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REVIEW

Probabilistic assessment of corroded concrete structures – systematic literature review

Avaliação probabilística de estruturas de concreto sob corrosão – revisão sistemática da literatura

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Abstract: The evaluation of service conditions of concrete structures has still been carried out through implicit knowledge based on the expertise and knowledge of inspectors, who classify structures based on subjective criteria. The main degradation mechanism of reinforced and prestressed concrete structures is the corrosion of steel reinforcements, with expressive maintenance and repair costs. The phenomenon of corrosion in concrete structures has a complex behavior and presents several uncertainties, and deterministic analyzes can produce very conservative responses, which can unnecessarily increase maintenance costs, thus justifying probabilistic approaches. This article then presents a systematic literature review of articles that address the evaluation of concrete structures under reinforcement corrosion using a probabilistic approach. In this regard, 94 journal articles obtained through an appropriate review protocol were reviewed. Thus, the summary of the main proposed methodologies was carried out, as well as the identification of research gaps on the subject.

Keywords: corrosion, reliability, concrete, systematic literature review.

Resumo: A avaliação das condições de serviço de estruturas de concreto ainda tem sido realizada através de conhecimentos implícitos, baseados na experiência e no conhecimento de inspetores, que classificam as estruturas a partir de critérios subjetivos. O principal mecanismo de degradação das estruturas de concreto armado e protendido é a corrosão das armaduras de aço, com custos diretos de manutenção e reparo bastante expressivos. O fenômeno da corrosão em estruturas de concreto possui comportamento complexo e apresenta diversas incertezas, e análises determinísticas podem produzir respostas muito conservadoras, que podem, desnecessariamente, aumentar os custos de manutenção, justificando assim abordagens probabilísticas. Esse artigo apresenta então uma revisão sistemática da literatura dos artigos que abordam a avaliação de estruturas de concreto sob corrosão das armaduras através de abordagem probabilística. Para isso, 94 artigos, obtidos através de um protocolo de revisão adequado, foram revisados. Desse modo, a sumarização das principais metodologias propostas foi realizada, bem como a identificação de lacunas de pesquisa sobre o tema.

Palavras-chave: corrosão, confiabilidade, concreto, revisão sistemática de literatura.

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1 INTRODUCTION

The corrosion deterioration of reinforced concrete (RC) and prestressed concrete (PSC) structures is a major concern problem. The total direct cost of corrosion estimated by the Federal Highway Administration (FHWA) from 1999 to 2001 was 276 billion dollars per year, and a considerable part of which was infrastructure costs. The total impact of corrosion on highway bridges, including steel bridges, has been estimated at 8.29 billion dollars annually [1]. In 2013, the global cost of corrosion was estimated to be 2.5 trillion dollars, which is equivalent to 3.4% of the global Gross Domestic Product (GDP) [2]. In 2015, the cost of corrosion in China was approximately 310 billion dollars, representing about 3.34% of GDP, and the transportation and electronics industries were the two that generated the highest costs among all those surveyed [3].

The corrosion damage can degrade the mechanical behaviors of the corroded reinforcement, the surrounding concrete, and the interaction between them [4]. Several studies presented analytical and numerical approaches, generally through the finite element method, to evaluate corroded RC/PSC elements.

Although corrosion can lead to structural failure of concrete elements, frequently, only the service limit state of corrosion initiation or even corrosion cracking is considered. In certain situations, the corrosion propagation period can be a significant part of the total service life of a structure [5]. Therefore, the evaluation of strength capacity is essential in the deterioration assessment of corroded RC structures [6].

The phenomenon of corrosion of reinforcement in RC/PSC elements has several uncertainties, which can be listed: intrinsic uncertainties associated with the phenomenon of corrosion itself, errors in measurement and quantification of factors that affect corrosion, such as environmental conditions, physical properties of concrete elements, or even structural model error [7].

Thus, as corrosion includes several uncertainties, the deterministic approach to assessing the deterioration of RC/PSC structures can lead to very conservative structural responses, which aim not to impair structural safety but can increase maintenance costs [8]. Therefore, in this context, probabilistic approaches have been widely used to properly assess the service life of these structures and propose appropriate intervention strategies.

Therefore, as there is no specific review, as far as the author's knowledge, of the probabilistic evaluation of corroded RC/PSC structures, this article attempts to fill this gap by performing a systematic literature review of this subject. Thus, the main objective of this paper is to identify and evaluate, through a systematic literature review (SLR), the main methodologies for the probabilistic evaluation of corroded RC/PSC structures, emphasizing gaps in corrosion damage modelling, probabilistic approach and monitoring, and future advancement.

2 REVIEW PROTOCOL

This paper presents a Systematic Literature Review (SLR) in the scope of the structural assessment of corroded reinforced and prestressed concrete structures under uncertainties. The computational tool called StArt (State of the Art through Systematic Review) [9] was used to support this SLR.

First, to find relevant content for review, keyword research in the Scopus database and Web of Science was proceeded, through an appropriate search string, including ('assessment' or 'analysis' or 'modeling' or 'evaluation') and ('reinforced concrete' or 'rc' or 'prestressed concrete') and ('reliability' or 'risk' or 'uncertainty' or 'probabilistic' or 'probability' or 'variability' or 'stochastic') and ('corrosion' or 'corroded'). The search was filtered to journals with Scopus CiteScore 2021 metric greater than 2, document type journal article, publication language English, and publication date in last ten years (01/2012 - 04/2022). This initial research results in 299 different articles.

