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Seismic Fragility Curves of RC Elements Considering Its Corrosion Effects

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ABSTRACT

Seismic fragility of reinforced concrete (RC) elements is defined as the conditional probability that the seismic demand exceeds the corresponding capacity, specified for a certain performance level, for given seismic intensity measures. However, the structural properties of RC elements change over time due to the onset of corrosion in the reinforcing steel. Therefore, seismic fragility of RC elements changes during an element lifetime. The study proposes a method to estimate the seismic fragility of corroding RC elements. Structural capacities are defined using probabilistic models for deformation and shear capacities of RC elements. Fragility curves are useful tools for showing the probability of structural damage due to earthquakes. The main aim of the study is to develop the fragility curves for RC elements considering its corrosion effects. Push over analyses and Incremental dynamic analyses were performed for those sample RC elements using the seismic intensity and the corrosion effects to determine the fragility and collapse capacity of each sample RC elements. OpenSEES is a software framework for creating models and analysis methods to simulate structural and geotechnical systems.

Keywords: Fragility curves, OpenSEES, RC elements, Corrosion, Analytical Study.

I. INTRODUCTION

Recent earthquakes have shown that the reinforced concrete (RC) structures, such as buildings and bridges are vulnerable to earth- quake actions [1–3]. These structures were either designed only considering gravity loads or not in accordance with the current generation of seismic codes as a consequence they are usually characterised by inadequate reinforcement details, such as insufficient transverse reinforcement for the columns. The insufficient detailing is particularly critical because it can potentially lead to premature shear failure of columns under seismic loadings. Fragility curves are defined as the probability of reaching or exceeding a specific damage state under earthquake excitation. The fragility curves are established to provide a prediction of potential damage during an earthquake. The fragility curves represent a useful tool for assessing the seismic vulnerability of underground structures. The seismic vulnerability of a structure can be defined as its susceptibility to being damaged by a ground- shaking of a given intensity. The fragility curve represents the relation between the probabilities of achieving a specified level of damage for a prescribed level of seismic hazard.

II. CORROSION EFFECTS ON RC ELEMENTS

Reinforced concrete (RC) is now the most widely used building material in the world. The main reason for reinforcing concrete with steel bars and mats is to eliminate the weakness of concrete in tension. Therefore, steel reinforcement is placed in tension zones of RC elements. Efficiency of reinforced concrete as a structural material mostly depends on mutual compatibility between concrete and embedded reinforcing steel. It is known that concrete and reinforcing steel have approximately the same coefficient of thermal expansion. Additionally, a good quality concrete of appropriate mix proportion, compacting and curing provides an excellent protective environment for steel. The cover concrete acts as a physical barrier to the access of aggressive species. Concrete’s high alkalinity solution within the pore structure of cement paste matrix provides the chemical protection due to the presence of sodium and potassium oxides in the cement, as well as calcium hydroxide produced in the hydration reactions of cement components (e.g., Barneyback and Diamand, 1981; Mehta, 1997). The range of high pH values of typical concrete (12.5-13.5) is within the pH domain in which insoluble oxides of iron are thermodynamically stable. This gives rise to passivation of the metal surface in which significant corrosion is hindered due to the anodic formation of a protective surface film.

Corrosion effects on the reinforcement and on the cover concrete of RC structures

The uncontaminated cover concrete provides a physical barrier preventing the direct exposure of the steel surface to the outside environment. It also provides a highly alkaline chemical environment that protects steel from corrosion. Moisture and oxygen are two essential elements for active corrosion to occur. In general, these elements are present in the cover concrete and on the surface of the steel reinforcement embedded in concrete. The two major mechanisms of corrosion in reinforced concrete structures are chloride-induced corrosion and carbonation- induced corrosion (Liu 1996). The chloride ions from seawater and anti-icing/de- icing salts might penetrate through the cover concrete and reach the surface of steel reinforcement. A notable difference between the chloride induced corrosion and carbonation- induced corrosion is that the former causes localised and/or pitting corrosion whereas the latter causes uniform or general corrosion. Therefore, chloride-induced corrosion typically causes localised cracking and spalling of the cover concrete, whereas carbonation-induced corrosion typically causes more widespread and uniform cracking and spalling. The corrosion products of steel have more volume than the non-corroded steel. This volumetric expansion causes a high expansive pressure on the cover concrete. As the rust products accumulate, the pores around the corroded reinforcing steel are not sufficient to accommodate this volumetric expansion.

