Life-Cycle Seismic Resilience Assessment of Reinforced Concrete Bridges in Aggressive Environments

Jie Zhao[a] and Xianming Shi[b]

[a] Ph.D., Department of Civil and Environmental Engineering, Washington State University, Email: jie.zhao2@wsu.edu
[b] Ph.D., P.E., Department of Civil and Environmental Engineering, Washington State University, Email: xianming.shi@wsu.edu

Abstract

Reinforced concrete (RC) bridges in seismic-prone areas may experience multiple earthquakes during their service periods. The exposure of RC bridges in aggressive environments can exacerbate structural deteriorations and reduce their capacity to withstand seismic events. In the meantime, structural damages due to earthquakes may increase the exposure of reinforced steel to aggressive environments and expedite the chloride-induced corrosion processes. Thus, a comprehensive understanding of the interactions of the effects of corrosion and seismic events on structural deterioration is considerably important to provide a realistic assessment of bridge life-cycle resilience. However, most existing studies have mainly estimated the effect of corrosion-induced deterioration on structural capacity against hazards. While it is really necessary, the impacts of structural damages following earthquakes on the time-dependent corrosion processes have not been investigated in any depth. In light of this, this project contributes to filling the research gaps by proposing a comprehensive framework that combines structural damage due to seismic events and the exposure to non-uniform corrosion for RC bridges. First, the probability seismic hazard analysis (PSHA) is utilized to generate a stochastic set of seismic events with multiple levels of magnitudes and the ground motions at the bridge location. Then, the time-dependent bridge deterioration model is developed by incorporating the effects of seismic events on structural corrosion behaviors, and subsequently used for the assessment of life-cycle resilience. Finally, a RC bridge in Seattle, WA is applied as the case study to illustrate this proposed framework. By doing so, the proposed framework can provide a more realistic resilience assessment for RC bridges under the combined effect of corrosion and seismic event, which can help bridge managers to determine effective resilience-enhancing strategies in long-term development planning.

1. Introduction

RC bridges in aggressive environments are exposed to chloride-induced corrosion, which is known to be a major cause of structural deterioration (Ahmad, 2003), and the subsequent repair costs are incredibly high. Based on Federal Highway Administration, approximately 30% of the bridges are structurally deficient due to corrosion, and about US$90 billion will be required to rehabilitate or replace these bridges (Federal Highway Administration, 2000). In addition to chloride-induced corrosion, RC bridges in seismic-prone areas may experience several earthquakes during their service periods, creating potential disruptions to bridge performance and leading to significant negative economic impacts. Bridge deterioration can reduce the structural capacity to withstand a disastrous earthquake (Pang et al., 2020), while structural damages due to seismic events (e.g., concrete crack), in turn, may expedite the corrosion process (Dey and Sil, 2021). In light of this, bridge performance subjected to the combination of aggressive environments and seismic events is important for bridge managers to develop effective bridge management planning.

In recent years, resilience is widely used to effectively measure RC bridge functionality in responding to seismic events, which is defined as the ability of a bridge structure to withstand and recover rapidly from functionality disruptions (Bruneau et al., 2003; Decò et al., 2013). As the resilience of RC bridge can also be affected by chloride-induced corrosion during its service life, this project uses the life-cycle resilience assessment to quantify the long-term bridge performance under the combined effect of corrosion and seismic event. More specifically, bridge resilience, *R*, is the area below the performance curve as shown in Figure 1 and can be mathematically expressed by (Bruneau et al., 2003):

$$R = \int_0^T [Q(t)]dt \tag{1}$$

where $Q(t)$ = the performance/functionality of a RC bridge (unit: percent) under the combined effect of corrosion and seismic event; and T = the service life of a RC bridge.

To assess the life-cycle seismic resilience of RC bridges in aggressive environments, many approaches have been developed over the past several decades, which can be classified into two categories: experimental and simulation methods. The former method mainly designed a set of cyclic experiments for RC bridges with different levels of corrosion damage (Guo et al., 2015), while the latter one modeled the structural behaviors by the computational framework (e.g., FE model) to include several sources of uncertainty (Alipour and Shafei, 2016; Pang et al., 2020). Existing studies based on both methods indicated that the increased level of corrosion can degrade the seismic performance of RC structures (Guo et al., 2015; Alipour and Shafei, 2016). However, existing studies on seismic resilience of RC structures have mainly focused on the analysis of structural seismic performance under corrosion, and ignored the impact of structural damages on the corrosion process. Therefore, it is important to investigate the effects of seismic events on structural corrosion behaviors to fill the research gaps. Moreover, most of these studies have assessed the seismic performance of corroded structures by assuming one or two scenario earthquakes. As bridges in seismic-prone areas would experience a lot of earthquakes of various magnitudes, each of them can cause associated structural damages and affect the corrosion processes for RC bridges. In light of this, existing research may overestimate the bridge life-cycle resilience, and the results could be deviated from reality, leading to unexpected consequences in risk management planning.

To address the limitations of current methodologies, this study presents a comprehensive probabilistic framework for assessing the life-cycle seismic resilience of RC bridges in aggressive environmental conditions. The proposed approach incorporates probabilistic seismic hazard analysis (PSHA) to generate a stochastic suite of seismic events and corresponding ground motions at the bridge site (Baker, 2008). It further integrates the effects of seismic-induced structural damage on the corrosion progression to evaluate long-term resilience. By explicitly accounting for the effect seismic damage on structural corrosion, this framework offers a more realistic and reliable assessment of bridge performance over its service life. The results can support bridge managers in making informed, cost-effective decisions to enhance resilience. A key contribution of this work lies in the reliable consideration of how structural damage accelerates corrosion under harsh environmental conditions, as well as the development of a unified probabilistic model to evaluate resilience throughout the bridge's operational lifespan.