After that, a selection was conducted to select only the studies that present methodologies with generalization, applicability, and validity of results. Furthermore, several studies focus only on corrosion initiation, and generally, only the depassivation of the reinforcement and the concrete cracking is considered failure criteria. Then, an inclusion criterion was established where only articles that address the ultimate limit state of the structural element were included. Lastly, 94 articles were finally accepted, and a full-text review proceeded where relevant information was extracted and summarized using an appropriate quantitative and qualitative approach (Figure 1).

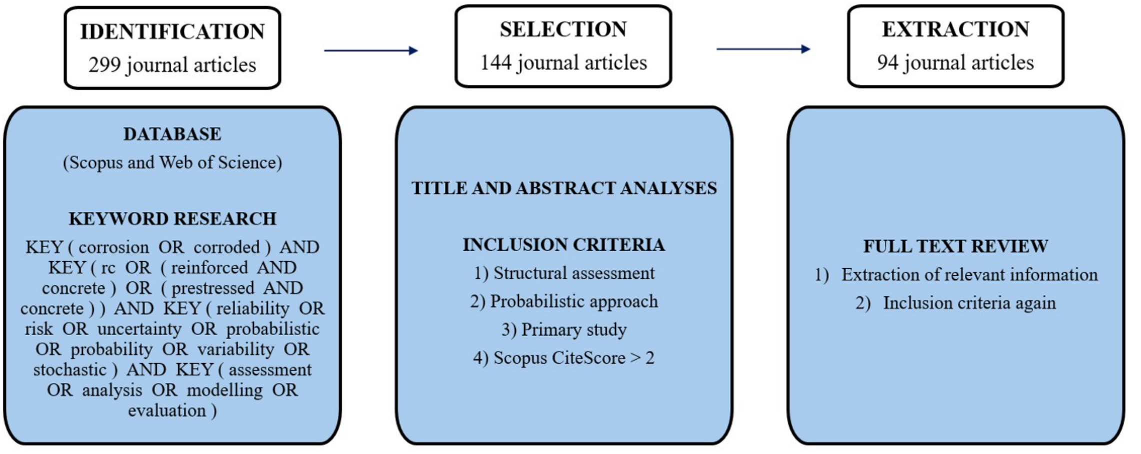

Figure 1. Flow Diagram of Systematic Literature Review

3 BIBLIOMETRIC ANALYSIS

In this section, a bibliometric analysis of the 94 articles reviewed is performed. The data were summarized according to relevant categories through tables and figures, which allows the visualization of exciting aspects of the state-of-the-art review.

3.1 Year of publication

First, the reviewed articles were categorized according to their year of publication, as shown in Figure 2. It is noted that there was an increase in the number of publications from the year 2018, with 65% of the articles published from that year onwards. This growth in the publication of articles on the subject of analysis of corroded concrete structures under uncertainty indicates the relevance of these studies today.

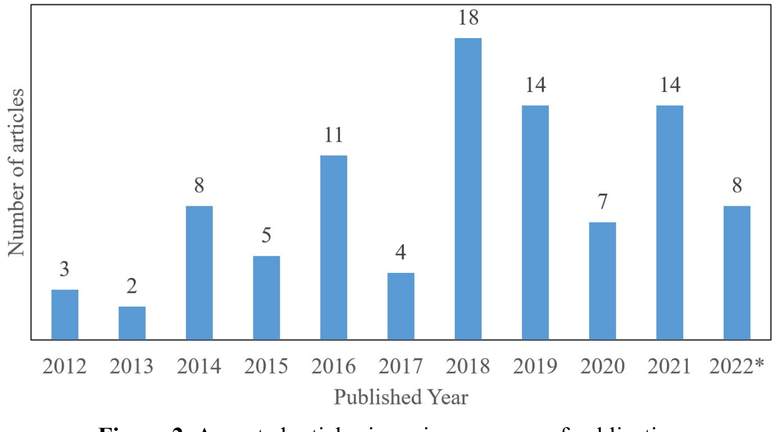

Figure 2. Accepted articles in review per year of publication

3.2 Authors

The authors with the highest number of publications and the respective articles published in this systematic review are summarized in Table 1. The authors with the highest number of publications are Frangopol D.M., Akiyama M., and Zhang J., with 10, 7, and 6 publications each, respectively.

Frangopol D.M. and Akiyama M published several papers and presented studies mainly addressing pitting corrosion and spatially variable corrosion, using monitoring and experimental data. Zhang J. presented articles focusing on the combined effect of corrosion and fatigue of reinforcement.

Table 1. Authors with more accepted articles in review (authors with four or more articles)

Author Name	Country	Number of articles	Articles published
Frangopol D.M.	US	10	[10]–[19]
Akiyama M.	Japan	7	[10]–[12], [15], [17]–[19]
Zhang J.	China	6	[6], [20]–[24]
Gardoni P.	US	5	[25]–[29]
Firouzi A.	Australia	5	[30]–[34]
Ma Y.	China	5	[6], [20], [21], [23], [24]
Wang L.	China	5	[6], [20], [21], [23], [24]
Gu X.	China	4	[35]–[38]
Huang Q.	US	4	[39]–[42]
Chiu C.	Taiwan	4	[43]–[46]
Jia G.	US	4	[26]–[29]
Neves L.A.C.	UK	4	[47]–[50]

3.3 Journals

To carry out a quantitative analysis of the main sources of articles accepted in the review, journals with a minimum number of three articles are presented in Table 2, with the number of citations received by the accepted papers of each journal.