Internal pressure builds up around the corroded area of reinforcing steel, leading to the cracking of the cover concrete. For a corroding RC structure subject to general corrosion, the volumetric expansion of rust products happens around the circumference of the corroded reinforcing steel and results in the cracking in the cover concrete. The cracking of the cover concrete induces detrimental effects on RC structures. Not only does the cracking degrade the strength and stiffness of a structure, but also it accelerates the corrosion process due to the ingress of corrosive agents through the cracks.

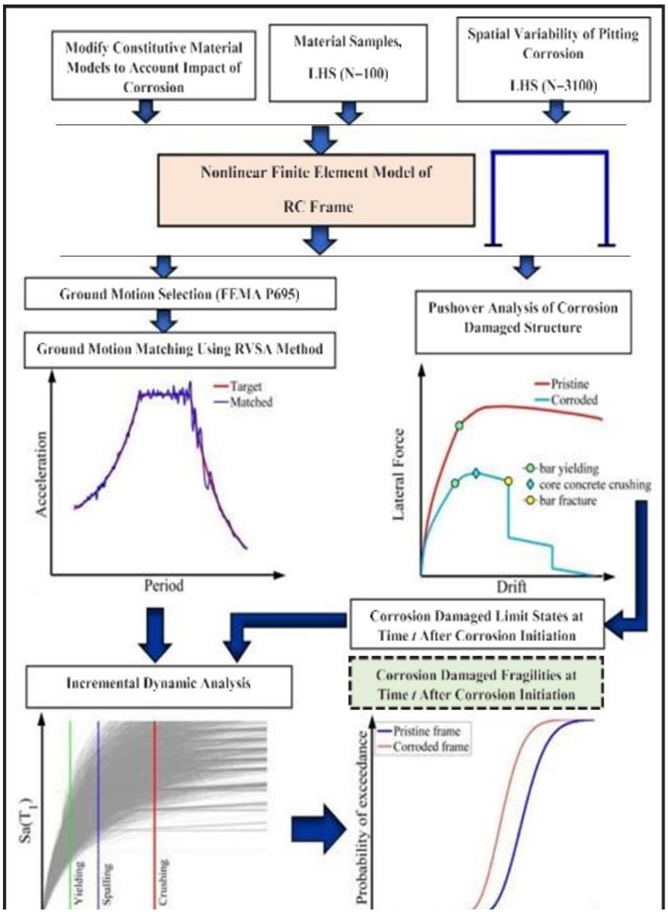


Figure 2.1: Overview of the proposed probabilistic framework for fragility assessment of corrosion damaged RC frames.

Probabilistic models for loss of reinforcing steel and stiffness degradation

The corrosion-induced deterioration process can be divided into four phases.

- The propagation of corrosive agents onto the surface of reinforcing steel before corrosion initiates due to a diffusion process through the concrete and a permeation through the capillaries of the concrete.
- The initiation of the corrosion process due to the presence of excessive corrosive agents that leads to the formation of rust products gradually filling out the pores around the corroded reinforcing steel.
- The initiation of cracking after the pores are all filled out with rust products and the corrosion pressure increases.
- The cracking propagation induced by the volumetric expansion associated to the formation of rust products with a continuous deterioration of the cross- section of RC structures up to the time when the cracking reaches the outer surface of the cover concrete.2.2.1.Hooked steel fiber.

Figure 2.2: Model of corrosion-induced damage developing with time in a RC element, where ti is the time of corrosion initiation, tcr1 the time of first cover crack initiation, tdel the time of concrete cover delamination and tu the time of failure of a RC element.

III. REVIEW OF LITERATURE

Ji-Gang Xu et al. (2020) [1] investigated Seismic fragility analysis of shear-critical concrete columns considering corrosion induced deterioration effects. Shear-critical reinforced concrete structures such as older columns with insufficient transverse reinforcement details or short columns are found to be vulnerable to earthquake loading. Meanwhile, in the aggressive environment, RC structures tend to be more vulnerable to earthquake since corrosion of reinforcements will cause deterioration of the material properties. He proposed framework adopts time-variant structural capacities as obtained from the proposed numerical model in the fragility analysis. The developed framework is demonstrated with a shear-critical bridge column. The results clearly indicate the adverse effects of corrosion on seismic fragility of shear-critical columns, especially at severer damage states. Using flexure model and time-invariant capacity index will underestimate seismic fragility compared with the results obtained using the proposed method.

Xingquan Guan et al. (2020) [2] investigated on Python-based computational platform to automate seismic design, nonlinear structural model construction and analysis of steel moment resisting frames. He presents a Python-based platform that automates the seismic design, nonlinear structural model generation, and response simulation of steel special moment resisting frames (SMRFs). The first module of the automatic seismic design and analysis (AutoSDA) plat- form takes building configuration, loads, and site parameters as input and outputs SMRF designs that comply with the latest building code provisions while accounting for ease of construction. A second module constructs two- dimensional nonlinear structural models in OpenSees based on the generated designs and performs nonlinear static and dynamic analyses towards a comprehensive evaluation of seismic performance.

