Framework for the seismic vulnerability assessment of reinforced concrete structures considering climate change effects

Estefanía Cervantes

Universidad San Francisco de Quito USFQ, Quito, Ecuador

University of Minho, Guimarães, Portugal

Jose C. Matos

University of Minho, Guimarães, Portugal

Eva Lantsoght

Universidad San Francisco de Quito USFQ, Quito, Ecuador

Delft University of Technology, Delft, the Netherlands

Contact: ecervantes@usfq.edu.ec

Abstract

Reinforced concrete structures (RCSs) face increasing vulnerability due to aging, deterioration, and climate change, compounded by seismic events. This paper proposes a framework that integrates time-dependent deterioration mechanisms, climate projections, and seismic vulnerability analyses. The methodology develops deterioration profiles using site-specific data while employing Performance-Based Earthquake Engineering (PBEE) to evaluate seismic risks. Climate scenarios from the IPCC address non-stationary climate impacts, such as accelerated corrosion. This research represents a first step toward defining a systematic process for assessing these combined effects. The proposed framework addresses critical gaps in traditional vulnerability assessments and contributes to improving the resilience of aging infrastructure under combined environmental and seismic hazards.

Keywords: aging infrastructure; corrosion; climate change; deterioration mechanisms; fragility analysis; IPCC scenarios; performance-based earthquake engineering.

1 Introduction

Infrastructure is a fundamental pillar for the economic, social, and urban development of any nation. However, over their service life, infrastructure assets are exposed to extreme natural events such as earthquakes, floods, storms, and wildfires, which pose significant risks to their functionality and safety. Among these hazards, earthquakes stand out due to their frequency and the damage they can cause in structural performance [1].

The vulnerability of reinforced concrete structures (RCSs) to seismic events is further exacerbated by the effects of aging, deterioration, and the intensifying impacts of climate change [2]. Over time, these processes reduce structural capacity, compromising both the serviceability, safety, and overall performance of these critical structures [3]. Recent research highlights that climate change accelerates these deterioration mechanisms while simultaneously increasing the frequency and severity of extreme natural events [4], [5].

Despite the potential effect of deterioration of aging bridges on their seismic performance, the combined effect of seismic loading, the effects of aging and deterioration, and climate change impacts has not been addressed yet. Therefore, this paper proposes a comprehensive framework for assessing the seismic vulnerability of RCSs, explicitly incorporating the effects of climate change on both loading and capacity sides of the rating equation. This research represents a first step toward defining a clear and structured process to evaluate these combined effects in a systematic and replicable manner.

2 Reinforced concrete deterioration

Deterioration refers to the gradual loss of structural capacity over time and may involve the degradation of the concrete matrix itself or corrosion-induced damage to the steel reinforcement [4], [6]. Cervantes et al. [4] categorized the primary causes of deterioration into four main types: mechanical, physical, chemical, and biological. These common causes are summarized and illustrated in Figure 1.