The journal with the highest number of publications in the last ten years in the area of probabilistic evaluation of concrete structures under corrosion of reinforcement was 'Engineering Structures', with 26.6% of the total of accepted articles. Subsequently, the journals ‘Structure and Infrastructure Engineering’ and ‘Engineering Failure Analysis’ present 13,8% and 7,4% of the accepted articles.

In addition, the journal with the highest number of citations of accepted articles was ‘Structure and Infrastructure Engineering’ with 582 citations, still obtaining the highest number of citations per article, 44.8. Next, 'Engineering Structures', 'Structural Concrete', and 'Engineering Failure Analysis' have 513, 157, and 155 citations, respectively.

Table 2. Number of accepted articles in review per source (sources with three or more articles)

Source	Articles	Citations	Citations per article
Engineering Structures	**25**	513	20,5
Structure and Infrastructure Engineering	13	**582**	**44,8**
Engineering Failure Analysis	7	155	22,1
Structural Concrete	5	157	31,4
Structural Safety	5	49	9,8
Construction and Building Materials	4	39	9,8
Journal of Bridge Engineering	4	59	14,8
Advances in Structural Engineering	3	15	5,0
Journal of Performance of Constructed Facilities	3	26	8,7
Journal of Structural Engineering (United States)	3	22	7,3
Reliability Engineering and System Safety	3	44	14,7

3.4 Citations

Finally, in this bibliometric analysis, the reviewed articles with the highest number of citations according to Scopus in each year were summarized in Table 3, with the average number of citations per year of each of these articles. Akiyama and Frangopol [19] published in 2014 the article with the highest number of Scopus citations, with 110 citations, approaching the seismic performance of corroded reinforced concrete bridge pier, and Bagheri et al. [51] published in 2020 the article with the highest average number of citations per year, with 22 citations per year, focusing on chloride-induced corrosion considering epistemic uncertain thought determination of a fuzzy time-dependent reliability index.

Table 3. Most cited articles per year, according to Scopus

Year	Most cited article per year (title)	Scopus Citations	Citations per year
2012	Risk-based life-cycle maintenance strategies for corroded reinforced concrete buildings located in the region with high seismic hazard [46]	33	3,0
2013	Analysis of lifetime losses of low-rise reinforced concrete buildings attacked by corrosion and earthquakes using a novel method [45]	28	2,8
2014	Long-term seismic performance of RC structures in an aggressive environment: emphasis on bridge piers [19]	**110**	12,2
2015	Hybrid Uncertainty Quantification for Probabilistic Corrosion Damage Prediction for Aging RC Bridges [23]	86	10,8
2016	Reliability of a corroded RC beam based on Bayesian updating of the corrosion model [52]	65	9,3
2017	Effects of the axial force eccentricity on the time-variant structural reliability of aging r.c. cross-sections subjected to chloride-induced corrosion [53]	88	14,7
2018	Redundancy-based service life assessment of corroded reinforced concrete elements considering parameter uncertainties [54]	67	13,4
2019	Stochastic life-cycle analysis: renewal-theory lifecycle analysis with state-dependent deterioration stochastic models [27]	46	11,5
2020	Uncertain time-dependent reliability analysis of corroded RC structures applying three-term conjugate method [51]	66	**22,0**
2021	Life-cycle probabilistic seismic risk assessment of high-rise buildings considering carbonation induced deterioration [25]	26	13,0
2022*	Assessment of remaining service life of deteriorated concrete bridges under imprecise probabilistic information [47]	4	4,0

4 BIBLIOGRAPHIC SYNTHESES

This section presents the main contributions of the reviewed articles within the following categories: Corrosion Damage and Structural Modeling, Experimental and Monitoring, and Probabilistic approaches.

This synthesis makes it possible to gather the main relevant aspects in the probabilistic approach on the evaluation of corroded concrete structures and identify research gaps and potential future research.

4.1 Corrosion Damage and Structural Modeling

In this review, 84 articles address the evaluation of reinforced concrete structures under corrosion, while only 10 present analyses of prestressed concrete structures. Regarding the type of structural element analyzed, most works present the evaluation of beam elements, 51 (54.3%) articles. Then, analyses of corroded columns, frames, and slabs are also addressed in some works, 13, 10, and 4 articles, respectively. Finally, 19 articles address the deterioration of bridge elements.

Most studies reviewed, 75 (79.8%) articles, consider corrosion by chlorides as the cause of initiation. On the other hand, only 7 (7.4%) articles consider carbonation-induced corrosion. This difference in the number of articles can be explained by the intensity of the deterioration of chloride corrosion, although carbonation-induced corrosion can also have severe structural deterioration.

Although most works address chloride-induced corrosion, uniform corrosion is considered in 46 (48,9%) articles. Pitting corrosion is addressed in 53 (56,4%) articles, 32 of which model it as spatially uniform and 21 as spatially variable, which better represents the phenomenon of pitting corrosion.

Most articles, 56 (59,6%), use flexural strength as a failure criterion. Then, 18 (19,1%) studies use the shear strength and 5 (5,3%) the axial force-bending moment resistance. In studies that address seismic analysis, displacement of the structure and column curvature are the most used failure criteria, with 11 (11,7%) and 6 (6,4%) articles, respectively.

