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A defect-based framework for predictive life-cycle assessment of corroded RC bridges

Federica Di Criscio[a]* , Livio Pedone[a] , Stefano Pampanin[a]

[a]*Sapienza University of Rome, Department of Structural and Geotechnical Engineering, Via Eudossiana 18, 00184, Rome, Italy*

Abstract

The structural vulnerability assessment of reinforced concrete (RC) bridges affected by corrosion phenomena represents a crucial topic within civil engineering, particularly in the context of managing aging infrastructure. According to current regulations and guidelines, the degradation state of bridges is first evaluated through visual inspections and classified in terms of defect indices. However, although defect classification forms are available for the identification and categorization of damage, a direct and quantitative correlation between these qualitative descriptors and the reduction in structural capacity is still missing. Therefore, this study proposes a methodological framework to address this gap by integrating defect-based classification tools with mechanical degradation models. The aim is to quantify the impact of observed deterioration mechanisms on the structural performance of bridges through a simplified, yet mechanically-based, assessment procedure. Moreover, the proposed methodology allows for the development of predictive life-cycle models to inform both ordinary and extraordinary maintenance planning, thereby contributing to a more informed and efficient management of existing infrastructure assets. The effectiveness of the proposed approach is demonstrated for a case-study RC bridge. Several defect-index-based degradation scenarios are considered. A fiber-based section analysis is carried out to evaluate the load-carrying capacity of each structural component. This capacity is then locally and progressively reduced over time using deterioration models available in the literature. The significant uncertainty associated with the visual assessment of corrosion processes is also evaluated and considered for the structural safety evaluation over time. Results highlight the potential of the framework as a decision-support tool for proactive infrastructure asset management.

Keywords: Reinforced Concrete Bridges, Corrosion-induced Degradation, Pitting corrosion, Structural Capacity Assessment, Life-Cycle Performance, Defect-Based Classification, Time-Dependent Structural Safety.

* Corresponding author. Tel.: +0-000-000-0000 ; fax: +0-000-000-0000 .
E-mail address: dicriscio.1893319@studenti.uniroma1.it

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1. Introduction

The Italian infrastructure network comprises a vast number of bridges and viaducts, most of which designed and constructed between the 1960s and 1970s, i.e. before the widespread adoption of modern seismic design principles and performance-based durability standards. Consequently, a large portion of these structures now exhibit evident signs of deterioration, which could result in a loss of load-bearing capacity and possibly insufficient structural/seismic safety. These deficiencies may have a direct impact on the continuity of the transportation system and, more broadly, on the socio-economic robustness of the territory. Focusing on reinforced concrete (RC) bridges, among the primary degradation mechanisms affecting their durability, corrosion of steel reinforcement plays a dominant role. Corrosion in reinforced concrete occurs mainly as uniform (from carbonation) and localized pitting (from chlorides), with the latter causing more severe, concentrated reinforcement loss (Alonso et al., 1998; Tuutti, 1997)

Significant research effort has been devoted in the last decades to better understanding the mechanical effects of corrosion on reinforced concrete structures through either experimental (e.g., Maeda et al., 2014) or numerical (e.g., Molaioni et al., 2021; Bernardini et al., 2024) investigations. The modification of mechanical material properties, such as stress-strain relationships and bond degradation, due to corrosion phenomena has also been addressed by past research (e.g., Imperatore et al., 2017). Moreover, numerous studies have investigated the quantification of increasing fragility and the reduction of seismic safety for deteriorating RC bridges (Cui et al. 2018; Gentile et al. 2021; Otárola et al., 2022).