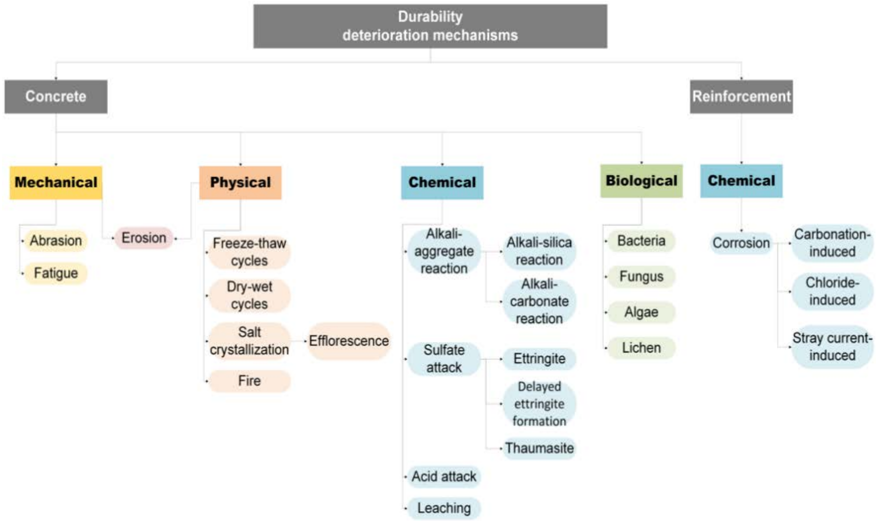

Figure 1. Common causes of deterioration of reinforced concrete structures [4]

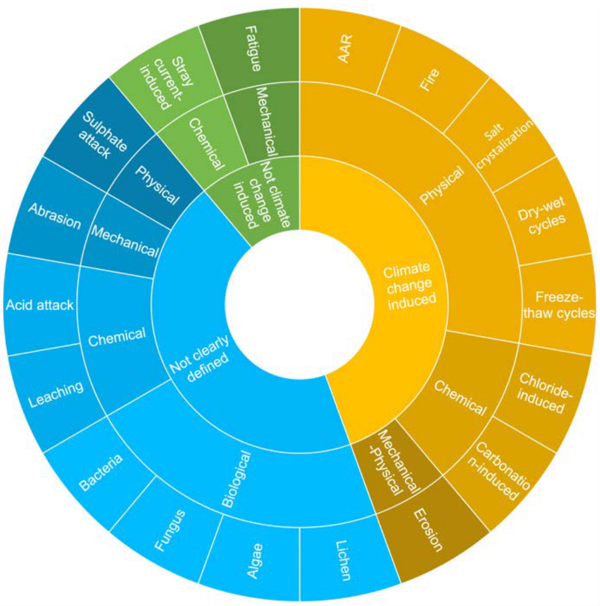

Figure 2. Potential impacts of climate change on the durability of RC structures [4].

Furthermore, studies have shown that the rate of deterioration is not solely determined by the material composition and construction processes but is also significantly influenced by the climatic conditions experienced throughout the structure's service life [7]. Thus, changes in atmospheric CO_2 concentration, temperature, and relative humidity accelerate certain deterioration mechanisms [4], [8], [9], as shown in Figure 2. Moreover, climate change has increased the frequency and intensity of several natural hazards, resulting in higher demands on civil infrastructure [5]. In addition, compounding risks, such as wildfires followed by heavy rainfall causing slope erosion, or flooding exacerbated by intense storms combined with rising sea levels, can further undermine the performance of structures like bridges [5].

3 Climate change impact

3.1 Introduction

Compared to the preindustrial period, the global climate is changing at an unprecedented rate, as evidenced by variations in climate variables such as temperature, CO_2 levels, relative humidity, sea level, and precipitation patterns, among others [7]. However, current design guidelines rely on stationary climate conditions, which are increasingly inadequate given that the lifespan of civil infrastructure often spans several decades [5].

3.2 Climate change scenarios

The Intergovernmental Panel on Climate Change (IPCC) has developed scenarios to analyze and project potential future trajectories of greenhouse gas (GHG) emissions. These scenarios are not predictions or forecasts, but rather hypothetical representations based on a set of assumptions about factors such as population growth, economic patterns, technological advancements, and environmental policies [7]. The IPCC primarily uses two types of scenarios to assess climate change: the Representative Concentration Pathways (RCP) and the Shared Socioeconomic Pathways (SSP) [7]. The description and relationship of scenarios are described in Table 1.

Table 1. Description and relationship of IPCC scenarios

Category description	GHG emissions scenarios	SSPx-y*	RCPy**
Limit warming to 1.5 °C	Very low	SSP1-1.9	
Limit warming to 2 °C	Low	SSP1–2.6	RCP 2.6
Limit warming to 3 °C	Intermediate	SSP2–4.5	RCP 4.5
Limit warming to 4 °C	High	SSP3–7.0	
Exceed warming of 4 °C	Very high	SSP5–8.5	RCP 8.5

*SSP-based scenarios are referred to as SSPx-y, where 'SSPx' refers to the SSP, and 'y' refers to the level of radiative forcing resulting from the scenario in the year 2100.