The objective of this study is to provide a realistic estimation of the long-term seismic performance of RC bridges subjected to aggressive environmental conditions. To achieve this objective, the paper is structured as: Section 2 presents the proposed life-cycle seismic resilience framework, which integrates the impact of seismic-induced structural damage on the corrosion process. Section 3 introduces a case study involving an RC bridge located in Seattle, Washington, to demonstrate the application of the proposed framework. Section 4 provides a discussion of the key findings, implications, and limitations of the study.

2. Overall Framework

This section outlines the proposed framework for evaluating the long-term seismic performance of RC bridges in aggressive environments. The framework is composed of three key components: (1) a probabilistic approach for generating seismic event scenarios, (2) an investigation of the effects of seismic-induced structural damage on the corrosion process, and (3) the development of a comprehensive probabilistic model for assessing the life-cycle resilience of RC bridges. The following subsections provide detailed explanations of each component of the framework.

2.1. Probabilistic Modeling of Seismic Hazard

Hazard Analysis can be performed deterministically or probabilistically. The ground motion hazard is evaluated based on a particular seismic scenario in Deterministic Seismic Hazard Analysis (DSHA), while PSHA incorporates uncertainties in size, location, and occurrence rate of earthquakes in the estimation of seismic hazard (Cornell 1968). Based on the PSHA methodology, the seismic events that can affect a bridge location are simulated by defining the surrounding earthquake faults and their characteristics, assuming representative earthquakes for each fault, calculating the ground motions, and summing all the hazards, expressed as (Baker, 2008):

$$G(\mathrm{GM}) = \sum_{f=1}^{F} \lambda_{f,m}(M > m_{min}) \sum_{m=1}^{M} \sum_{r=1}^{R} G_f(GM|m_m, r_r)\, P_f(M = m_m)\, P_f(R = r_r) \quad (5)$$

where, $G(\cdot)$ = the probability of exceedance (POE); GM = ground motion parameter a bridge site; m_{min} is the lower threshold for magnitude of interest; $\lambda_{\mathrm{f,m}}(\mathrm{M} > \mathrm{m_{min}})$ is the rate of earthquakes with magnitudes greater than m_{min} for f^{th} fault; $P_f(M = m_m)$ & $P_f(R = r_r)$ = the PDF of magnitude distribution for f^{th} fault and distance distribution between f^{th} fault and bridge site, respectively.

Finally, a stochastic seismic catalog is generated based on the PSHA method, incorporating fault characteristics, spatial distribution, and seismicity parameters. This catalog represents a diverse set of potential earthquake events that reflect the underlying seismic hazard at the bridge location. It serves as a critical input for evaluating the long-term seismic performance of RC bridges under uncertainty.

2.2. Impact of Seismic-Induced Damage on Corrosion Progression

The corrosion deterioration process of embedded steel reinforcements in RC structures can be separated into two phases: (a) corrosion initiation phase; and (b) corrosion propagation phase (Mortagi and Ghosh, 2022), as presented in Figure 1. The first phase elapses from the first exposure to a sufficient concentration of chlorides at the reinforced steel depth to initiate corrosion (Liu and Shi, 2012). Then, the initiation corrosion of reinforced steel will cause the expansion of the corroding steel, surface cracking, and subsequently spalling of the cover concrete in the second phase (Kirkpatrick et al., 2002).

