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Effect of pounding on nonlinear seismic response of skewed highway bridges

Jingyi Chen[a], Qiang Han[a,*], Xiao Liang[b], Xiuli Du[a]

[a] *Key Laboratory of Urban Security and Disaster Engineering of Ministry of Education, Beijing University of Technology, Beijing, China*
[b] *Department of Civil, Construction and Environmental Engineering, Iowa State University, IA, USA*

A R T I C L E I N F O

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A B S T R A C T

Skewed bridges are more vulnerable to earthquake-induced failure than straight bridges due to pounding at expansion joints between the bridge superstructure and abutments. This study focuses on analyzing pounding effect and rotation mechanism of highway bridges with prestressed concrete box girder and seat-type abutments when subjected to bi-directional near-fault ground motions, especially seismic response with respect to abutment skew angle. These analytical models include nonlinear characteristics of skewed bridge components, especially pounding effect between the superstructure and abutment in both longitudinal and transverse directions. Nonlinear time history analyses were performed to predict the pounding force and its effect on the seismic response of skewed highway bridges using the Kelvin model. The analytical results indicate that the pounding of skewed bridge causes significant seismic displacement response and local damage of superstructure. In addition, the pounding in the transverse initial gap reduced the rotation response of the skewed bridge, and the skew angle has significant effect on the seismic behavior of skewed highway bridges. The pounding force and back-fill response decreased with an increasing skew angle, but deck displacement in longitudinal direction and torsion response increased apparently. Bridges with skew angle increased demand on shear keys under the strong earthquake excitation.

1. Introduction

Skewed highway bridges are commonly used as overcrossings in highway intersections and interchanges, especially in complex intersections and crowded urban areas to overcome the space constraint. However, the seismic behavior of these highway bridges is quite complicated due to the skewed geometry, nonlinear structural behavior, pounding between segments, ground motion characteristics, etc. Past earthquakes demonstrated that skewed bridges suffered more severe damages, i.e., unseating or even collapse, due to pounding at joints between superstructure and abutments (EERL [1], EERI [2], Han et al. [3]). Earthquake-induced pounding is one of the major reasons that contributes to unseating of skewed bridges under strong earthquake excitations and has been studied extensively after Loma Prieta earthquake (M7.0, 1989) in the USA (Priestley et al. [4]). The coupling between the longitudinal and transverse response is induced by the oblique impact at the expansion joints and ultimately causes the unseating of bridge deck, as shown in Fig. 1.

Based on various analytical methods, a number of studies have investigated the unique seismic response for skew bridges subject to pounding occurred in longitudinal expansion joint between the abutments and the deck. Margakis and Jennings [5] investigated the rigid body motions of a short skewed bridge and revealed that the rotation response are induced by the skewed geometry and the impact between the deck and the abutments in the longitudinal direction. Bignell et al. [6] performed nonlinear pushover analyses with typical Illinois bridges to estimate the variation in bridge characteristics, and verified that the skewed deck-abutment contact caused the coupling of the displacements response. Dimitrakopoulos [7] adopted a non-smooth rigid body approach to analyze the oblique impact between a rigid deck and an abutment of skewed bridges. Huo and Zhang [8] used the fragility function method to study the effects of pounding and skewness on the seismic behaviors of typical multi-span RC highway bridges, and found that pounding results in increased damages of skewed bridges with large skew angles.

There are also a number of researches highlighted the consideration to study the pounding occurred in transverse direction of bridge. Maleki [9] studied the pounding effect of the superstructure on the bearing retainers of straight and skewed slab-girder bridges, and suggested that gap introduces nonlinearity in the seismic analysis of skewed bridges. Deng [10] used nonlinear time-history integration method to study the pounding effects between girders and side retainers when subjected to transverse earthquake excitation and built a pounding model that considered the energy dissipation of pounding. Goel and Chopra [11]

* Corresponding author.
E-mail address: qhan@bjut.edu.cn (Q. Han).

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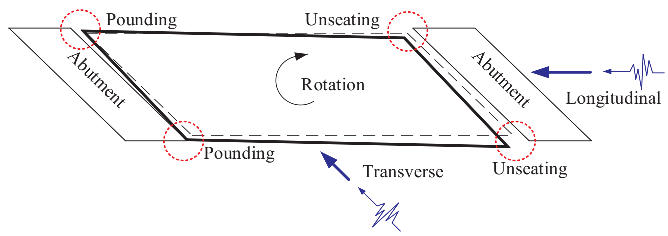

Fig. 1. Bridge deck unseating due to the oblique impact subjected to bi-directional ground motions.

investigated the role of shear keys located at bridge abutments in affecting the seismic behavior of bridges crossing fault-rupture zones, and stated that ignoring shear keys provided conservative estimates of seismic demands in bridges.

