17th World Conference on Earthquake Engineering, 17WCEE

Sendai, Japan - September 13th to 18th 2020

SEISMIC ANALYSIS FOR BRIDGES CROSSING ACTIVE FAULT-RAPTURE ZONES

N. Wang (1), X.J. Li (2), A.W. Liu (3), R.F. Yu (4), Y.S. Wang (5)

(1) Assoc. Res., Institute of Geophysics, China Earthquake Administration, Beijing, 100081, China, ningwang_cea@163.com
(2) Professor, College of Architecture and Civil Engineering, Beijing University of Technology, Beijing 100124, China, beerli@vip.sina.com
(3) Res., Institute of Geophysics, China Earthquake Administration, Beijing, 100081, China, Law73@163.com
(4) Res., Institute of Geophysics, China Earthquake Administration, Beijing, 100081, China, yrfang126@126.com
(5) Assoc. Professor, College of Architecture and Civil Engineering, Beijing University of Technology, Beijing 100124, China, wangyushi1982@126.com

Abstract

Post-earthquake surveys show that bridges crossing active fault-rapture zones suffer high risk of irreversible damage or even collapse of the entire structure due to the intense and long period velocity pulse as well as permanent ground displacement from fault rupture. Given the importance of bridge structures to urban transport systems, this study aims to assess the seismic performance of a bridge structure crossing active fault. For this purpose, a three-dimensional (3D) Finite-Element (FE) model for a typical multi-span bridge configuration in China is developed using the earthquake engineering simulation software framework OpenSees (Open System for Earthquake Engineering Simulation). Seismic responses of the bridge structure subjected to spatially uniform and spatially varying earthquake excitations are presented and compared. The effects of fault movement are analyzed by comparing the simulated bridge responses with and without consideration of the permanent ground displacement. This study demonstrates the effects of fault rupture on the seismic response of the bridge structure and provides guidance for the design of bridge crossing active fault-rapture zones.

Keywords: Bridges crossing active fault-rapture zones, Permanent ground displacement, Seismic responses, Multi-support excitation, Finite-Element (FE) model;

1. Introduction

Damages of bridges resulting from tectonic fault movements are complex and diverse, including beam falling caused by failure of superstructure connections, bending and shear failure of piers due to insufficient ductility, abutment rotation, pile foundation tilting and bending caused by soil nonlinearity and so on. Recent destructive earthquakes demonstrated the vulnerability of bridges that cross fault-rupture zones. For example, in the 1999 Chi-Chi Earthquake in Taiwan China, Kocaeli earthquake and Duzce earthquake in Turkey, a number of bridges across faults suffered extensive damages, such as excessive movement of superstructures and bridge supports, failure of seismic isolation and energy dissipation systems resulting from the tectonic ground movement[1-3]. Although, many countries' codes prohibit the construction of bridges across active faults, or require a certain distance from active faults to reduce the risk of seismic damage to bridge structures[4-6]. Due to the constraints of topography, construction in regions of high seismicity, urban planning and other factors, construction of bridge structures crossing faults is inevitable.

Researchers have carried out a lot of work on the seismic performance of bridges across faults, including a series of analyses from aspects of ground motion input methods, fault crossing locations and angle, and structure configuration, etc. Choi et al. [7]investigated near-fault ground motion effects on typical reinforced concrete bridge columns and the fault-rupture effects on seismic response of a bridge system that crosses an active fault. Park et al. [8], Güney et al.[9], and Ucak et al. [10] performed nonlinear finite element analysis on the seismic performance of the cross-fault Bolu viaduct which was severely damaged during the Turkish earthquake. The analysis results show that the displacement of the superstructure relative to the pier exceeds the bearing capacity of the support, causing serious damage to the support and energy dissipation unit. It is pointed out that the longitudinal and transverse shear keys play an important role in preventing bridge deck collapse. Goel et al. [11-13] conducted seismic response analysis of ordinary reinforced concrete bridges in California, and found that the abutment shear resistance of the bridge abutment had a significant effect on the dynamic response of the bridge across the fault, and proposed response spectrum method and linear / non-linear quasi-static analysis method for the fault crossing Bridge. Yang and Li [14] take a simplely-supported bridge across faults as an example, and use non-uniform excitation time-history analysis methods to study the cross-fault effects on structural seismic responses The results show that the bending moment at the bottom of the pier and the lateral bearing displacement at the top of the pier near the fault are much larger than those at other positions.