R. Couto et al. (2020) [3] investigated the Seismic capacity and vulnerability assessment considering ageing effects: case study—three local Portuguese RC buildings. His results have shown that the number of walls and the orientation of the columns are decisive in determining the capacity of RC buildings. In addition, this is related to the pre- mature brittle shear collapse, as was clearly identified at the beginning of the pushover curves in all cases. Therefore, a retrofitting scheme focused on solving the shear problems should be taken into account to improve the seismic performance of these RC buildings. Besides, the influence of the infills has been more critical in the case of the model with- out walls, i.e. in the framed building.

Nicholas C et al. (2018) [4] investigated the Collapse Fragility Curves for RC Buildings Exhibiting Brittle Failure Modes. The main scope of the paper was to address analytically the issue of brittle failure modes in existing RC buildings designed without seismic code provisions and to quantify through fragility curves their probability of collapse. The study may serve as practical tools for quick assessment of strength and collapse potential of a structure, but also in deciding on pertinent retrofit strategies and consequent strengthening measures.

Do-Soo Moon et al. (2018) [5] investigated the Fragility Analysis of Space Reinforced Concrete Frame Structures with Structural Irregularity in Plan. The study derive more accurate and appropriate seismic fragility curves for space RC frame structures with different degrees of plan irregularity with their three-dimensional models and investigate the effect of structural irregularity on their seismic vulnerability. Instead of simplified models, three- dimensional analytical models are adopted to take into account true nonlinear coupled lateral-torsional responses. To address the significant computational challenge associated with the use of three-dimensional models, this study establishes a computational framework that integrates structural and reliability analysis. The study delivers seismic fragility curves for typical low- rise space RC frame structures with varying plan irregularity, but the general application may be limited because seismic performance could be very different depending on the structural configuration and the damage state definition.

Meng Zhang (2018) [6] uses SAP2000 software to build the finite element model of a six-storey-three-span reinforced concrete (RC) frame structure. The numerical simulation of the seismic performance of the RC frame structure incorporating different levels of rebar corrosion was conducted using pushover analysis method. The degradation characteristics of the seismic performance of the corroded structure under severe earthquake were also analyzed. The results show that the seismic performance of the RC frame decreased significantly due to corrosion of the longitudinal rebars. And the interstory drift ratios increase dramatically with the increasing of the corrosion rate. At the same time, the formation and development of plastic hinges (beam hinges or column hinges) will accelerate, which leads to a more aggravated deformation of the structure under rare earthquake action, resulting in a negative effect to the seismic bearing capacity of the structure.

Ebrahim Afsar Dizaj et al. (2017) [7] investigated on exploring the impact of chloride-induced corrosion on seismic damage limit states and residual capacity of reinforced concrete structures. Computational platform for time-dependent capacity assessment of corroded RC structures using non- linear FE analysis is developed. The proposed non-linear FE model includes the impact of corrosion on inelastic buckling and low-cycle fatigue degradation of longitudinal reinforcement. The FE models of the corroded and uncorroded columns are verified against experimental results. The verification results show that when the effects of buckling and low-cycle fatigue degradation of reinforcing bars are included, the simulation results are in good agreement with the observed experimental results. The validated FE model is extended to conduct a parametric study on time-dependent capacity assessment of two hypothetical RC columns, varied in axial force ratios, mass loss ratios, cover crack widths and confinement levels.

Sopna S Nair et al. (2017) [8] investigated the Vulnerability Assessment Using Fragility Curves. One of the effective ways to lessen the impact of earthquake disaster on buildings/infrastructure is accurate risk assessment and implementation of methods to mitigate the same. Hence damage and loss estimation is a key tool in earthquake disaster management and fragility curves can be used for the purpose. In the survey of series of papers by previous researchers who dealt with fragility curves were analysed. Fragility curves can be used for reliability and vulnerability assessment of buildings. Fragility curves developed for a building can be effectively used as a tool for predicting the damage levels for buildings of similar type.

Literature outcome

- Fragility curves are nothing but finding out the vulnerability of building. It is the graph of peak ground acceleration (PGA on X axis) and % of damage on Y axis.
- The fragility curves show that buildings may suffer minor damage for the design earthquake and that there is a safety margin before severe damage appears.
- The analyses of seismic fragility curves can be done by push over analyses and incremental dynamic analyses.
- Corrosion has a major effect on the most important form of degradation for materials and structures, both for wide diffusion and the amount of danger it presents.
- Fragility curves are developed for the reinforced concrete buildings, for use in the systemic seismic vulnerability and risk analysis of the urban area.

