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Consideration of time-evolving capacity distributions and improved degradation models for seismic fragility assessment of aging highway bridges

Jayadipta Ghosh [a],*, Piyush Sood [b]

[a] Department of Civil Engineering, Indian Institute of Technology Bombay, Mumbai 400076, India
[b] School of Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta 30318, USA

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ABSTRACT

This paper presents a methodology to develop seismic fragility curves for deteriorating highway bridges by uniquely accounting for realistic pitting corrosion deterioration and time-dependent capacity distributions for reinforced concrete columns under chloride attacks. The proposed framework offers distinct improvements over state-of-the-art procedures for fragility assessment of degrading bridges which typically assume simplified uniform corrosion deterioration model and pristine limit state capacities. Depending on the time in service life and deterioration mechanism, this study finds that capacity limit states for deteriorating bridge columns follow either lognormal distribution or generalized extreme value distributions (particularly for pitting corrosion). Impact of column degradation mechanism on seismic response and fragility of bridge components and system is assessed using nonlinear time history analysis of three-dimensional finite element bridge models reflecting the uncertainties across structural modeling parameters, deterioration parameters and ground motion. Comparisons are drawn between the proposed methodology and traditional approaches to develop aging bridge fragility curves. Results indicate considerable underestimations of system level fragility across different damage states using the traditional approach compared to the proposed realistic pitting model for chloride induced corrosion. Time-dependent predictive functions are provided to interpolate logistic regression coefficients for continuous seismic reliability evaluation along the service life with reasonable accuracy.

1. Introduction

The last decade and especially the past few years have witnessed significant efforts towards quantifying the seismic vulnerability of deteriorating highway bridges. Given that across the globe a significant percentage of these critical infrastructure elements are nearing the end of their useful service life, the time is opportune to investigate joint seismic and aging threats to bridge structures, especially for those located in moderate to high seismic zones. For instance, the average age of highway bridges within the US inventory at present is 42 years [6] and approximately 234,238 bridges out of over 600,000 within the inventory are located in moderate to high seismic zones [24]. While such comprehensive statistics maybe difficult to track for all regions across the globe, deterioration of infrastructure systems alone (primarily due to corrosion) contributes to over 3% of the GDP of industrialized countries [68]. The dollar impact of environmental deterioration coupled with seismic threats necessitates the vulnerability assessment of aging highway bridges to ensure the socio-economic welfare of a nation.

Multiple degradation mechanisms may potentially affect the structural performance of highway bridges during its service life, such as erosion, fatigue, sulfate and acid attacks on concrete, carbonation and chloride induced corrosion of steel components, freeze-thaw cycles in bridges in cold regions, oxidation of rubber bearing pads, amongst others [21,29]. Amongst these, corrosion deterioration (particularly from chloride ions) has received significant attention with reference to vulnerability quantification of bridges located in seismic zones. This deterioration mechanism potentially affects multiple critical bridge components comprising of embedded or exposed steel elements, such as reinforced concrete (RC) columns, steel bearings, bearing anchor bolts or dowel bars, reinforced deck slabs and exposed steel girders [12,2,27,39,63]. The vulnerability of aging as well as pristine (as-built or non-deteriorating) highway bridge structures under seismic shaking is typically expressed in the form of seismic fragility curves which quantifies the likelihood of meeting or exceeding a particular damage state given the intensity of ground motion.

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* Corresponding author.
E-mail address: jghosh@iitb.ac.in (J. Ghosh).

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While several researchers have focused on the component and system level development of seismic fragility curves for different highway bridge types and chloride exposure conditions, several potential drawbacks still exist. Firstly, corrosion deterioration due to chloride ions stemming from deicing salt exposure or marine sources typically results in the formation of spatially distributed localized corrosion pits in addition to general uniform loss of steel area along the length of the embedded rebar [64,8]. These pit formations can result in localized weakening in RC columns and remarkably reduce the lateral load carrying capacity during extreme events, such as earthquakes. Presently, almost all existing literature on the impact of chloride-induced corrosion on seismic fragility of highway bridges only considers uniform section loss of embedded reinforcement area [1,13,27,3]. Although such simplistic assumptions may aid in the ease of deterioration modeling and subsequent fragility analysis using finite element bridge models, it may lead to significant under-predictions of aging bridge failure probabilities. These underestimation of seismic fragility at bridge level are also likely to be propagated during life-cycle analysis of deteriorating bridges [17,67] as well as in reliability estimation of aging bridge transportation networks [40,59].

