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REVIEW ARTICLE

Semi-probabilistic methods for existing concrete structures under climate change: Review

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ABSTRACT

The assessment of the residual performance of existing structures over their life cycle usually involves a wider spectrum of uncertainties compared to a standard approach for designing new structures. The differences are related to the uncertainties linked to the time-variant aging and deterioration processes, as well as concerning the different lifetime considered in the assessment with respect to the design stage. Additionally, climate change has a significant impact on this evolution. In order to account for these aspects, full-probabilistic approaches are often employed 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 the essence. This paper aims at providing a review of recent accomplishments and available literature regarding semi-probabilistic methodologies for the assessment of existing reinforced concrete (RC) structures, focusing on different steps of the calibration process, highlighting research contributions that proposed the integration of climate change effects on these methodologies, and discussing the benefits, limitations, and research gaps of the reviewed approaches.

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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, as highlighted in the scientific literature (Biondini & Frangopol, 2016, 2018) and by national and international authorities (ASCE, 2021; Belin, 2022). The exploitation of conservative simplified approaches tailored for the design of new structures may lead, in several cases, to expensive and unnecessary repairs due to the intrinsic differences in the assessment of existing systems (Luechinger et al., 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 (JCSS, 2001a).

Following the international standards ISO 13822 (2001) and ISO 2394 (2015), the decision process regarding both the design of new structures and the 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 important guidance for engineers to deal with common design situations and uncertainties within a reasonable range of time and complexity. In general, semi-probabilistic methodologies are calibrated according to reliability requirements (Rackwitz, 2000; Sørensen et al., 1994). For this reason, the focus of the proposed analysis is mainly devoted to reliability-based code calibration procedures.

Several international design standards, e.g. Eurocodes (CEN EN1990, 2002), exploiting the partial factors concepts, American Association of State Highway and Transportation Officials AASHTO (2020) and American Society of Civil Engineers ASCE 7-22 (2021), implementing the so-called load and resistance factor design (LRFD) format (Ravindra & Galambos, 1978), propose the semi-probabilistic format for the design of new structures. These methods provide, for a selected parameter a, the reference design values a_d through characteristic values a_k and safety factors γ. Reliability requirements are defined in order to determine a_k and γ, usually referring to this procedure as code calibration.

Specifically, the semi-probabilistic assessment of existing structures is a critical issue to be dealt with by practitioners and researchers, and a significant effort has been provided along these research lines (Caspeele et al., 2013; Diamantidis & Bazzurro, 2007; Steenbergen & Vrouwenvelder, 2010; Sýkora et al., 2015). In the last decade, the growing interest on this thematic led to the proposition of specific regulations for existing structures, e.g. Swiss Society of Engineers

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and Architects SIA 269 (2011), Australian Standard (2017), Czech Technical Standard (2019) and Royal Netherlands Standardization Institute (2020). In the European context, the second generation of Eurocodes is answering this need through the prEN 1990-2 (2024) along with the new Model Code 2020 (Matthews et al., 2018; Walraven & Dieteren, 2023). Moreover, general guidance on the definition of partial factors tailored for evaluating existing structures is provided in *fib* Bulletin N°80 (2016).

Structural safety assessment may be addressed as a decision problem involving uncertainties in which the resistance $R = R(t)$ should be no lower than the demand $S = S(t)$ over time t. The uncertainties involved in this problem are evolving during the system's lifetime mainly due to aging and structural deterioration, leading to a decay of the resistance, and to possible alterations of the demand related either to changes in external loadings or internal stress redistributions.

Climate change due to anthropogenic activities is an unequivocal reality leading to several unprecedented changes (IPCC, 2022, 2023), which is observed to have an impact on both structural loading (Mishra & Sadhu, 2023), 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 (Bastidas-Arteaga & Stewart, 2016; Stewart et al., 2011, 2012). During the last decades, representative scenarios have been elaborated in order to provide researchers and policymakers with the tools to formulate comparable results when considering climate change (Riahi et al., 2017; Van Vuuren et al., 2011). In this context, the proper assessment of the performance of existing structures considering the long-term evolution of environmental parameters is crucial (Retief, 2022). For this reason, further development in the research is needed in order to incorporate the impact of the changing climate, e.g. non-stationarity, in structural reliability analysis (Li et al., 2015; Madsen, 2013; Saini & Tien, 2017).

Current standards and codes for structural design are still based on historical climatic data and associated loads under the assumption of stationarity. Recently, research and implementation of life-cycle assessment, prediction, and optimal management of structures and infrastructure systems under uncertainty considering the effects of climate change have been part of a collaborative research effort involving about 40 researchers within a Special Project supported by the Structural Engineering Institute (SEI) of the American Society of Civil Engineers (Biondini et al., 2024). Among other goals, this project explored methods to incorporate non-stationarity in code regulations and to provide engineers and practitioners the tools to analyze the existing structural systems considering the impact of climate change both on resistance and demand.

This paper provides an overview of recent accomplishments and discusses the current research concerning the calibration of semi-probabilistic codes focusing on the assessment of existing structures under climate change, including a discussion on present and future challenges. Firstly, a discussion of different methodologies for calibration is presented. Secondly, the semi-probabilistic code format is addressed, focusing on the definition of the reliability target, characteristic and design values for structural capacity and demand, and partial safety factors, which engage research studies specifically dealing with the assessment of existing RC structures. The benefits and drawbacks of the presented methodologies are addressed with emphasis on the possible incorporation of long-climate prediction impacts on structural capacity and demand models. A flowchart of the selected review methodology is reported in Figure 1.