In Italy, in response to the growing need for effective infrastructure management, the Italian Ministry of Infrastructure and Transports (MIT, 2020) recently introduced a regulatory document that defines a multi-level methodology for assessing the condition of existing bridges, based on a risk-informed and condition-based approach. In this document, building on the existing state-of-art bridge risk management procedures, observed defects are quantified using a Relative Defect Index (DR) calculated as a weighted sum (Eq. 1):

$$DR = \sum_i G_i K1_i K2_i \tag{1}$$

where G_i is the base score for defect i, k1 is an intensity coefficient, and k2 is an extension coefficient. Based on the value of the DR index, the bridge is classified into a risk class ranging from “high” to “low”. For low-risk categories, the guidelines prescribe routine inspections and minor maintenance; differently, for high-risk categories, a “Level 4” assessment is required, involving detailed numerical (software-based) simulation and capacity vs. demand checks. For intermediate cases, a preliminary assessment (i.e., “Level 3”) is suggested. However, for this task, the document only provides some basic principles, without specifying a detailed methodology for performing a simplified, yet reliable, mechanically-based safety assessment. Moreover, a quantitative correlation between defect indices (including their localization within the bridge) and the expected mechanical degradation of the bridge’s components is still missing. Finally, the guidelines do not provide explicit thresholds to justify escalation from routine inspections to detailed assessments.

To address these gaps, this study proposes a mechanically-based simplified framework for assessing the residual capacity of RC bridges affected by corrosion phenomena. Building on the scientific advances developed over the years, the present work aims to integrate defect-based classification with degradation concepts to estimate time-dependent capacity curves. These curves are used for evaluating structural safety over time, predicting long-term performance, and supporting both ordinary and extraordinary maintenance planning. The remaining part of the paper is structured as follows: the proposed methodology for residual capacity assessment of corroded RC bridges is presented in Section 2; Section 3 provides an illustrative application; finally, conclusions are given in Section 4.

2. Framework

The proposed assessment framework is designed to provide a practical and quantitative tool to bridge the gap between visual inspections and a mechanically-informed safety evaluation of corroded RC bridges. The framework is schematically illustrated in Fig. 1. Each step is discussed below, focusing on the seismic safety assessment.

2.1. Data collection and defect indices assessment

The first phase of the framework focuses on collecting input data from bridge census forms, including structural typology, static scheme, construction materials, year of construction, and, most importantly, geographical location. The latter is essential for determining both seismic demand and environmental exposure parameters, which are key inputs for modelling the corrosion-driven degradation process. In parallel, this task requires collecting defect survey forms to provide information on defect/damage observed during visual inspections. These qualitative defect/damage indicators are then correlated with a quantitative mechanical parameter consistent with the expected corrosion progression. This parameter, referred to as *Mloss*, represents the percentage mass loss of the reinforcing steel.