Seismic fragility analysis of highway bridges is a typical *demand-capacity* reliability problem wherein aging and deterioration invariably affects the seismic demand imposed on bridge components as well as the component-specific capacities. The second limitation in existing literature lies in the assumption of time-invariant limit state capacity distributions of critical bridge components, such as RC columns. While researchers have highlighted the influence of chloride induced corrosion (albeit with uniform area loss assumption) on the seismic demand of aging RC columns, little attention has been given to the impact on capacity estimates. As a consequence, seismic fragility curves in a majority of studies are based on the assumption of pristine or non-deteriorated limit states for corroding bridge columns [17,27,3,31]. Experimental tests conducted by multiple researchers, such as Aquino [4], Kato et al. [35], Aquino and Hawkins [5], Li and Gong [38], among others, have highlighted the reduced performance and capacity (under monotonic pushover and cyclic loads) of corroding bridge columns for specified levels of deterioration compared to pristine bridge conditions. While these tests helped to understand the impact of the nature and severity of corrosion on the performance of corroding columns, determination of probabilistic column capacity distribution would ideally require these experiments to be repeated multiple number of times for a particular column configuration and a given level of deterioration. Given that such tests are likely to be cost and labor-intensive, researchers have resorted to analytical techniques to estimate capacity distributions by conducting pushover analysis of finite element reinforced concrete column models. For corroding highway bridge columns, only recently the impact of corrosion on column capacity estimates has been analytically investigated by Ni Choine et al. [48], but for uniform area loss assumption without the consideration of pitting corrosion. Additionally, capacity limit state distributions for pristine as well as deteriorating highway bridge columns are typically assumed to follow lognormal distribution [3,47,50,56]. The best-fitting distribution type for column capacity limit states under realistic pitting corrosion conditions needs to be explored.

Addressing such drawbacks, this paper offers a framework to develop seismic fragility curves for aging highway bridges using best representative features for chloride induced corrosion: a) Pitting corrosion deterioration model for reinforced concrete bridge columns, and b) time-evolving distributions of column capacity estimates for different damage states. Firstly this paper proposes a time-dependent area loss model due to pitting corrosion based on the recommendations by Stewart [65] followed by development of time-varying capacity limit state distributions using pushover analysis of finite element column samples via a Monte Carlo approach. In addition to pitting corrosion, this paper also develops time-varying column capacity distributions for the uniform corrosion deterioration models which may be adopted by researchers and bridge engineers for prompt but relatively precise (compared to pitting) estimates of bridge fragility using the simplistic uniform corrosion model and time-independent capacity estimates. Subsequently, full-scale high fidelity finite element bridge models are developed for a case study multi-span continuous (MSC) steel girder bridge in Central and Southeastern US undergoing corrosion deterioration from uniform and pitting corrosion due to chloride exposure from marine sources. For both deterioration mechanisms, fragility curves are developed at component and system level using time-dependent seismic demand (obtained via nonlinear time-history analysis) and developed capacity distributions. Since traditionally aging bridge fragility curves were developed using pristine (non-deteriorating) bridge damage state distributions, comparisons are drawn between fragility curves obtained using the realistic pitting corrosion model with time-evolving capacities and uniform corrosion model with time-invariant (pristine) capacities. Additionally a sensitivity analysis is conducted to assess the influence of critical deterioration parameters on the seismic vulnerability of deteriorating bridge columns. The results presented in the paper offer interesting insights and new understanding of impact of chloride induced corrosion on the seismic fragility of deteriorating bridge structures.

The present study is organized as follows: the next section focuses on assessment of sectional area loss of steel in reinforcing bars due to uniform and pitting corrosion, and incorporation of these deterioration mechanisms while developing finite element reinforced concrete columns for highway bridges. A Monte Carlo framework for developing time-evolving capacity distributions using pushover analysis of pristine and deteriorating bridge columns is also discussed. Then, the case-study MSC steel bridge is introduced and discussions on modeling of other critical bridge components in addition to corroding RC columns are included. This is followed by the development of bridge specific time-dependent seismic demand and capacity distributions for uniform and pitting corrosion. For these two deterioration mechanisms fragility curves are developed at component and system level using logistic regression analysis. The subsequent sections provide comparative assessment between the fragility curves developed in this study with those obtained using state-of-the-art method in literature. Predictive quadratic functions for prompt estimation of fragility at different time periods and relative to traditional methods are presented. A sensitivity analysis in the end highlights the impact of critical deterioration parameters affecting the seismic fragility of aging bridges. The paper ends with discussions on the results, concluding remarks and opportunities for future research.

2. Corrosion deterioration modeling and capacity estimation

Almost all elements in nature, structural or otherwise, tend to gradually change to lower levels of energy and in the process undergoes spontaneous degradation throughout their service life. Depending on the exposure condition, the deterioration process of highway bridge components may manifest in the form of corrosion, erosion, or other forms of chemical and physical deterioration [46]. Typically the loss of structural strength in aging bridge columns to resist lateral forces during seismic events is primarily attributed to the corrosion deterioration of reinforcing steel bars. This degradation process leads to reduction in cross sectional area, alterations in steel material properties, and secondary effects such as cracking, loss of confinement, and spalling of the concrete cover [10,20]. The nature and extent of area loss of steel depends on multiple factors,