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Semi-probabilistic methods for the assessment of existing concrete structures: An overview

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ABSTRACT: Life-cycle assessment of the residual performance of existing structures usually involves a wider spectrum of uncertainties compared to a standard approach for designing new structures. The main differences are related to the modification of structural capacity and demand in time, f.i. due to aging and structural deterioration processes. Furthermore, climate change has a significant impact on this evolution. In order to account for these aspects, full probabilistic approaches are often exploited for assessing existing structural systems. However, these methodologies are time-consuming and may require significant knowledge and expertise for numerical implementation. Therefore, the development of semi-probabilistic methodologies for existing structures considering the impact of climate change, including proper validation and calibration for incorporation in design codes and standards, is nowadays of essence. This paper provides an overview of recent accomplishments and available literature regarding semi-probabilistic code formats for the assessment of existing reinforced concrete structures, including insights on how to incorporate climate change effects on these methodologies.

1 INTRODUCTION

The evaluation of the residual performance of structural systems, such as bridges and infrastructural facilities, is currently a key issue since a large stock of existing structures is approaching the end of the design service life (Fabio Biondini & Frangopol 2016, 2018). The exploitation of conservative simplified approaches tailored for design of new structures may lead, in several cases, to expensive and unnecessary repairs due to the intrinsic differences with the assessment of existing systems (JRC 2015). Moreover, although existing constructions may not fulfill actual requirements for new design, in many cases these systems may still have adequate levels of performance for a target service life.

Structural design may be addressed as a decision problem involving uncertainties, in which the structural resistance $R=R(t)$ is required to be larger than the demand $E=E(t)$ over time t . The uncertainties involved in this problem are modified during the lifetime of the system, mainly due to aging and structural deterioration, leading to a decay of the resistance and possible evolution of the demand, related either to changes in loadings or internal stress redistributions. Furthermore, climate change is observed to have an impact on both structural loading (Mishra & Sadhu 2022), e.g. snow load or wind speed, and structural capacity (Nasr et al. 2021), e.g. enhancing deterioration mechanisms such as chloride- and carbonate-induced corrosion. In this context, it is important to properly assess the performance of existing structures considering the long-term evolution of environmental parameters (Retief 2022).

Following the international standards ISO 13822 (2001) and ISO 2394 (2015), the decision process regarding both the design of new structures and assessment of existing systems should be based on probabilistic evaluations which may be carried out at different levels of detail, from risk-informed decision-making to semi-probabilistic design. The latter methodology usually involves the lowest level of detail; nonetheless, it represents an important guidance for engineers to deal

with common design situations and uncertainties within a reasonable range of time and complexity. Several international design standards, e.g. Eurocodes (CEN EN1990 2002), AASHTO (2020) and ASCE 7-22 (2022), exploit the so-called load and resistance factor design (LRFD) format (Ravindra & Galambos 1978) for new structures providing, for a selected parameter a , the reference design values a_d through characteristic values a_k and partial safety factors γ . Reliability requirements are defined in order to determine a_k and γ , usually referring to this procedure as code calibration.

This paper provides an overview of recent accomplishments on the calibration of semi-probabilistic code format focusing on the assessment of existing structures. Firstly, a discussion of different methodologies for calibration is presented. Secondly, the semi-probabilistic code format is addressed based on research studies specifically dealing with the assessment of existing Reinforced Concrete (RC) structures. Finally, an insight into recent code calibration methodologies accounting for climate change effects on structural safety is also presented. The benefits and drawbacks of the methodologies discussed are addressed with emphasis on possible incorporation of long-climate prediction impacts on structural capacity and demand models.

2 BACKGROUND ON SEMI-PROBABILISTIC CODE FORMAT CALIBRATION

Code calibration may be described as the determination of the values of all parameters in a given code format (ISO 2394 2015), and it has been performed following different methodologies, based on past experiences, judgment, fitting, or a combination of these. In a broader sense, the calibration approach may be considered as a decision problem involving risk and uncertainties.