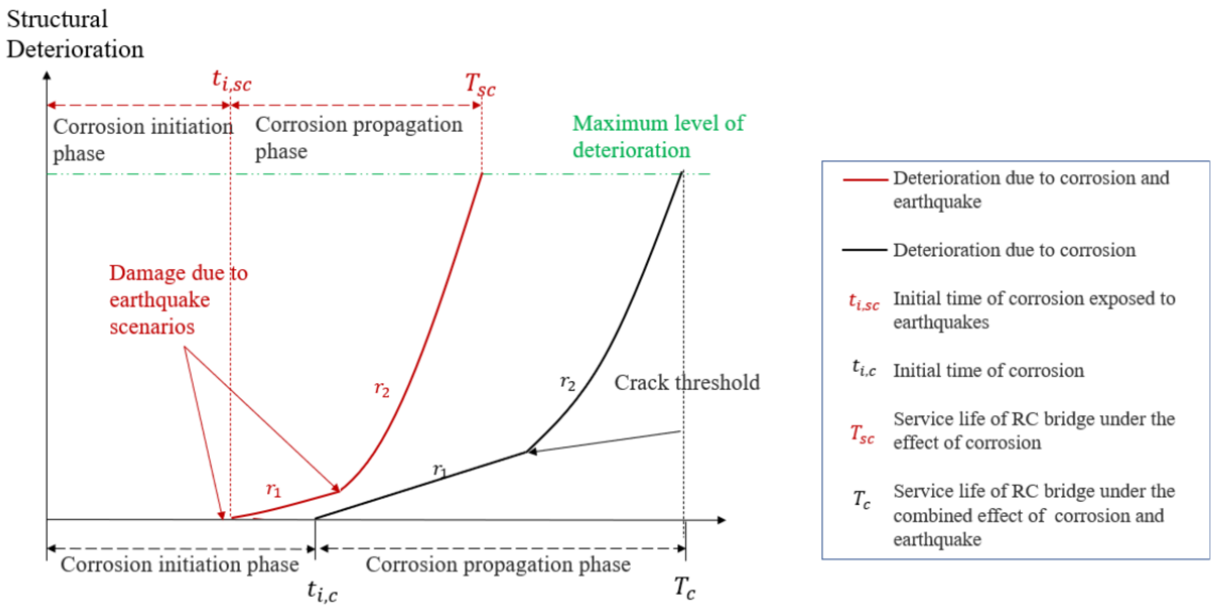

Figure 1. Structural deterioration due to corrosion and seismic events

During the initiation phase, the chloride diffusion process can be modeled as described in Liu and Shi (2012),

$$C(x,t) = C_0(1 - \text{erf}\,(\frac{x}{2\sqrt{Dt}})) \tag{2}$$

where $C(x,t)$= chloride concentration at depth x mm of concrete cover at year t; D= the diffusion coefficient; C_0= the surface chloride concentration. When the chloride concentration at a depth of 50 mm reaches the threshold value ($C_{threshold} = C/C_0$ = 0.68%), the corrosion process of the embedded steel reinforcement is significantly activated, marking the transition to the propagation phase (Sun et al., 2020; Chen et al., 2021). This propagation stage is characterized by electrochemical reactions involving the formation of anodic and cathodic sites on the surface of the reinforcement. These reactions lead to the oxidation of iron into rust products, which accumulate on the steel surface. The rate of effective steel mass, denoted as Q_{eff}, can be defined as described by Du (2005),

$$Q_{eff} = 1 - Q_{corr} = 1 - 0.046 * \frac{r_{corr}}{d} * t \tag{3}$$

Where Q_{corr}= the rate of mass loss of steel bar; r_{corr}= is the corrosion rate of steel bar in a RC structure under certain environmental condition; d= the diameter of non-corroded steel bar. Given the established positive correlation between the corrosion rate of steel reinforcement and the surface crack width in concrete (Du, 2025), this study considers two distinct corrosion rates (r_1 and r_2) based on a defined crack width threshold ($W_{threshold}$). Specifically, when the surface crack width is less than $W_{threshold}$, the corrosion rate is assumed to be r_1; otherwise, a higher rate r_2 is adopted to reflect the accelerated corrosion due to increased exposure. In this study, the crack width threshold is assumed to be 0.1 mm, following the findings of Chen et al. (2021).

Accordingly, the effective mass rate of the steel reinforcement, Q_{eff}, can be further evaluated as described by Chen et al. (2021).

$$Q_{eff} = \begin{cases} 1 - \int_{t_{i,c}}^{t} \left(0.046 * \frac{r_1}{d} * t\right) dt\,, & if\ W < W_{threshold} \\ 1 - \int_{t_{i,c}}^{t} \left(0.046 * \frac{r_2}{d} * t\right) dt\,, & if\ W \geq W_{threshold} \end{cases} \tag{4}$$

RC bridges located in moderate to high seismic risk regions are susceptible to deterioration caused by both chloride-induced corrosion and seismic events throughout their service life. Figure 1 illustrates the structural deterioration process under the combined effects of corrosion and seismic events. As depicted, earthquakes can accelerate the corrosion initiation phase by causing damage to the RC structure, such as generating or extending concrete cracks and deforming the reinforcing steel, which facilitates the rapid ingress of chlorides to the depth of the reinforcement, effectively advancing the initiation time to $t_{i,sc}$. Moreover, the corrosion propagation phase can also be accelerated by seismic damage. Specifically, if the crack width induced by the damage exceeds the predefined crack width threshold, the corrosion rate may abruptly increase from r_1 to r_2 , thus hastening the deterioration process and consequently shortening the service life of the RC bridge. Therefore, considering the influence of seismic events on corrosion progression is essential for accurate life-cycle resilience assessment.

2.3 Life-Cycle Seismic Resilience Assessment Framework

This section proposes a life-cycle seismic resilience assessment framework that integrates the corrosion process and seismic effects into a combined and comprehensive model. In this framework, the impact of seismic damage on corrosion progression is explicitly considered. Figure 2 illustrates the simulation procedure for the proposed life-cycle seismic resilience framework. Initially, as described in Section 2.1, a stochastic seismic catalog is generated. Subsequently, N sample paths representing different scenarios are produced from this catalog using a Monte Carlo simulation method, reflecting various realizations over the planning horizon T. For the n^{th} scenario, given the timing and location of seismic events, bridge performance is evaluated at each time step. If no seismic event occurs at year t, the simulation assesses bridge resilience based solely on the structural corrosion process. When a seismic event occurs at year t, structural damage to the bridge is computed, and the resulting cracks may accelerate the corrosion process if the crack width exceeds the defined threshold. This accelerated corrosion effect is incorporated into the bridge performance evaluation. The entire simulation operates iteratively over the planning horizon T, continuing until either bridge fails, and the maximum service life is reached. Bridge failure is defined as the point when the effective mass of the steel reinforcement, Q_{eff}, falls below a specified failure threshold. Specifically, when more than 10% corrosion loss has occurred, corresponding to 90% of Q_{eff} remaining (Chen et al., 2021). Due to inherent uncertainties in seismic events, each scenario yields a unique long-term performance trajectory. Finally, the effective mass of steel reinforcement is used as an indicator of bridge performance, and the life-cycle seismic resilience for each scenario is computed based on Equation (1).