**RCP-based scenarios are referred to as RCPy, where 'y' refers to the level of radiative forcing resulting from the scenario in the year 2100.

The RCPs, introduced in earlier reports [10], are a set of possible future scenarios modeled in terms of GHG emissions. Each RCP represents a specific radiative forcing trajectory, a measure of the energy imbalance in the Earth's atmosphere expressed in watts per square meter (W/m^2), projected for the year 2100. The main scenarios include RCP2.6, which corresponds to a low-emissions scenario with strong mitigation strategies aimed at limiting global warming to below 2 °C; RCP4.5 and RCP6.0, which represent stabilization pathways where emissions peak and then decline; and RCP8.5, a high-emissions scenario without significant mitigation measures.

On the other hand, the SSPs, used in more recent reports [7], integrate socioeconomic trajectories with emissions projections, reflecting how economic development, public policies, and mitigation capacities can shape the future. Designed as a complement to the RCPs, the SSPs provide a more comprehensive approach by considering not only emissions but also the social, economic, and political dynamics that drive them, enabling a more thorough analysis of potential impacts and responses to climate change. The five main scenarios include SSP1, which describes a sustainable world with low emissions; SSP2, which follows historical trends with moderate challenges; SSP3, which represents a fragmented world with low international cooperation and high emissions; SSP4, centered on pronounced inequality between regions and sectors; and SSP5, which describes rapid development driven by fossil fuels, resulting in a significant increase in emissions.

4 Proposed framework

4.1 Description of framework

This research proposes a framework to assess the seismic vulnerability of aging RCSs considering climate change. The approach begins by establishing a deterioration profile focused on structural durability, following the methodology outlined in recent research [4]. Subsequently, a seismic vulnerability analysis must be performed. This process is repeated to account for time-dependent effects, such as deterioration mechanisms accelerated by climate change, as illustrated in Figure 3.

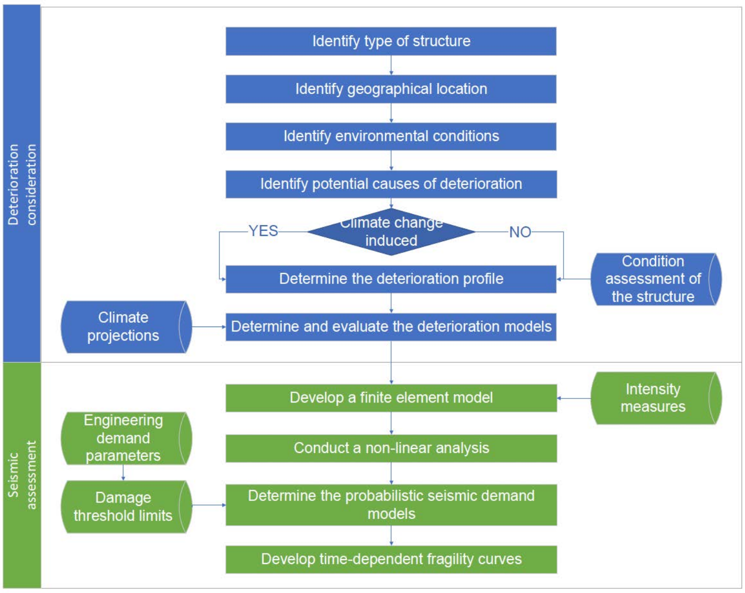

Figure 3. Proposed framework

4.2 Deterioration profile

The procedure for establishing a deterioration profile begins by classifying the structure and identifying its geographical location. Climatic characteristics are then analyzed and local environmental conditions are further evaluated to understand site-specific factors such as temperature variations and humidity levels. This information is combined with condition assessment data to identify potential causes of deterioration, such as chloride-induced corrosion, sulfate attack, and alkali-aggregate reaction, based on the classifications in Figure 1 and Figure 2. These mechanisms are then categorized as critical, significant, or minor, depending on their severity, frequency, and impact on the structure's durability. Finally, the categorized mechanisms are consolidated into a comprehensive deterioration profile, enabling the identification, categorization, and prioritization of deterioration mechanisms, with an emphasis on the influence of climate change on structural durability.