The main effects of corrosion in the modeling of reinforced concrete structures are presented in the studies, namely: Reduction of the steel area of the longitudinal bars (LA) and stirrups (SA); Changes in the strength (StrS), stiffness (SS) and ductility (DS) of steel bars; Changes in strength and ductility of concrete under compression (SDC), due to cracking induced by the expansion of steel bars; Deterioration of bond between steel bars and concrete (BSC); Reduction of concrete confinement due to stirrup corrosion (CC).

The studies that present the most robust models regarding corrosion damage modeling are summarized in Table 4.

Table 4. Most robust corrosion damage modeling

Authors	Type of element	LA	SA	StrS	DS	SDC	BSC	SS	CC
Pugliese and Di Sarno [8]	frame	✓	✓	✓	✓	✓	✓	✗	✗
Pugliese et al. [55]	beam/column	✓	✗	✓	✓	✓	✗	✗	✓
Habibi et al. [56]	beam	✓	✓	✓	✓	✓	✓	✗	✓
Yu et al. [4]	frame	✓	✗	✓	✓	✓	✓	✗	✗
Xu et al. [57]	bridge	✓	✓	✓	✗	✗	✗	✓	✓
Fan et al. [58]	bridge	✓	✗	✓	✗	✓	✓	✗	✓
Dizaj et al. [59]	frame	✓	✗	✓	✓	✓	✓	✗	✓
Allaix et al. [60]	beam	✓	✗	✓	✓	✓	✓	✗	✗
Guo et al. [35]	beam	✓	✗	✗	✓	✗	✓	✓	✗
Cui et al. [61]	bridge	✓	✗	✓	✓	✗	✗	✗	✓
Aslani and Dehestani [62]	beam	✓	✗	✓	✓	✗	✗	✓	✗
Firouzi et al. [31]	column	✓	✓	✗	✗	✓	✗	✗	✓
Mortagi and Ghosh [63]	bridge	✓	✗	✓	✗	✓	✗	✗	✓
Zhang et al. [64]	bridge	✓	✗	✓	✓	✗	✓	✗	✗
Liang et al. [65]	bridge	✓	✓	✗	✗	✗	✓	✗	✓
Sajedi and Huang [42]	beam	✓	✗	✓	✓	✗	✓	✗	✗

Reduction of the steel area of the longitudinal bars (LA) and stirrups (SA); Changes in the strength (StrS), stiffness (SS) and ductility (DS) of steel bars; Changes in strength and ductility of concrete under compression (SDC), due to cracking induced by the expansion of steel bars; Deterioration of bond between steel bars and concrete (BSC); Reduction of concrete confinement due to stirrup corrosion (CC).

The following subsections present the main topics in recent articles on modeling corroded concrete structures.

4.1.1 Corrosion rate

Although reinforcement corrosion has several effects that impact the structural capacity, as mentioned earlier, the main effect is the reduction of the cross-sectional area of steel bars, and the corrosion rate is a quantitative parameter that indicates the intensity of corrosion by measuring the flow of electrons. Some recent studies have considered the corrosion rate at different stages, depending on the state of deterioration of the concrete or even different zones of structure [58], [66].

Feng et al. [67] modeled the corrosion rate in two critical phases, the phase from the beginning of corrosion until the cracking of the concrete cover and the phase from the cracking of the cover until the steel area reduces to zero. The corrosion rate is adopted constantly in each of the phases.

Similarly, Ma et al. [23] proposed an accelerated coefficient in the corrosion rate model, after concrete cracking, based on results obtained by Cao et al. [68].

Cui et al. [69] presented seismic fragility analyses of corroded bridge substructure. They showed that neglecting the increase in corrosion rate after concrete cracking underestimates the deterioration, although most studies adopt a constant corrosion rate. The authors proposed a three phases time-dependent corrosion rate model that accounts for the increase in corrosion rate after concrete cracking based on available experimental data. Cui et al. [61] later present an improved time-dependent seismic fragility model with this same corrosion rate model.

In addition to accelerating corrosion propagation, concrete cracking caused by loading can also influence corrosion initiation. Jia and Gardoni [27], [29] present a state-dependent deterioration model to simulate the initiation and propagation (corrosion rate) of corrosion according to the occurrence of seismic events.

4.1.2 Pitting corrosion and spatial variability

Especially in chloride-induced corrosion, sectional reduction of steel bars can occur with significant spatial variation (pitting corrosion). Although some studies still consider uniform corrosion, the structural behavior of spatially variable corrosion models has been extensively studied recently.

Vatteri et al. [7] consider the effect of pitting corrosion and the stress concentration associated with this phenomenon, through the reduction of the yield strength of the steel reinforcement, depending on the degree of strength of the bar. However, the decrease in the steel yield strength, in reality, can be explained by the reduction of the effective cross-sectional area of the steel bars. Therefore, the yield strength of the real steel is not changed [70].

Ghosh and Sood [71] model the spatial variability of pitting corrosion based on the Stewart and Al-Harthy [72] study, where the reinforcing bars are divided into elements of 100 mm length, and the pitting corrosion in each element is obtained by the Gumbel distribution for pitting factor *R*. Zhang et al. [11] studies the Gumbel distribution parameters via regression analysis for different element lengths (100, 50, and 25 mm) and perform reliability analyses of corroded RC beam considering the correlation of steel loss between elements.