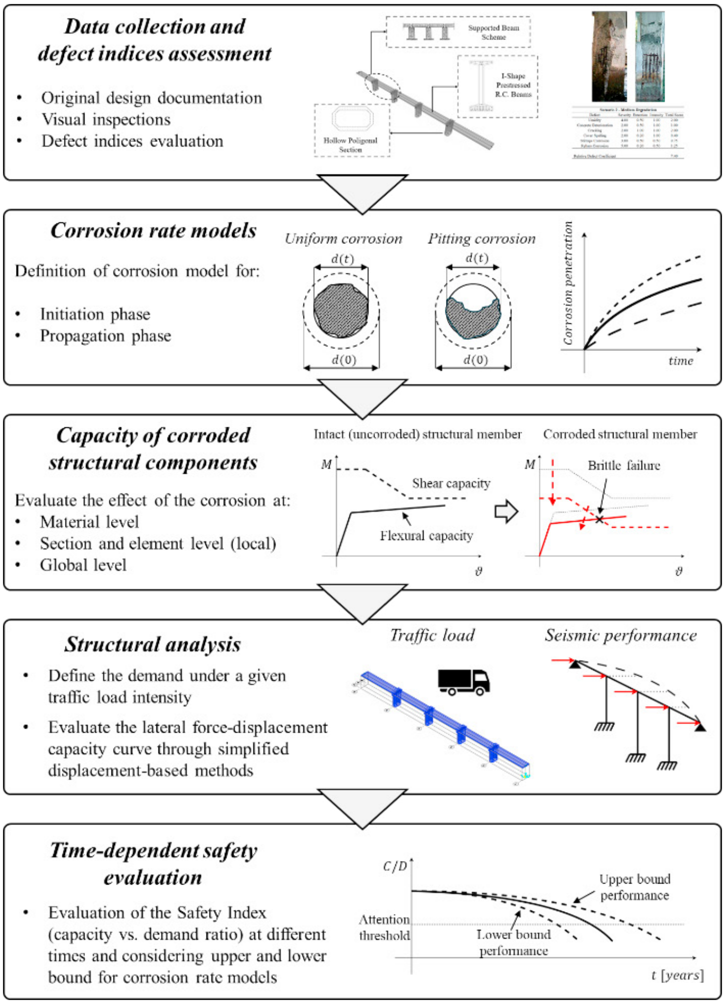


Fig. 1. Framework for time-dependent safety evaluation of existing RC bridges.

2.2. Corrosion rate model

The degradation of reinforced concrete structures due to corrosion is described using a time-dependent model comprising three main phases: initiation, propagation, and structural deterioration (e.g., Tuutti 1997). In this study, a semi-probabilistic approach is adopted, focusing on pitting corrosion. In regions of the model characterized by high uncertainty, a Monte Carlo approach is adopted to compute the expected values of key random variables, which are subsequently used as inputs in deterministic formulations to balance accuracy with computational efficiency.

Assuming a constant surface chloride concentration and defining corrosion initiation as the moment when the critical chloride threshold is reached, the DuraCrete (2000) model, based on Fick's second law of diffusion, is adopted to estimate the initiation time. DuraCrete (2000) also categorized exposure conditions into four environments: submerged, tidal, splash and atmospheric. For each category, probabilistic distributions are provided for the relevant parameters. The corrosion propagation is modelled deterministically. In this phase, pitting corrosion depth increases over time as a function of the pitting corrosion rate, which is estimated using Faraday's law, and the pitting factor R. The latter is derived from the study by Pugliese et al. (2022), which analyses experimental data from the literature to identify an appropriate statistical distribution for this parameter. The time of cracking is assumed to occur when pitting depth reaches a critical threshold, and is evaluated according to Cui et al., (2018). The critical value of pitting corrosion is considered as the product of the pitting factor and the critical depth. According to Alonso et al. (1998), this depth is linearly related to the ratio between the concrete cover and the bar diameter. Finally, the time of spalling is estimated based on crack width evolution, with 1 mm commonly considered the threshold. Following Vidal et al., (2004), crack width is calculated as a function of steel area loss. To estimate the loss of steel cross-section due to pitting corrosion, the hemispherical cavity model by Val and Melchers, (1997) is used.

2.3. Capacity of corroded structural components

Corrosion in reinforced concrete member is expected to reduce their capacity in terms of stiffness, strength, and ductility. Firstly, the degradation effects due to corrosion phenomena are evaluated at the material level as a function of the *Mloss* (derived from steel area loss), as conceptually shown in Fig. 2.

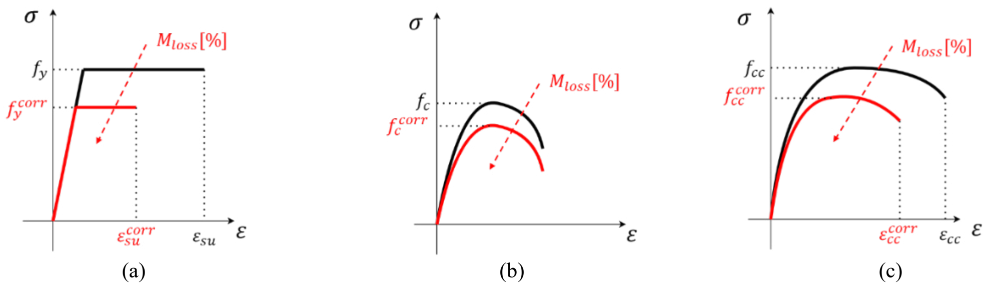


Fig. 2. Schematic degradation of (a) Steel, (b) Unconfined concrete, (c) Confined concrete mechanical properties as a function of *Mloss*

Steel deterioration is modelled using the degradation laws proposed Imperatore et al., (2017). The concrete compressive strength is also reduced according to the model proposed by Coronelli and Gambarova (2004). Finally, the possible loss of confinement due to a reduction of the yielding strength of corroded stirrups is taken into account according to the model proposed by Mander et al. (1988).