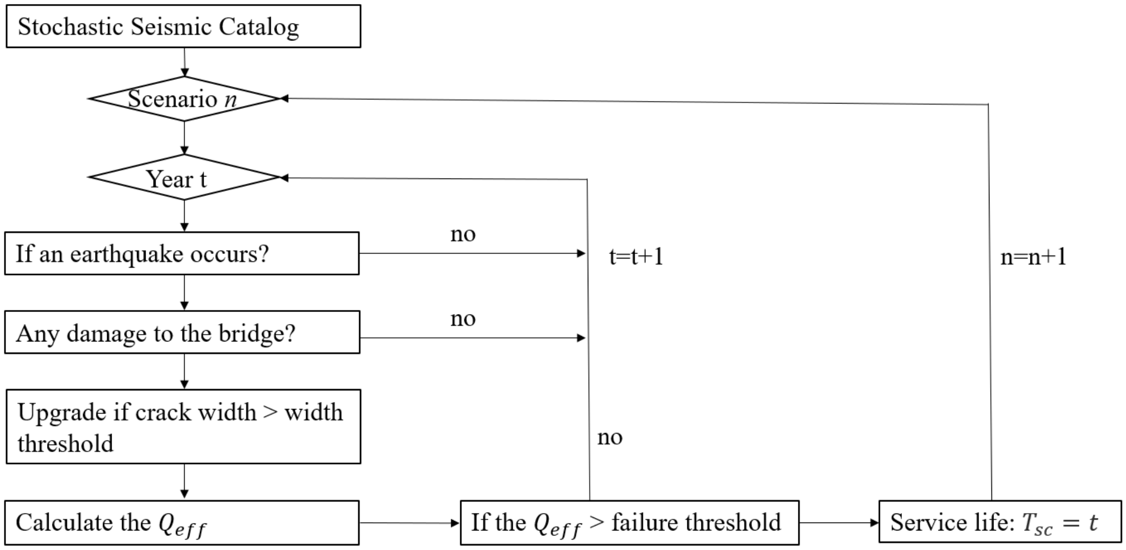

Figure 2. Simulation procedure for life-cycle seismic resilience framework

3. Case Study to illustrate the proposed framework

3.1. Case study and simulation process

In order to illustrate the proposed framework and test its feasibility, a RC bridge located in Seattle, Washington, is selected as the case study. The bridge information used in this study is adapted from Hazards U.S. Multi-Hazard (HAZUS-MH) (FEMA, 2003), as listed in Table 1. Since the bridge is situated in a moderate to high seismic hazard zone, earthquakes are considered as the primary hazard events in this case study. Figure 4 illustrates the modeling of bridge damage and its associated effects on structural corrosion behavior. First, 17 active faults and fault segments in Washington State are identified based on the 2008 USGS National Seismic Hazard Maps (Petersen et al., 2008), as their ruptures and related earthquakes may impact this RC bridge. Earthquake occurrences under each scenario are modeled using a Poisson distribution, with the annual mean rate set as the sum of probabilities of all earthquake events in the seismic catalog. The Monte Carlo Simulation (MCS) method is then employed to sample seismic events from the catalog, thereby realizing the location, magnitude, and corresponding ground motion intensity for each event. As a result of this stochastic seismic event generation process, 425 earthquake scenarios, with associated magnitude and annual probability, are sampled and represented in the seismic catalog. Finally, ground motions at the bridge site for each earthquake scenario are computed using OpenSHA (Field et al., 2003).

Table 1. Bridge information for case study

Bridge Name	STATE ROUTE 99
Bridge ID	WA000363
Bridge Type	State Highway
Latitude	47.651670000000003
Longitude	-122.348330000000004

The next step involves estimating bridge damage resulting from seismic events. As illustrated in Figure 4, bridge damage following seismic events is assessed using fragility analysis. Fragility curves represent the probability of different damage states as a function of seismic intensity, which is quantified by ground motion at the bridge location. In this study, fragility curves are adopted from the HAZUS-MH analysis, considering four damage states: slight, moderate, extensive, and collapse. According to the definitions, slight damage refers to minor cracking in concrete elements, while moderate damage indicates slight spalling of concrete without exposure of reinforcement. Minor cracking is considered not to affect the structural functionality, and ACI 224R-01 suggests that crack widths should remain below 0.3 mm. For simplification, this study assumes that any damage state leads to the formation of cracks that directly transition the corrosion process into the propagation phase, characterized by a higher corrosion rate. This assumption applies regardless of whether the bridge is initially in the corrosion initiation or propagation stage. Since this study primarily focuses on the impact of bridge damage on the corrosion process, maintenance activities are not addressed in the current analysis, will be explored in future research. Furthermore, all corrosion-related data used in this study are sourced from Chen et al. (2021). Given the bridge's geographical location, the coastal environmental conditions are considered in this case, as it is widely recognized that corrosion processes differ significantly between coastal and inland environments.

