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Damage assessment of older highway bridges subjected to three-dimensional ground motions: Characterization of shear–axial force interaction on seismic fragilities

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ABSTRACT

This study presents the influence of vertical ground motions on the seismic response and fragility of typical older highway bridges. The fragility is investigated using a set of functions that estimate exceedance probabilities of structures under seismic events. For this purpose, this study selects a typical older two-span single frame concrete box-girder bridge constructed in California in 1967. The bridge column has insufficient design details such as wide spacing of transverse reinforcement and low ratio of shear span to section depth resulting in an increased potential of shear–axial failure. The column shear response model accounts for the fluctuation in column axial force using an existing Zeus-NL material model and is validated through comparison of simulated and experimental results reported in the literature. Using this shear–axial force interaction model, a bridge system model is created in Zeus-NL to perform nonlinear time-history analyses. The response results are used to generate demand models, and component and system fragility curves of the bridge. Finally, fragility curves are compared for two bridge models with column shear model under constant axial force and with column shear model under axial force variation. The comparative results indicate that the shear model accounting for varying axial force increases the probability of exceeding the severe damage state by about 10% across the entire range of an intensity measure and reduces the median intensity measure by more than 15%. This observation highlights the importance of shear–axial force interaction in the seismic performance of older bridges.

1. Introduction

Many of current seismic design codes and damage estimation tools do not include the effect of vertical ground motions on the seismic response of structures and especially columns. However, the observed damage on the columns (diagonal shear cracks) during historical seismic events such as the 1994 Northridge earthquake and the 1995 Kobe earthquake was partly attributed to the effect of vertical motions [1,2]. The influence of vertical ground motions on the seismic response of highway bridges has been investigated in a number of prior studies.

Field and analytical evidence by Papazoglou and Elnashai [3] indicated that strong vertical earthquakes can cause a significant fluctuation in the axial force in columns, resulting in a reduction in their shear capacity and compression failure of some of the columns. Saadeghvariri and Foutch [4] evaluated the inelastic response of two-span bridges using artificial records. Their analysis results indicated that vertical ground motions may generate forces of high magnitude in abutments and foundations, cause unstable hysteresis loops, and increase column ductility demands. Yu [5] analyzed the impact of vertical motions on responses of columns, foundations, hinges, and bearings of three overpass bridges. The analyses results showed a 20% increase in the axial force and a 7% increase in the longitudinal moment of columns as a result of the addition of vertical ground motions. Button et al. [6] evaluated conditions in which vertical motions are crucial in determining deck shear and moments and column axial forces. Relying

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primarily on linear dynamic analysis, the study considered six bridges and the conditions included various characteristics of ground motions and structural systems. From the set of linear analyses, it was concluded that column axial forces can be significantly affected, especially at bridge sites with a near fault distance less than 10–20 km. Moreover, these authors recommended design guidelines to account for the effects of vertical ground motions. To account for the effect of axial force variation, Lee and Elnashai [7] carried out analytical studies for the Santa Monica Bridge damaged by the 1994 Northridge earthquake using a shear–axial interaction model which has the ability to capture shear response transition with varying axial force. The results indicated that the shear–axial force interaction increases the transverse column displacement by over 20% and reduces the transverse column shear capacity by over 20%. Kunnath et al. [8] undertook dynamic analyses for a two-span highway bridge with a double-column bent including six different structural configurations to assess the provisions in the Seismic Design Criteria [9]. The results revealed that vertical motions cause significant amplifications in moment demands in girders at both the mid-span and the face of the bent cap. In addition, they significantly influence the axial force demand in columns. Kim et al. [10] investigated the impact of various ratios of peak vertical to horizontal ground accelerations and the time lag between the arrival of the peak horizontal and vertical accelerations on the inelastic vibration period and column response for two bridges. It was observed that the inclusion of vertical motions notably influence the inelastic response vibration periods and considerably increase or decrease the lateral displacement. It was also noticed that the arrival time has a minimal effect on the axial force variation and shear demand. Additionally, recent studies [6,10–12] have demonstrated that the 2/3rd spectral rule (vertical-to-horizontal spectral acceleration ratio), commonly used in the earthquake engineering community, may underestimate the effect of vertical motions on structural responses in near-fault regions.