The structural capacity of reinforced concrete (RC) sections is then assessed through a moment–curvature (M–ϕ) analysis. Depending on the complexity of the cross-section, the M–ϕ relationship can be derived through simplified analytical methods or detailed fiber-based modelling. Moment–curvature relationships for corroded structural members are expected to show a reduction in terms of stiffness, strength, and ductility capacity when compared to the "as-built" configuration. In the case of RC piers, the M–ϕ curves are then converted into force–displacement (F–δ) relationships by assuming a cantilever-type behaviour with a fixed base. In the presence of localized corrosion, it is assumed that the plastic hinge is more likely to form at the corroded section, where stiffness and ductility are reduced. This condition influences the effective cantilever length L_{cant}. The obtained force–displacement response is then compared with the degrading shear capacity of the element. Shear resistance is evaluated according to the Italian building code (MIT, 2019), accounting for strength deterioration due to corrosion-induced degradation of transverse reinforcement. Finally, the global seismic capacity of the structure depends on the bridge configuration. For simply supported spans, each pier behaves independently, and the global capacity is governed by the most critical (weakest) pier. In contrast, for continuous-span bridges, the global capacity can be obtained through simplified displacement-based approaches (e.g., Dwairi and Kowalsky, 2006).

2.4. Structural analysis and seismic safety assessment

Seismic response analysis is then performed according to state-of-the-art methodologies in the literature. Seismic safety is thus evaluated through a capacity vs. demand comparison performed in the Acceleration Displacement Response Spectrum (ADRS), in line with the Capacity Spectrum Method (ATC, 1996). To quantify seismic safety, a "safety index" ζ_e (i.e., capacity vs. demand ratio at the Life Safety limit state) is considered. Clearly, by carrying out safety evaluations at different times of the bridge's life, it is possible to estimate the decay of the safety index over time.

2.5. Time-dependent safety evaluation

The final step of the methodology involves defining time-dependent capacity curves to capture the progressive deterioration of the structural element. Predefined *Mloss* levels are used to compute corresponding safety indices, which are then linked to exposure times through the corrosion model. This approach enabled the construction of degradation curves over time. These curves provide a forecast of structural performance and should be considered adaptive and updatable: if future inspections reveal a corrosion rate different from the initial assumption, the curves can be recalibrated accordingly, as for a live 'digital twin' approach

3. Illustrative application

3.1. Description of the case study bridge

The selected case study is based on an archetypal bridge proposed by Gentile et al., (2021), who analysed the most common characteristics of bridges across Italy through a comprehensive database of existing structures. The bridge consists of four 30-meter spans, with a deck composed of precast I-shaped beams in prestressed concrete, using 7-wire straight-profile tendons. The piers - which are the main focus of the present analysis due to their role in the seismic response - are 10 m high and are made of reinforced concrete, with a hollow polygonal cross-section (a solution aimed at reducing self-weight while maintaining structural efficiency). Figure 3a illustrates the main components of the bridge structure, while Figure 3b provides the geometric details of the pier. Material properties were assigned based on mean values obtained from national distributions of mechanical parameters for existing Italian bridges, resulting in a concrete design compressive strength of fcd=26.8 MPa and a steel design yield strength of fyd=370 MPa. structure is assumed to be located in the high-seismicity L'Aquila area, with a nominal service life of 100 years and classified as strategic infrastructure (Use Category IV; B soil type; peak ground acceleration PGA = 0.45 g).