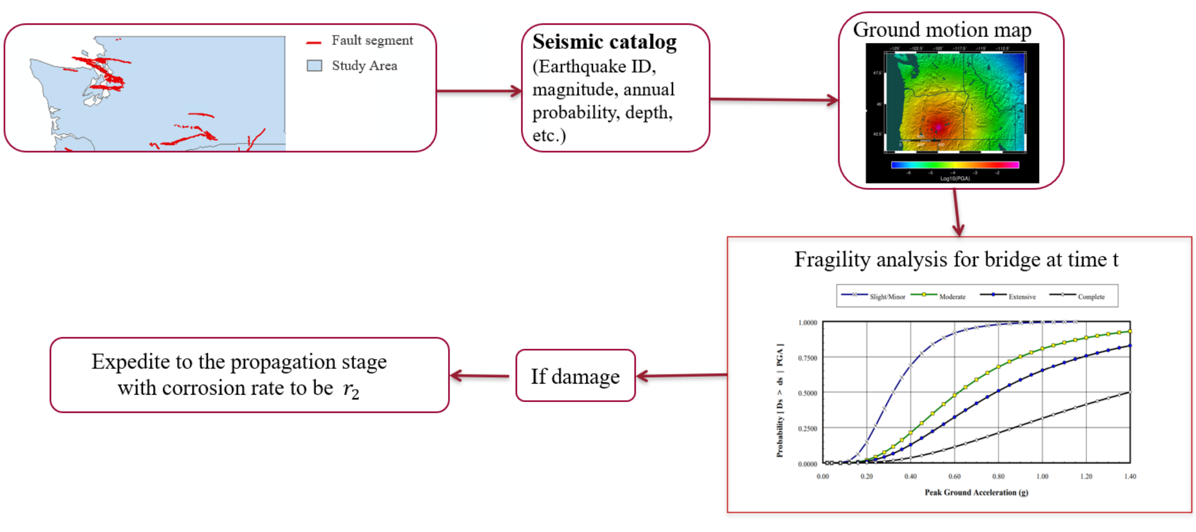

Figure 4. Example to model the bridge damage and associated effect on the structural corrosion behaviors

3.2. Result Analysis

In this study, 1000 scenarios are generated by integrating both seismic events and the structural corrosion process, where bridge damage can accelerate corrosion. Although increasing the number of scenarios better captures future uncertainties, 1000 scenarios are chosen here to balance computational cost and result reliability. Due to inherent uncertainties, the number and timing of seismic events vary across scenarios, with events occurring at different times and locations. The seismic events and corrosion processes are combined within each scenario, and the combined impacts on bridge performance and the life-cycle resilience are analyzed to evaluate bridge performance over its service life. This process is repeated for all 1000 plausible scenarios.

The effective mass of steel reinforcement, Q_{eff}, is used as the indicator of long-term bridge performance. Figure 5 illustrates the bridge's long-term performance considering only the corrosion process. The initial corrosion stage lasts approximately 34.6 years, during which the performance remains unchanged. After this, the bridge enters the propagation stage. As previously mentioned, a performance threshold of 90% is defined as failure. For the case study bridge located in a coastal environment, the total service life is approximately 66.7 years. Figure 5 highlights two distinct sub-phases within the corrosion propagation stage, each governed by different corrosion rates. The transition between these phases is triggered when the surface crack width exceeds a defined threshold, resulting in a significant increase in the corrosion rate and a corresponding change in the slope of the performance degradation curve.

To further examine the environmental influence on corrosion, the study compares bridge performance under both coastal and normal environmental conditions, as illustrated in Figure 5. Corrosion rates are notably higher in coastal environments, where the rates are set at 1 and 10, compared to 0.5 and 1 in normal environments. As a result, the bridge exposed to coastal conditions (represented by the orange line) exhibits a much steeper decline in performance during the propagation stage, underscoring the accelerated deterioration caused by the harsher environmental exposure.

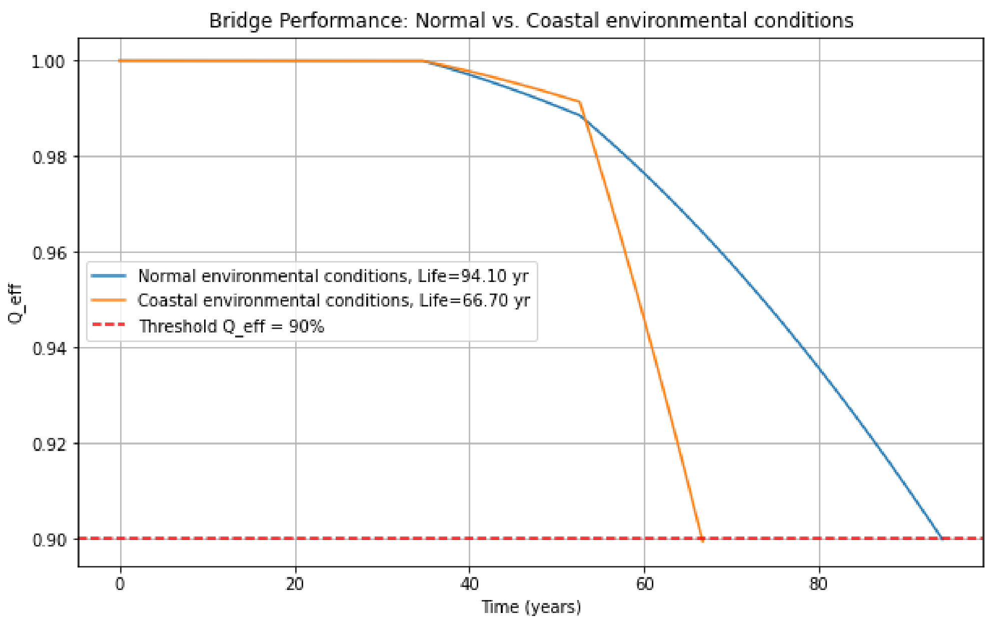

Figure 5. Bridge performance under corrosion-only conditions: comparison between normal and coastal environments

This study focuses on evaluating the life-cycle seismic resilience of RC bridges in aggressive (e.g., coastal) environments by incorporating the influence of seismic-induced damage on the corrosion process. Figure 6 illustrates bridge performance over time when the effects of seismic events are included. Unlike the corrosion process, which progresses in a consistent and deterministic manner in this study, seismic events are modeled probabilistically, resulting in varying hazard conditions across scenarios. Consequently, the bridge performance curves under seismic effects are not uniform but vary due to the randomness of event occurrence and intensity.

