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The potential of quality control in structural safety: A case study on shear resistance models without shear reinforcement

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Abstract

Normally, quality control strategies are used to verify whether a produced structural building material complies with the specified properties. In general, quality control has a favourable effect on the outgoing distributions of material and geometric properties of incoming inspected batches. Previous studies concerning concrete compressive strength demonstrated that this effect could influence the reliability level of concrete structures. Such benefits can be quantified by using Bayesian statistics in combination with reliability-based techniques such as First or Second Order Reliability Methods (Level II methods) or simulation methods as Crude Monte Carlo or Monte Carlo methods with variance reduction (Level III methods). Presented as a case study, this paper aims to illustrate the influence of quality control on the structural safety of a steel reinforced beam verified for shear resistance without shear reinforcement according to DIN EN 1992-1-1+NA. The positive results on the structural safety of beams highlight the relevance of considering quality control information in safety assessments and their potential to unlock structural safety margins.

Keywords

Quality control, Bayesian statistics, Structural reliability, Shear design

1 Introduction

Structural engineers often face challenges to solve complex statistical and probabilistic problems. Background code activities on the basis of reliability analyses are, usually, required for code calibration of new materials (e.g., textile reinforced concrete) as well as for conventional materials (e.g., steel reinforced concrete) and, thus, guaranteeing a continuous enhancement of structural codes.

Previous investigations have demonstrated the potential offered by quality control methods and their influence on the safety level of structural components and structures. The development of parametric studies with the support of reliability-based methods are vital for an accurate assessment of failure probabilities and reliability indices β (typically used as measures of structural safety) and, ultimately, to ensure a sufficient safety level of structures regarding to shear failure. It is also desired that the provisions of design codes should be a clear to prevent errors of interpretation and application. For example, for reasons of simplification, DIN EN 1992-1-1+NA [1] provides only a restrictive set of partial factors (partial safety factor) for the ultimate limit state design of steel reinforced concrete members (e.g., γ_C for concrete and γ_S for reinforcing steel). Complementary, the base structural code DIN EN 1990+NA [2] gives some information to derive design values from experimental data and provides basic instructions regarding reliability analysis procedures.

Besides these generic provisions offered by DIN EN 1990 or DIN EN 1992-1-1+NA, several additional reliability-based methods are available to assess the safety level of a component and to derive partial factors, which are thoroughly described in literature (e.g., [3],[4],[5]). For example, the First or Second Order Reliability Methods (FORM or SORM, respectively) (Level II methods) or simulation methods as Crude Monte Carlo or Monte Carlo methods with variance reduction (Level III methods), are well established techniques.

The above-mentioned process of code calibration and the development of partial factors requires knowledge of statistical, mathematical and engineering methods. This is

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particularly important for unconventional reliability problems, such as those that also consider quality control measurements. Thus, to understand the background assumptions needed to perform such reliability-based analyses while guaranteeing an adequate usage of the design codes, it is important that engineers are comfortable with reliability and stochastic concepts.

Meanwhile, a new DAfStb guideline [6] has been developed. This guideline will be published shortly and consists of different parts, with additional sections potentially including quality control in the future. In general, quality control strategies are used to verify whether a produced structural building material complies with the specified properties. Quality control influences the outgoing distributions of material and geometric properties of incoming inspected batches. Previous studies concerning concrete compressive strength demonstrated that this effect could influence the reliability level of concrete structures (e.g., [7],[8],[9]).

Benefits can be quantified by using Bayesian statistics in combination with reliability-based techniques. Presented as a case study, this paper aims to illustrate the influence of quality control on the structural safety of a steel reinforced beam verified for shear resistance without shear reinforcement according to DIN EN 1992-1-1+NA [1]. To this, different quality control levels – by means of pre-defined conformity control criteria – were considered. The results demonstrate the positive influence of quality control assessment on the structural safety of beams and highlight the relevance of considering quality control information in safety assessments and their potential to unlock structural safety margins.

2 Description of used Software Tools

This section describes the used open-source software library for reliability analysis in a general way. An advantage of this open-source platform in software language *R* allows a further scientific collaboration.

The used self-made software library which was developed in the context of a research project *TesiproV* [10] is a so-called *R* package in open-source programming software *R* [11]. The package called *TesiproV* [12] can carry out systematic parameter studies using different probabilistic reliability methods (e.g., FORM, SORM, Monte Carlo). Based on this, an overview on the probabilistic reliability methods implemented in the package as well as results of first parametric studies are given. The developed package allows to perform systematic and large parameter studies and provides different algorithms of reliability analysis in an effective way. The general structure of the software tool is shown in Fig. 1.