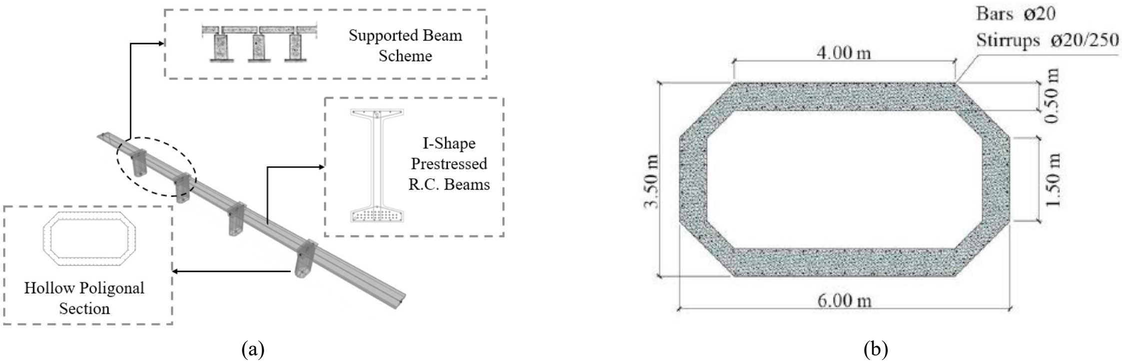


Fig. 3. Italian Archetype bridge: (a) main structural elements (b) detailed pier geometry

To account for different possible conditions of the structure, three degradation scenarios were considered, corresponding to low, medium, and high levels of damage severity (Fig. 4a). These scenarios were defined based on the computation of the Defect Score (DS). In addition, different corrosion locations within the structural element were considered (Fig. 4b).

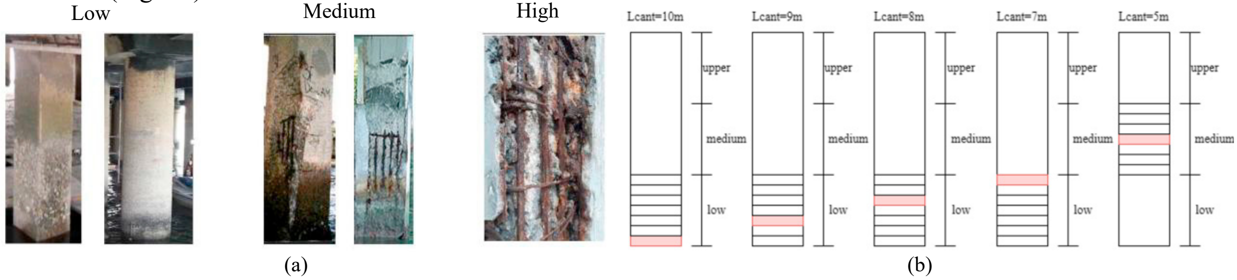


Fig. 4. (a) Examples of low, medium, and high degradation scenarios; (b) localization of the corroded cross-section.

3.2. Corrosion evolution and capacity of corroded RC piers

Firstly, the corrosion rate model is evaluated. Fig.5 illustrates the evolution of the corrosion process, showing the steel mass loss over time (Fig.5a) and (b) the corresponding crack width development and onset of spalling. Results highlight that, according to the selected corrosion rate models, corrosion degradation is expected to start after almost 50 years, while concrete cover spalling occurs after almost 73 years.