2. Bridge Configuration and FE Model

The studied 6-span bridge across the fault is a simply supported steel box girder structure with a beam height of 2.8 m and a deck width of 32 m. The superstructure is supported by hollow rectangular reinforced concrete piers with heights varying from 27.3 to 33.1 m. The span combination is 2 × 58 + 60 + 3 × 58 m. The connections between spans allow movement of the deck in longitudinal and transversal direction with expansion joints. Below the bridge pier are two 3 m thick 8.7 m × 9.2 m pile caps, each of which is supported by four steel pipe piles with a diameter of 2.0 m. The abutments, piers and decks are denoted herein as A1, P2-P6, and A7 respectively, from East to West (Fig. 1).

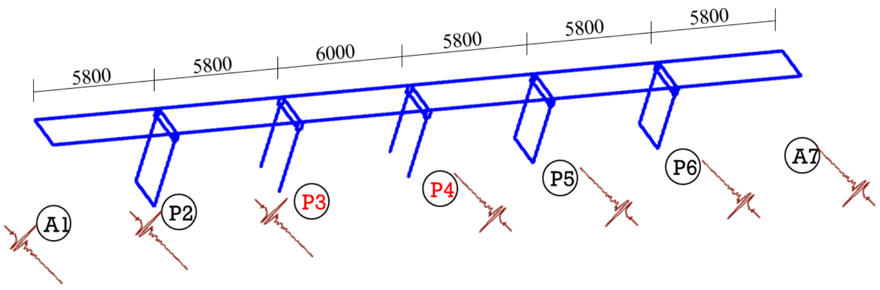

Fig. 1 – Beam-column FE model of the Bridge

In order to analyze the influence of cross-fault ground motion on the dynamic response of bridges qualitatively and quantitatively, the seismic response of the bridge structure is studied using the open-source finite element analysis platform OpenSees (Open System for Earthquake Engineering Simulation)[15, 16]. The bridge piers and steel box girders of this simple-supported bridge are assumed to remain linear elastic and modeled as elastic beam-column elements, with E = 3.25 $\times 10^7$ kPa and G = 1.354167 $\times 10^7$ kPa and a gravity of 25.5 kN / m^3 (Fig. 1). Since horizontal relative displacement between the bridge piers and beams is allowed and the bending moment of the bearings under stress is 0, the *twoNodeLink* element is employed to simulate the bearings between the bridge girders and the pier top. The bearing material employs the uniaxial isotropically strengthened Guiffre-Menegotto-Pinto steel constitutive model with yield strength of 432.0 kPa and initial stiffness of 21600.0 kPa. Linear foundation springs located at the bottom of the piers is simulated with zero-length elements. The structural damping is Rayleigh damping (Fig. 2), where values of a_0 and a_1 were selected to be 0.538559 and 0.002274 to keep the damping ratio to be about 5% in most significant modes of the selected systems. Soil-structure interaction was not explicitly considered in this investigation. Eigenvalue analysis is performed and bridge model natural frequencies are listed in Table 1.