Similarly, Lim et al. [17] present a study with spatial variability in corrosion that was modeled by varying the cross-sectional area of bars based on the steel loss measured by an X-ray photogram. The reinforcements were modeled with truss elements in the same manner as Srivaranun et al. [10]

Dias-da-Costa et al. [48] evaluate the definition of element length and suggest an element length of 0.45 m, considering that after corrosion initiation, the reliability index must not change abruptly. Therefore, in this study, the elements are considered statistically independent.

Several other authors present a similar approach for statistical modeling of the pitting factor R through Gumbel distribution.

Studies of pitting corrosion in prestressing steel are rarer. In that way, Tu et al. [16] adopted the experimental-based model presented by Darmawan and Stewart [73] to simulate the spatial variability of pitting corrosion of prestressed wires where pit depth follows Gumbel distribution and corrosion occurs only on the outer wires. The maximum pit depth depends on the corrosion degree and the wire length. Liu et al. [36] developed a probabilistic model for the stress impact factor of high-strength prestressing wires due to pitting corrosion and showed that minimum Gumbel distribution fitted it well.

4.1.3 Corrosion and fatigue

In modeling corroded RC/PSC structures, the combined effect of pitting corrosion and steel fatigue has significant repercussions and has been extensively studied.

Pitting corrosion starts with small pit nucleation and propagates over time through fatigue, and corrosion propagation, which increases the pit area, resulting in local stress concentration and rapid cracking growth [24], [74].

Some studies [20], [21], [74]–[76], adopt the concept of competition between corrosion and fatigue crack growth proposed by Kondo [77] to determine which phenomenon governs crack formation. In this case, the two rates are estimated, and the higher one is chosen as the crack formation rate.

Bigaud and Ali [74], Bastidas-Arteaga [75], and Saad et al. [76] adopted the fatigue crack growth rate estimated by Paris–Erdogan law.

Saad et al. [76] performed a reliability-based design optimization of the life cost cycle of an RC bridge considering the coupled effect of corrosion and fatigue.

Guo et al. [21] evaluate the combined effect of corrosion and fatigue using two corrosion pit models. In the first model, the corrosion pit is modeled as a notch, while in the second, the corrosion pit is treated as a surface crack. Based on the results found, the authors suggest using the corrosion pit model as a notch, although the second model is simpler and can be used for cases of low traffic frequency.

Ma et al. [24] developed a framework for the corrosion fatigue evaluation based on fracture mechanics. After, Ma et al. [20] proposed a model to estimate the fatigue crack growth considering the interaction between the corrosion pit and fatigue crack based on fracture mechanics theory.

4.1.4 Concrete damage model after cracking

As for the impact of corrosion on concrete material, there are two main effects. The first is the deterioration of the concrete cover due to cracking or even spalling of concrete due to the increasing volume of the corrosion products. The second would be the reduction in concrete confinement due to corrosion of the transverse reinforcement.

The effect of cracking or spalling of the concrete cover on structural capacity can be considered through the reduction or exclusion of the deteriorated concrete area or even by the decrease of the resistance of the concrete cover.

Ghodoosi et al. [78] and Pugliese et al. [55] considered, in a simplistic way, that after spalling of the concrete cover, the concrete does not present any contribution to the resistance capacity of the structural element.

Firouzi et al. [31] adopted the empirical model presented by Xia et al. [79] to compute the effective concrete cross-section that steel contributes to the structural capacity of corroded RC columns.

Berto et al. [80] simply assumed that the compressive strength of concrete deteriorated by corrosion is equal to 70% of the compressive strength of undamaged concrete.

To compute the deterioration of concrete cover due to corrosion, Coronelli and Gambarova [81] proposed a reduced compression strength of concrete based on the modified compression field theory of Vecchio and Collins [82]. Several authors adopt that model [4], [8], [10], [14], [17], [53], [60], [83]. Chen [84] proposed a linear softening in the stress-strain relationship to model concrete cracking.

For the sake of considering the effect of reduced confinement of concrete due to corrosion of stirrups, some works [71], [83] adopt the uniaxial constitutive model of concrete in compression proposed by Mander et al. [85], reducing the volumetric ratio of transverse reinforcement due to steel corrosion.

4.1.5 Bond modeling

Some works consider, in modeling concrete structures under corrosion, the reduction or loss of bond between the concrete and the reinforcement due to corrosion propagation since this phenomenon can change the type of structural failure and reduce the resistance capacity of the element.

Allaix et al. [60] adopted the bond model of the fib Model Code [86], considering the residual bond resistance depending on corrosion penetration depth. Lim et al. [17] used the residual bond stress-slip model presented by Kallias and Rafiq [87] to model the bond interface element for corroded RC beams. Similarly, Aslani and Dehestani [62] considered the bond deterioration through appropriated stress-strain relationships in interface elements.

The bond deterioration can change the failure mode of RC beams. Chen [84] evaluated the residual flexural capacity considering rebar bond degradation by simple analytical expressions, with and without loss of anchorage of the steel bars. On the other hand, Sajedi and Huang [42] collected in literature results of 240 eccentric pull-out/beam specimens and developed a regression model of bond strength. Later, Soraghi and Huang [39] presented a probabilistic model to predict the failure mode based on bond testing of 132 beam-end specimens subjected to monotonic and cyclic loading.