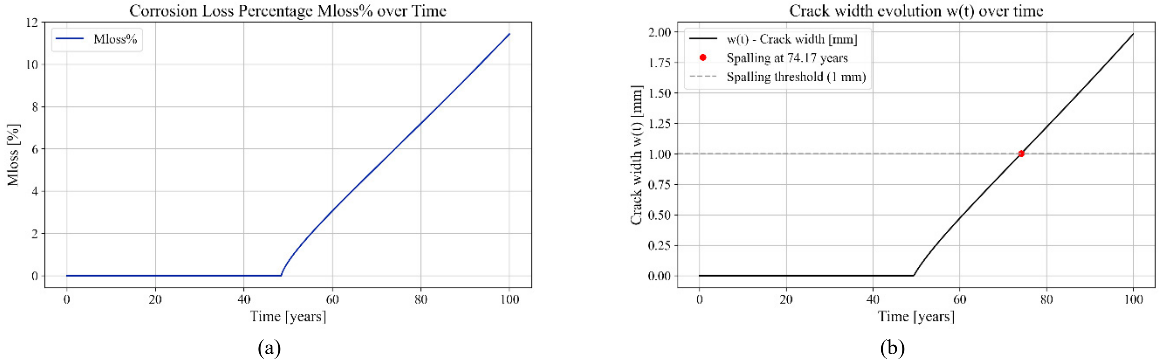


Fig. 5. (a) Corrosion loss percentage Mloss, and (b) crack width evolution over time

Based on these results, *Mloss* values equal to 5%, 10%, and 15% are assigned to the low, medium, and high degradation scenarios, respectively. For each Mloss level, capacity curves are derived using a fiber-based section analysis implemented in OpenSeesPy (Zhu et al. 2018). Fig. 6a illustrates the variation of global force-displacement capacity for different corrosion levels, assuming a fixed position of the corroded section.

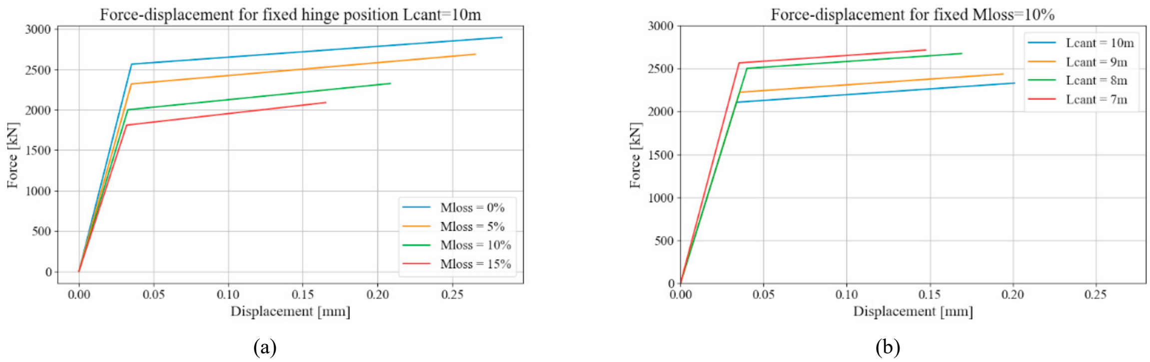
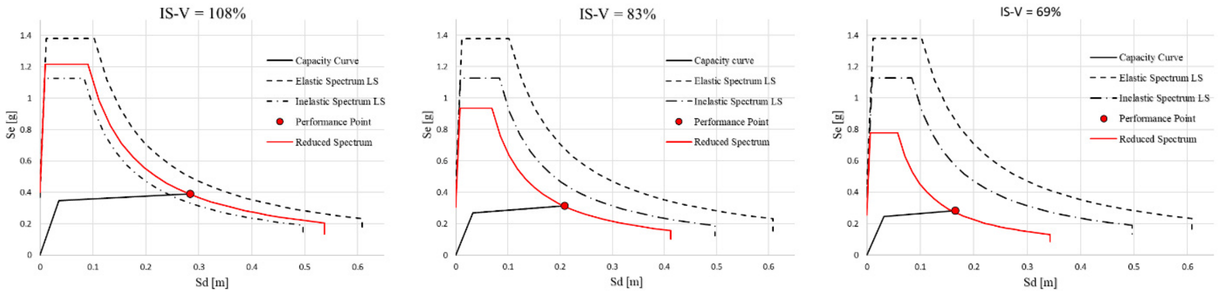


Fig. 6. Results in terms of force-displacement capacity curves considering: (a) fixed hinge position and varying *Mloss*; and (b) fixed corrosion level and varying hinge position.