4.3 Performance-Based Earthquake Engineering (PBEE)

4.3.1 Procedure

As the next step, to assess seismic vulnerability considering the effects of deterioration, a performance-based approach can be used. This approach represents an advanced method in earthquake engineering that focuses on predicting and optimizing the performance of structures during and after earthquakes [11].

The PEER PBEE methodology consists of four successive analyses: hazard analysis, structural response modeling, and detailed damage and loss assessments to achieve specific performance objectives [12]. The hazard analysis assesses the uncertainty in the earthquake characteristics and is mathematically characterized by the variable Intensity Measure (IM) [12]. The structural analysis examines the structural response to these hazards, considering uncertainties, such as geometric and material properties or damping, as well as characteristics of the seismic excitation, such as differences in ground motion corresponding to the same hazard level [12]. This step is mathematically characterized by the variable Engineering Demand Parameters (EDP), which describe structural responses in terms of deformations, accelerations, or other quantities determined through simulations of the structure under the input ground motions [13]. The damage analysis estimates the degree of damage that could be sustained by the structure based on its response and is characterized by the Damage Measure (DM), which describes the condition of the structure and its components [12], [13]. Finally, the loss analysis translates this damage into economic terms by calculating potential losses, categorized by the Decision Variable (DV) expressed as repair costs [12], [13].

4.3.2 Hazard Analysis

Seismic hazard refers to the probability of experiencing a specified intensity of damaging effects from an earthquake in a specific location within a given period [14]. This value is widely quantified using a probabilistic seismic hazard analysis (PSHA) which, unlike deterministic methods, eliminates the need to define a single earthquake by considering all possible earthquakes, of various magnitudes and distances, and calculating their probability of occurrence based on their frequency [14]. The constituent models of a PSHA include identifying seismic sources, earthquake recurrence frequency, ground motion attenuation, and ground motion occurrence probability at a site [14].

When referring to seismic sources, it is important to know where earthquakes are likely to occur and how far their epicenters are from the location of interest. To do this, scientists traditionally draw boundaries around areas where seismic activity is likely to occur, such as seismic zones and active faults [14]. These boundaries are based on available data about the Earth's geology, physics, and past earthquakes, which help identify patterns of seismic activity in specific regions [14].

Earthquake recurrence frequency is usually estimated through statistical analysis of historical earthquake records [14]. PSHA typically assumes that earthquakes occur independently of each other, but in areas with a strong historical and geological record, like the San Francisco Bay area, time-dependent models are used to forecast future earthquakes more accurately [14].

Empirical ground motion attenuation relationships are commonly used to estimate how strong the shaking from an earthquake will be at a specific location [14]. Engineers typically focus on certain ground motion parameters like peak ground acceleration (PGA), response spectral acceleration (PSA), response spectral velocity (PSV), and spectral displacement (SD) [14]. To apply these relationships accurately, it's important to understand details about the earthquake's fault, such as the depth of the rupture, the angle of the fault, and the type of fault movement. These details are influenced by the tectonic environment of the area being studied [14].

Finally, to estimate the likelihood of experiencing a certain level of shaking at a site within a specific period, a probability distribution for ground motion amplitudes is needed. Typically, the Poisson model is used, which assumes that earthquakes occur randomly and independently over time [14]. This model works well for most engineering purposes. However, in some cases where a single earthquake source significantly influences the hazard at a site, a time-dependent model, which doesn't follow the Poisson assumption, might be more appropriate [14].

