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Effect of seismic degradation on the fragility of reinforced concrete bridges

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ABSTRACT

In seismic regions, structures are likely to experience multiple seismic events during their service lives. As a result, the seismic reliability of structures may degrade from the design standard with each passing earthquake. Therefore, there is a need to investigate the effect of seismic degradation on the reliability of structures in subsequent earthquakes. In the existing literature, performance of RC structures under a sequence of earthquakes has received limited attention. More work is required to understand the effects of seismic degradation mechanisms in different structural systems.

This paper investigates the seismic degradation of reinforced concrete (RC) highway bridges and the effect of degradation on the performance and reliability of bridges subject to future seismic events. In particular, the focus is on the degradation of bridge columns that are typically the primary lateral load resisting components in highway bridges. For this purpose, probabilistic models are developed to predict the effect of past earthquakes on the structural properties of RC bridge columns and their steel reinforcement. The proposed models are assessed using seismic degradation data generated through nonlinear time history analyses of RC bridges subject to ground motions obtained using detailed finite element (FE) models. The developed degradation models are then used to assess the effects of seismic degradation on the seismic vulnerability of an example RC highway bridge with one single-column bent. The results show that seismic degradation in RC columns can significantly increase the seismic vulnerability of RC highway bridges.

1. Introduction

Studies on seismic vulnerability of bridges have primarily focused only on the as-built state of bridges (e.g., [22,7,8,4,28,12]. However, often we need to assess the seismic vulnerability of bridges that have experienced structural degradation during the past earthquakes and are therefore likely to have unsatisfactory performance in future earthquakes. The importance of assessing the future seismic performance of seismically degraded structures can be understood from the recent seismic events witnessed in New Zealand (2011) and in Northern Italy (2012), where multiple damaging earthquakes occurred within a span of six months allowing limited time for repairs. Also, Kumar and Gardoni [13] found that bridges that have experienced a damaging earthquake early in their service life, still have a considerable probability of experiencing one or more damaging earthquakes in their remaining service life.

The existing literature on seismically damaged RC bridges primarily focuses on post-earthquake repairs [20,26,14,21]. However, the justification for conducting repairs can be provided only by analyzing the performance of a damaged bridge. Huang et al. [11] computed the deformation and shear capacities and the corresponding fragilities of seismically damaged RC columns based on the information obtained from non-destructive testing (NDT) of bridges, where fragility was defined as the conditional probability that a given deformation or shear force demands exceeds the corresponding predicted capacities. While NDT can provide structure specific information, it may not be economically feasible to use it for a large network of bridges. Also, NDT cannot be used in life-cycle costs analyses to account for future earthquakes that a bridge has not experienced yet. Sunasaka and Kiremidjian [23] compared the damage to reinforced concrete (RC) highway bridges caused by main shocks and aftershocks. However, the study computed seismic damage based on cumulative seismic damage model by Park and Ang [18] which does not account for

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the degradation in the stiffness of columns that can result in the amplification of the seismic demands. Kumar and Gardoni [13] computed the fragility of RC bridge columns accounting for existing low-cycle fatigue damage to longitudinal steel. However, low-cycle fatigue damage models for steel do not account for the seismic degradation of other important properties such as pre-yield stiffness of columns. In addition, the fragility assessment should not be limited to RC columns conditioning on the deformation and/or shear force demands on the column but considering the entire RC bridges conditioning on measures of ground motion intensity. Developing bridge fragilities requires considering the effects of degradation not only on the structural capacity but also on the system demand.

This paper investigates the effect of seismic degradation on the future seismic vulnerability of RC bridges. Particularly, we focus on the degradation of the bridge columns that are the primary lateral load resisting components in bridges. The static pushover curve of a bridge column plays a major role in the determination of the seismic demands on the bridges [8,12]. Therefore, this paper models the change in the static pushover curve of RC columns caused by earthquakes. The proposed models are assessed using the seismic degradation data generated in virtual experiments, where we perform nonlinear time history analyses (NTHA) and static pushover analyses of RC bridges using detailed finite element (FE) models. The data generated in the virtual experiments is used to develop the proposed models using the Bayesian updating method [1]. The developed models are used to assess the effect of seismic degradation on the seismic vulnerability of an example RC bridge. The example bridge is representative of single-column highway bridges designed according to the current seismic codes.

The remaining part of the paper is organized into five sections. First, we describe the various types of seismic degradation processes in RC structures and the proposed modeling. The next section explains the procedure followed to conduct virtual experiments in order to generate the data required for calibrating the proposed probabilistic models. Then, we discuss the development of the probabilistic models using the generated data. Next, we use the developed degradation models to study the effect of seismic degradation on the seismic vulnerability of the typical RC bridge. Finally, we present the conclusions derived from this work.