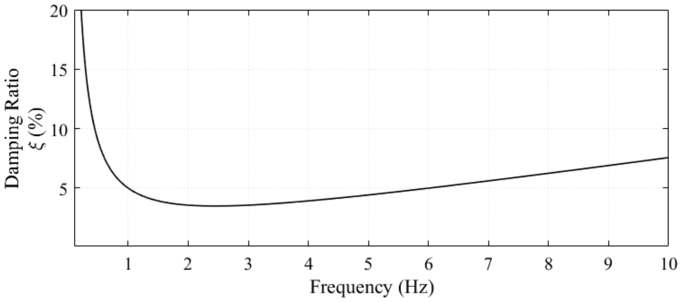

Fig. 2 – Rayleigh damping curve

Table 1 – Bridge model natural frequencies

Mode	1	2	3	4	5
Natural Frequency (Hz)	0.6851	0.7317	0.8511	0.9054	0.9399

3. Near-fault Ground Motions

The seismic intensity of the bridge construction site is Ⅷ. The peak ground acceleration (PGA) with a 10% probability of being exceeded in 50 years is 0.35 g, and a 2% probability of being exceeded in 50 years is 0.59 g. According to the seismic survey at the bridge site, three faults were found intersecting almost perpendicularly with the bridge, among which an active normal fault is formed by the M7.5 Qiongshan earthquake in 1605. In this study, the impact of fault rupture is considered with a vertical displacement of 1.4 m, and a horizontal displacement of 0.8 m to investigate the relationship between the cross-fault ground motion permanent displacement and structural response.

In general, near-fault ground motion effects can be divided into two aspects: the fault-normal ground motion effect with long period and large-velocity pulse and the fault-parallel ground motions with permanent ground displacement. Bridge structures crossing the fault zone are usually subject to these two types of seismic effects experiencing substantial damage. As such, this study investigates the seismic response for the selected bridge subjected to two scenarios of ground motion excitations: I) spatially uniform ground motion along the bridge resulting from near-field earthquake without permanent displacement; and II) spatially-varying ground motion considering fault rupture with a permanent fault-parallel displacement. The bridge model is excited with three components of ground motions, that is in vertical, transverse (parallel to the fault) and longitudinal (normal to the fault) directions.

Near-fault ground motion recorded during the 1992 Landers earthquake (M 7.3) was selected and modified based on site-specific seismological analysis. The Joyner-Boore Distance from the station was 2.2 km with a peak ground acceleration of 0.789 g, and a permanent ground displacement of 113.87 mm. The employed synthetic ground motion was generated by matching the target motions to multi-damping response spectra. [17, 18]. Fig. 3 and Fig. 4 show acceleration, and displacement time history with time interval of 0.005 s, where the peak ground acceleration is 0.48 g in transverse direction (TRAN), 0.44 g in longitudinal direction (LONG) and 0.40 g in vertical direction (VERT). The peak ground displacement is 140.97 cm, 111.75 cm and 213.97 cm in the transverse, longitudinal and vertical directions, respectively. For both loading scenarios, spatially-uniform excitation without permanent displacement is applied in the longitudinal direction (fault-normal direction). For loading scenario II, fault-parallel permanent displacement on the east side of the fault (A1, and P2-P3) are identical with 146.68 cm in vertical direction and 91.04 cm in transverse direction (parallel to the fault direction). However, motions for Pier P4-P6 and A7 on the west side of the fault are identical without permanent displacement. Response acceleration of 5% damping ratio reaches highest value at 0.31 s in LONG and TRAN (Fig. 5).

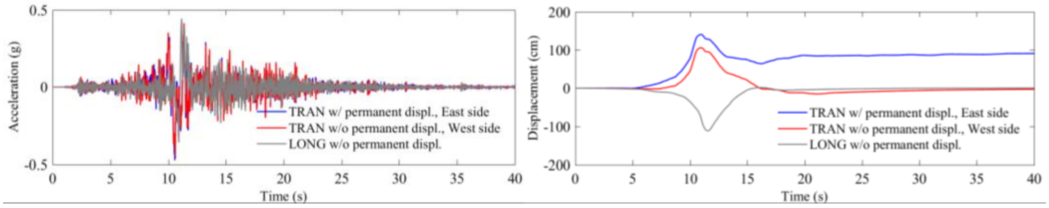

Fig. 3 – Horizontal acceleration and displacement time histories of synthetic ground motions

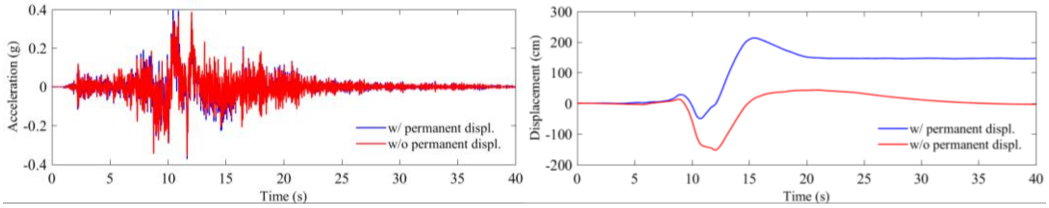

Fig. 4 – Vertical acceleration and displacement time histories of synthetic ground motions