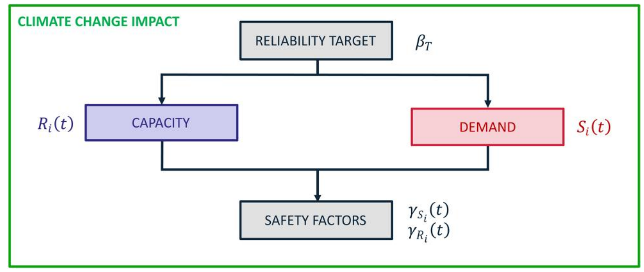

Figure 1. Flowchart of the review methodology.

2. 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 that may be achieved by exploiting simplified methodologies. Indeed, a simpler alternative is represented by a reliability-based decision (Level 3). This approach relies on the satisfaction of predefined reliability requirements, e.g. the reliability target, which can be based on experience or formal calibration through the Level 4 approach. The requirement may depend on the consequences and the cost of the specific decision implementation, although these are not explicitly evaluated 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).

Table 1. Levels of decision methodologies according to ISO 2394 (2015), based on Baravalle and Köhler (2016) and Köhler and 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 and consequences.	Fulfillment of reliability requirements.	Probabilistic codes, e.g. JCSS (2001b).
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).

The semi-probabilistic approach relies on the satisfaction of the safety deterministic criterion stating that the design capacity R_d must be larger than the design demand S_d. The design values are generally determined through the multiplication or division of the characteristic values by the partial safety factors, which are calibrated 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 and defined by the target reliability β_T, should be assured by the definition of the reliability elements of the code (Allen, 1975; Gayton et al., 2004), e.g. partial safety factors γ and combination factors ψ. The purpose of the 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 society. In this context, code calibration for a semi-probabilistic design is usually formulated as an optimization problem (Frangopol, 1985; Galambos et al., 1982; Rackwitz, 2000, 2002; Rosenblueth, 1986), which should be solved in order to retrieve the required reliability-based design factors. Nevertheless, the semi-probabilistic methodologies used in structural codes may result in over-conservative design or assessment due to the lack of accuracy of the exploited models. A comparison of semi-probabilistic and full-probabilistic safety formats for RC structures based on limit states and partial factors is presented in Biondini et al. (1999). Discussion on the hidden safety in structural standards is provided in Teichgräber et al. (2022), referring to Eurocodes and investigating the effect of hidden safety with respect to the adopted wind load model.

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 (intrinsic physic, parameter, and model uncertainty), and suggesting the probabilistic models for the basic random variables (JCSS, 2001b). However, the selection of the models should always be tailored to the examined case study. A study on the treatment of model uncertainties for RC structure is provided by Taerwe (1993). In the context of JCSS, a detailed discussion on the reliability-based assessment of existing structures is provided by Diamantidis et al. (2025), focusing on the current level of knowledge and the limitations of further implementation in the practice of risk-informed and reliability-based methodologies. Moreover, additional effort should be devoted to integrating the impact of climate change, such as non-stationarity, into civil engineering practice, by considering its influence on the different sources of uncertainty affecting the problem (Biondini et al., 2024).

3. Semi-probabilistic calibration procedures for existing structures under climate change

3.1. Reliability-based 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 (JCSS, 2001a). Furthermore, the built environment is experiencing a change in environmental conditions which are likely not the ones considered during the design anymore; these climatic changes are reported to have an impact on both the evolution of structural capacity and demand. For this reason, it is nowadays fundamental to address code calibration of semi-probabilistic design format accounting for the actual evolution of the structural performance in a changing climate.

Code calibration has been systematically researched in the past decades, e.g. by Cornell (1969), Allen (1975), Ravindra et al. (1978), Galambos et al. (1982), Thoft-Christensen and Baker (1982), Faber and Sørensen (2003), Madsen et al. (2006), and Ditlevsen and Madsen (2007). Based on the sustained effort on this research line, a standardization, specifically regarding reliability-based calibration, for semi-probabilistic design code is reported in ISO 2394 (2015). A review concerning the developments and future prospective of code calibration is presented by Köhler et al. (2025).

Reliability analysis may be performed by exploiting different techniques (Der Kiureghian, 2022; Melchers & Beck, 2018) such as the First Order Reliability Methods (FORM), the Second Order Reliability Methods (SORM), and numerical simulations. Concerning reliability-based code calibration, standardization committees exploited extensively the FORM due to its relative simplicity in the application and the accuracy of the results, despite the iterative nature of the methodology and the need for information not always easily acquirable.

In the approach proposed by Arrayago et al. (2022), the calibration procedure is based on First Order Second Moment (FOSM), a simplified methodology belonging to the family of FORM, considering both U.S. and E.U. frameworks, and eventually compared with the results obtained exploiting 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 is addressed only to steel structures subjected to gravity and wind loads and it is limited to a specific sensitivity factor assumed for the calibration. In Arnold and Kraus (2022), a methodology for the determination of reliability elements of the code considering non-stationarity due to climate change is proposed. The study exploits the time window-shifting concept incorporated into FORM-based calibration.

Based on this discussion, the revision of reliability elements of the code as the characteristic values of capacity and demand and the safety factors considering non-stationarity is a crucial step. In the following, these interconnected subjects are described focusing on the assessment of existing structures and accounting for the impact of the changing climate.

3.2. Selection of the reliability target

The reliability of a structural system may be defined as a function of its capacity and demand. Indeed, considering the time-variant measures of the structural capacity $R = R(t)$ and demand $S = S(t)$, the probability of failure within a given time interval $t = [t_i, t_{ref}]$ may be evaluated by the integration of the joint density function $f_{R,S}$ (r,s) within the failure domain $\Im$ (t)= $\{r, s \mid r(t) < s(t)\}$:

$$p_f(t) = P[R(t) < S(t)] = \int_{\Im(t)} f_{R,S}(r,s)dr\ ds \tag{1}$$

where $r(t)$ and $s(t)$ are the outcomes of the random variables $R = R(t)$ and $S = S(t)$ within the time interval $t = [t_i, t_{ref}]$.