IV. METHODOLOGY PROPOSED MODELING METHODOLOGY FOR CORRODED SHEAR-CRITICAL COLUMNS

A two-dimensional (2D) nonlinear FE model is developed in Open- Sees for simulating seismic behavior of corroded reinforced con- crete columns. As illustrated in Fig. 3, a fiber based beam-column element is used for flexure response simulation; a zero-length spring element is used for shear response simulation and a zero-length fiber section element is used for rotational slip response simulation. In this way, the flexure response, shear response are all well considered and coupled at the element level.

Flexure response

The flexure response of the corroded column is modelled with a beam-column element assigned with a fiber section. The fiber section is divided into concrete fibers and steel fibers with unique constitutive stress- strain relationship. However, as discussed before, because of the corrosion of steel reinforcement, the mechanical properties of steel and concrete will deteriorate. Thus, the time-dependent deteriorated constitutive stress-strain relationship of steel and concrete fibers are used for corroded concrete column. Besides, the material Steel02 and Concrete01 in OpenSees are adopted for simulating the steel reinforcements and concrete fibers, respectively.

Rotational slip response

Because of the strain penetration or bond slip of the longitudinal reinforcing bars anchored into the column footing, additional column end rotation, and hence lateral displacement, could be generated due to rigid body rotation. This phenomenon could be more significant for corroded columns as corrosion will also reduce bond strength of longitudinal bars. In order to capture this behaviour, a zero-length fiber section element is added at the column-footing interface for slip response simulation. This element adopts the same fiber configuration with the flexure beam-column element but with different stress-strain relationship for steel fibers.

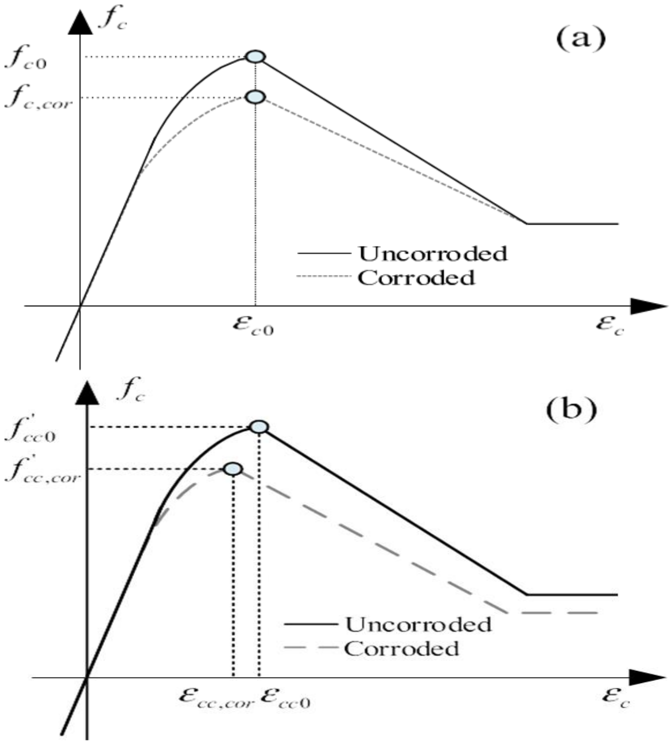


Figure 4.1: Mechanical properties of concrete: (a) cover concrete; (b) core concrete.

Shear response

A zero-length shear spring element is added at the end of the column for shear response simulation. Corroded shear-critical columns may experience shear failure under seismic loading, leading to significant deterioration in terms of strength, unloading and reloading stiffness, as well as pinching. Thus, the shear spring element should have the ability to represent the complex degradation behaviors of the corroded columns. Two additional deformation parameters, namely pre-peak plastic deformation Δp and post-peak deformation Δpc, can be calculated from the three basic characteristic points, as shown in Fig. 4.