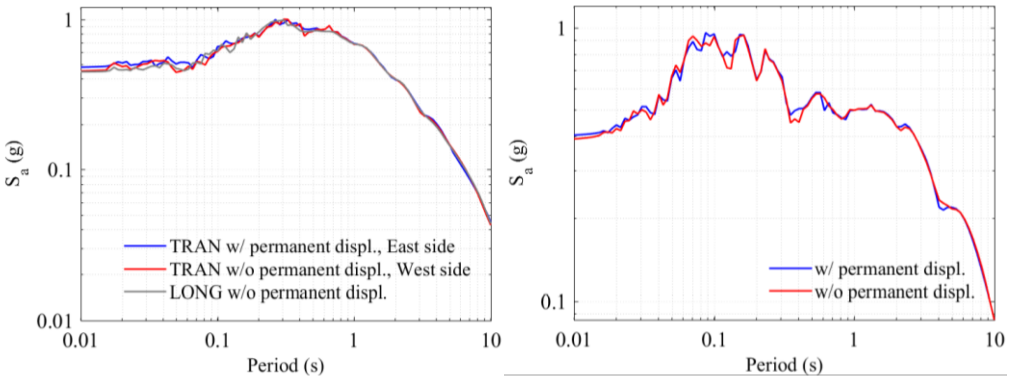

Fig. 5 – Response spectrum of horizontal and vertical synthetic ground motion

4. Seismic Response of the Bridge

Since uniform seismic input motion without permanent displacement is adopted in the longitudinal direction of the bridge for both scenarios, piers on both sides of the fault have similar responses with relative displacement close zero at pier tops after earthquake shaking. Therefore, we focus on the deformation of column (relative displacement of pier top to its base) and girder-pier top relative displacement in the transverse direction in this study.

For scenario II, the absolute displacements of pier top at P3 and P4 in transverse direction are shown in Fig. 6, where P3 has a maximum absolute displacement of 146.6 cm (30.7% larger compared to scenario I) and a residual displacement of about 89.5 cm. As illustrated in Fig. 7, the transverse relative displacement of P3 is 15.1% larger compared to P4 with peak of 6.02 cm and residual deformation of 1.30 cm after the earthquake shaking, which is about 22% of its maximum response. Relative displacements between girder and pier top in transverse direction at P3 and P4 show that bearings suffer great deformation due to the large permanent displacement of the fault (Fig. 8).