4.3.3 Structural Analysis

Given the IM and input ground motions, the next step is to perform structural simulations to calculate EDPs, which characterize the response in terms of deformations, accelerations, induced forces, or other appropriate quantities [13]. To achieve this, a numerical model of the bridge is created. Uncertainties in the bridge's properties, such as weight, flexibility, stiffness, and strength, are considered and these factors are adjusted in the model to account for a variety of possible conditions [12].

Researchers at the PEER have developed an open-source software called OpenSees to help with these simulations. OpenSees is considered one of the best tools for automating the analytical simulations needed during the structural analysis stage of the methodology. However, other software can be used to achieve this purpose [12], [15].

4.3.4 Damage Analysis

The next step in the process is to conduct a damage analysis, which involves correlating the EDPs to DMs. The purpose of the damage analysis is to estimate the physical damage to parts of the bridge, such as its piers, deck, and supports, based on how the bridge responds during the earthquake [12]. DMs include quantitative descriptions of damage to the structural and non-structural elements of the bridge and its major components [12]. This detailed quantification is essential to accurately assess the necessary repairs, potential disruptions to the bridge's operation, and any safety risks that may arise [11], [12], [13]

The probability of structural damage due to different levels of earthquakes is usually expressed by a damage probability matrix or a fragility curve [16]. The damage probability matrix describes the probability of different damage states at a specific level of earthquake, while the fragility curve describes the damage probability corresponding to a specific damage state at various levels of ground shaking [16].

In recent years, fragility analysis (FA) has emerged as a major focus area for researchers investigating the seismic performance of various structures, such as highway bridges [17], [18]. Researchers have introduced a variety of approaches for the development of fragility curves, including expert judgment, field observations, advanced computer simulations, and hybrid methods combining different techniques [17]. However, over the past two decades, the development of fragility curves has evolved from being based primarily on empirical observations to incorporating more sophisticated analytical methods. This evolution has resulted in more accurate and reliable fragility curves, improving our ability to predict how structures will respond to seismic events [17]. Unfortunately, they often involve high computational costs, requiring significant processing power and resources. The process is also time-consuming, requiring extensive simulations and data analysis [17]. Furthermore, choosing the right analysis technique and defining damage states (DS) accurately can be challenging. Finally, selecting the right probability distribution function adds another complexity, as it affects how uncertainties in the analysis are modeled and interpreted [17].

Fragility functions can be developed using a variety of analytical methods such as elastic spectral analysis, PSDMs using a Bayesian approach, nonlinear static analysis, and linear/nonlinear time history analysis (NLTHA) [17]. Each of these methods offers a different way to estimate how structures might behave during an earthquake, helping to generate fragility curves. NLTHA is considered the most reliable method for generating fragility curves, despite being one of the most computationally intensive [19]. This method is widely used because it accurately predicts how bridges will behave under dynamic loading and considers both geometric nonlinearity and material inelasticity [17].

4.3.5 Loss Analysis

In the final stage of the PEER PBEE methodology, known as loss analysis, damage data obtained from damage analysis is converted into DVs that are crucial to the design process and stakeholder decision-making [12]. The most used DVs include fatalities, which represent the number of deaths directly caused by damage to the facility; economic losses, which represent the monetary costs associated with repairing or replacing damaged components; repair duration, which indicates the time required to restore the facility to full operation; and injuries, which represent the number of injuries resulting from the damage [12]. These variables, often referred to as the “3 Ds” (deaths, dollars, and downtime), provide essential information for assessing the overall impact of seismic events on structures [12]. Additional resilience considerations may include functionality issues, such as the loss of community service or facility use, and recovery challenges, such as delays in restoring system functionality and increased costs that affect the restoration of other systems [20]. These considerations are closely tied to the results of the "3 Ds", as they directly influence the overall impact on infrastructure and the efficiency of recovery efforts.