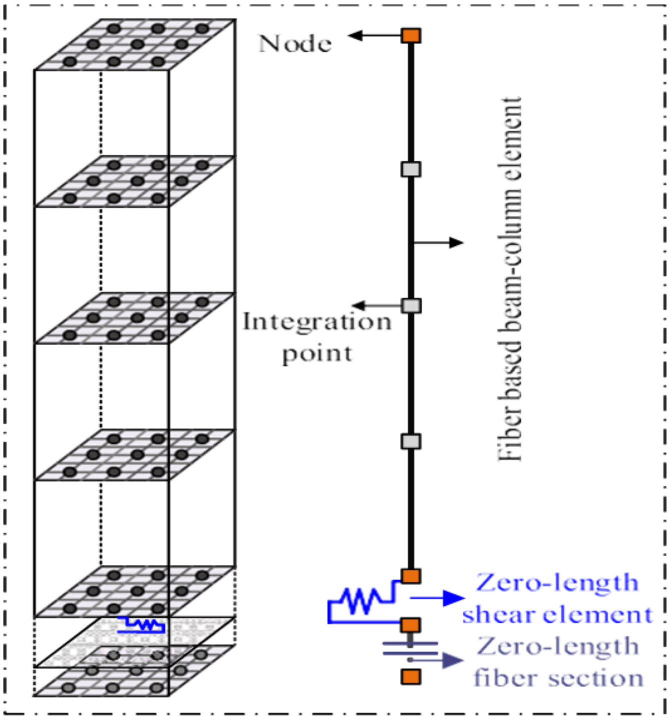


Figure 4.2: Proposed modeling concept for corroded columns considering flexure- shear interaction (FSI).

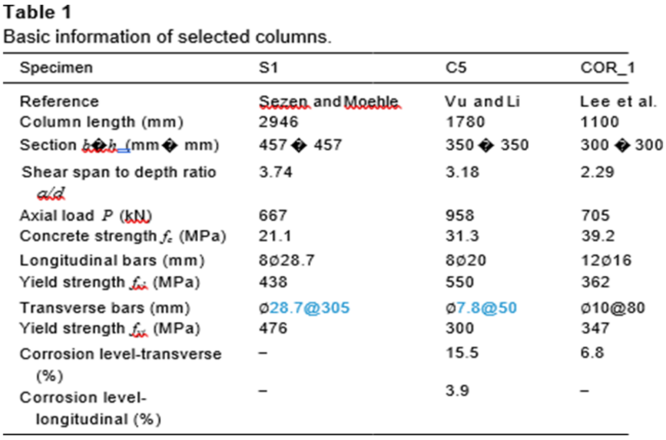


Table 1
Basic information of selected columns.

Specimen	S1	C5	COR_1
Reference	Sezen and Moehle	Vu and Li	Lee et al.
Column length (mm)	2946	1780	1100
Section b�h (mm� mm)	457 � 457	350 � 350	300 � 300
Shear span to depth ratio a/d	3.74	3.18	2.29
Axial load P (kN)	667	958	705
Concrete strength f_c (MPa)	21.1	31.3	39.2
Longitudinal bars (mm)	8ø28.7	8ø20	12ø16
Yield strength f_{yl} (MPa)	438	550	362
Transverse bars (mm)	ø28.7@305	ø7.8@50	ø10@80
Yield strength f_{yt} (MPa)	476	300	347
Corrosion level-transverse (%)	–	15.5	6.8
Corrosion level-longitudinal (%)	–	3.9	–

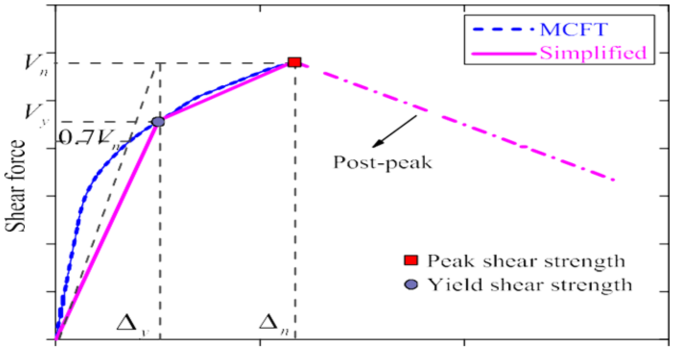


Figure 4.3: Determination of skeleton response of shear response.

V. FRAMEWORK FOR TIME-DEPENDENT SEISMIC FRAGILITY ASSESSMENT

Adopting the numerical modeling methodology proposed herein for realistically describing FSI which characterised the behaviour of corroded RC columns, the time- dependent seismic fragility of shear- critical RC columns can be analysed. The first major step is to check whether or not corrosion initiates at a given year under consideration; if corrosion initiates, the deteriorated material properties will be computed. The second major step is to develop a numerical analysis model realistically representing the structures considered using the proposed method described earlier. The final major step is to conduct the seismic vulnerability analysis of the structures considered. This step includes structural capacity analysis that defines the time-dependent structural limit states, and the development of seismic demand model of interested engineering demand parameter (EDP). In this study, the seismic demand model is obtained using the incremental dynamic analysis (IDA) method. More details are provided in the case study presented in section.