Past earthquake reconnaissance have demonstrated that pounding effect on the seismic response of skewed bridge produces serious damages of bridges. However, most researchers have ignored the initial gap between deck and the shear keys in seismic analysis of skew bridges with seat-type abutments, as the overall dynamic response of skew bridge may be changed especially for near-field earthquake motion. Near-fault ground motions are different from far-field motions for containing strong coherent dynamic long period pulses and permanent ground displacements [12–14]. These features make near-fault ground motions impose more severe demands on the structure, particularly for skew bridges [15–18]. Therefore, it is of great importance to assess the dynamic behavior of skewed bridges and analyze the pounding effect based on a three-dimensional model with comprehensive consideration of the nonlinear pounding occurred both in expansion joints and initial gaps under near-fault ground motions.

In order to recognize the complexities involved with the pounding problem, the rotation behavior and geometrical characteristics, this study uses nonlinear time history analysis to investigate the seismic responses of skewed bridges under near-field earthquake motion. First, three models based on different assumption of transverse pounding were built up to investigate the pounding behavior in transverse direction through nonlinear time history analysis. Subsequently, the rotation mechanism on seismic response of a skewed bridge with comprehensive consideration of pounding effect both in transverse and longitudinal was clarified. Finally, the trends in the seismic response of a typical two-span bridges comprehensively investigated by considering various skew angles (0°, 15°, 30°, 45°, 60°), as well as near-fault ground motion characteristics contained pronounced velocity pulses. The findings of this study, along with recommendations geared specifically to skewed bridges that may be helpful in seismic design, are summarized and provided in this paper.

2. Numerical modeling

In order to capture nonlinear seismic response characteristics and estimate accurate seismic behavior of skew bridges, improved three-dimensional nonlinear finite element model of the entire bridge system was developed, column ductility, soil-abutment-superstructure interaction, abutment shear keys, soil-pile interaction, bearing pads were taken into consideration, especially the nonlinear pounding occurred in expansion joints between the deck and abutments. The nonlinear time-history analyses were performed on skewed bridges subjected to bi-directional ground motions with high velocity pulses with SAP2000 14.0.0 Advanced. The nonlinear modeling assumptions for various structural descriptions will be introduced in the following Table 1.

3. Effects of pounding for the skew bridge

3.1. Bridge configurations and pounding model in transverse

In order to understand the pounding behavior occurred in initial gaps between the deck and bridge shear keys, a typical single-span bridge with 30° skew alignment is first investigated without complex bridge columns. The bridge span is 30 m. The superstructure is a three-cell prestressed concrete box girder. The bearings are pot rubber bearings placed under each web of the box girder. The abutments are seat-type abutments filled with typical clay, and back-walls are 10.5 m in width and 1.92 m in height. The abutment back-walls limit the movement of the superstructure in the longitudinal direction. The exterior shear keys also limit the movement of the superstructure in the transverse direction. The two types of structural expansion gap are both 0.04 m.

3.2. Pounding model in transverse

Pounding at the gaps is a complex phenomenon, which may produce excessive deformation, concrete crushing, shear key failure, abutment tilting and even span unseating. Therefore, various impact analytical models have been proposed to study the dynamic response due to pounding under earthquake attack. The stereomechanical approach is based on the momentum conservation principle and the contact approach based on the relationship between force and deformation which includes linear spring model (Maison and Kasai [33,34]), Kelvin model (Anagnostopoulos [35,36]), Hertz model (Davis [37], Jing [38], Jankowski et al. [39]), Hertz-damp model (Muthukumar and DesRoches [40]), modified Hertz-damp model (Jankowski [29]), and 3D contact friction model (Zhu [41]). Kelvin model was adopted to simulate the pounding effect at the initial gaps in the transverse direction in this study for its ability to simulate the dissipated energy during pounding [29–31].

Aiming to investigate the effect of pounding occurred in initial gaps between the deck and bridge shear keys, three models are built on the basis of the benchmark bridge, named Model 1, Model 2, and Model 3 respectively. Model 1 has not considered the pounding effect or shear keys capacity in transverse direction of the bridge. Model 2 has abutment shear keys and the initial gaps between the deck and the shear keys. The contact between the deck and shear keys in transverse was simulated by a gap element in Model 2. The shear keys would limit the deck displacement in transverse when gaps close. In Model 3, the pounding behavior between the deck and shear keys was simulated by a Kelvin model. It has the ability to consider energy dissipation mechanisms during pounding. The parameters can be calculated by same method used above in Table 1.

3.3. Nonlinear time history analyses

Nonlinear time history analysis was conducted on the models. The direct integration method of Newmark's linear acceleration algorithm was used for the dynamic analysis. The models were assigned with 5% Rayleigh damping in the first and second modes of vibration. The models were excited by the earthquake motion with high-velocity pulses from the 1979 Imperial Valley earthquake. Fig. 2 shows the acceleration, velocity and displacement time histories of the two components of the motion Imperial Valley. The component with the larger velocity pulses were applied in the longitudinal direction. The longitudinal and the transverse components of the motion are applied along and perpendicular to the bridge abutments, and the larger horizontal component input in longitudinal direction.