of existing concrete columns is investigated, considering both the application of unchanged partial factors compared to new structures and partial factors adjusted according to the Adjusted Partial Factor Method. The performance of the different estimation methods are evaluated and compared using Monte Carlo simulations and FORM analyses. The relative performance of the estimation methods seem to be rather independent of the partial factor approach applied, however the Adjusted Partial Factor Approach allows to achieve a coherent performance with respect to a target reliability index and alternative reference period. The performance of the classical coverage method and a Bayesian method with vague prior information are comparable and yield a higher safety level when more than 5 test samples are considered. In case only very few concrete samples are used for the assessment (i.e. 3–5), the EN 13791 yields a comparable safety level, mainly due to the reduced variability with respect to the estimation error. Finally, the analysis also showed that for the investigated situation, taking more than about 8 test samples into account does not lead to an increase in assessed safety level.

1. Introduction

In contrast to the design of new structures, the assessment of existing structures often relies on the subjective judgement of the investigating engineer. However, in a previous analysis the authors have showed that an objective verification format for existing structures is feasible and they proposed an Adjusted Partial Factor Method for existing structures [1,2], which was elaborated and analyzed in detail in [3] and was also extended to be applied to temporary structures [4], enabling a rather simple and straightforward, but objective and coherent safety evaluation of concrete structures by practitioners in case of changed parameter assumptions. This framework is compatible with the current

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Eurocodes for the design of new structures, but additionally enables to incorporate alternative values for the target reliability level (see e.g. [18–20]), alternative values for the reference period (i.e. or remaining working life) and also updated information of variable uncertainty based on e.g. on-site inspection data and data from testing, as all these effects can considerably influence the partial factors in the structural reliability assessment of existing structures.

In case of concrete structures, the estimation of the characteristic strength values from limited data is a difficult, but important task when assessing the performance of existing structures. There are currently different estimation methods available in literature. First of all, the classical coverage method can be used for this assessment of the characteristic in situ compressive strength $f_{ck,is}$ from n test results (see e.g. [5]). Otherwise, based on the standards ISO 12491 [6], ISO 13822 [7] and ISO 2394 [8], the characteristic strength may also be determined using a prediction method which is referred to as a 'Bayesian procedure with vague prior distributions', which is also incorporated in the European Standard EN 1990 [9]. Finally, the assessment can also be based on the rather recent European Standard EN 13791 [10], which considers criteria which are closely linked to conformity assessment. A probabilistic analysis of the performance of these different estimation methods is available in [11].

These estimation methods inherently result in an additional uncertainty with respect to the variables considered in structural reliability analyses and as such these phenomena are important to consider when assessing the structural safety level as well as when comparing the risk-based performance of different partial factor methods. Hence this contribution focuses particularly on the quantification of the performance of different estimation methods on the safety level of concrete elements, by evaluating their influence on the structural reliability index calculated based on a FORM analysis [13] and taking into account the previously mentioned partial factor approach.

In Section 2 an overview is given of the estimation methods which are considered herein and will be compared with respect to their influence on the structural reliability index. Section 3 summarizes the previously developed Adjusted Partial Factor Method which will be applied for the structural evaluation. Consequently, the novel framework for the incorporation of the performance of estimation methods in structural reliability calculations and the comparison of the different estimation methods with respect to structural safety considerations is elaborated in Section 4, resulting in a set of conclusions which are summarized in Section 5.

Although specifically applied to concrete strength, this contribution provides an original analysis framework, as – to the best knowledge of the authors – no such information in order to combine the performance of estimation methods with structural reliability calculations is available in literature. Furthermore, the proposed methodology can also be applied to other structural parameters which have to be assessed when dealing with existing structures (e.g. the nominal cover depth, yield strength, reinforcement area, etc.).

2. Available estimation methods applicable to concrete strength assessment

In this first section a brief overview is provided with respect to the available commonly used estimation methods for concrete strength assessment based on destructive concrete compressive testing on a limited number of samples. Three methods are considered, namely the classical coverage method, a Bayesian method with vague prior information and the method provided in the European Standard EN 13791. A detailed numerical analysis of the performance of these different methods with respect to their bias and estimation variability is available in [11], from which is was found that the classical coverage method and the Bayesian method with vague prior information yield comparable, but rather conservative results. The estimation method described in EN 13791 was found to lead to a significant (unsafe) overestimation of the in situ characteristic concrete strength.

2.1. The classical coverage method

The classical coverage method allows to estimate the lower $\hat{x}_\alpha$ fractile $\hat{x}_\alpha$ of a population in such a way that the probability that the estimated $\hat{x}_\alpha$ is lower than the exact fractile x_α is equal to a chosen confidence level γ, which yields Eq. (1).

$$P[\hat{x}_\alpha \leqslant x_\alpha] = \gamma \tag{1}$$

This confidence level γ is often assumed to be 0.75, 0.90 or 0.95 [5].

If concrete strength is considered as a normally distributed variable and the coefficient of variation δ_X is unknown, the sample standard deviation s_X needs to be calculated and the estimated value for the in situ characteristic concrete compressive strength $\hat{f}_{ck,is}$ is calculated as:

$$\hat{f}_{ck,is} = \bar{x}(1 - \lambda d_X) \tag{2}$$

with $\bar{x}$ the sample mean, λ a coefficient depending on n and γ and $d_X = s_X/\bar{x}$ the sample coefficient of variation.

Hence, the coefficients λ depend on the sample size n and on the confidence level γ. The most important advantage of this method is the explicit knowledge of γ, which is the probability that the estimate $\hat{f}_{ck,is}$ will be on the safe side of the actual value $f_{ck,is}$. To take account of statistical uncertainties, a value of $\gamma = 0.75$ is recommended for this case in ISO 2394 [8].

Table 1 provides an overview of the coefficients λ in case the aforementioned coverage method is used (under the assumption of a normal distribution) and the coefficient of variation is unknown (which is a common assumption in case of concrete strength assessment of existing structures). In case a non-normal distribution is assumed to represent the concrete strength population, appropriate values for the coefficients λ can be obtained from [12].

The λ values from Table 1 can be calculated according to (see e.g. [12]):

$$\lambda = \frac{1}{\sqrt{n}} F^{-1}_{T;\nu;\eta}(\alpha) \tag{3}$$

with $F^{-1}_{T;\nu;\eta}(\alpha)$ the α fractile of the non-central t-distribution with parameters $\nu = n - 1$ and $\eta = \Phi^{-1}(\alpha)\sqrt{n}$.

2.2. Bayesian method with vague prior information (EN 1990)

In Annex D of the European Standard EN 1990 [9], which is in agreement with the International Standards ISO 2394 [8], ISO 12491 [6] and ISO 13822 [7], an estimation method is mentioned, which is called a 'Bayesian prediction method with vague prior distributions'. Based on the assumption of a normal distribution, this

Table 1
λ Values for the classical coverage method with unknown coefficient of variation [8].

	n							
	3	4	5	6	7	10	20	∞
$\gamma = 0.75$	3.15	2.68	2.46	2.34	2.19	2.10	1.93	1.64
$\gamma = 0.90$	5.31	3.96	3.40	3.09	2.75	2.57	2.21	1.64
$\gamma = 0.95$	7.66	5.14	4.20	3.71	3.19	2.91	2.40	1.64