In ISO 2394 (2015), three different decision methodologies are defined for the design and assessment of structures considering different levels of detail. The risk-informed decision represents the highest level of detail (Level 4). In this case, the decision-making process should explicitly consider economic and safety consequences, as well as the modeling of uncertainties, aiming to maximize the expected utility. Although this approach is very powerful and flexible, it is not usually applied in engineering practice due to complexity and time constraints. Furthermore, in the context of code regulation, standardization and replicability are important aspects which may be archived exploiting simplified methodologies. Indeed, a simpler alternative is represented by reliability-based decision (Level 3). This approach relies on the satisfaction of predefined reliability requirements, which can be based on experience or on formal calibration through the Level 4 approach. The requirement may depend on the consequences and the cost of the specific decision implementation, although the consequences are not explicitly treated in the reliability considerations. Similarly, a reliability-based decision problem can be afforded involving simplified uncertainties representation and reliability computation (Level 2). Eventually, the semi-probabilistic approach corresponds to the lowest level of detail (Level 1).

The semi-probabilistic approach relies on the satisfaction of the safety deterministic criterion stating that the design resistance must be larger than the design demand. The design values are generally determined through the multiplication or division of the characteristic values by the partial safety factors, which are calibrated in order to meet the prescribed reliability requirements. This approach is proposed by several national and international design standards, such as the Eurocodes (CEN EN1990 2002), when dealing with common situations in terms of uncertainties and consequences. It should be noted that the described approaches, even if related to a different level of detail, are strongly interconnected; indeed, higher-level methodologies should be compliant and used in order to calibrate the lower levels. The different levels of decision-making strategy are reported in Table 1.

Consistently, semi-probabilistic code format calibration is usually based on reliability considerations where a given level of safety, measured by the reliability index β , should be assured by the definition of the reliability elements of the code, e.g. partial safety factors γ and combination factors ψ . The purpose of calibration of a semi-probabilistic code format, in addition to the formulation of a safe, economically efficient and simple tool for the design of ordinary structures, is to optimally select the parameters of the code by maximizing the benefits for the society. In this context, code calibration for a semi-probabilistic design is usually formulated as an optimization problem, which should be solved in order to retrieve the required reliability-based design factors.

Table 1: Levels of decision methodologies according to ISO 2394 (2015), based on Baravalle & Köhler (2016) and Köhler & Baravalle (2019).

Approach	Applicability	Objective	Norm
Risk-Informed (Level IV)	Exceptional design situations with respect to uncertainties and consequences.	Maximization of the expected utility for the decision maker.	Guidelines, e.g. ISO 2394 (2015).
Reliability-Based (Level III and II)	Unusual design situations with respect to uncertainties.	Fulfillment of reliability requirements.	Probabilistic codes, e.g. JCSS (JCSS 2001).
Semi-Probabilistic (Level I)	Usual design situations with respect to uncertainties and consequences.	Achievement of deterministic design criteria.	Semi-Probabilistic codes, e.g. EN1990 (2002).

Furthermore, appropriate treatment of uncertainties and the consequent selection of probabilistic models is fundamental in the calibration procedure. Indeed, structural engineering models are associated with a certain level of uncertainty, affecting both the structural demand and capacity. The Joint Committee on Structural Safety (JCSS) provides guidelines for the appropriate characterization of uncertainties, categorizing three main sources of uncertainty (intrinsic physic, parameter and model uncertainty), and suggesting the probabilistic models for the basic random variable (JCSS 2001), although the selection should always be tailored to the peculiar case study.

3 REVIEW ON SEMI-PROBABILISTIC CALIBRATION FOR EXISTING STRUCTURES

3.1 *Semi-probabilistic format calibration*

Calibration of the structural standards is currently a critical research issue, especially concerning existing structures. Indeed, for the aforementioned case, the semi-probabilistic format should be able to incorporate the potential updated information on geometry, loadings, materials and the different reliability requirements, in order to avoid non-effective decisions (Diamantidis 2001). Furthermore, the built environment is experiencing a change in environmental conditions which are likely not anymore the ones considered during the design; these climatic changes are reported to not have a negligible impact on both the evolution of structural capacity and demand. For this reason, code calibration of semi-probabilistic design format accounting for the actual evolution of the structural performance in a changing climate is fundamental.

