Reliability-Based Assessment of Corroded Reinforced Concrete Bridge Girders Under Limit State Criteria

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Abstract. The design and assessment of reinforced concrete structures rely on limit state principles, which define structural performance based on safety (ultimate limit state) and functionality (serviceability limit state). The ultimate limit state ensures that applied loads do not exceed the structural capacity, preventing collapse, while the serviceability limit state addresses the conditions required for proper usage over time. Although the ultimate limit state for flexure rarely governs the design of prestressed bridge girders - except in short spans - it must always be verified to confirm adequate capacity. This study introduces a reliability-based framework to evaluate the time-dependent performance of reinforced concrete bridge girders affected by pitting corrosion by taking into account both the ultimate limit state (ULS), which is connected to the beam's bending failure, and the serviceability limit state (SLS), which is related with the reinforced steel's onset of corrosion. Advanced numerical simulations, combined with the Monte Carlo method, are employed to analyze the probabilistic behavior of structural degradation. Both temporal and spatial variables are modelled as uniformly distributed random variables, allowing for a comprehensive understanding of corrosion effects. Additionally, the study investigates the influence of varying concentrations of the corrosive agent and examines the evolution of failure probability over time. The proposed approach is applied to a corroded reinforced concrete bridge girder, and the results are compared to a benchmark example from the literature. The methodology provides a robust decision-making tool for maintenance planning and resource allocation, ensuring long-term structural safety and durability.

Keywords: structural safety; reliability analysis; Monte Carlo simulation; limit states; pitting corrosion.

1 Introduction

Based on Ababneh et al. [1], concrete is a durable and adaptable building material. Nevertheless, it is susceptible to environmental elements including salty conditions and cycles of heating and cooling. Hazardous materials, especially chloride ions, which are frequently added by deicing chemicals like magnesium and calcium chlorides, can enter concrete due to its natural porosity. Nayak et al. [2] suggest that predicting long-term durability and performance in concrete requires an understanding of the variables that affect the diffusion of chloride ions in the material. One important component is the concrete matrix's permeability, which may be greatly changed by the existence of tiny fissures or voids that form throughout the course of the structure's lifetime. Furthermore, the composition of the concrete, such as the kind and proportion of aggregates and binders, might influence how resistant it is to ion penetration. According to Shiao et al. [3], because of concentration gradients, chlorides can penetrate into the concrete. Water, oxygen, and chloride cause damage the protective layer on the surface of a

steel bar when the concentration of chloride reaches a certain threshold at the depth of the bar.

Revert et al. [4] emphasize that the limit state and the associated degree of reliability, expressed through the probability of failure, are fundamental in defining the design service life of reinforced concrete structures. The service life of such structures is typically divided into the initiation and propagation phases. The initiation phase refers to the period during which deleterious agents penetrate the concrete cover before the onset of corrosion. In this phase, harmful elements, particularly chloride ions, gradually breach the protective layer, ultimately compromising the passive film on the reinforcement. As a result, corrosion initiates, leading to cracking and spalling of the concrete cover, accompanied by a reduction in the cross-sectional area, strength, and deformation capacity of the reinforcement [5]. During the subsequent propagation phase, damage such as corrosion continues to accumulate until the deterioration reaches a level deemed unacceptable [4].

Recent investigations (e.g., Pugliese, De Risi and Di Sarno [6]; Di Sarno and Pugliese [7]) have demonstrated that a considerable number of reinforced concrete (RC) structures worldwide, particularly bridges, are undergoing accelerated deterioration due to exposure to aggressive environmental conditions coupled with increased live loads resulting from escalating traffic volumes. The anticipated service life of these bridges is often further reduced by insufficient or entirely lacking maintenance, which, in severe cases, can lead to structural collapse. Although corrosion processes are inherently complex and stochastic—posing significant challenges to accurate modeling and simulation—it is essential to assess the remaining capacity of aging RC infrastructure through advanced structural reliability methodologies.