The analytical solution of the integral reported in Eq. (1) may not always be achievable. An alternative measure of structural safety is provided by means of the time-variant reliability index $\beta = \beta(t)$. Equation (2) provides an exact relationship only if the capacity and demand are normal variates, even if it is often generalized and applied to estimate the reliability index for non-normal variates:

$$p_f(t) = \Phi(-\beta(t)) \tag{2}$$

in which, $\Phi(\cdot)$ is the standard normal cumulative density function.

Based on this, the selection of the reliability target β_T, where the subscript T stands for target, is a fundamental step in the context of reliability-based code calibration since it implicitly defines the minimum safety level to be assured by the design or the assessment of a structural system. Nevertheless, β_T is often incoherent between different regulations and limited to prescribed lifetimes common to civil structures, e.g. 50 or 100 years for buildings and bridges, respectively.

In the international standard ISO 2394 (2015), different values of the reliability target are proposed considering the relative cost of safety measures and the possible consequence of failure for a 1-year reference period. The values, defined at the Ultimate Limit State (ULS), are reported in Table 2.

Table 2. Target reliability for a 1-year reference period at the ULS, based on monetary optimization (ISO 2394 2015; JCSS, 2001b).

	Consequences of failure		
Relative cost of safety measure	Small	Medium	Large
Large	3.1	3.3	3.7
Medium	3.7	4.2	4.4
Small	4.2	4.4	4.7

In the European context, the reliability target proposed by the Eurocodes (CEN EN1990, 2002) considers only the importance of the structure with respect to a possible collapse in terms of consequence classes, without including the cost for the implementation of the eventual safety measure, as depicted in Table 3.

Table 3. Target reliability for 1-year and 50-year reference periods at the ULS, based on EN1990 (2002).

	Minimum β_T	
Consequence level	1-year reference period	50-years reference period
Large	5.2	4.3
Medium	4.7	3.8
Small	4.2	3.3

In Baravalle and Köhler (2017) and Köhler et al. (2019), a discussion regarding the selection of β_T for design codes is provided, addressing the benefits and drawbacks of the current methodology exploited for calibration. In Köhler et al. (2019), the calibration of partial safety factors for design codes is studied, comparing the obtained results with propositions of the Eurocodes (CEN EN1990, 2002). The average reliability levels retrieved in the study are observed to be significantly lower than the reliability target $\beta_T = 4.7$ assumed in the Eurocodes (CEN EN1990, 2002) for medium consequence level and yearly reference period, highlighting the need of a revision of the current Eurocodes (CEN M/515, 2012). Furthermore, Baravalle and Köhler (2019) proposed a comprehensive approach to code calibration of the reliability target through all levels of design, providing the background regarding the selection of β_T and defining a possible alternative to reliability-based calibration. In the study, a risk-based calibration problem is formulated, 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.

Concerning the Serviceability Limit State (SLS), the value of 1.5 for the reliability target is recommended in the Eurocodes (CEN EN1990, 2002) for irreversible states and a 50-year reference period. In *fib* Model Code (2013) and ISO 2394 (2015), the same value is proposed for the remaining service life and reference design lifetime respectively, while the JCSS (2001b) proposed values for the reliability target at the SLS considering the relative costs of safety measures and 1-year reference time. In Van Nierop et al. (2017), the β_T for SLS is defined by exploiting reliability-based calibration and considering different consequence classes and costs. The general procedure proposed by Van Nierop et al. (2017) is exploited by Lenner et al. (2019) for the specific case of a water-retaining structure. Quan and Gengwei (2002) discussed the definition of the reliability target at the SLS for RC beams considering the maximum crack width. A review of reliability levels for ULS, SLS, and fatigue considering different standards is provided by Ghosn et al. (2016).

The previous discussion addressed the definition of reliability target β_T for new structures. In the case of existing systems, the target probability of failure could be higher than the one accepted for the design of new structures within the considered time interval $t = [t_i, t_{ref}]$ due to the higher cost of upgrading, the shorter remaining lifetime, and the possible increased level of information with respect to the new structural systems (Val & Stewart, 2002; Vrouwenvelder, 2002; Vrouwenvelder & Scholten, 2010). Consequently, the reliability target for existing structures should be tailored by considering these aspects in order to avoid misleading maintenance decisions and interventions. In this context, different studies recently proposed methodologies for the definition of β_T for existing structures (Table 4).

Eventually, the definition of simple analytical equations exploitable by practitioners for the definition of an appropriate value of reliability target is a critical step for the achievement of an integrated semi-probabilistic methodology tailored for existing structures. Based on the study of more then 100 collapses of buildings, Tanner and Hingorani (2010, 2015) proposed an empirical relationship between the number of casualties n and the collapsed area A_{col} related to the failure of the structural member. Considering the previously mentioned study and the research in Steenbergen et al. (2015), a formulation of β_T for existing buildings in terms of Consequence Class (CC), collapsed area A_{col}, and remaining or reference lifetime t_{ref} is provided in *fib* Bulletin N°80 (2016). The consequence classes are defined with respect to the probability of loss of human life, distinguishing low, medium, and high consequences as CC1, CC2, and CC3, respectively. Different formulations for the definition of the reliability target β_T concerning the assessment of existing bridges are reported in Table 5.