Code calibration has been systematically researched in the past decades, e.g. by Cornell (1969), Ravindra et al. (1978), Thoft-Christensen & Baker (1982), Faber & Sørensen (2003), Madsen et al. (2006) and Ditlevsen & Madsen (2007). Based on this research, a standardization, specifically regarding reliability-based calibration, for semi-probabilistic design code is reported in ISO 2394 (2015). Among others, the selection of a target reliability β_T is a fundamental assumption in reliability-based calibration. In Baravalle & Köhler (2017) and Köhler et al. (2019) a discussion regarding the selection of β_T according to different strategies, addressing the benefit and drawbacks of each methodology, is presented. The definition of target reliability level for existing structures considering economic optimization and the marginal life-saving costs principle is addressed by Sýkora et al. (2017). Furthermore, Baravalle & Köhler (2019) proposed a comprehensive approach to code calibration of the reliability target through all levels of design. This article provides a background regarding the selection of the target reliability defining an extension of existing approaches for code optimization. A framework for reliability-based calibration of the load partial safety factor is proposed by Köhler et al. (2019). In this study, a generic limit state is considered for the calibration of the load safety factors of the Eurocodes. The results indicate that the partial safety factors proposed in the code are higher for permanent loads and lower for live loads. It is also observed that the reliability target assumed in the Eurocodes is higher than the average reliability level implied by the current safety factors.

A risk-based calibration problem is formulated by Köhler & Baravalle (2019), where economic considerations are explicitly considered in the optimization problem through the definition of a minimum expected cost. This is observed to be more consistent with respect to reliability-based optimization for which the definition of a generally accepted reliability target is observed to be hardly achievable.

In the approach proposed by Arrayago et al. (2022), the calibration of reliability indices and partial safety factors is based on First Order Second Moment (FOSM), considering both US and EU frameworks, and eventually compared with the results obtained exploiting First Order Reliability Methods (FORM). The results show that this simplified formulation is sufficiently accurate for the definition of reliability indices and partial safety factors, and it may provide a reference to the specification committees in the calibration process. Nevertheless, it is important to highlight that the comparison between the FOSM and FORM developed in the research involves only steel structures subjected to gravity and wind loads and it is limited to a specific sensitivity factor assumed for the calibration.

3.2 Assessment of existing RC structures

A comparison of semi-probabilistic vs full-probabilistic safety formats for RC structures based on limit states and partial factors of Eurocode 2 (2005) are presented in Biondini et al. (1999). The application of proper probabilistic models to the non linear analysis allows to assess the actual safety level with reference to the computed random distributions of structural response. The results include information about the large scattering of the reliability index, the sensitivity of the structure to the production control of higher level and the capacity of plastic adaptation under the applied load distributions. Semi-probabilistic approaches explicitly addressing the assessment of existing structures can be found in the *fib* Bulletin N°80 (2016). The described methodologies consider the residual service life, information from in situ and laboratory tests, measurements of variable actions, and reduced target reliability levels according to both economical and human safety criteria, focusing on standard RC structures. Specifically, two methodologies devoted to the recalibration of the partial safety factors for existing structures are presented: the design value method (DVM) and the adjusted partial factor method (APFM). The DVM, which has been introduced in the ISO 2394 (2015) and then adopted in the Eurocodes (CEN EN1990 2002), provides formulas for the calibration of partial safety factors of both material resistances and actions, exploiting appropriate probabilistic models derived by from the prior knowledge, test results, and observations related to the existing structure under investigation. The APFM (Caspeele & Taerwe 2012) is a simpler approach that allows to update the partial safety factors defined by Eurocodes for new structures, by means of “adjustment coefficients”.