In this context, structural reliability assessments typically involve evaluating two primary limit states: the ultimate limit state (ULS) and the serviceability limit state (SLS). The ULS pertains to structural safety, ensuring that catastrophic failure or collapse does not occur, whereas the SLS addresses aspects of durability and functional performance under normal operational conditions. Consequently, both limit states must be rigorously examined to achieve a holistic reliability appraisal. As emphasized by [8], optimal design of RC structures not only safeguards safety and serviceability but also enhances material efficiency, effectively balancing cost considerations with structural reliability requirements. Comparing the acceptable and actual probability of failure (Pf) is essential for assessing structural performance, and in this regard, structural reliability methods offer a robust framework for evaluating the condition of infrastructure throughout its life cycle, explicitly incorporating relevant uncertainties. As demonstrated by Frangopol et al. [9], such approaches are vital for informed decision-making regarding maintenance and safety interventions.

This study conducts a structural time-dependent reliability analysis on a representative beam segment extracted from a reinforced concrete bridge exhibiting corrosion of the steel reinforcement, as originally characterized by Li et al. [8], thus offering a simplified yet meaningful representation of a real-world case. The adopted methodology, based on Li J et al. [8], explicitly incorporates pitting corrosion effects by considering a time-variant chloride diffusion coefficient within a stochastic framework. To quantify the progressive loss of cross-sectional area in both longitudinal and transverse reinforcement due to corrosion, a straightforward degradation model is employed. The time-dependent reliability of the RC beam is then evaluated under two critical scenarios: corrosion initiation in the reinforcing steel, corresponding to the serviceability limit state (SLS), and bending failure of the beam, representing the ultimate limit state (ULS). In this investigation, corrosion of the steel reinforcement is treated as the sole ageing mechanism affecting structural performance. Uncertainties inherent in material properties, environmental exposure, and degradation processes are propagated through Monte Carlo simulations, enabling the probabilistic characterization of both the bending capacity and demand of the girder over time.

2 Limit States

Both in the service and ultimate limit states, reinforced concrete buildings have lost their load-bearing capability due to corrosion deterioration in recent decades. Rust stains appear on the artifact's surface as the first sign of corrosion deterioration; this is followed by concrete cracking and the loss of steel–concrete interaction, a rise in corrosion rate, and a decrease in the reinforcement section. Depending on environmental aggression, ductility and flexural strength can be significantly diminished if not properly countered, which reduces the service life, as discussed by Bossio et al. [10]. Often, just the service limit state of corrosion start or even corrosion cracking is taken into consideration, even though corrosion can cause structural collapse of concrete parts. In some cases,

a structure's overall service life may be significantly impacted by the corrosion propagation period. Thus, when assessing the degradation of corroded RC structures, evaluating their strength capacity is crucial [11].

According to Way et al. [12], the serviceability limit state takes into account a structure's or its members' ability to function normally, user comfort, and the structure's aesthetic appeal. As seen in Fig. 1, the boundaries between safety and failure are well-defined in the ULS but not in the SLS. There is a "transition" area between safety and failure in common SLS scenarios, including cracking, deflection, vibration, and stress limitation, and the moment at which the failure region is achieved is relatively arbitrary.

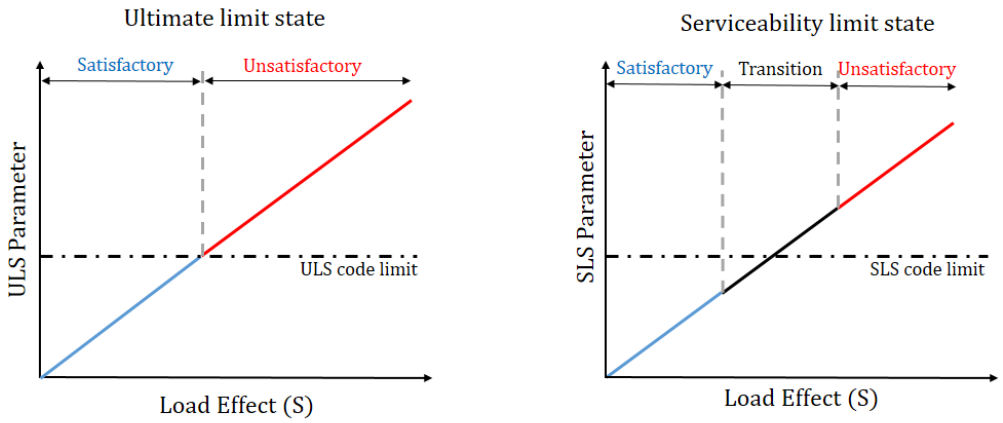


Figure 1. Defined ULS limits vs subjective SLS limits adapted from Way et al. [12].