The mean performance curve and the 95% confidence interval, representing the variability of outcomes across all scenarios, are shown as the shaded area in Figure 6. The results indicate that seismic-induced damage can significantly shorten the bridge's service life, with an average life expectancy reduced to approximately 26.7 years. This reduction is primarily due to seismic damage that occurs during the initial corrosion phase. If an earthquake induces damage early in the bridge's life, it can accelerate the corrosion process by transitioning it prematurely into the propagation phase. This early shift leads to a more rapid decline in structural integrity, thereby shortening the overall service life of the bridge.

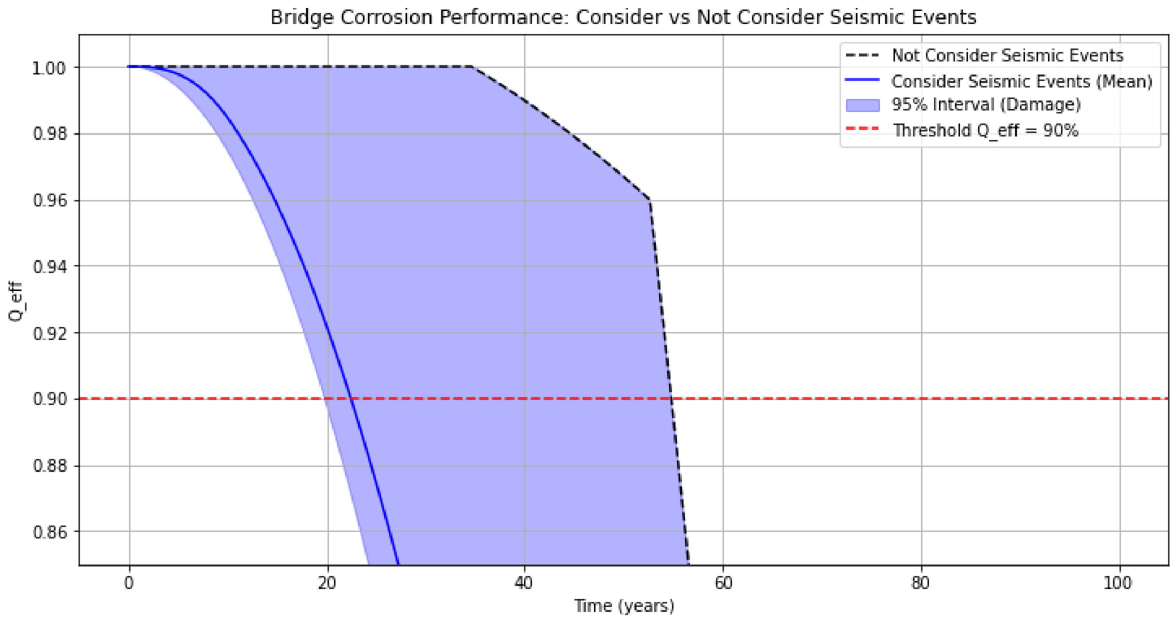

Figure 6. Bridge performance considering the impact of seismic events on the corrosion process

In this study, bridge performance curves are used to quantify life-cycle seismic resilience, with resilience for each scenario computed as the integral of the performance function over time from year 0 to the end of service life, as defined by Equation (1). This approach yields a distribution of resilience values across all simulated scenarios. Figure 7 presents the distribution of life-cycle resilience values under two conditions: (1) considering only the corrosion process, and (2) incorporating the effect of seismic-induced damage on the corrosion process. As shown in the figure, the resilience value when only corrosion is considered is 54.4. However, when seismic damage is included, thereby accelerating the corrosion process, the average resilience drops significantly to 26.1, with a median of 19.8. The resilience values across all scenarios range from a minimum of 19.1 to a maximum of 54.4.

The histogram in Figure 7 reveals that over 80% of the resilience values fall within the range of 19 to 23, indicating a substantial reduction in bridge resilience under most scenarios involving seismic damage. A smaller portion (approximately 20%) of the scenarios exhibit resilience values close to the corrosion-only baseline. These cases likely correspond to scenarios where either no seismic damage occurs, or damage occurs after the corrosion has already progressed into the propagation stage, thus exerting limited influence on the overall corrosion rate. Furthermore, scenarios in which seismic damage occurs during the initial corrosion stage (i.e., approximately 34.6 years before), lead to a rapid transition to the propagation phase, significantly accelerating corrosion and sharply reducing bridge resilience. This highlights the compounding impact of early-stage seismic events on long-term infrastructure performance in aggressive environments.