The application of DVM and APFM has been performed in the past years for different RC structures by several researchers. In Sýkora et al. (2013), the DVM is applied to the pier and the slab of an existing RC bridge subjected to permanent and traffic loading. The results show that the semi-probabilistic format recommended for structural design in current codes may lead to conservative results and non-optimal decisions concerning rehabilitation of existing RC bridges. Caspeele et al. (2013) exploited the DVM and APFM for the assessment of an existing RC beam and a short column subjected separately to wind and imposed variable loads, providing a framework for the application of the latter methodology. Gino et al. (2020) use the methodologies proposed in *fib* Bulletin 80 (2016) in order to evaluate the residual safety and performance of an existing prestressed RC bridge. The obtained outcomes are eventually compared with the results obtained based on the Eurocodes (CEN EN1990 2002), showing that recalibration of partial safety factors accounting for updated information may avoid expensive and not useful interventions. Nevertheless, the authors highlighted the absence of a definition for the probabilistic models to update partial safety factors for prestressing and imposed deformations in *fib* Bulletin 80 (2016) and the need of further research on this issue. The DVM and APFM methodologies are applied in Orcesi et al. (2021) for the assessment of two different existing RC bridges. The study illustrates the procedure for the application of the methodologies and provides a discussion regarding the assumption involved in both the approaches. It is evidenced that major simplifications rely on the consideration of statistical uncertainty associated with the new measurements only in the estimate of characteristic values of basic variables and the assumption of standardized sensitivity factors or types of probabilistic distributions.

An important limitation common for the aforementioned studies regards the detrimental processes affecting RC structures, e.g corrosion, which are assumed to be negligible. Moreover, no explicit consideration concerning the impact of climate change for the calibration of resistance and demand partial safety factors is addressed. In the context of calibration of partial safety factors for the assessment of existing RC structures subjected to corrosion-induced deterioration, preliminary considerations are undertaken by Tanner et al. (2011). In this paper, the uncertainties

related to the resistance models for corrosion-damaged RC beams are estimated, showing how the partial safety factor for resistance should be incremented in the case of existing structures affected by corrosion. Nonetheless, the results obtained are not exploitable for the direct calibration of partial safety factors since more refined modeling should be devoted to characterize the resistance of deteriorating structures. An explicit formulation for the calibration of partial safety factors considering chloride-induced corrosion in RC structures is reported in Holicky et al. (2008). The research compares the partial safety factors obtained accounting and neglecting deterioration for different reliability targets, highlighting how the reliability level over time is strongly influenced by detrimental processes and, consequently, the calibration of partial factors. In this case, the limitation relies on the fact that the obtained results are significantly dependent on the model used. Consequently, more advanced corrosion modeling should be exploited, implementing the impact of climate change on the initiation and propagation phases, as well as more refined load modeling considering different ratio between permanent and variable loading. The calibration of the partial safety factors for the assessment of anchorage capacity in existing RC structures under corrosion is addressed in Blomfors et al. (2019). In this study, the partial safety factors of the are calibrated for different levels of corrosion, and considering the presence or the absence of stirrups. The obtained results are verified by exploiting Monte Carlo simulation for several design situations. The discussed methodology may, in principle, be extended to the calibration of partial safety factors for existing structures subjected to chloride-induced corrosion or carbonate-induced corrosion. Nevertheless, further research is needed for the quantification of the sensitivity factors in deteriorating structures.

The Technical Specification CEN/TS 17440 (2020) focuses on the assessment of existing structures suggesting the exploitation of the partial safety factors format of the Eurocodes (CEN EN1990 2002) as the initial method for the verification of the structural safety. In Lara et al. (2021), the assessment of an RC beams of an existing industrial building is performed, following the indication of the technical specification CEN/TS 17440 (2020) and applying both the DVM and APFM to compare the results with the outcomes of a full probabilistic analysis. The comparison shows that DVM incorporates the updated information more accurately than APFM. Furthermore, the full probabilistic assessment is reported to be in good agreement with the results obtained from DVM and APFM.