Durability-focused design codes such as the fib Model Code [13] and ISO 16204 [14] emphasize depassivation as the primary serviceability limit state due to the lack of international consensus on predictive models for cracking, spalling, and residual load-bearing capacity. Verification under these frameworks typically relies on comparing the concrete cover depth with the critical chloride content, considering uncertainties inherent in material variability, environmental exposure, and degradation kinetics, as explained by Monteiro et al. [15]. However, limiting durability assessments to serviceability criteria—such as cracking or depassivation—without explicitly incorporating the ultimate limit state performance neglects the progressive nature of structural degradation, especially in advanced stages of corrosion. Structural reliability is inherently a probabilistic construct: failure is not binary, but distributed along performance thresholds. Therefore, the joint consideration of SLS and ULS within a unified probabilistic framework is essential to accurately evaluate the residual safety margins, guide intervention decisions, and ensure long-term performance under uncertainty [16].

In this context, reliability-based assessment methods that integrate both SLS and ULS are not merely complementary—they are structurally inseparable. By coupling durability indicators (e.g., corrosion depth, cracking width) with mechanical thresholds (e.g., load-bearing capacity, ductility loss), engineers can quantify risk more rigorously and establish performance-based maintenance or retrofit strategies that align with safety and serviceability requirements throughout the service life [8].

3 Overview of Time-Dependent Reliability Analysis

According to Li et al. [8], in engineering practice, the design, construction, and operation of structures are invariably subject to various sources of uncertainty. Such uncertainties are typically modelled through random variables or stochastic processes. Within the framework of time-dependent reliability assessment, a generalized limit state function (LSF) incorporating temporal effects can be expressed as G(X, Y(t), where *X* denotes a vector of random variables, Y(t) denotes a vector of stochastic processes, and *t* represents the time parameter.

As discussed by Song and Kawai [18], the probability of failure may be estimated using either analytical or numerical integration techniques. However, analytical integration is applicable only in rare and idealized cases, which often have limited practical relevance. Due to its convergence rate being largely unaffected by the dimensionality of the input variables or the complexity of the limit state function, Monte Carlo Simulation (MCS) has become a widely adopted method in structural reliability studies. Unlike surrogate-based approaches, MCS directly samples the input variables and repeatedly evaluates the limit state function without approximation.

In this study, the reliability assessment was performed using the MCS method, with the random variables specified in Table 1 for the serviceability limit state (SLS) and in Table 2 for the ultimate limit state (ULS). The simulations were implemented in MATLAB, spanning a time horizon of T=100 years (evaluated annually) and employing $N = 10^5$ samples.

4 Reliability Assessment under Serviceability Limit State (SLS)

The failure function for the corrosion start of reinforced steel can be written as Eq.1.

$$G(X,Y(t),t) = Ti - t = \left\{ \frac{c^2}{4Dref\left(\frac{28}{365}\right)^{0,4}} \left[erf^{-1}\left(1 - \frac{Ccr}{Cs}\right)\right]^{-2} \right\}^{\frac{1}{1-0,4}} - t. \qquad (1)$$

Table 1. Random variables considered for the reliability method, considering SLS by Li et al. [8]

Parameter	Distribution	Mean	Coefficient of variation
C_{cr} (kg/m^3)	Uniform	0.9	0.20
C_s (kg/m^3)	Lognormal	3.5	0.20
c (mm)	Normal	30	0.20
D_{ref} (m²/s)	Lognormal	12 x 10^{-12}	0.20

C_{cr} (kg/m^3) is the chloride threshold level; C_s (kg/m^3) is the surface chloride concentration; c (mm) is the concrete cover depth of steel; D_{ref} (m²/s) is the chloride diffusion coefficient.