The three formulations proposed in Table 5 account for the remaining lifetime t_{ref} of the structure which is critical when assessing a structural system. Nevertheless, the lack of coherence between the different proposals should be highlighted. Moreover, the expressions proposed by *fib* Bulletin N°80 (2016) and Zhang et al. (2022) are based on limited data and calibrated on very specific case studies. Eventually, climate change may have an impact on the economic and human safety considerations at the base of the reliability target calibration. Further effort on this research line is necessary to evaluate the possible impact (Biondini et al., 2024).

3.3. Structural demand under climate change

Calibration of semi-probabilistic design formats has been usually performed under the assumption of a stationary climate. Nowadays, climate change is recognized as a concerning reality, as reported by the Intergovernmental Panel on Climate Change assessments (IPCC, 2022, 2023), and its impact on structural demand and capacity is addressed in a large number of studies (Mishra & Sadhu, 2023; Nasr et al., 2021; Orcesi et al., 2022). Moreover, climate change is significantly impacting the intensity and frequency of extreme

Table 4. Research findings on reliability target values for existing structures.

Findings	References
Discussion on the difference between the reliability target for new and existing structures. Proposition of a reduction factor $\Delta\beta = 1.5$ when existing structures are considered. Optimization of the value $\Delta\beta$ is recommended if specific cases are analyzed.	Vrouwenvelder and Scholten (2010); Vrouwenvelder (2012).
Specification of two different reliability levels for existing buildings and bridges: the minimum target β_{T0} for a reliable structure and the level β_{Tup} for an optimum upgrade strategy. The reliability target values are defined based on the analysis of historically collapsed buildings and bridges.	Steenbergen et al. (2015).
Discussion on unambiguous recommendations for values of reliability target considering existing civil engineering systems. Introduction of minimum reliability target for minimum safety level and optimal upgrading. Limitations of the definition are discussed.	Sýkora et al. (2016, 2017);
General framework for the definition of annual reliability target for new and existing structures, independently of the design working life.	Steenbergen et al. (2018).
Definition of reliability target values considering different risk criteria: individual, societal, and marginal lifesaving cost principles. A parametric study is proposed for assessing the impact of different factors on the definition of β_T, i.e. probabilistic distributions, uncertainties in structural demand and resistance, and probability of potential fatalities.	Liu et al. (2021).
General framework for the definition of reliability target for non-stationary time series, i.e. incorporating the impact of climate change compliant with European standardization. The time window concept is exploited for the incorporation of the non-stationarity and the evaluation of the target reliability for the entire lifetime of the structure.	Arnold and Kraus (2022).

Table 5. Analytical formulation of reliability target tailored for existing bridges.

Formula	Parameters	References
$\beta_T = \Phi^{-1}\left\{\left[\Phi(\beta_{1y})\right]^{t_{ref}/t_0}\right\}$	Remaining lifetime t_{ref} and basic period t_0 for independent failure (1 year in the case of dominant climatic or traffic actions, 5–10 years for dominant imposed loads or $t_0 = t_{ref}$ for dominant permanent loadings).	Sýkora et al. (2016)
$\beta_T = \begin{cases} 1.8 \;\; for \;\; CC1 \\ \max(2.3; \beta_{T,hs}) for \;\; CC2 \\ \max(2.8; \beta_{T,hs}) for \;\; CC3 \end{cases}$ where $\beta_{t,hs} = -\Phi^{-1}\left[\frac{2.75\cdot 10^{-5}\cdot(0.09\cdot S)^{-2}\cdot t_{ref}}{0.055}\right]$	Consequence Class CC, span length S, and remaining lifetime t_{ref}	Steenbergen et al. (2015); *fib* Bulletin N°80 (2016)
$\beta_T = \begin{cases} 4.7 \;\; 0 \le t_{ref} \le 14 \\ 4.63205 + 0.03339 \; e^{\frac{t_{ref}}{25.74022}} \;\; 14 < t_{ref} \le T \end{cases}$	Remaining lifetime t_{ref}; calibrated considering carbonate-induced corrosion	Zhang et al. (2022)

events, and different researchers investigated this issue to assess the possible effect on new or existing structural systems in order to provide adaptation strategies with respect to extreme events, e.g. hurricanes (Bjarnadottir et al., 2011; Lee & Ellingwood, 2017; Li et al., 2016), tsunamis (Alhamid et al., 2022; Nazarnia et al., 2020; Sepúlveda et al., 2021), and floods (Bhatkoti et al., 2016; Cea & Costabile, 2022; Kim et al., 2017). Additionally, the concept of return period is significantly connected to the assumption of stationarity in structural codes, leading to the necessity of proposing different formulations in the context of climate change (Rootzén & Katz, 2013).

Consequently, nowadays design standards are beginning to consider the impact of the changing climate in the calibration of semi-probabilistic formats for appropriately estimating structural safety and performance. Recent studies have proposed calibration strategies for the definition of structural demand explicitly considering climate change. In Croce et al. (2019), a general procedure to assess the impact of climate change on climatic actions is proposed, based on the analysis of historical and future environmental projections. Furthermore, a framework to evaluate the non-stationary characteristic values using climate model projections is discussed in Abrahamczyk and Uzair (2023). In the following, a general overview of the state of the research for standardization of structural demand in different macro-geographic areas is provided, and eventually, the focus is directed to the European context.

In the United States, extreme wind and heat waves are analyzed for the Washington, DC, area considering different airports by Lombardo and Ayyub (2015). A slight decrease in wind speed was observed over the last 50–70 years while a significant increase was noticed for heat wave intensity and frequency. The need for an implementation in the structural codes of the impact of future climate projections on these actions is highlighted. Al-Rubaye et al. (2022) reviewed the developments concerning the calibration of snow loads under climate change. A discussion on the necessity to consider non-stationarity for the definition of design standards with a focus on new climatic loading design maps is discussed in Ghosn and Ellingwood (2024), starting from a review of the current U.S. regulations. A simple scaling procedure is proposed for addressing climate change impact both in the design phase as well as for the evaluations of existing structural systems and applied in the case of wind loading.