VI. CASE STUDY PROTOTYPE RC COLUMN

A RC column is selected from a typical two span continuous box-girder bridge which has been in service for many years. The shear span to depth ratio is 3.6 for both of the longitudinal direction (double curvature bending) and transverse direction (single bending), and the transverse reinforcement spacing of the column is 305mm. With these design de- tails, the column can be considered as a shear- critical column as checked by Jeon et al. The cover thickness is 30mm, and the diameter of longitudinal rebar is 36mm and that of transverse reinforcement is 13mm. The concrete strength is 27MPa and the yield strength of the steel reinforcement is 303MPa. The assumed exposure condition of the bridge is the marine tidal-zone, wherein the bridge column is subjected to alternate wetting and drying cycles from the sea water containing chloride, which is considered to be a major deterioration mechanism for bridge columns.

Corrosion modeling

For the assumed exposure condition of the bridge, the parameters introduced into the corrosion initiation model are adopted.For these parameters, the calculated corrosion initiation time for transverse reinforcement is 5.6 years, and it increases to 17.3 years for longitudinal reinforcement due to the thicker embedded depth. After corrosion initiates, the time-dependent deteriorating material properties can be computed with the method discussed in Section 2.3. It can be clearly seen that the two types of reinforcement will suffer different corrosion levels over time. For instance, the corrosion levels of transverse reinforcement are 12.8%, 23.3% and 37.9% at 25 year, 50 year and 100 year, respectively; while the corresponding corrosion levels of longitudinal reinforcement will be 1.8%, 5.1% and 9.5%. The time-dependent yield strength of the reinforcements is shown in Fig. 14(b). The figure indicates that the transverse reinforcement has a higher deterioration rate of yielding strength than longitudinal reinforcement.

VII.RESULT AND DISCUSSION

6.1. Reinforced beam with size (150mm x 200mm x 2100mm)

1. The effects of time-dependent corrosion and modeling methods on seismic drift demands of shear-critical RC columns are firstly assessed. Typical hysteretic responses of the bridge columns at different investigated times are shown in where illustrates hysteretic responses obtained using FSI-model shows the results obtained using flexure model. From, it can be seen that, due to the use of corrosion-induced reduced material properties, the drift demands of the bridge columns increase under the sample ground motion. The maximum drift ratio for the pristine column is 0.96%, while the drift demands will increase to 1.47% and 1.71% at 50 year and 100 year, respectively. Similar finding is obtained using the flexure-only model as illustrated in. The drift demand placed on the pristine column using the flexure model is 0.43%, and subsequently increases to 0.62% and 1.00% at 50 year and 100 year, respectively. The results also reveal that the modeling method for shear- critical columns has significant effect on drift demands. The FSI-model generates larger drift demands of columns at different investigated times, while using the flexure model which only accounts for flexure response tends to underestimate markedly the drift demands of shear-critical columns.

Based on the above seismic fragility analysis framework, the time- dependent fragility curves for the shear-critical RC columns are obtained. Shows the analysis results of the fragility curves for the column case. The curves illustrate the probabilities of exceeding four damage states of the bridge column from 0 year to 100 year with a 25 year time interval. It can be seen that corrosion has slight effects with respect to light damage state, although the vulnerability for the damage state increase with increase in time. This is mainly because the column will experience damage at low ground motion intensities and as such the corrosion effect is not yet fully reflected. However, corrosion effects on seismic fragility becomes more pronounced at severer damage states, and marked increased probabilities of exceeding extensive damage state and collapse prevention damage state. The median collapse capacity is approximately 0.63g for the pristine column, and the capacities will reduce to 0.54g and 0.50g at 50 years and 100 years, i.e. a reduction of 14.3% and 20.6%, respectively. The above results indicate that corrosion should be taken into consideration in structural seismic fragility assessment, especially for severer damage states.

In order to compare the effectiveness of using the traditional method, which considers only flexure response and a time-invariant structural capacity index, and using the proposed evaluation method in this paper for the fragility analysis, the probability differences from using the two methods are also assessed. For the traditional method, the damage state definition are adopted from Refs, which are taken as 0.5%, 1.0%, 2.0% and 2.5% for SD, MD, ED and CP damage states respectively. The analysis results are presented in Fig. 8.1, where the graphs on the left hand side show the comparison of seismic fragility curves using the two methods, and graphs on the right hand side show the probability differences over PGA.