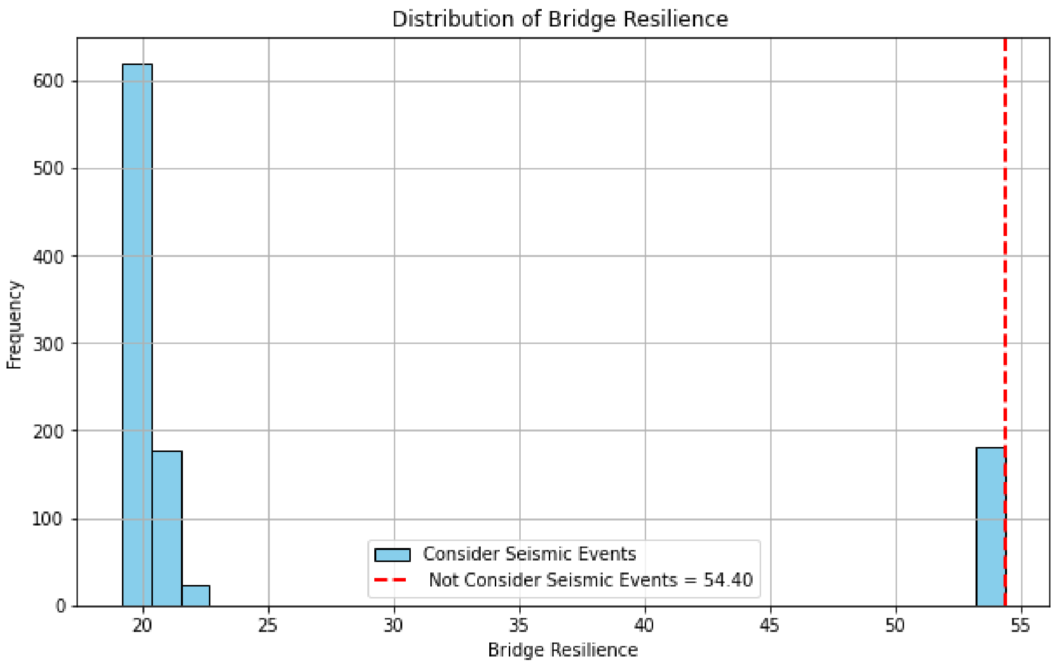

Figure 7. Distribution of bridge resilience in aggressive environment

4. Conclusion

This study developed a comprehensive life-cycle resilience assessment framework for reinforced concrete (RC) bridges exposed to both seismic hazards and aggressive environmental conditions. Unlike most existing models that treat seismic damage and corrosion deterioration independently, this framework captures their interaction, recognizing that seismic damage can accelerate the corrosion process by increasing the exposure of reinforcement to environmental agents, especially in coastal settings. By integrating a probabilistic seismic hazard analysis (PSHA), Monte Carlo simulation for scenario generation, and a coupled deterioration model, this framework allows for the evaluation of long-term structural performance across 1,000 plausible seismic-corrosion scenarios.

Using a representative RC bridge in Seattle, WA, the study demonstrates how seismic events, when occurring during the initiation stage of corrosion, can significantly reduce the bridge's service life by rapidly advancing the onset of corrosion propagation. The proposed framework quantifies bridge performance over time through the effective mass of steel, with resilience calculated as the integral of performance over the bridge's lifetime. Results show that the average life-cycle resilience drops from 54.4 (corrosion-only condition) to 26.1 when seismic damage is incorporated, with significant variability across scenarios.

While this approach offers a more realistic understanding of bridge deterioration in multi-hazard environments, it has several limitations. Most notably, the corrosion process is modeled deterministically, without accounting for its inherent stochastic nature due to limited data availability. Additionally, the framework does not consider any maintenance or repair strategies, which could influence the performance outcomes. Future research should focus on incorporating stochastic corrosion modeling and optimal maintenance planning to enhance decision-making for resilience-based infrastructure management.

Overall, this framework provides a novel and practical tool for engineers and decision-makers to assess and manage the life-cycle resilience of RC bridges under the combined effects of earthquakes and corrosion. It paves the way for more informed infrastructure investment and maintenance planning in seismically active and corrosive environments.

5. Reference

Ahmad, S. (2003). Reinforcement corrosion in concrete structures, its monitoring and service life prediction—a review. *Cement and Concrete Composites*, *25*(4-5), 459–471. https://doi.org/10.1016/s0958-9465(02)00086-0

Alipour, A., & Shafei, B. (2016). Seismic resilience of transportation networks with deteriorating components. *Journal of Structural Engineering*, *142*(8). https://doi.org/10.1061/(asce)st.1943-541x.0001399

Alipour, A., Shafei, B., & Shinozuka, M. (2011). Performance evaluation of deteriorating highway bridges located in high seismic areas. *Journal of Bridge Engineering*, *16*(5), 597–611. https://doi.org/10.1061/(asce)be.1943-5592.0000197

Baker J.W. (2008). An Introduction to Probabilistic Seismic Hazard Analysis (PSHA), 214 *Stanford University*.

Bruneau, M., Chang, S. E., Eguchi, R. T., Lee, G. C., O'Rourke, T. D., Reinhorn, A. M., . . . Winterfeldt, D. V. (2003). A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities. *Earthquake Spectra,19*(4), 733-752. doi:10.1193/1.1623497

Chen, S., Duffield, C., Miramini, S., Raja, B. N. K., & Zhang, L. (2021). Life-cycle modelling of concrete cracking and reinforcement corrosion in concrete bridges: A case study. *Engineering Structures*, *237*, 112143.