Moreover, target structural performances have been investigated in terms of resilience and sustainability under climate change effects and other hazards by the committee on adaptation to a changing climate of the American Society of Civil Engineers (ASCE, 2018). An extensive review of available information on climate change to identify methodologies and tools that would help the civil engineering profession address the impacts of climate change on the life-cycle safety of structures and infrastructure facilities is also available as the result of a SEI/ASCE special project (Biondini et al., 2024).

In the Canadian context, significant research on the evolution of the values of characteristic loadings due to climate change is performed, particularly focusing on wind and snow. Hong et al. (2021) performed a reliability-based code calibration in the context of possible implementation in the National Building Code of Canada (NBCC), focusing on the definition of design values of wind and snow loads, as well as load factors. In the study, the stationary extremes derived from observed meteorological data and the non-stationary climate change effects are considered. Based on the performed analysis and the results from the climate change modeling, load scaling factors accounting for climate change effects are calibrated for different regions in Canada. Despite the load factors being specifically computed for the Canadian environment and climate change significantly varying from region to region, the proposed calibration procedure may be exploited in other geographical contexts. Li (2023) assessed the impact of climate change on structural reliability for Canada. The study provides a general methodology for the integration of non-stationarity in design values of loads, eventually focusing on wind speeds and ground snow loads. In Pandey and Lounis (2023), a methodology to develop a stochastic load model accounting for non-stationary changes in the frequency and intensity of loading events is proposed based on the exploitation of the non-homogeneous Poisson process. An illustrative example is discussed to address the effect of non-stationary climate with respect to design percentiles, return period, and annual probability of failure, highlighting the influence of the change in climate and the need for a revision of the current standards.

European institutions already highlighted the need for a reviewed version of the current Eurocodes, specifically addressing the development of regulations for existing structures and an extension of the current scope of the standards considering the impact of climate change (CEN M/515, 2012; CEN/TC250, 2013). The Joint Research Center (JRC) of the European Union addressed the current and future impact of climate change on structures and infrastructures in Europe through different reports regarding thermal design (Athanasopoulou et al., 2020), snow load (Croce et al., 2016b), river flood risk (Dottori et al., 2020) and coastal flood risk (Vousdoukas et al., 2020). Moreover, in the context of European Standardization, the work by Arnold and Kraus (2022) focused on the calibration of semi-probabilistic code format considering the evolution of climate. In the mentioned research, the FORM methodology is extended to a non-stationary approach deriving the reliability index and sensitivity factor for the sake of calibration. A practical application is presented involving a simply supported beam subjected to snow action in order to exploit the proposed framework. Nevertheless, it is highlighted that the uncertainties involved in climate projection and the selection of the time window may significantly influence the results.

In Table 6, different studies investigating the definition of characteristic and design values of structural loadings under the impact of climate change are summarized, focusing on the European standardization context.

3.4. Structural capacity under climate change

Civil structures and infrastructures are affected by several deterioration phenomena during their lifetime, leading to an evolution of the capacity of the affected structural system. Specifically, in RC structures, these processes coupled with aging may adversely affect structural reliability (Biondini & Frangopol, 2016, 2018). In this context, climate change may have a severe impact on these detrimental processes, enhancing mechanical, physical, chemical, and biological mechanisms causing material deterioration and consequently, negatively influencing structural capacity evolution over time. Different research groups have addressed this risk and the possible adaptation focusing on critical structures, i.e. bridges (Mondoro et al., 2018; Nasr et al., 2020, 2021; Nava et al., 2023, 2024). The possible impact of climate change on structural health monitoring of bridges when dealing with long-term damage detection is studied by Figueiredo et al. (2024).

Focusing on RC structures, climate change is reported to have an impact on freeze-thaw cycles which are connected to the physical deterioration of concrete (Meyer & Weigel, 2011). In Pakkala et al. (2014), this degradation mechanism is assessed in Finland, finding that the current Finnish regulations are sufficient to withstand the evolution in freeze-thaw cycles. It should be highlighted that the previous result is not globally valid and specific regional assessment should be performed to evaluate the micro-climatic trend in the analyzed location. Moreover, the evolution of the frequency and intensity of wildfires due to climate change (Lozano et al., 2017; Strydom & Savage, 2017) may also lead to a deterioration of concrete structural capacity. Scour is observed to be one of the most common causes of bridge collapse (Briaud et al., 2014; Cook et al., 2015), affecting the structural capacity at the foundation level and the overall stability of the system. The extreme precipitation and wind events due to climate change are predicted to enhance scour rate and damage, impacting significantly the structural resistance of existing bridges (Khandel & Soliman, 2019; Nasr et al., 2023; Yang & Frangopol, 2019). Eventually, the more frequent exploitation of deicing salt under climate change may also represent an indirect risk for reinforced concrete structures (Darwin et al., 2007; Nasr et al., 2021), being a possible source for chloride-induced corrosion.

Among the different detrimental processes affecting the capacity of RC structures, corrosion is recognized as the most critical (Bertolini et al., 2013; Tuutti, 1982) and the induced damage may be enhanced by climate change. Recent reports by the JRC assessed this issue at the European level (Dimova et al., 2024; Raposo De et al., 2020). Corrosion induced processes may lead to different damages, such as reduction of the steel cross-section and ductility primarily (Biondini & Vergani, 2015; Coronelli & Gambarova, 2004), but also the possible spalling of the concrete cover and deterioration of the bond between concrete and steel (Prieto et al., 2016; Prieto & Tanner, 2021). Furthermore, corrosion initiation and propagation into RC structures are particularly influenced by the evolution of environmental conditions during the lifetime of the structure, and different researchers proposed methodologies to account for this evolution, especially concerning the impact of changes in temperature and relative humidity (Andrade et al., 2002; DuraCrete, 2000; Guo et al., 2015; Saetta et al., 1993; Yoon et al., 2007). In Table 7, different studies addressing the impact of climate change on corrosion-induced processes, and consequently on structural capacity, are reported focusing on RC structures.