The assessment of existing structures may require the evaluation of the structural capacity at the system level exploiting nonlinear finite elements analyses (NLFEAs). In this context, Pimentel et al. (2014) propose the application of the global resistance safety factor approach into the semi-probabilistic format. The proposed methodology, which is consistent with the guidelines provided in the Swiss Standard for existing structures (SIA 2010; Brühwiler et al. 2012) and CEN EN1992-2 (2005), relies on the application of the partial safety factors to the overall system resistance. The main assumptions deal with the selection of a lognormal probability density function for the resistance and the estimation of the coefficient of variation. It is shown that the global resistance safety factor format may be more accurate than the partial safety factor, even at the member level. Nevertheless, the assumed lognormal distribution is not always adequate for the analysis. A discussion about a semi-probabilistic approach compliant with NLFEAs for the assessment of existing RC structures using different safety formats is presented in Castaldo et al. (2019). Methods for the assessment of uncertainties and estimation of the coefficient of variation of the resistance of RC structures are also presented in Novák et al. (2022).

3.3 Insight into calibration considering climate change

Calibration of a semi-probabilistic design format has been usually performed under the assumption of a stationary climate. Nowadays, climate change is extensively reported in the Intergovernmental Panel on Climate Change assessments (IPCC 2022), and its impact on structural demand and resistance is recognized in a large number of studies (Nasr et al. 2021; Mishra & Sadhu 2022). Consequently, design codes should incorporate considerations regarding climate change when calibrating the semi-probabilistic format in order to appropriately estimate structural safety and performance. Recent studies have tried to perform code calibration explicitly considering climate change.

Target structural performances have been investigated in terms of resilience and sustainability under climate change effects and other hazards (ASCE 2018). In Hong et al. (2021), a reliability-based design code calibration is performed in the context of possible implementation in the

National Building Code of Canada (NBCC), focusing on the definition of design wind load, design snow load, and companion load factors. In the study, the stationary extremes derived from observed meteorological data and the nonstationary climate change effects are considered. Based on the performed analysis and the results from the climate change modeling results, sets of load scaling factors accounting for climate change effects are calibrated for different regions in Canada. Despite the calibrated load factors for climate change effects are specifically addressed to the Canadian environment and climate change effects may significantly vary from region to region, the proposed calibration procedure for nonstationary extremes is amenable to generalization. An extensive review of available information on climate change to identify methodologies and tools that would help the civil engineering profession to address the impacts of climate change on the life-cycle structural safety of structures and infrastructure facilities is currently ongoing within a SEI/ASCE special project (SEI/ASCE 2022).

In the context of European Standardization, the work proposed in Arnold & Kraus (2022) focused on the calibration of semi-probabilistic code formats considering the evolution of climate. In this research, FORM methodologies are extended to a nonstationary approach incorporating the reliability index and sensitivity factor and exploited for calibration. A practical application is presented involving a simply supported beam subjected to snow action in order to describe the proposed framework. The drawbacks of the work rely on the uncertainties involved in climate projection and on the selection of the time window which may significantly influence the results.

4 CONCLUSIONS

In this paper, recent research advances addressing the assessment of existing RC structures based on a semi-probabilistic approach are discussed. The aim of the study is to provide an overview of the current state-of-the-art for semi-probabilistic format code calibration and application, aiming at future implementation of the climate change impact on these methodologies.

The concepts of decision-making in engineering and calibration are introduced. A review of several studies is proposed concerning:

1. General calibration strategies for the semi-probabilistic code format applicable to different types of structures and analyses.
2. Methodologies for the definition of semi-probabilistic code key elements, as safety factors, for existing RC structures.
3. Calibration of the semi-probabilistic code format considering the impact of climate change on structural safety.

The review highlighted the significant amount of research advances in these fields, but also that further research is needed to appropriately calibrate semi-probabilistic formats for the assessment of existing RC structures subjected to detrimental processes such as corrosion. Moreover, the changes in current and future climate are affecting structural systems, and in general the built environment, influencing both structural capacity and demand. Further developments are needed also along these lines of research in order to provide semi-probabilistic methodologies for the assessment of RC structures subjected to detrimental processes in a changing climate. Eventually, although some studies analyzed the non-stationary evolution of climate and its impact on environmental actions, more steps for the characterization of uncertainties and the definition of basic assumptions are needed for the consequent calibration of semi-probabilistic design codes.

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