Cornell, C. A. (1968). Engineering seismic risk analysis. *Bulletin of the seismological society of America*, *58*(5), 1583-1606.

Decò, A., Bocchini, P., & Frangopol, D. M. (2013). A probabilistic approach for the prediction of seismic resilience of bridges. *Earthquake Engineering & Structural Dynamics*, *42*(10), 1469–1487. https://doi.org/10.1002/eqe.2282

Dey, A., & Sil, A. (2021). Advanced corrosion-rate model for comprehensive seismic fragility assessment of chloride affected RC bridges located in the coastal region of India. *Structures*, *34*, 947–963. https://doi.org/10.1016/j.istruc.2021.08.045

Du, Y. G., Clark, L. A., & Chan, A. H. C. (2005). Residual capacity of corroded reinforcing bars. *Magazine of Concrete Research*, *57*(3), 135-147.

Federal Highway Administration. (2000). Our nation's highways—selected figures and facts, U.S. Department of Transportation.

Federal Emergency Management Agency (FEMA). (2003). HAZUS-MH MR4 Technical Manual. *National Institute of Building Sciences and Federal Emergency Management Agency (NIBS and FEMA), 712.*

Field, E. H., T. H. Jordan, & C. A. Cornell. (2003). OpenSHA: A Developing community-modeling environment for seismic hazard analysis, *Seismological Research Letters 74*, 406-419.

Glass, G. K., & Buenfeld, N. R. (2000). The influence of chloride binding on the chloride induced corrosion risk in reinforced concrete. *Corrosion Science*, *42*(2), 329–344. https://doi.org/10.1016/s0010-938x(99)00083-9

Guo, A., Li, H., Ba, X., Guan, X., & Li, H. (2015). Experimental investigation on the cyclic performance of reinforced concrete piers with chloride-induced corrosion in marine environment. *Engineering Structures*, *105*, 1–11. https://doi.org/10.1016/j.engstruct.2015.09.031

James, A., Bazarchi, E., Chiniforush, A. A., Panjebashi Aghdam, P., Hosseini, M. R., Akbarnezhad, A., Martek, I., & Ghodoosi, F. (2019). Rebar corrosion detection, protection, and rehabilitation of reinforced concrete structures in coastal environments: A Review. *Construction and Building Materials*, *224*, 1026–1039. https://doi.org/10.1016/j.conbuildmat.2019.07.250

Kirkpatrick, T. J., Weyers, R. E., Anderson-Cook, C. M., & Sprinkel, M. M. (2002). Probabilistic model for the chloride-induced corrosion service life of Bridge Decks. *Cement and Concrete Research*, *32*(12), 1943–1960. https://doi.org/10.1016/s0008-8846(02)00905-5

Liu, Y., & Shi, X. (2012). Stochastic modeling of service life of concrete structures in chloride-laden environments. *Journal of Materials in Civil Engineering*, *24*(4), 381–390. https://doi.org/10.1061/(asce)mt.1943-5533.0000399

Mortagi, M., & Ghosh, J. (2022). cc

O'Connor, J. S. (2010). *Post-earthquake bridge inspection guidelines* (No. C-06-14). Multidisciplinary Center for Earthquake Engineering Research (US)

Otieno, M., Beushausen, H., & Alexander, M. (2016). Chloride-induced corrosion of steel in cracked concrete—part II: Corrosion rate prediction models. *Cement and Concrete Research*, *79*, 386–394. https://doi.org/10.1016/j.cemconres.2015.08.008

Pang, Y., Wei, K., & Yuan, W. (2020). Life-cycle seismic resilience assessment of highway bridges with fiber-reinforced concrete piers in the corrosive environment. *Engineering Structures*, *222*, 111120. https://doi.org/10.1016/j.engstruct.2020.111120

Petersen, M. D., Frankel, A. D., Harmsen, S. C., Mueller, C. S., Haller, K. M., Wheeler, R. L., … Rukstales, K. S. (2008). Documentation for the 2008 update of the United States National Seismic Hazard Maps. *Open-File Report*. https://doi.org/10.3133/ofr20081128

Shekhar, S., Ghosh, J., & Padgett, J. E. (2018). Seismic life-cycle cost analysis of ageing highway bridges under chloride exposure conditions: Modelling and recommendations. *Structure and Infrastructure Engineering*, *14*(7), 941–966. https://doi.org/10.1080/15732479.2018.1437639

Sun, D., Shi, H., Wu, K., Miramini, S., Li, B., & Zhang, L. (2020). Influence of aggregate surface treatment on corrosion resistance of cement composite under chloride attack. *Construction and Building Materials*, *248*, 118636.

Topçu, İ. B., Boğa, A. R., & Hocaoğlu, F. O. (2009). Modeling corrosion currents of reinforced concrete using ann. *Automation in Construction*, *18*(2), 145–152. https://doi.org/10.1016/j.autcon.2008.07.004

Val, D. V., & Melchers, R. E. (1997). Reliability of deteriorating RC Slab Bridges. *Journal of Structural Engineering*, *123*(12), 1638–1644. https://doi.org/10.1061/(asce)0733-9445(1997)123:12(1638)

Zhang, L., Smith, D. W., Gardiner, B. S., & Grodzinsky, A. J. (2013). Modeling the insulin-like growth factor system in articular cartilage. *PloS one*, *8*(6), e66870.