The evaluation of the characteristic and design values of the capacity of deteriorated existing RC structures under climate change is still an open issue due to the significant uncertainties involved and the lack of experimental data. For this reason, a full-probabilistic analysis is often recommended in these cases instead of the application of semi-probabilistic methodology. Further research should be devoted in the next years to address this research gap in order to provide the practitioners with the tools to assess existing aging structures under climate change exploiting the semi-probabilistic approach.

4. Safety factors for existing RC structures

4.1. Partial safety factors

The assessment of existing structural systems is a complex task which gained importance over the last decades because large stocks of structures are reaching the end of the prescribed service life (ASCE, 2021; Belin, 2022). Due to the uncertainties related to this problem, it is generally preferable to perform a full-probabilistic study in order to appropriately evaluate the residual structural performance of the

Table 6. Research findings on characteristic and design values of loadings considering climate change in the European standardization.

Research proposal	Loading	Findings	References
General framework for assessing possible changes in characteristic values of climatic actions, focusing on extreme wind speed in North Western Europe. The impact on the natural variability of wind with respect to the definition of design velocity is also discussed.	Wind	Climate change leads to a modification of −0.8% and +2.3% in the hourly mean wind speed with 50-year return period.	Steenbergen et al. (2012)
Procedure for the derivation of ground snow load from daily temperature and precipitation; furthermore, the snow characteristic value of the load is deduced for future climate projections. Results are provided for different Italian regions.	Snow	Snow loads, under climate change scenarios, are generally expected to increase in the northern and eastern Italian regions, while the opposite trend is observed in western and southern regions.	Croce et al. (2016a, 2018a, 2018b)
General methodology to evaluate the impact of climate change on climatic actions; the results are reported in terms of changes in characteristic values for Italy and Germany, considering different climate models and climate scenarios.	Temperature, precipitation, snow, and wind	Climate change is reported to have a significant impact on temperature, precipitation, and snow loadings while wind velocity is not particularly affected for the 2 considered regions.	Croce et al. (2019)
Research on ground snow load considering non-stationary extreme values models in the French context.	Snow	Return levels under climate change are observed to exceed the standards by 15 % on average for the French building code under a stationary assumption, although a historical decrease in snow load.	Le Roux et al. (2020)
Methodology for the definition of characteristic and design values of loadings considering non-stationarity, applying the time window approach.	Snow	Design and characteristic values of snow load are expected to decrease in time, for the case study considered, under climate change.	Arnold and Kraus (2022)
Framework to evaluate the non-stationary characteristic values of structural loadings using climate observations and model projections.	Temperature	The non-stationary characteristic values of temperature are expected to increase in time due to climate change.	Abrahamczyk and Uzair (2023)
Framework for the elaboration of climate maps for thermal loading exploiting public datasets and harmonized methodologies. A case study for Italy is proposed.	Temperature	An increase of characteristic values of maximum temperature as well as limited variations in spatial extent and magnitude of characteristic values of minimum temperature are predicted considering climate change scenarios.	Rianna et al. (2023)
Studies on the impact of climate change concerning the evolution of climatic loadings, specifically focusing on the definition of minimum and maximum uniform temperatures for the case of a cable-stayed viaduct located in France. The obtained results are compared with respect to the original design and Eurocode regulations.	Temperature	The characteristic values of maximum and minimum temperatures are expected to increase under climate change for the considered case study. The results show that the maximum and minimum uniform components of temperature loading are respectively underestimated and overestimated with respect to the original design and Eurocode regulations.	Casti et al. (2024a)

analyzed system. Nevertheless, full-probabilistic methodologies require a high level of expertise and are often significantly time-consuming. In this context, semi-probabilistic approaches may be simple and reliable tools for practitioners to assess existing structures if properly calibrated. Different research groups explored the calibration of safety factors in the context of civil engineering, as reported in Table 8.

Concerning semi-probabilistic approaches explicitly addressing the assessment of existing RC structures, guidance 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 adopted in the Eurocodes (CEN EN1990, 2002), provides formulas for the calibration of safety factors of both material resistances and actions, exploiting appropriate probabilistic models derived from the prior knowledge,

Table 7. Research findings on the impact of climate change on the capacity of RC structures under corrosion.