As corrosion progresses, a clear reduction in both flexural strength and ductility is observed, along with a slight decrease in initial stiffness. This highlights the impact of corrosion-induced section loss on the nonlinear flexural response. Fig. 6b shows the influence of the vertical position of the corroded section along the pier height, for a fixed corrosion level. The lowest flexural strength capacity is observed when the corrosion affects the base section. Differently, as the corrosion moves upward from the base, strength capacity increases, but a reduction in global ductility is observed. Notably, when the corroded section is located beyond approximately 7 m, it no longer governs plastic hinge formation, which then reverts to the base of the pier.

3.3. Time-based seismic safety evaluation.

Finally, safety evaluation is performed through the Capacity Spectrum Method for both the as-built and the corroded configurations. Fig. 7 shows, as an example, the capacity vs. demand evaluation in the ADRS domain for increasing levels of corrosion (*Mloss* = 0%, 10%, and 15%), considering the damage at the base of the pier. As expected, increasing the *Mloss* leads to a lower safety index (i.e., capacity/demand ratio) for the case-study bridge.



(a) (b) (c)

Fig. 7. Seismic Performance for three different levels of corrosion: (a) *Mloss* = 0%; (b) *Mloss* = 10%, and (c) *Mloss* = 15%.

The degradation of the safety index over time is finally shown in Fig. 8. The time-dependent analysis reveals that corrosion location critically affects the structural safety trajectory. The curve corresponding to corrosion at the base of the pier starts to degrade earlier; yet the seismic safety decreases more gradually. Conversely, when corrosion is located higher up along the pier, the degradation of safety begins later but occurs more abruptly. This behaviour is due to the observed reduction in global ductility capacity when the plastic hinge forms at a higher section. As a result, a crossing between the curves over time is observed, suggesting that the location of the defect may significantly affect the decision-making regarding maintenance strategies.

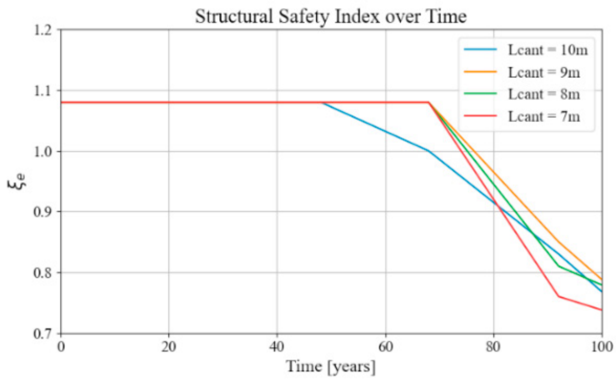


Fig. 8. Safety Index degradation over Time

4. Conclusions

This study presented a simplified, yet mechanically informed, framework for the predictive life-cycle assessment of RC bridges affected by corrosion, integrating qualitative defect classification tools with quantitative structural degradation models. By linking defect indices, currently used in visual inspection protocols, with time-dependent deterioration of mechanical properties, the methodology provides a practical tool to evaluate the residual capacity of aging infrastructure. The proposed framework enables the derivation of time-dependent capacity curves, offering predictive insights into the evolution of structural reliability under different damage scenarios. The application to a case-study bridge highlights several key findings: (i) corrosion localization significantly influences the degradation pattern of structural performance; and (ii) corrosion at the base of the pier leads to an earlier, gradual decline in capacity, while corrosion higher along the pier causes a delayed but more abrupt reduction in safety, due to a low-ductile collapse mechanism. Overall, the framework can represent a valuable decision-support tool for maintenance prioritization, inform the escalation of assessment levels, and ultimately enhance the long-term safety and resilience of existing RC bridge networks. Future developments would focus on incorporating probabilistic approaches that explicitly account for uncertainties inherent in visual inspections, corrosion progression, and mechanical response.

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