Performing seismic analyses, Liang et al. [65] studied the effect of bond deterioration on corroded RC bridges subject to ground motion through fragility analyses during service life. They concluded that bond slip increases the failure probability. Yu et al. [4] compare different corrosion damage models proposed in the literature for the bond-slip behavior by analyzing the impacts of the deterioration of the bond strength and slip deformation on seismic fragility.

4.1.6 Structural Modeling

As for the structural modeling of corroded RC elements, numerical models, more specifically finite element models, have been primarily used to incorporate the different effects of corrosion propagation in the structure.

For the sake of simplicity and to reduce the computational cost, especially in reliability analyses, where several analyses must be carried out, one-dimensional finite element models are commonly adopted.

Allaix et al. [60] and Schmuhl et al. [88] used a similar one-dimensional displacement-based finite element model, with a beam element representing the concrete, and a truss element, representing the reinforcement, the first study to analyze RC beams and the second one for PSC pile. Tu et al. [16] adopted a grillage model to analyze a multi-girder prestressed concrete bridge.

Kashani [89] developed an advanced fibre-based nonlinear beam-column finite element model that approaches the corrosion damage on reinforcing steel, inelastic buckling, and low-cycle fatigue degradation through a uniaxial material model for steel reinforcement based on experimental results. This model has been implemented in the OpenSees [90], a finite element-based open-source software developed to perform structural and geotechnical seismic analyses. Thus, several authors [4], [8], [14], [49], [57], [59], [63]–[65], [69], [71], [83], [91], used this one-dimensional model to simulate different types of structures, mainly for dynamic analysis of corroded RC structures.

Different one-dimensional modeling strategies are presented, highlighting the studies of Xu et al. [57] and Zhang et al. [64] that used a zero-length shear spring element to capture shear failure at the end of the corroded RC column.

Other studies [11], [17], [35], [36], [50], [92]–[95] approach the corroded RC structures through two-dimensional finite element models, where usually the concrete is modeled using plane elements (thickness equal to the beam width), and steel reinforcement modeled using truss elements or even smeared reinforcement. With this type of analysis, the bond deterioration between concrete and corroded reinforcement can be accurately modeled using an interface element between concrete and reinforcement with an appropriate bond-slip relationship model. Hajializadeh et al. [96] adopted plate elements to analyze an RC slab bridge.

Among two-dimensional models, the model presented by Habibi et al. [56] to evaluate corroded RC members can be emphasized. The authors developed an advanced nonlinear finite element model based on the modified compression field theory Vecchio and Collins [82] that can capture several behaviors such as compression softening, confinement, tension stiffening, tension softening, shear slip along crack interfaces, and regarding corrosion propagation, effects of cover cracking, bond strength degradation, and steel deterioration.

Finally, due to the high computational cost, few works [6], [42], [58], [62] use three-dimensional finite element models to evaluate corroded RC/PSC structures. In those studies, concrete is modeled using solid elements and reinforcing by truss elements.

4.2 Probabilistic approaches

Regarding probabilistic approach for evaluating corroded RC/PSC structures, most studies carry out reliability analyses to compute failure probabilities over the service life of the structure, and most of these studies use Monte Carlo Simulation (MCS) in their reliability analyses. Although MCS is a numerical approach that can be applied to any structural model, the high computational cost due to the need to carry out many simulations can make the solution unfeasible. Thus, other probabilistic approaches recently used to assess the performance of corroded RC/PSC structures are presented below.

4.2.1 Stochastic modeling approaches

Unlike the MCS, some authors present closed-form solutions in order to compute corrosion deterioration along service life, which, although not able to generalize to different problems as in the MCS, are computationally more efficient.

Tolentino and Carrillo-Bueno [97] developed a new closed-form to approach structural capacity deterioration due to corrosion using a second-degree polynomial function.

Soltanian et al. [34] and Firouz et al. [31], [32] applied a closed-form solution proposed by Firouzi et al. [98] to compute the first passage probability (up-crossing) modeling the steel corrosion as a nonstationary Gaussian process.

Other authors [62], [84], [94] also use the gamma process for time-dependent stochastic modeling of corroded RC structures.

Finally, it is important to emphasize the state-dependent stochastic models (SDSMs) for modeling RC corrosion deterioration.

Tesfamariam et al. [99] modeled chloride-induced corrosion deterioration through a stationary Markov chain. The deterioration process is represented by three states, chloride ingress, initial corrosion propagation, and cover cracking propagation. The transition matrices are computed using MCS.

Jia and Gardoni [27], [28] developed a time-dependent reliability analysis framework using state-dependent stochastic models (SDSMs) to assess the impact due to multiple deterioration processes and their interactions.

4.2.2 Fragility analysis and robustness

Several studies [61], [65], [69], [71], [83], [91], [100]–[103] evaluate the performance of corroded RC structures through seismic fragility analysis, where seismic performance is measured, by computing the probability of failure concerning a specific limit state for different levels of seismic intensity.

Other authors performed fragility analyses for different types of load cases. Xu et al. [57] proceeded fragility analysis to evaluate corroded RC bridges subjected to tsunami hazards. Liu et al. [104] developed blast fragility analyses of corroded RC columns.

Similar to fragility, robustness can be defined as the ability of the structure to withstand accidental actions without the damage caused being too severe. Cavaco et al. [49], [50] analyzed the robustness of corroded RC structures. The authors assumed that damage came from corrosion loss.