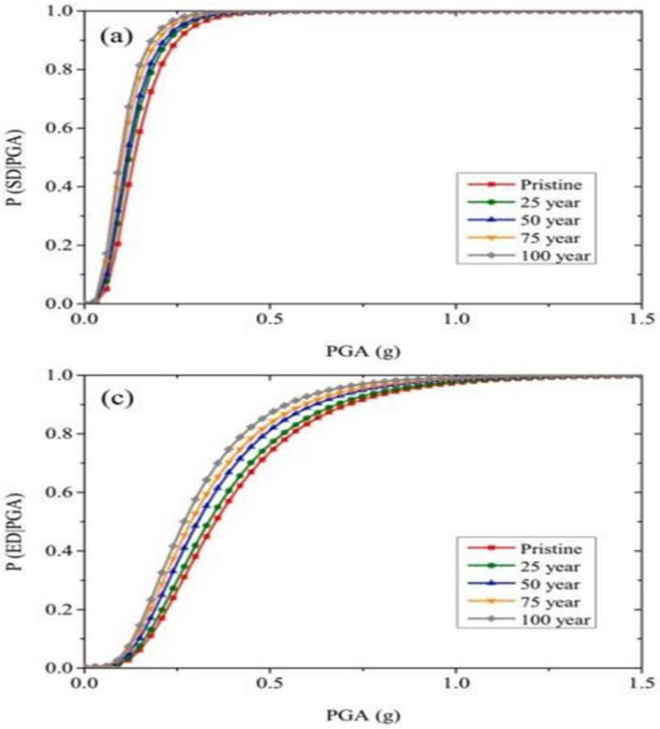


Figure 7.1: Time-dependent fragility curves of shear-critical columns: (a) slight damage;
(c) extensive damage;

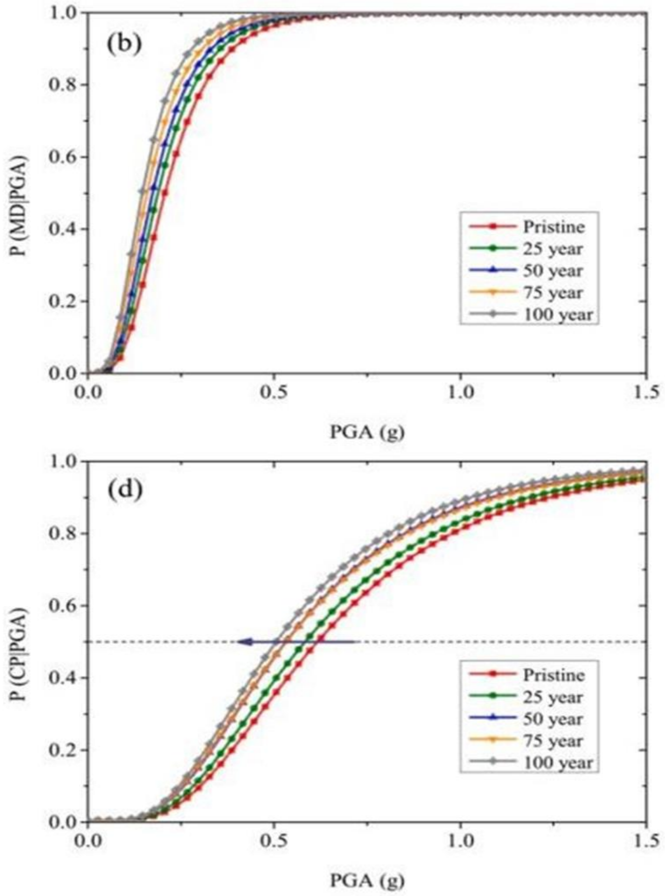


Figure 7.2: Time-dependent fragility curves of shear-critical columns: (b) moderate damage; (d) collapse prevention

VIII. CONCLUSION

A framework for seismic fragility analysis for shear-critical reinforced concrete columns considering corrosion induced deterioration effects is presented in this paper. The framework comprises a corrosion modeling part which defines the corrosion initiation time and time- variant deteriorating material properties of the columns. Especially, the differences of corrosion levels between transverse and longitudinal steel reinforcements in reality are taken into account. A new model is proposed for corroded shear-critical columns to account for shear performance deterioration due to corrosion and the flexure-shear interaction behaviors of columns under seismic loadings.

The model is validated by comparing simulation results with experimental test results of shear-critical columns and the results indicate that the proposed model can reasonably simulate the hysteretic response of uncorroded shear-critical columns as well as corroded shear-critical columns. The proposed framework also adopts time-variant structural capacity for seismic fragility analysis where the time-dependent structural capacity is obtained with the proposed FSI-numerical model.