Research proposal	Environmental parameters[a]	Findings	References
Probabilistic approach for the estimation of corrosion initiation and damage, i.e. loss in reinforcement area, for RC infrastructures subjected to chloride and carbonation-induced corrosion under climate change scenarios.	C_{CO_2}, *T* and *RH*.	Carbonation and chlorides-induced risk may increase respectively by over 400% and 15% in the Australian temperate area by 2100.	Stewart et al. (2011).
Probabilistic methodology accounting for the impact of climate change on corrosion detrimental processes. The proposed approach is exploited for the assessment of the probability of failure of a RC bridge beam subjected to chloride-induced corrosion considering future climate scenarios.	*T* and *RH*.	Climate change may reduce the failure time by up to 31%, or shorten the service life by up to 15 years for moderate levels of environmental aggressiveness.	Bastidas-Arteaga et al. (2013).
Study on the impact of climate change on the initiation and propagation of carbonate-induced corrosion. The application of the proposed assessment is performed for RC facades and balconies of a building.	C_{CO_2}, *T* and *p*.	Corrosion initiation and propagation are predicted to be accelerated by the future evolution of temperature and precipitation in Finland.	Köliö et al. (2014).
Stochastic framework for the evaluations of the combined impact of chloride-induced corrosion and cyclic loading under climate change. The methodology is applied to study the performance of an RC bridge girder.	*T*, *RH*, and *R*.	The change in climate leads to reductions in the lifetime of the structure ranging between 1.4 and 2.3 % neglecting fatigue. If cyclic loading is considered, the lifetime reduction may increase up to 7%.	Bastidas-Arteaga (2018).
Evaluation of corrosion rate changes in 223 coastal areas in the U.S., assessing the impact of these changes on the service life of structures, and consequently evaluating direct economic losses over the period 2000-2100 under climate change scenarios.	*T*, *RH* and v_s.	The service life of RC structures may decrease by 1.7–2.7% under the climate change most pessimistic scenario by the end of the twenty-first century.	Zhang et al. (2022).
Simulation-based framework for life-cycle structural reliability analysis under climate change scenarios. The approach is exploited for the evaluation of an RC bridge pier cross-section exposed to chloride-induced corrosion.	*T* and *RH*.	The impact of climate change leads to a larger reliability index β decay, approximately 20% and 30% for the most optimistic and pessimistic scenario, with respect to the neglection of climate change.	Nava et al. (2023).

[a]Atmospheric CO_2 concentration C_{CO_2}, Temperature *T*, Relative Humidity *RH*, Precipitation *p*, Duration of cold or dry season *R, and* Wind Speed v_s.

Table 8. Calibration of semi-probabilistic partial factors for different structural systems.

Definition of partial factors for loads due to special vehicles on road bridges.	Lenner et al. (2014); Lenner and Sýkora (2016).
Risk and reliability-based calibration of design codes for submerged floating tunnels.	Baravalle and Köhler (2016).
Definition of partial factors for imposed loads in areas for storage and industrial use.	Lenner and Sýkora (2017).
Calibration of safety factors for offshore wind turbine concrete structures subjected to fatigue.	Velarde et al. (2020).

test results, and observations related to the existing structure under investigation. The APFM (Caspeele & Taerwe, 2012) is a simpler approach that allows updating the partial safety factors defined by Eurocodes for new structures, using "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 the 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 methodologies. Gino et al. (2020) used 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 based on the Eurocodes (CEN EN1990, 2002), showing that recalibration of partial safety factors accounting for updated information may avoid expensive and ineffective 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 for further research on this issue.

The influence on the structural assessment of existing structures of different methodologies for the estimation of concrete strength is studied in Caspeele and Taerwe (2014), analyzing a concrete column both with APFM and standard partial factors for the new structure. The DVM and APFM methodologies are applied by 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 assumptions involved in both approaches. It is shown 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. Following the previously discussed contribution, Orcesi et al. (2023) provided an analysis of the current state of the art concerning the definition of partial factors for the assessment of existing structures, discussing the benefits and drawbacks between the exploitation of prescribed fixed partial factors, tailored partial factor derived for the considered case, and full probabilistic methodologies.

The European Committee for Standardization provided a Technical Specification CEN/TS 17440 (2020) 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 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.

A parametric study addressing the influence of uncertainties on the calculation of partial safety factors for an existing RC bridge girder under bending is provided by Alam et al. (2023). The study highlighted the traffic load and the yielding strength of steel as the most dominant variables for the considered bridge. Finally, an overview of the recent accomplishments concerning semi-probabilistic methods for the assessment of existing concrete structures is provided in Casti et al. (2023).

A summary of recent studies computing tailored partial factors for the assessment of existing RC structures is provided in Table 9.

Table 9. Partial factors for existing structures.

Reference	Structural type	Variable loads	Parameters[a]
Sýkora et al. (2013)	Slab and pier	Traffic	γ_s γ_c γ_g γ_q
Caspeele et al. (2013)	Beam and column	Wind, Imposed	γ_s γ_c γ_g γ_q
Gino et al. (2020)	Box girder deck	Wind, Traffic	γ_s γ_c γ_g γ_q
Lara et al. (2021)	Building Beam	Imposed	γ_s γ_c γ_g γ_q
Orcesi et al. (2021)	Bridge deck	Wind, Traffic	γ_s γ_c γ_g γ_q
Cosenza and Losanno (2021)	Orthotropic deck	Wind, Traffic	γ_s γ_c γ_g γ_q
Casti et al. (2024b)	Box girder deck	Traffic	γ_s γ_c γ_g γ_q

[a] γ_s, γ_c, γ_g and γ_q are respectively the partial safety factor for steel, concrete, permanent and variable load.

4.2. Global safety factors

The assessment of existing structures may require the evaluation of the structural performance at the system level by exploiting Non-Linear Structural Analysis (NLSA). In this context, different studies propose the application of the Global Resistance Format (GRF) strategies (Allaix et al., 2013; *fib*, 2013; Pimentel et al., 2014; Zhang et al., 2014, 2018). The proposed methodology, which is consistent with the guidelines provided in the Swiss Standard for existing structures (Brühwiler et al., 2012; SIA, 2011) and the Eurocodes (CEN EN1992-2, 2005), relies on the application of a global safety factor to the overall system resistance. The exploitation of partial factor methodologies associated with NLSA may lead to unreliable results (*fib*, 2016), especially when dealing with existing RC structures, and for this reason, global resistance methodologies are usually adopted (Blomfors et al., 2016; Slobbe et al., 2020). This safety format accounts for the mean values of material resistance and the nominal value of geometry with respect to the design values considered in the partial factor format.