In Figure 2, the probability of failure exhibits a steep initial increase, surpassing 0.6 within the first 20 years and approaching unity as the service life progresses. This rapid rise reflects the early onset of serviceability issues - here associated with corrosion initiation in the reinforcing steel - which occur well before structural capacity is critically compromised. The curve's asymptotic approach toward Pf =1.0 indicates that, over a long-term horizon, the SLS inevitably becomes violated for virtually all realizations of the stochastic variables, confirming its conservative nature in reliability assessment.

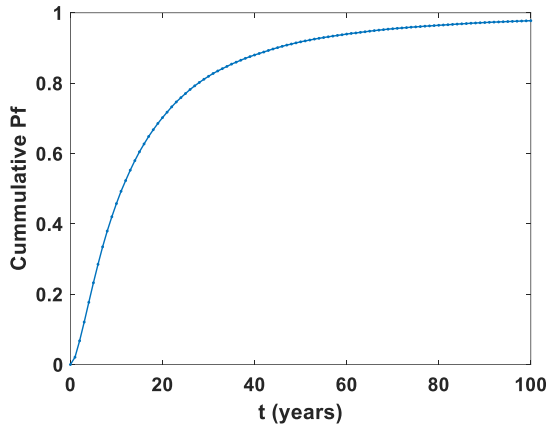


Figure 2. Probability of failure using the MCS method for the analysis with SLS.

5 Reliability Assessment under Ultimate Limit State (ULS)

A numerical reliability assessment under the ultimate limit state (ULS) is carried out, addressing the bending failure mechanism of a reinforced concrete beam. As illustrated in Figure 2, the structural element is modeled as a rectangular cross-section with width b, height h, and ns = 4 longitudinal steel reinforcement bars embedded within the concrete. The beam is subjected to a time-dependent bending moment Ma(t).

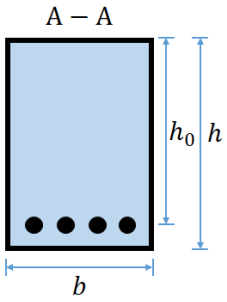


Figure 2. Representation of the RC beam cross-section adapted from Li et al. [8]

The bending moment capacity of the RC beam is detailed in Eq.2. The effective height h_0 is a normally distributed random variable.

$$M_u(t) = f_y A_s(t) \left[h_0 - \frac{f_y A_s(t)}{2 f_c b}\right]. \qquad (2)$$

The failure function for the bending failure of the beam can be written as Eq.3.

$$G(\boldsymbol{X}, \boldsymbol{Y}(t), t) = M_u(t) - M_a(t) = f_y A_s(t) \left[h_0 - \frac{f_y A_s(t)}{2 f_c b}\right] - M_a(t). \qquad (3)$$

Where t represents the time variable varying within [0, T]; X=[C_{cr}, C_s, c, D_{ref}, λ, b, h, fy, fc, D_0]^T are random variables; Y(t)=[c (x)] is a Gaussian process; $As(t)$ is the remaining cross-sectional area of a reinforcing steel at time t, due to pitting corrosion; and $Ma(t)$ is the applied load effect at time t.

Table 2. Random variables considered for the reliability method, considering ULS by Li et al. [8]

Parameter	Distribution	Mean	Coefficient of variation
C_{cr} (kg/m^3)	Uniform	0.9	0.20
C_s (kg/m^3)	Lognormal	3.5	0.20
c (mm)	Normal	30	0.20
D_{ref} (m²/s)	Lognormal	12 x 10^{-12}	0.20
λ	Gumbel	6	0.20
b (mm)	Normal	600	0.05
h (mm)	Normal	800	0.05
f_y (MPa)	Lognormal	400	0.10
fc (MPa)	Lognormal	30	0.15
M_a(t) (kNm)	Gaussian process	200	0.25
D_0 (mm)	Normal	18	0.05

Ccr (kg/m3) is the chloride threshold level; Cs (kg/m3) is the surface chloride concentration; c (mm) is the concrete cover depth of steel; Dref (m²/s) is the chloride diffusion coefficient; λ is the ratio coefficient that varies from 4 to 8; b (mm) is the width of the beam; h (mm) is the height of the beam; f_y (MPa) is the steel yield stress; fc (MPa) is the concrete compressive strength; M_a(t) (kNm) is the applied load effect at time t; D_0 (mm) is the initial diameter of steel bar.