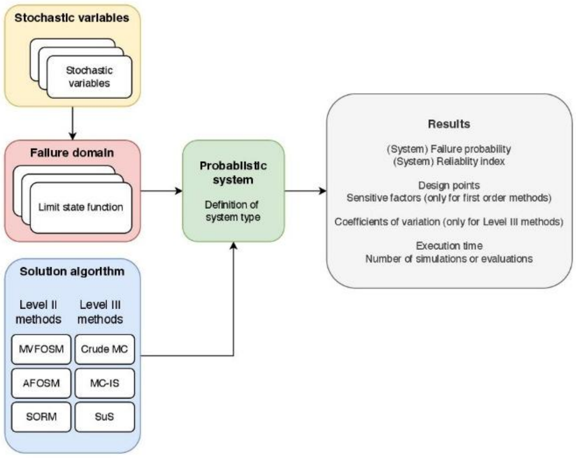

Figure 1 Structure of the software tool

The algorithm used for the parameter studies were Level II (FORM, SORM) as well as Level III (Crude Monte Carlo, MC with Importance Sampling, MC with Subset Sampling) methods.

This study was conducted within the scope of a project supported by the German Institute for Building Technology (in German: *Deutsches Institut für Bautechnik, DIBt*), which aimed to investigate the influence of quality control procedures on the safety level of structural components for practical applications. *An additional* goal of this DIBt-research project is to extend the capabilities of the above-described TesiproV software package from the perspective of quality control considerations on structural safety.

3 Structural safety and influence of quality control on reliability

A rough summary of methods to quantify the influence of quality control is given in this section.

3.1 Reliability theory

The safety elements (e.g., nominal values, characteristic values, partial factors) in the construction standards (e.g., Eurocodes) have remained largely unchanged since the 1980/1990s, although technological progress has taken place in the construction industry since then. The current standards define specific partial factors, such as $\gamma_C = 1.5$ for concrete and $\gamma_S = 1.15$ for reinforcing steel [1] in the permanent and temporary design situation. These constant partial factors suggest that the existing safety level is always at the same level for every design assessment regardless of geometry, material parameters or quality control influences, among others. The current standards allow for reduced partial factors to be utilised for specific cases, e.g., for precast elements with factory-made and continuously monitored production ($\gamma_{C,red} = 1.35$ according to the current DIN EN 1992-1-1, Annex A [1]) or for existing structures ($\gamma_{C,red} = 1.35$ according to DBV guideline [14]). So far, utilising existing reserves and taking into account the positive influence of quality assurance measures, have not yet been considered yet.

3.2 Bayesian statistics

Bayesian statistics forms a basis, for example, for updating the distributions of material parameters if additional information from quality control is available (e.g., [9],[13]). To update the statistical distributions of material and product properties, not only direct test results are used, but also indirect information, e.g., from conformity control assessments, can be considered to update the statistical distribution. These updated distributions are, the, directly utilised into the calculation of the probability of failure to determine the reliability of the components or supporting structures.

On the basis of Bayesian statistics, *Rackwitz* [15],[16] has proposed an analytical method for evaluating the filtering effect for some common basic conformance criteria. In practice, however, there are also more complex criteria. Monte-Carlo Simulations can used to transform such conformity criteria into the OC curve [9].

Conformity control criteria are, normally, described in standards or codes of practice. For example, in Germany, conformity control criteria for concrete compressive strength are provided in DIN EN 206 [18] and DIN 1045-2 [19] as well as in DAfStb booklet 526 [20]. Conformity control criteria for reinforcing steel can be found in DIN 488-6 [22] and in EN 10080 [21]. For more complex and further information with information about attribute and variable inspection additional references are available (e.g., [36],[37],[38]).

3.3 Filtering effect

Quantifying the filter effect is relatively straightforward by using the Bayesian Statistics if the operating characteristic is available. The so-called operating characteristic (OC) of a certain conformity criterion – also called OC curve – is a function $P_a(\theta)$, which indicates the probability P_a that an inspection lot characterised by the error proportion θ is accepted. The fraction defectiveness θ is the proportion of the population that is below a certain characteristic value X_k of a certain material property such as concrete compressive strength. The characteristic value is often defined as the 5% quantile of the distribution of the property. Further details are available, for example, in [13] and [17].

4 Reliability studies

4.1 Boundary conditions

Based on the conclusions drawn from the results found in literature, it could be noted that the increase in width b does not distinctly influence the shear strength [24],[25],[26],[27]. Therefore, the structural system used in [23] was used.