4.4 Extension to deterioration

This section focuses on incorporating advanced deterioration modeling to refine seismic vulnerability assessments to integrate deterioration effects within the proposed framework (Figure 3). Currently, design standards for RCSs typically follow a prescriptive approach, outlining specific requirements to ensure durability under certain environmental conditions. While these standards aim to minimize the risk of deterioration, many RCSs still experience significant damage within their service life [5]. This is particularly evident in cases of corrosion [2], which weakens the structural reliability and often leads to expensive repairs or, in extreme cases, catastrophic failures [21], [22]. This highlights the need for more robust analyses that consider the actual environmental conditions and long-term behavior of materials to address durability challenges effectively. To achieve this, models that simulate the deterioration of RCSs are essential, not only for the design of new structures but also for the assessment of existing ones. Val et al. [23] compiled existing probabilistic deterioration models that can be used for corrosion, freeze/thaw cycles, AAR, sulfate attack, and fatigue.

For structures in the design phase, this research suggests developing a deterioration profile based on expected degradation mechanisms informed by data from similar structures in comparable conditions. For existing structures, field testing methods such as vibration analysis, load tests, and visual and non-destructive inspections provide valuable insights into the current condition and progression of deterioration [24], [25], [26]. This information can be combined with previously available data to refine predictive models and incorporate mechanisms actively affecting the structure. However, uncertainties such as measurement inaccuracies, limited data availability, and the indirect nature of certain assessments (e.g., estimating the remaining cross-sectional area of corroded reinforcing bars) [23] must be addressed to improve model accuracy and reliability.

Finally, climate projections, such as those provided by the IPCC, must be incorporated into deterioration models to evaluate how future climate-related variables might accelerate or alter deterioration processes.

5 Discussion

This research presents a framework for assessing the seismic vulnerability of RCSs under the combined effects of deterioration and climate change. The proposed framework addresses a critical gap in existing methodologies by integrating time-dependent deterioration mechanisms, climate change projections, and seismic vulnerability analyses. This integration ensures a more realistic and comprehensive evaluation of RCSs' performance under evolving environmental and loading conditions.

In comparison to existing studies, this research builds upon previous work that emphasizes the role of deterioration in seismic performance [4], [23]. However, these studies often focus on stationary climate conditions, which are increasingly seen as inadequate when considering the long-term impacts of climate change. In contrast, this framework incorporates non-stationary climatic variables, such as temperature fluctuations and increased CO_2 levels through climate change scenarios from the IPCC, which are shown to accelerate several deterioration mechanisms. This approach aligns with recent findings by [5], that argue that considering climate change in vulnerability assessments is critical for more accurate predictions of infrastructure performance.

While the present paper focuses on the conceptual foundation and detailed structure of the proposed framework, future research should focus on validating the framework through case studies on RCSs in different geographical and climatic contexts. This will be crucial to confirm whether the framework integrates meaningful parameters and supports improved vulnerability assessment. Refining the deterioration models with additional SHM data and extending the framework to include socioeconomic impacts, such as disruption costs and network effects, could further improve its applicability. Finally, addressing the multi-hazard nature of climate change could significantly improve the framework's ability to evaluate the combined effects of various hazards on structural performance.

6 Conclusions

This paper introduces a novel framework for assessing the seismic vulnerability of RCSs by integrating the effects of aging, deterioration, and climate change. The framework provides a systematic approach to incorporate time-dependent deterioration mechanisms and evolving climate variables, addressing significant gaps in traditional vulnerability assessments. The proposed framework emphasizes key considerations:

- Aging and material degradation significantly affect the structural capacity of RCSs over time. Incorporating these mechanisms into vulnerability assessments is essential for understanding how structures evolve throughout their service life.
- Climate change alters environmental conditions, such as rising temperatures, fluctuating humidity, and increased CO_2 concentrations, which accelerate deterioration processes and affect structural performance. These changes must be considered, using IPCC climate scenarios, to evaluate the long-term impacts of non-stationary climate variables on structural durability and seismic performance.
- Advanced seismic vulnerability techniques, including fragility curves and PBEE, are crucial for accurately assessing the response of RCSs to seismic loading. These methods account for uncertainties in structural response and help capture the combined impact of seismic hazards and deterioration mechanisms.
- Identify and prioritize deterioration mechanisms by considering site-specific climatic and environmental conditions, as these factors influence both the deterioration processes and the structural response to external hazards, with local data being essential for developing accurate deterioration profiles.