A representative bridge column is analysed to demonstrate the pro- posed framework and its effectiveness for time-dependent seismic fragility analysis for shear-critical columns. The results show that corrosion has significant effects on seismic fragility of the column, especially for severer damage states. The median collapse capacity is approximately 0.63g for the pristine column, and the capacities will reduce to 0.54g and 0.50g at 50 year and 100 year, with a reduction of 14.3% and 20.6%, respectively.

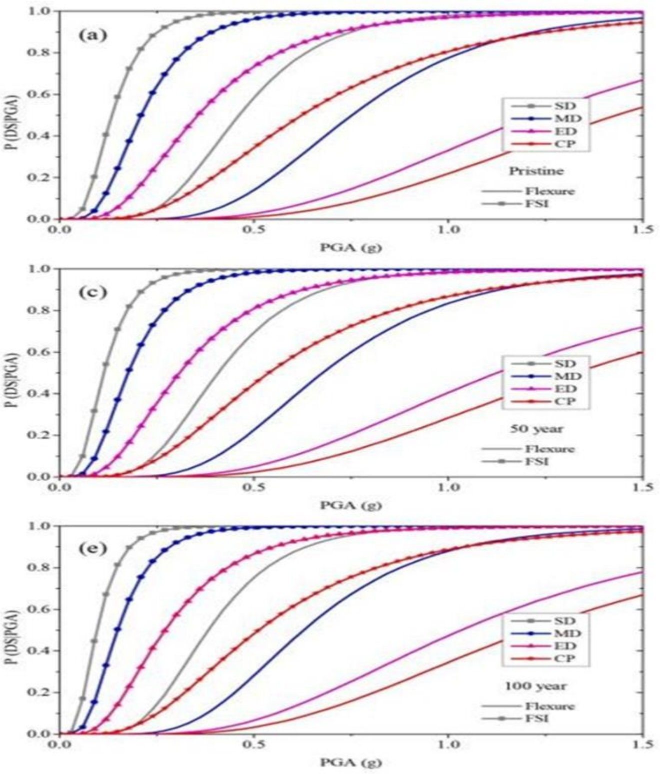
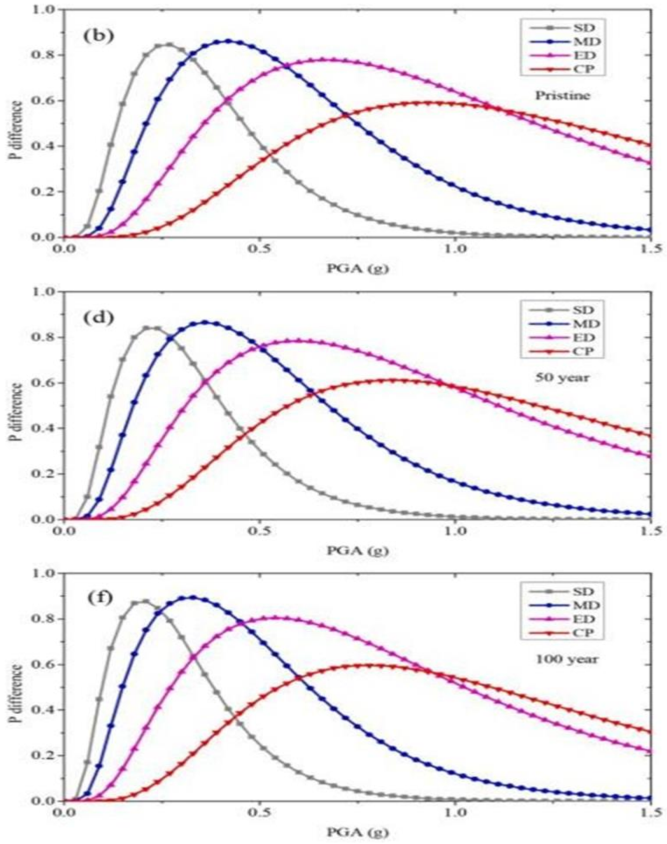


Figure 8.1: Effects of evaluation methods on fragility analysis results of shear-critical column: (a), (b): pristine column; (c), (d): column at 50 years; (e), (f): column at 100 years (Left: seismic fragility curves; Right: probability difference).

Comparison of the modeling methods indicates that, for corroded shear-critical columns, using the traditional flexure modeling method with time-invariant structural capacities tends to significantly underestimate the seismic fragility. The proposed method, which considers the differences in the longitudinal and transverse reinforcement corrosion over time, time- variant structural capacitie as well as time- dependent shear and flexure-shear interaction behaviors, reflects reasonably the increased seismic fragility for corroded shear-critical columns.

The proposed framework paves a way for more realistic seismic fragility analysis of shear-critical RC columns considering the effect of corrosion.



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