Although seismic fragility models of various structures subjected to horizontal ground motions have been developed by many researchers, studies on probabilistic seismic risk assessment of structures under combined horizontal and vertical motions are yet scarce. One of these studies is the work of Gulerce et al. [12], who developed seismic demand models for typical highway bridges with two spans designed in accordance with the seismic design criteria proposed by the California Department of Transportation (Caltrans) [9]. To investigate the effect of vertical motions, the demand models with and without vertical motions were generated for engineering demand parameters (EDPs) such as maximum compressive axial load in the columns and peak positive/negative moments at the mid-span and interior support of girders. The simulation results indicated that vertical motions significantly affect the above EDPs. However, their study did not examine the effect of vertical motions on horizontal responses of columns substantially affecting lateral and axial load-carrying resistances in the bridge system. In addition, this study used force-based EDPs that are not appropriate to capture demands of older bridge components exhibiting softening behavior (increased damage with increasing deformation demands).

The main objective of this paper is to develop displacement-based fragility curves for older reinforced concrete (RC) bridges subjected to near-fault vertical ground motions. To achieve this goal, a numerical model that captures the shear behavior of nonductile columns is created in Zeus-NL [13], and the modeling approach is validated by comparing simulation and experimental results. To model the column shear response in a bridge system, a typical older bridge designed prior to 1971 (before the 1971 San Fernando earthquake) is selected from the California bridge inventory. This bridge class has RC column(s) with a 305 mm spacing of D13 transverse reinforcement regardless of column size or size of longitudinal rebars (higher potential of shear failure) while modern bridges designed after 1994 (after the 1994 Northridge earthquake) have columns with tight confinement reinforcement less than 100 mm spacing in plastic hinge zones [14]. Moreover, an existing suite of near-fault ground motions [12] is used and applied to the bridge model to monitor maximum component responses (EDPs) in nonlinear time-history analyses (NTHAs). Using the response data and associated ground motion intensities, component demand models are generated and then convolved with capacity (limit state) models to develop component fragility curves. Finally, system fragility curves are developed using Monte Carlo simulations on the basis of demand and capacity models. Finally, the influence of vertical motions and column shear models on the damage exceedance probabilities resulting from component and system fragility curves is examined.

2. Numerical model of shear-dominant columns

This section describes the numerical modeling of older columns with shear failure dominating the structural performance. In addition, the validation of the modeling approach is presented through the comparison of simulation results with existing experimental results.

2.1. Model description

Fig. 1 illustrates the Zeus-NL [13] element configuration for simulation of shear response for a column. The column is modeled with a zero-length shear spring (shear response) and fiber-based beam elements (flexural response). Shorter fiber-based beam elements at the end of the column and longer fiber-based elements away from the end of the column are used to capture inelastic flexural response in plastic hinge zones. For the fiber sections, unconfined and confined concrete are simulated using the model of Mander et al. [15] and longitudinal reinforcement is modeled using a bilinear model with a hardening factor of 0.01. Two Gauss points along one element are used for numerical integration in the program. The fiber-section at each Gauss point is divided into 200 monitoring points (fibers).

Shear response is simulated using a zero-length shear spring located at the end of the column. Lee and Elnashai [7,16] developed two shear models and implemented them in Zeus-NL to simulate the shear response of the column: *Hysteretic shear model under constant axial force* [16] and *Hysteretic shear model under axial force variation* [7]; either one can be employed to capture the shear response. Fig. 2(a) shows the envelope curve of the hysteretic shear model under constant axial force, which is defined by a quadrilinear symmetric relationship comprising cracking, yielding, and ultimate conditions. The response parameters on the curve are determined by the modified compression field theory (MCFT) developed by Vecchio and Collins [17]. The MCFT has been widely used by many researchers [7,16–19] to characterize the shear response of columns, and their work showed good correlations with experimental results. The MCFT used in this study revises the original formulation by Vecchio and Collins [17] to account for the confinement effect of concrete due to hoops or spirals and the hardening of longitudinal rebars [16]. In the case of RC

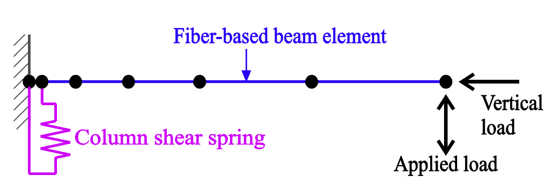

Fig. 1. Column response model.