For calculations which are conducted later, a common beam is shown in Figure 2. It is also shown the initial values of the main influencing variables, which were varied in the ongoing parametric studies.

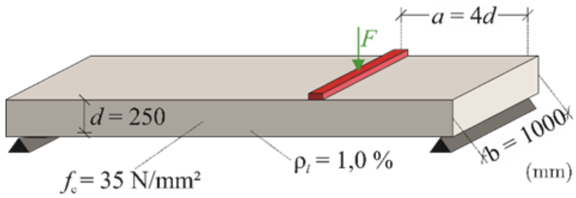

Figure 2 Initial values for the parameter studies on shear [23], [24]

A basic formulation of the limit state function $g(x)$ for the one-way shear capacity of RC members without shear reinforcement was formulated in accordance to DIN EN 1992-1-1+NA [1] as:

$$g(x) = K_R\, 0.15 \min\left\{1 + \left(\frac{200}{d}\right)^{0.5}; 2\right\} (100\, \rho_l\, f_c)^{\frac{1}{3}}\, bd - V_{Rd,c} \qquad (1)$$

To this, the effect of conformity control on the reliability index of this beam subjected to shear without shear reinforcement was quantified through the utilisation of reliability-based techniques (see section 5).

4.2 Basic variables

The stochastic models for the basic variables involved in the shear resistance model were retrieved from the JCSS Probabilistic Model Code [30]. Yet, alternative models can be defined on the basis of, for example, [32], [34]. The model uncertainty of the limit state function of shear resistance is characterized by the stochastic model of the basic variable K_R, derived from statistical analyses [23], [24]. A summary of underlying data is with the number of selected tests depending on ranges of values of influencing variable is given in Figure 3.

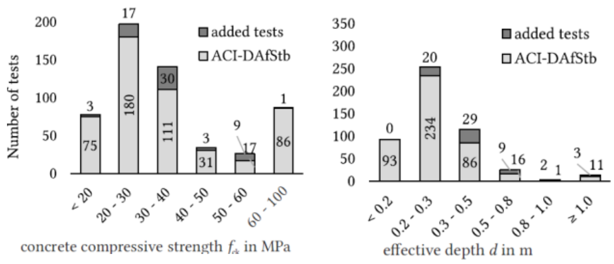

Figure 3 Number of selected tests depending on ranges of values of influencing variables [24], [25]

A summary of all the stochastic models for the basic variables which influence the limit state function for the parametric studies are given in in Table 1.

Table 1 Stochastic models for the basic variables (with literature [23],[30])

X	Variable	Dist.	X_k	μ_X	δ_X
f_c	Concrete compressive strength (C35/45; $\gamma_C = 1.5$) [MPa] [30]	LSt(*)	35	47.4	0.12
h	Height [m] [30]	N	0.3	0.3	0.01
d	Position reinforcement axis [m] [30]	N	0.25	d + 0.01	0.01
b	Width [m] [30]	N	1.0	1.0	0.01
ρ	Reinf. Ratio [-] [30]	N	1.0	1.0	0.02
K_R	Model uncertainty for resistance [-] [23]	LN	1.0	1.18	0.14

LSt: Log-student-t distribution; LN: Lognormal distribution; N: Normal distribution; GA: Gamma distribution; GU: Gumbel distribution of maximum values; μ_X: Mean value; δ_X: Coefficient of variation

(*) Hyperparameters for the Log-student-t distribution from PMC $m = 3.85$; $s = 0.12$; $n = 3$; $\nu = 6$ [30]

5 Reliability analyses

Parameter studies were carried out for the initial verification of the safety level of the resistance models for shear force without shear reinforcement based on stochastic parameters (see section 4.2).

5.1 Methods

For this investigation, two different reliability-based methods were applied: First Order Reliability Method (FORM) and Monte Carlo simulations (MC) in comparison. MC were used to determine whether Level II methods deliver appropriate results for the considered resistance model. As the initial partial factors, $\gamma_C = 1.5$ was used for the resistance side to calculate $V_{Rd,c}$ in Equation (1).

5.2 Results

Based on the indicated geometries and details, the considered parameter is varied while the others are kept constant. The deterministic values are taken as the nominal value of the basic variables, while stochastic models for basic variables are treated as random variables (see section 4). In a first step, the concrete strength was varied while only quality control in accordance with DIN EN 206 [18] was considered. In a second step also, the effective depth was varied to identify the effect to the reliability index considering only quality control in accordance with DIN EN 13670 [31].