To fully realize the benefits of this framework, future research should focus on its application through case studies involving existing RCSs in diverse geographical and climatic contexts. This paper represents a first step toward developing an integrated methodology considering climate-induced deterioration and seismic vulnerability. Additionally, the integration of SHM data and the inclusion of socioeconomic impacts can further strengthen its applicability.

7 References

[1] E. O. L. Lantsoght, M. Mahamid, T. Andres Sanchez, and M. Valenzuela, “Post-earthquake observations of bridge damage,” presented at the IABSE Congress 2024: Beyond Structural Engineering in a Changing World (pp. 1110-1118)., IABSE, 2024.

[2] B. Ge, Y. Yang, and S. Kim, “Time-dependent multi-hazard seismic vulnerability and risk assessment of deteriorating reinforced concrete bridges considering climate change,” *Structures*, vol. 55, pp. 995–1010, Sep. 2023, doi: 10.1016/j.istruc.2023.06.068.

[3] J. Ghosh and J. E. Padgett, “Aging Considerations in the Development of Time-Dependent Seismic Fragility Curves,” *J. Struct. Eng.*, vol. 136, no. 12, pp. 1497–1511, Dec. 2010, doi: 10.1061/(ASCE)ST.1943-541X.0000260.

[4] E. Cervantes, J. Matos, and E. Lantsoght, “Durability Deterioration of Reinforced Concrete Structures: A Framework Considering Climate Change Impacts,” presented at the IABSE Symposium 2025 Environmentally Friendly Technologies and Structures - Focusing on Sustainable Approaches, Tokyo, Japan, May 2025.

[5] D.-C. Feng *et al.*, “Climate Change Impacts on the Risk Assessment of Concrete Civil Infrastructures,” *ASCE OPEN Multidiscip. J. Civ. Eng.*, vol. 2, no. 1, p. 03124001, Feb. 2024, doi: 10.1061/AOMJAH.AOENG-0026.

[6] D. Breysse, “Deterioration processes in reinforced concrete: an overview,” in *Non-Destructive Evaluation of Reinforced Concrete Structures*, C. Maierhofer, H.-W. Reinhardt, and G. Dobmann, Eds., in Woodhead Publishing Series in Civil and Structural Engineering. 2010.

[7] K. Calvin *et al.*, "IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change," Intergovernmental Panel on Climate Change (IPCC), Jul. 2023. doi: 10.59327/IPCC/AR6-9789291691647.

[8] L. Capacci and F. Biondini, "Resilience-based seismic risk assessment of aging bridge networks under climate change," in *Bridge Maintenance, Safety, Management, Life-Cycle Sustainability and Innovations*, 1st ed., H. Yokota and D. M. Frangopol, Eds., CRC Press, 2021, pp. 2085–2093. doi: 10.1201/9780429279119-283.

[9] S. Lakusic, Ed., "Climate change effect on durability of bridges and other infrastructure," *J. Croat. Assoc. Civ. Eng.*, vol. 75, no. 09, pp. 896–906, Oct. 2023, doi: 10.14256/JCE.3756.2023.

[10] Intergovernmental Panel on Climate Change (IPCC), Ed., "Summary for Policymakers," in *Climate Change 2013 – The Physical Science Basis: Working Contribution to the Fifth Assessment Report of the IPCC*, Cambridge: Cambridge University Press, 2014, pp. 1–30. doi: 10.1017/CBO9781107415324.004.