2. Modeling seismic degradation of RC bridge columns

During an earthquake, various damage mechanisms are initiated in RC components that contribute to the overall seismic degradation of the components. Some important damage mechanisms are: the cracking of concrete, the weakening of the bond between concrete and reinforcing steel, the loss of confinement pressure applied by the transverse steel on the core concrete and the accumulation of low-cycle fatigue damage in reinforcing steel. In order to estimate the vulnerability of a damaged RC component, the net effect of all the damage mechanisms on the demands and capacities corresponding to the various modes of failure of the component must be modeled.

The failure of an RC bridge column, during an earthquake, occurs mostly in the lateral deformation or the shear mode. In the former mode of failure, the lateral drift in the column caused by an earthquake exceeds the drift capacity of the column and in the later, the shear force in the column exceeds the shear capacity of the column section. The seismic shear and the deformation demands on an RC bridge column are largely influenced by the static pushover curve of the column [8,12]. This is primarily because the natural period of vibration of the bridge depends on the pre-yield slope of the static pushover curve. Therefore in this paper, we model the degradation of the static pushover properties of a column that includes the reduction in the pre-yield lateral stiffness K of the column and the shift in the yield point (Δ_y, V_y), where Δ_y is the displacement at yield, V_y is the shear force at yield and $V_y = K\Delta_y$. The reduction in K and the shift in (Δ_y, V_y) may result in a net increase in seismic deformation demand and hence increase the probability of failure. Such degradation is primarily caused by the reduction in the stiffness of concrete caused by its internal cracking and the degradation of the bond between reinforcing steel and concrete. In this work, we only consider the effect of cracking of concrete, which most uniaxial material models for concrete (e.g., [10]) already capture. This is because seismically designed bridge columns have sufficient lateral confinement steel to overcome the effects of bond degradation.

In addition, we develop a model to predict low-cycle fatigue damage in the longitudinal reinforcing steel of RC columns. Low-cycle fatigue of reinforcing steel is caused by large strain reversals caused by cyclic loading [2]. The accumulation of low-cycle fatigue damage in the longitudinal reinforcing steel results in reduction of ultimate curvature capacity of an RC section ϕ_u [13] which results in the reduction of lateral deformation capacity of RC columns. Kumar and Gardoni [13] provides the value of ϕ'_u, the degraded value of ϕ_u due to low-cycle fatigue of longitudinal steel. Low-cycle fatigue of reinforcing steel is a cause of concern for seismically designed bridge columns because they are expected to withstand several cycles in the inelastic range during an earthquake.

3. Virtual experiments

To generate the degradation data, we conduct 1200 virtual experiments in which we perform NTHA of representative RC bridges for selected ground motions and static pushover analyses of the RC bridges before and after the NTHA. The analyses are conducted using the FE software OpenSees [16]. The representative bridges and ground motions capture the variability in the structural properties, site properties and ground motion parameters. We use the experimental design developed by Huang et al. [12] that provides the values of design parameters for RC bridges with one single-column bent designed as per Caltrans seismic design specifications [3]. The experimental design was originally created for developing probabilistic seismic demand models for RC bridges with one single-column bent. The experimental design consists of 60 RC bridges described by 12 geometrical and material parameters (see Table 1), and 200 ground motions described by the site-to-source distance (R), moment magnitude (M), type of soil. Ten bins with 20 ground motions each are created. There are 5 bins based on M and R: (i) $5.5 \leqslant M \leqslant 6.5$, $15\ \text{km} \leqslant R \leqslant 30\ \text{km}$ (ii) $5.5 \leqslant M \leqslant 6.5$, $30\ \text{km} \leqslant R \leqslant 50\ \text{km}$ (iii) $6.5 \leqslant M \leqslant 7.5$, $15\ \text{km} \leqslant R \leqslant 30\ \text{km}$ (iv) $6.5 \leqslant M \leqslant 7.5$, $30\ \text{km} \leqslant R \leqslant 50\ \text{km}$ (v) $6.5 \leqslant M \leqslant 7.5$, $0\ \text{km} \leqslant R \leqslant 15\ \text{km}$. The described 5 bins are created for 2 groups of soil conditions: Group (i) USGS soil type A and B with soil thickness $\leqslant 20$ m, Group (ii) USGS soil type C, D and E with soil thickness $\geqslant 20$ m. Each of the 60 bridges is subject to 20 ground motions selected randomly without replacement from the set of 200 ground motions. More details regarding this experimental design can be found in Huang et al. [12].

3.1. Finite element model

Fig. 1 shows the FE model of the bridge type considered in the virtual experiments. The bridge consists of 4 parts: one single-column bent, one two-span deck, two abutments and one pile foundation. The column has height H_c and a circular cross-section of diameter D_c. The cross-section of the column is modeled using an uniaxial fiber-section model available in OpenSees to model RC sections. The cross-section is divided into an inner core and an outer concentric circular strip representing the cover region.