In Pimentel et al. (2014), it is shown that the global resistance format may be more accurate than the partial safety format, even at the member level. System reliabilities of different steel structures have been investigated by H. Zhang et al. (2014, 2018) accounting for the uncertainties in loads, resistances, and stiffnesses as well as uncertainties in initial geometry and imperfections of the structures. The papers discuss the peculiarities, benefits and drawbacks of these alternative methodologies to steel structure design, highlighting that partial factor methodologies might not be appropriate for assuring system reliabilities.

The estimation of the Coefficient of Variation (CoV) of the global structural resistance associated with the aleatory uncertainty of material properties $V_{R,m}$ is a crucial step for the application of global factor format associated with NLSA (Castaldo et al., 2022), which may be performed exploiting different methodologies, e.g. the Estimation of Coefficient of Variation (ECoV) method (Cervenka, 2013). One of the main assumptions concerning the ECoV methodology is related to the selection of a lognormal probability density function for the resistance and the estimation of the coefficient of variation. Indeed, the assumed lognormal distribution is not always adequate for the analysis. Furthermore, the selection of an appropriate value for model uncertainties is fundamental when dealing with NLSA (Gino et al., 2021; Kadlec & Červenka, 2016).

A discussion about a semi-probabilistic approach compliant with NLSA 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. (2023). In Gino et al. (2024), the evaluation of the design value of the global structural resistance using NLSA in accordance with GRF is proposed, exploiting a novel strain-based methodology in order to account for the influence of aleatory uncertainties related to material properties on the global structural response.

4.3. Considerations on safety factors under structural deterioration

An important limitation of the aforementioned studies concerns the damage processes affecting RC structures, e.g. corrosion, which are assumed to be negligible. Moreover, no explicit considerations concerning the impact of climate change for the calibration of resistance and demand safety factors are addressed. In the context of calibration of safety factors for the assessment of existing RC structures subjected to corrosion-induced deterioration, preliminary considerations are undertaken by Tanner et al. (2011). In the proposed 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 implemented in the case of 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 characterizing the resistance of deteriorating structures. Further investigation related to model uncertainties of corrosion-damaged RC structure is provided in Sýkora et al. (2015).

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 by 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, appropriate and reliable corrosion modeling should be implemented, considering the impact of climate change on the initiation and propagation phases, as well as more refined load modeling considering different ratios between permanent and variable loading. The calibration of the safety factors for the assessment of anchorage capacity in existing RC structures under corrosion is addressed in Blomfors et al. (2019).

In the study, the partial safety factors 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 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. Eventually, different research groups propose the exploitation of Bayesian updating combined with field measurement in order to assess existing RC structures subjected to corrosion processes (Enright & Frangopol, 1999; Faroz et al., 2016; Jacinto et al., 2016; Liljefors & Köhler, 2023).

5. Conclusions

This paper proposed a review of past research and recent developments in the field of semi-probabilistic assessment of existing RC structures, with emphasis on the impact of climate change on the calibration and application of these methodologies. Firstly, the fundamental concepts and definitions concerning the different levels of detail for the evaluation of structural performance in civil engineering practice are discussed, highlighting the benefits and drawbacks of each strategy. Secondly, the focus is devoted to reliability-based calibration of semi-probabilistic methodologies for the assessment of existing structures. The findings of more than 180 studies are summarized to report the main differences between the design of new systems and the assessment of existing ones, considering the possible impact of climate change on the latter. Three crucial aspects are reviewed:

1. The definition of reliability target for the assessment of existing RC structures.
2. The derivation of characteristic and design values of structural demand and capacity for existing RC systems.
3. The calibration of semi-probabilistic code key elements, such as safety factors, for existing RC structures.

The analysis highlighted the effort made in the last years to provide a reliable procedure for the evaluation of residual structural performance to practitioners. This procedure is generally recognized coincident with the semi-probabilistic safety format, due to the simplicity and the replicability in the case of usual situations. A wide number of researchers underlined the need for the consideration of the changing climate in this methodology and several studies proposing frameworks for the incorporation of climate change impact are discussed and reviewed.

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 under climate change scenarios:

- The definition of reliability target for existing structures still remains an open issue for the lack of coherence between the different values proposed in the literature, the deficit of data for the analytical formulations, and the difficulties in the standardization of different RC structures. Moreover, climate change may have an impact on the economic and human safety considerations at the base of the reliability target calibration and this should be addressed in future studies.
- The derivation of the characteristic and design values for structural loadings accounting for climate change impact,

e.g. non-stationarity, is currently being addressed by different research groups. Nevertheless, considering characteristic and design values of structural resistance under climate change, aging, and environmental aggressiveness, for instance corrosion-induced processes, additional efforts are necessary to achieve a more complete understanding of the phenomena. This is due to several factors such as the combination of the uncertainty of climate change modeling with the one related to the environmental aggressiveness modeling, as well as the local nature of the detrimental processes that may be active only in delimited portions of the analyzed structures. Moreover, the modeling of these phenomena is often a complex task and the employment of the proposed models needs very high expertise. For this reason, the development of simplified and standardized methodologies, which may be used by practitioners, is a crucial step for the evaluation of aging existing structures subjected to detrimental processes under climate change.

- The calibration of safety factors tailored for the assessment of existing structures has been extensively investigated in the literature over the last decades considering both partial and global safety formats. The standardization of these semi-probabilistic methodologies has been proposed in different countries by national and international codes, even if further studies are needed for a wider exploitation in practice. The need for a refined characterization of the uncertainties affecting the existing structures as well as standardized prescriptions for dealing with significantly deteriorated structural elements are crucial aspects for future investigations.

In conclusion, the changes in current and future climate are affecting the structural systems and, in general, the built environment leading the hypothesis of stationarity assumed by several national and international standards to be questionable. Further developments are needed along these lines of research in order to revise 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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