Another similar way to measure the performance of RC structures subjected to corrosion is through redundancy indices. Botte and Caspeele [54] presented a probabilistic approach to assess corroded RC elements based on a redundancy factor. The redundancy index is measured by the change in the probability of failure of the intact and damaged system.

4.2.3 Life cycle costs and reliability-based design optimization

The reliability-based design optimization (RBDO) is usually attributed to structural optimization where the constraints are failure probabilities (or reliability index) of limit states. Some studies use this approach or even perform the optimization of the life cycle costs of corroded RC structures to plan inspections or even choose the more suitable initial design.

Saad et al. [76] performed reliability-based design optimization (RBDO) in the life cycle costs (direct and indirect) of RC bridges subjected to the coupled effect of fatigue and corrosion.

Sajedi et al. [41] proceeded a reliability-based multiobjective design optimization in order to obtain optimum design using different concretes on RC bridge beams subjected to corrosion. Later, Sajedi and Huang [40] developed a reliability-based optimization approach to compare the life cycle cost using six different groups of materials (concrete and steel) and determine the optimum corrosion management strategy of RC bridge beams.

Finally, reliability-based life-cycle optimization approaches are presented [13], [30] in order to plan maintenance actions by fiber reinforcement polymer (CFRP) strengthening of structural elements.

4.2.4 Epistemic uncertainty and fuzzy theory

An epistemic uncertainty refers to limitations of knowledge about the problem. Although this type of uncertainty is not usually considered in reliability analyses, epistemic uncertainties can be modeled by fuzzy theory.

Anoop et al. [105] presented a new methodology to evaluate corroded RC flexural elements considering fuzzy uncertainty from exposure environment characterization, using fuzzy set theory and the MCS technique.

Ma et al. [23] develop a framework to approach epistemic uncertainty in the evaluation of corroded RC structures, where the expert-based variables uncertainty is probabilistically quantified using the entropy method.

Bagheri et al. [51] perform time-dependent reliability analyses of corroded RC beams considering epistemic uncertainty using a hybrid version of the genetic algorithm and particle swarm optimization.

Alam et al. [47] proposed a methodology to account for the reliability of corroded RC structures by considering both aleatory and epistemic uncertainties separately through a Bayesian probability box. The authors show that the impact of considering the epistemic uncertainty can increase the probability of failure by almost two.

4.2.5 Bayesian updating

In reliability analysis, random variables can be obtained from initial information such as structural design, codes, previous research, or data from similar structures. Bayesian updating can be used to update variables with posterior information obtained from the inspection or monitoring of the structure.

In that way, Ma et al. [6] used field measurements and obtained posterior distribution of the variables: concrete cover thickness, concrete strength, and corrosion loss using Bayesian updating methodology to estimate the structural capacity of corroded RC beams accurately.

Allaix et al. [60] studied the model uncertainty of the flexural capacity prediction of corroded RC beams. The model uncertainty is modeled as a lognormal random variable, and the distribution parameters are computed through Bayesian updating.

Faroz et al. [52] developed a novel Bayesian updating approach for steel reinforcement loss based on data from monitoring.

Finally, Xu and Azhari [106] presented a framework for assessing the time-dependent reliability of prestressed concrete highway bridges. Based on data from nondestructive testing, the authors update the parameters: concrete cover thickness, current density, and surface chloride.

4.3 Experimental and Monitoring

Experimental tests of corroded elements in laboratory conditions can be carried out to formulate deterioration models of corroded concrete structures. In this review, 23 of 94 articles (24.5%) present experimental data [10]–[12], [17], [19], [20], [23], [27], [30], [35], [37], [38], [42], [44], [51], [53], [54], [80], [93], [107]–[110].

In the evaluation of corroded concrete structures, data from inspection and monitoring can be obtained to provide a more reliable analysis of the condition of the structure. In this review, 23 of 94 articles (24,5%) present real data from structures [6], [8], [10], [19], [22], [34], [38], [43], [45]–[47], [55], [74], [78], [80], [92], [94]–[97], [106], [109], [111].

4.3.1 Experimental testing (laboratory)

As previously mentioned, the corrosion rate is the main parameter used to measure the intensity of corrosion propagation in steel reinforcement. Therefore, the measurement of this important parameter is sometimes studied. In that way, Firodiya et al. [107] used the linear polarization resistance (LPR) technique to measure the corrosion rate of bar specimens to determine the frequency distributions of the corrosion rate and concluded that the lognormal distribution fit it well.

Recently, instead of measuring the intensity of corrosion propagation, some studies use laser scanning techniques [10]–[12], [17], [19], [37], [38], which allow visualization of steel loss and concrete cracking caused by corrosion.

Zhang et al. [38] applied a 3D laser scanning technique in extracted rebars of four corroded RC slabs casted and subjected to accelerated corrosion in the laboratory. They characterized the spatial variability of weight loss along the length by the Gumbel distribution depending on corrosion degree, element length, and reinforcement diameter. Similarly, Zhang et al. [11] studied the spatial variability of steel weight loss and concrete cracking depending on current density, concrete cover, rebar diameter, and fly ash in RC beams using X-ray radiography.

Lim et al. [17] used the X-ray technique to study the spatial variability in the weight loss of steel and concrete cracking along the corroded RC beams and compared the weight loss measured after the elements were destroyed, finding excellent accuracy (3% difference).