Figure 4 (ULS) shows a more gradual increase in *Pf* during the early years, followed by an accelerated growth phase starting around mid-life (approximately 40–60 years), before stabilizing near 0.9 toward the end of the 100-year period. This pattern reflects the fact that ultimate failure due to bending occurs later in the structure's lifespan, as the member retains a significant portion of its load-bearing capacity despite ongoing corrosion. The initial period of low failure probability, followed by a marked growth, underscores the delayed but more critical nature of ULS violations, which incorporate uncertainties related to both material degradation and load effects.

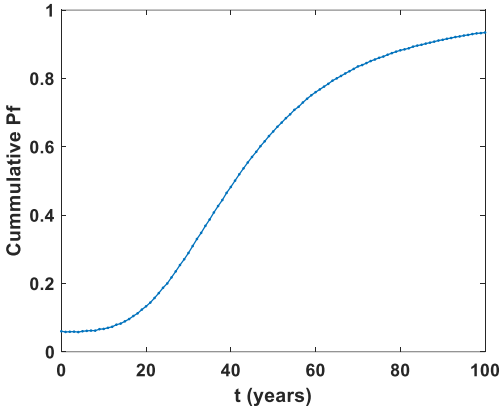


Figure 4. Probability of failure using the MCS method for the analysis with ULS.

A comparison between Figures 2 and 4 reveals that the choice of limit state function (SLS or ULS) leads to distinct outcomes in the reliability assessment. The results indicate that the SLS produces a more conservative estimate than the ULS, potentially leading to an underestimation of the service life of reinforced concrete (RC) structures. While corrosion affects the reinforcing steel, the RC beam retains a significant portion of its load-bearing capacity. As a result, over the time horizon of 0–100 years, the time-dependent probability of failure approaches 1.0 for the SLS, whereas it is approximately 0.90 for the ULS. In the initial service period, however, the ULS-based probability of failure exceeds that obtained using the SLS. This behaviour is attributed to the fact that the ULS incorporates the effects of structural loading, thereby introducing additional sources of uncertainty compared to the SLS.

6 Conclusions

In this study, a reliability-based framework was developed to assess the time-dependent performance of reinforced concrete bridge girders affected by pitting corrosion, considering both the ultimate limit state (ULS), associated with bending failure, and the serviceability limit state (SLS), related to the onset of corrosion in the reinforcing steel. The methodology integrates advanced numerical simulations with the Monte Carlo method, enabling the probabilistic evaluation of structural degradation over time.

The analysis incorporated temporal and spatial variability of corrosion parameters, modelled as uniformly distributed random variables, and examined the influence of different concentrations of the corrosive agent on the structural response. Results show a progressive increase in failure probability for both limit states, with the ULS remaining within safety thresholds over most of the service life, while the SLS exhibits earlier sensitivity to corrosive conditions, reinforcing its role as a governing criterion for long-term functionality. The accuracy and efficiency of the proposed method are validated through comparison with traditional Monte Carlo Simulation (MCS). The findings confirm that the framework is both feasible and computationally efficient, supporting its application in the design and life-cycle maintenance planning of reinforced concrete structures.

The proposed approach demonstrates consistency with patterns reported in the literature, while offering enhanced insight into the probabilistic behaviour of corrosion-induced deterioration. Its application to a corroded bridge girder, with direct comparison to a benchmark study, confirmed the framework's capacity to provide realistic and robust predictions. Beyond academic relevance, the methodology serves as a practical decision-support tool for maintenance planning and resource allocation, ensuring both the safety and durability of reinforced concrete bridge infrastructure throughout its service life.

Acknowledgements. The authors would like to thank FACEPE (Fundação de Amparo à Ciência e Tecnologia do Estado de Pernambuco), FINEP, Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) and Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) for the financial support of various research projects developed in this area by the group.

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