Reliability analyses were done to determine the lower bound of the reliability index β. The decisive combination should finally utilised to determine the design approach which meets the safety requirements according to codes [2], [33]. All calculations were performed using the software package *TesiproV* in R (see section 2).

The main results of parametric studies are summarised in Figures 4 and Figure 5. While First Order Reliability Method (FORM) and Monte Carlo simulations methods (MC) are used it can be distinguished by those with quality control and those without quality control. For concrete compression strength, the conformity criteria of DIN EN 206 [18] were utilised (Figure 4). Moreover, for the conformity control criteria on effective depth, the Tolerance Class 2 in DIN EN 13670 [31] was considered (Figure 5). Conformity control criteria on reinforcing steel were left outside the scope of this investigation.

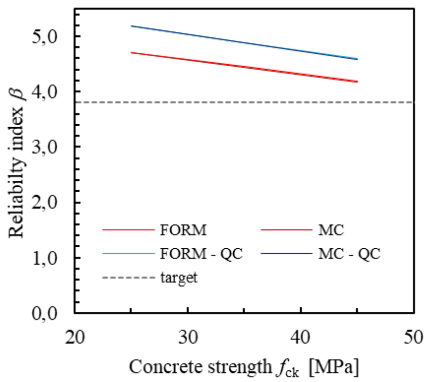

Figure 4 Example for shear with influencing the concrete strength for normal concrete

The influence of concrete compression strength is demonstrated in Figure 4. Overall, the figure demonstrates that high compression strengths tend to lead to smaller reliability index than those attained in small strengths. For small concrete compressive strength classes, the influence of conformity control criteria on the concrete compression strength is rather significative. For example, for a class C20/25, the reliability index β can rised to approxamitely 0.5 in each value of f_{ck}.

For a second parameter study, the influence of varying the effective depth lead to the following effects, which can be demonstrated in Figure 5.

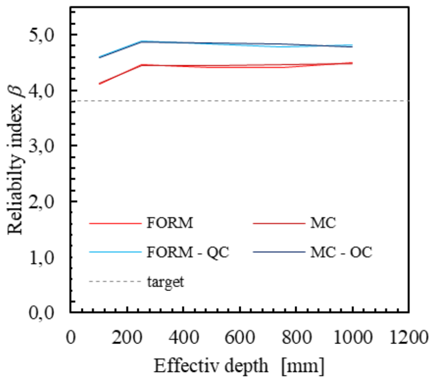

Figure 5 Example for shear with influencing the geometric property

The influence of conformity control criteria on effective depth is rather significant. The resulting reliability index β increased approximately in the order of 0.6 to 0.7. For low values of effective depth, the influence on the resulting reliability index does not appear to be very significant due to an absolute value of the standard deviation. However, this might not be a problem since effective depths tend to be higher than 100 mm in practical steel reinforced concrete members like beams.

6 Discussion and outlook

In this paper it is investigated how different reliability-based methods can be used to quantify the positive influence of quality control assessments (by means of conformity control criteria). The results of a first parameter study illustrate the correctness and functionality of the new software package as well the potential of the quality control quantification. The parametric study highlighted two important aspects. On the one hand, the implementation of reliability-based methods in civil engineering is an important step towards a wider application of statistical methods, to which this contribution should motivate. On the other hand, the parameter study presented shows the application of the probabilistic methods using a practical example with a nonlinear limit state function and non-normally distributed basic variables. Furthermore, advanced reliability methods (e.g. Monte Carlo Simulation) can be implemented in the new R package and work for many cases, special cases as well.

Based on this investigation, the following conclusions are reached:

- In the background of OC curves addressed in this investigation is the statistical inference needed for the Bayesian framework used to quantify the filtering effect of quality control on the distributional characteristics of geometric properties.

- For the analysed parameter range, the evaluations according to the current DIN EN 1992-1-1+NA, using a partial safety factor of γ_C = 1.5 (Resistance Class 2, RC 2) generally results in reliability indices above the limit value of 3.8 recommended in EN 1990 for RC 2. Regulations for shear force without shear reinforcement thus achieve the safety level required in EN 1990 for RC 2 safety level.

- Taking into account the filtering effect and the implementation of quality control, the reliability index increases significantly. It can be assumed that the partial safety factor decreases.

Further work may include larger parameter studies, which will support the development of practical guidance for the consideration of quality control in structural safety assessments. Furthermore, ongoing work shall include a wider range of conformity control criteria and several other aspects (e.g., different conformity control criteria).

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