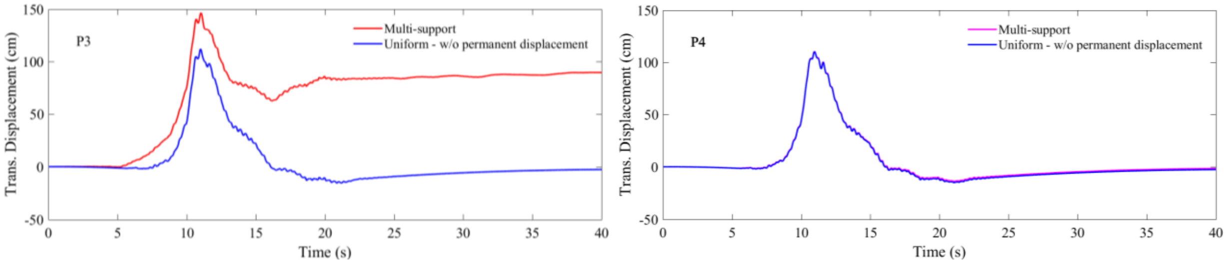

Fig. 6 – Transverse absolute displacement of pier top

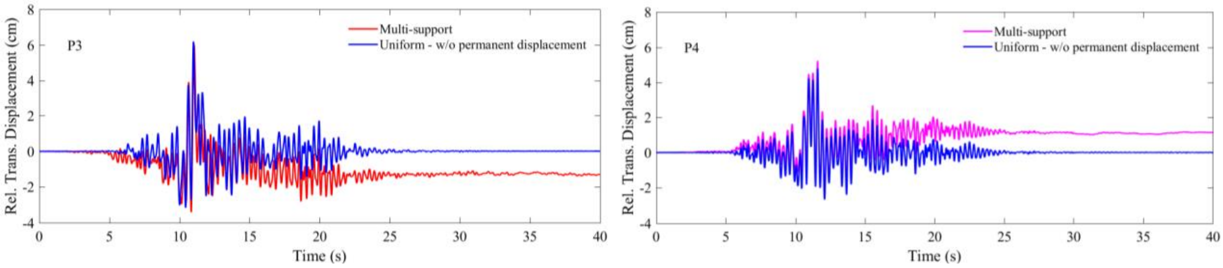

Fig. 7 – Transverse relative displacement of pier top

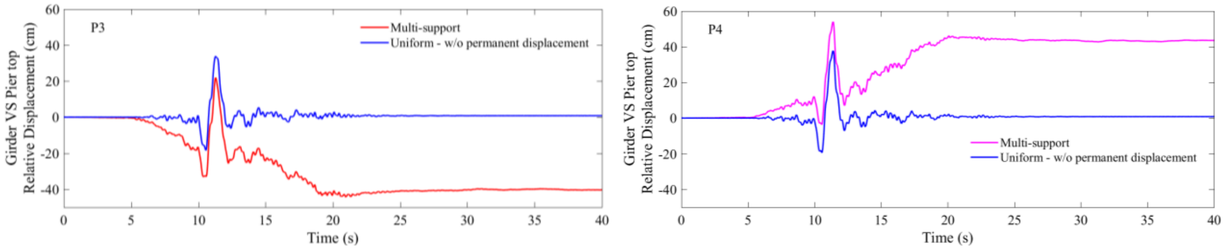

Fig. 8 – Relative displacement between girder and pier top

It is worth noting that the maximum shear forces and bending moments of P3 and P4 piers are basically the same for both scenarios of ground motion excitations. However, residual internal forces are observed at the end of shaking for scenario II. Due to the different ground movements of the piers on two sides of the fault, P3 and P4 suffer significant torsional moment (about 452.4% more compared to scenario I), and large residual torsional moment (about 85% of the peak) can be observed (Fig. 9).

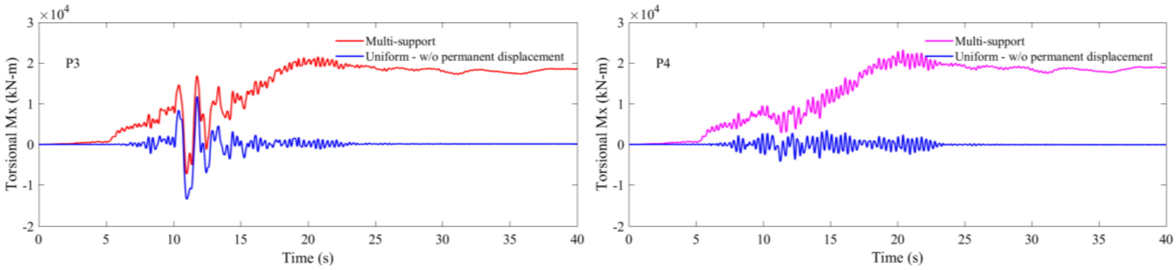

Fig. 9 – Torsional moment of pier bottom

5. Conclusions

Bridges crossing fault-rupture zones experience ground offset across the fault and hence spatially-varying ground motion. Recent earthquakes have demonstrated the vulnerability of bridges that cross fault-rupture zones. This study establishes the finite element model of the bridge across the fault and studies the structural seismic response considering permanent ground displacement. Effect of fault rupture on the seismic performance of bridge is presented with an emphasis on deformation of column and girder-pier top relative displacement. On this basis, the main observations and conclusions include:

1) The permanent ground displacement has significant influence on the seismic response of the bridge. Under the multi-support ground motion excitation considering fault rapture, residual bridge column deformation due to the large permanent ground displacement loading can be observed.

2) The results of numerical simulation show that the maximum value of torsional moment of pier across fault under multi-support excitation is 5.5 times of that under uniform excitation with considerable residual torsional moment. Therefore, the bridge may experience torsional failure when it is under multi-support excitation with permanent displacement.