[11] K. Porter, "An Overview of PEER's Performance-Based Earthquake Engineering Methodology," 2003.

[12] S. Günay and K. M. Mosalam, "PEER Performance-Based Earthquake Engineering Methodology, Revisited," *J. Earthq. Eng.*, vol. 17, no. 6, pp. 829–858, Aug. 2013, doi: 10.1080/13632469.2013.787377.

[13] J. Moehle and G. Deierlein, "A framework methodology for performance-based earthquake engineering," Jan. 2004.

[14] P. C. Thenhaus and K. Campbell, "Seismic hazard analysis," in *Earthquake Engineering Handbook*, 2002, pp. 8–1.

[15] The Regents of the University of California, "Getting Started - OpenSeesWiki."

[16] H. H. M. Hwang and J.-W. Jaw, "Probabilistic Damage Analysis of Structures," *J. Struct. Eng.*, vol. 116, no. 7, pp. 1992–2007, Jul. 1990, doi: 10.1061/(ASCE)0733-9445(1990)116:7(1992).

[17] A. H. M. Muntasir Billah and M. Shahria Alam, "Seismic fragility assessment of highway bridges: a state-of-the-art review," *Struct. Infrastruct. Eng.*, vol. 11, no. 6, pp. 804–832, Jun. 2015, doi: 10.1080/15732479.2014.912243.

[18] S. Rajkumari, K. Thakkar, and H. Goyal, "Fragility analysis of structures subjected to seismic excitation: A state-of-the-art review," *Structures*, vol. 40, pp. 303–316, Jun. 2022, doi: 10.1016/j.istruc.2022.04.023.

[19] M. Shinozuka, M. Feng, H.-K. Kim, and S. H. Kim, "Nonlinear procedure for fragility curves development," *J. Eng. Mech.*, vol. 126, pp. 1287–1295, Jan. 2000.

[20] Z. Lounis and T. P. McAllister, "Risk-Based Decision Making for Sustainable and Resilient Infrastructure Systems," *J. Struct. Eng.*, vol. 142, no. 9, p. F4016005, Sep. 2016, doi: 10.1061/(ASCE)ST.1943-541X.0001545.

[21] E. Cervantes, J. Matos, and E. Lantsoght, "Infraestrutura de pontes no Equador: desafios e soluções," *RAE — Rev. Ativos Eng.*, vol. 2, no. 2, pp. 087–103, Sep. 2024, doi: 10.29073/rae.v2i2.927.

[22] E. Cervantes, J. Matos, and E. O. L. Lantsoght, "ESTUDIO DE CAUSAS Y SOLUCIONES PARA LA GESTIÓN DE PUENTES EN ECUADOR," 2024.

[23] D. V. Val *et al.*, "Probabilistic modelling of deterioration of reinforced concrete structures," *Struct. Saf.*, vol. 113, p. 102454, Mar. 2025, doi: 10.1016/j.strusafe.2024.102454.

[24] E. Cervantes, K. Flores, E. Lantsoght, and J. Matos, "UAV-Visual Inspection: Bridge Condition Assessment Over a Decade," presented at the IABSE Congress 2024: Beyond Structural Engineering in a Changing World, Sep. 2024.

[25] E. Lantsoght, E. Cervantes, M. Santamaria, J. Matos, M. Akiyama, and X. Ruan, "Bridge testing field data for damage quantification and decision- making," presented at the IABSE Symposium 2025 Environmentally

Friendly Technologies and Structures - Focusing on Sustainable Approaches, Tokyo, Japan, May 2025.

[26] G. I. Zarate Garnica, E. O. L. Lantsoght, and Y. Yang, "Monitoring structural responses during load testing of reinforced concrete bridges: a review," *Struct. Infrastruct. Eng.*, vol. 18, no. 10–11, pp. 1558–1580, Nov. 2022, doi: 10.1080/15732479.2022.2063906.