Finally, a few studies experimentally investigate the behavior of the corroded structural element itself.

Ma et al. [6] developed an experimental study where forty-eight RC beams were submitted to accelerated laboratory corrosion and tested to carry out a probabilistic approach to modeling the structural capacity of corroded RC beams.

Qiu et al. [108] accomplish a non-destructive testing (NDT) technique, namely self-magnetic flux leakage (SMFL), to probabilistic evaluate the flexural capacity of corroded RC beams.

Lee et al. [93] manufactured three PSC beams and conducted four-point bending tests on specimens to compare the experimental results with the probabilistic finite element model presented in the article.

4.3.2 Inspection and monitoring of real structures

Ma et al. [6] and Yang et al. [22] presented inspection data (cover, concrete strength, corrosion loss, mechanical properties of steel bars) of three beams of the Jianggong bridge in order to validate a Bayesian updating framework proposed [6] and a new estimation method for the scale of fluctuation [22].

Zhang et al. [38] collected 20 naturally corroded rebars from RC beams of an existing building in Shanghai in 2005 to study the spatial variability of corrosion loss along rebar.

Chiu et al. [43] presented data of chloride deposits and corrosion rates of reinforcement steel submitted to natural chloride-corrosion to analyze seismic damage of corroded RC columns. The authors used test points at 100, 300, 1000, and 3000 m from the coastline.

Kim and Song [109] estimated the traffic load of the Hwayang-Jobal Bridge through the weigh-in-motion (WIM) technique using a probabilistic approach with Bayesian updating methodology in order to perform time-dependent reliability analyses of a corroded PSC box girder bridge.

Xu and Azhari [106] used inspection data of a PSC highway bridge in Anhui, China, built in 1972. The concrete strength, cover thickness, concrete resistivity, chloride content, and bridge traffic volume were used to update the failure probability using Bayesian Updating.

Pugliese et al. [55] obtained data for temperature, traffic volume, and concrete and steel reinforcement material properties to perform reliability analyses of an existing RC bridge.

Finally, Tang et al. [94] proceeded field investigation of drainage culverts submitted to corrosion deterioration. The longitudinal bars, concrete thickness, and concrete strength were examined.

5 CRITICAL REVIEW AND FUTURE RESEARCH

Through this systematic review of the literature, the growing number of studies on the theme of probabilistic assessment of corroded reinforced and/or prestressed concrete structures can be noted, with different methodologies being presented over the last few years. Although several studies have been presented, it is possible to highlight some gaps and possible future research.

In this sense, few studies referring to corroded prestressed concrete structures were found in the literature. As for the type of structures, most studies approach corroded RC bridges with a significant focus recently given to the coupled effect of corrosion and seismic, and corrosion and fatigue. Despite that, few studies address seismic performance in buildings submitted to corrosion deterioration, even though dynamic behavior associated with corrosion may be critical in the service life analysis of this type of structure. It is noteworthy that most of these works analyze the seismic damage by evaluating the displacements and deformations of the elements during the seismic event, without taking into account the structural failure.

As already presented, most works use empirical formulations to determine the corrosion rate or even simply attribute values, which are generally constant over time. Although a few studies address the effect of concrete cracking on the acceleration of corrosion propagation, the modeling of corrosion initiation as a function of the state of concrete cracking can still be explored.

Most works only address analyses of beam elements regarding the flexural capacity limit state, using finite element beam-column models or analytical expressions. In that way, the shear failure and other structural elements are hardly analyzed.

The impact of corrosion cracking on concrete cover and reinforcement corrosion on core concrete due to confinement reduction is considered in some models. However, the availability of concrete damage models due to corrosion is still limited in the literature.

Due to the complexity of models of deterioration of corroded RC/PSC structures, most works use Monte Carlo Simulation to perform time-dependent reliability analyses. However, the computational cost can be high.

Finally, although some theoretical studies present appropriate probabilistic approaches for updating random variables from inspection and monitoring data, a minority uses examples of real structures.

6 CONCLUSIONS

A systematic literature review was conducted, with 94 journal articles, published between 2012 and 2022, fully reviewed. The main studies that address the evaluation of corroded reinforced and/or prestressed concrete structures were figured out, allowing the identification of the significant methodologies already proposed and relevant future research.

The main effects of corrosion on structural capacity were highlighted. It was noticed that most of the works address the flexural failure of reinforced concrete beams, with some articles addressing shear failure and structural assessment of other elements such as columns and slabs. Some works, mainly focusing on seismic analysis, carry out the analysis of bridges, considering the entire structural system, from foundations, columns, and decks. Others works analyzed the joint effect of pitting corrosion and fatigue in reinforcement. The effects of reducing the strength of the cover concrete and reducing the adhesion between concrete and steel bars due to reinforcement corrosion are also considered in some works.

As for the probabilistic approach, most works use Monte Carlo simulation to determine the probability of failure over the service life, although some works present other methodologies, such as closed-form solutions, fragility, and robustness analyses. In order to update random variables, the Bayesian update methodology is generally used and allows the reduction of uncertainties in a simple and effective way.

Finally, some works were presented that used experimental results from the laboratory or even from real structures to evaluate corroded RC/PSC structures, where the main measured parameters were corrosion current, corrosion loss through X-ray, concrete cover, concrete strength, concrete resistivity, chloride content, and traffic load.

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