3) Based on the above analysis, it appears that the residual internal forces of bridge piers are caused by fault movement. Ignoring seismic demands for bridges subjected to spatially-varying ground motion with permanent ground displacement may lead to underestimation of some seismic demands in bridges.

6. Acknowledgements

The research presented in this paper was funded by the Natural Science Foundation of China (Grant No. 51708518), the National Key R&D Program of China（Grant No. 2017YFC1500400）and the Natural Science Foundation of China (Grant No. 51738001). This support is gratefully acknowledged.

7. Copyrights

8. References

[1] EERI (2000): 1999 Kocaeri, Turkey, Earthquake Reconnaissance Report. *Earthquake Spectra*, 16, 237-279.

[2] Ghasemi H, Cooper JD, Imbsen RA, Piskin H, Inal F, Tiras A (2000): The November 1999 Duzce Earthquake: Post-Earthquake Investigation of the Structures on the TEM. *No. FHWA-RD-00-146*, Federal Highway Administration, USA.

[3] Yen WP, Ghasemi H, Cooper JD (2001): Lessons Learned from Bridge Performance of the 1999 Turkish & Taiwan Earthquakes. *33rd Joint Meeting of the UJNR Panel on Wind and Seismic Effects*, Tsukuba, Japan.

[4] Caltrans (2012): Bridge Design Practice Manual. California Department of Transportation, Sacramento, CA.

[5] JTG/TB02-01-2008 (2008): Code for seismic design of buildings. *GB50011-2001*. Beijing: The press of people's transportation.

[6] TANABE T (1999): Comparative performances of seismic design codes for concrete structures. *Publication of Japanese Society of Civil Engineers*, 1.

[7] Choi H (2007): Effects of near-fault ground motion and fault-rupture on the seismic response of reinforced concrete bridges. University of Nevada, Reno.

[8] Park S, Ghasemi H, Shen J, Somerville P, Yen W, Yashinsky M (2004): Simulation of the seismic performance of the Bolu Viaduct subjected to near-fault ground motions. *Earthquake engineering & structural dynamics*, 33(13), 1249-1270.

[9] Güney D, Acar M, Özlüdemir M, Çelik R (2010): Investigation of post-earthquake displacements in viaducts using Geodetic and Finite Element Methods. *Natural Hazards and Earth System Sciences*, 10(12), 2579-2587.

[10] Ucak A, Mavroeidis GP, Tsopelas P (2013). The response of the seismically isolated bolu viaduct subjected to fault crossing. *Bridging Your Passion with Your Profession. 2013*, 817-826

[11] Goel RK, Chopra AK (2008): Analysis of ordinary bridges crossing fault-rupture zones. *Rep No UCB/EERC-2008*, 1.

[12] Goel RK, Chopra AK (2009): Linear analysis of ordinary bridges crossing fault-rupture zones. *Journal of Bridge Engineering*, 14(3), 203-215.

[13] Goel RK, Chopra AK (2009): Nonlinear analysis of ordinary bridges crossing fault-rupture zones. *Journal of Bridge Engineering*, 14(3), 216-224.

[14] Yang H, Li J (2015): Response Analysis of Seismic Isolated Bridge Under Influence of Fault-Crossing Groundmotions. *Journal of Tongji University (Natural Science)*, (8), 4.

[15] Elgamal A, Lu J, Mackie K (2014): MSBrindge: OpenSees Pushover and Earthquake Analysis of Multi-span Bridges - User Manual. *SSRP–14/04*, Department of Structural Engineering, University of California, San Diego.

[16] Mazzoni S, McKenna F, Scott MH, Fenves GL, Jeremic B (2006): Open system for earthquake engineering simulation (OpenSees). Berkeley, California.

[17] Zhao F, Zhang Y (2008): Time-domain superposition method for fitting multi-damping response spectra. *Nuclear Power Engineering*, 29(3), 35-40.

[18] Fengxin Z, Yushan Z (2007): Narrowband-time-history's superimposing method of generating response-spectrum-compatible accelerogram. *Engineering Mechanics*, 24(4), 87-91.