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STUDY ON THE SEISMIC VULNERABILITY OF A VIADUCT SUBJECTED TO NEAR-FAULT GROUND MOTIONS

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Piers, abutments and bearings of viaducts may suffer severe damage during earthquakes, so it's not insufficient to evaluate the seismic vulnerability of a bridge system only by plastic hinge curvature, which is adopted in seismic design guidelines. In this paper, the seismic vulnerability evaluation of a viaduct is conducted by incremental dynamic analysis under 30 near-fault ground motions, which are selected from PEER database. Then several damage measures are recommended to make an overall estimation for the seismic vulnerability of the viaduct, including plastic hinge curvature, shear failure and sliding displacement failure of bearings and pounding force between abutments and the girder. The analysis results show that the transversal seismic excitations may lead to more severe damage than the longitudinal ground motions. No matter in which direction the ground motions are inputted, the bearings' seismic vulnerability resulted by shear force or sliding displacement is higher than the plastic hinge of piers, which indicates that the seismic vulnerability of the bridge system is determined by the bearings to an extent. As a result, bearings should be designed according to both static and seismic analyses to guarantee the safety during earthquakes.

Keywords: Near-fault earthquake, Incremental dynamical analysis, First-order reliability principle, PGA, Damage measure.

1 INTRODUCTION

Near-fault ground motion records which always refer to the fault distance no more than 20 km, have a distinct pulse type ground motion caused by rupture directivity effect and fling-step effect (Mavroeidis and Papageorgiou 2003, Ambraseys and Douglas 2003). With a higher PGV/PGA than far field ground motions, near-fault earthquake records express a relative wide sensitive area of their acceleration response spectrums. A near-fault earthquake record with velocity pulses has longer period of response spectrum platform and its response spectra value is larger in the long period range than that without the pulse. Additionally, the incremental spectral value in the long period can enlarges the deformation of long-period bridges, which may lead to pounding response even dropping of superstructure (Loh *et al.* 2002). However, there is not a seismic design code for bridge supplying an explicit provision to take the near-fault ground motion effect in to account. Therefore, the incremental dynamic analysis (IDA) method is adopted to conduct a seismic vulnerability analysis of viaducts under near-fault earthquakes.

IDA method can reflect the structural seismic performance under different intensity for a same ground motion by the elasto-plastic time-history analysis (Vamvatsikos and Cornell 2002, Vamvatsikos and Cornell 2004). It can overcome disadvantages resulted in pushover method which execute a static process analysis instead of a dynamic one. Generally speaking, IDA method with enough ground motions is able to comprehensively analyze the seismic performance of bridges as long as the finite element model is reasonably and correctly built.

In general, IDA method is a reasonable way to take study on the seismic vulnerability on viaducts under near-fault ground motions. Based on the PEER Ground Motion Database, a set number of typical near-fault earthquake records can be selected to conduct IDA and analyze failure probability of viaducts. The correspondence between intensity measures of ground motions and damage measures of viaducts can be built, which can contribute to seismic vulnerability analysis of viaducts under near-fault earthquakes (Andreas *et al.* 2005).

2 STRUCTURAL FINITE ELEMENT MODEL AND NEAR-FAULT GROUND MOTIONS SELECTION

A continuous viaduct with spans 4×40 m is selected to conduct the IDA and evaluate the seismic vulnerability. The superstructure is single box with three cells, and the substructures are double-column piers and gravity abutments, as shown in Figure 1. The finite element model includes several nonlinear characteristics, such as plastic hinge of piers, pounding behavior between the girder and abutments, and hysteretic behavior of sliding bearings.

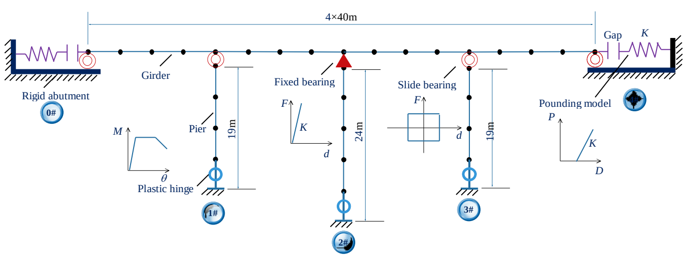


Figure 1. Finite element model of the viaduct.

30 near-fault ground motion records with impulse are chosen in PEER Database. Suppose the bridge site type is II, characteristic period is 0.45s, and seismic design intensity is Ⅶ degree. The distances between records site and earthquake rupture are all within 25km. The acceleration spectrum of selected records and target spectrum are shown in Figure 2.

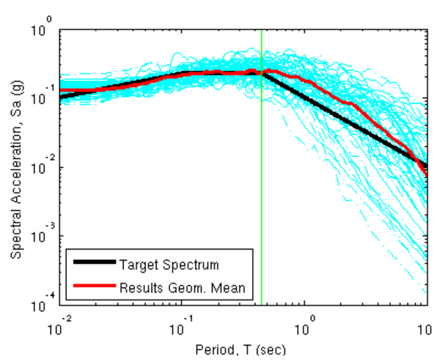


Figure 2. Comparison between target spectrum and the average spectrum of selected near-fault earthquake records.

3 SEISMIC VULNERABILITY ANALYSIS FOR TRANSVERSAL GROUND MOTIONS

3.1 IDA results

Viaduct piers are always flexible with the capacity design for shear performance under seismic excitations, so plastic hinges of piers are often adopted for failure evaluation in seismic design codes. However, under transversal ground motion input, the main seismic damage of a viaduct includes plastic hinge forming on piers and shear failure of all bearings. For plastic hinges at the bottom of piers, the recommended damage state division determined by curvature limit is shown in Table 1.

Table 1. Recommended damage states for plastic hinges.

Damage state	Description	Curvature limit
No damage (ND)	First yield	0.005
Slight damage (SD)	Crack	0.007
Moderate damage (MD)	Core concrete failure	0.015
Extreme damage (ED)	Collapse limit	0.025
Complete damage (CD)	Collapse	0.05

Bearings arrangement of the viaduct is shown in Figure 3. For shear damage of bearings, the damage status is determined by shear force limit. The first damage state should be the design limit in the transversal direction, and the second damage state represents complete shear failure of bearings, which refers to the transversal restriction between piers and the girder suffers destruction, corresponding to the failure of anchoring bolts of bearings.

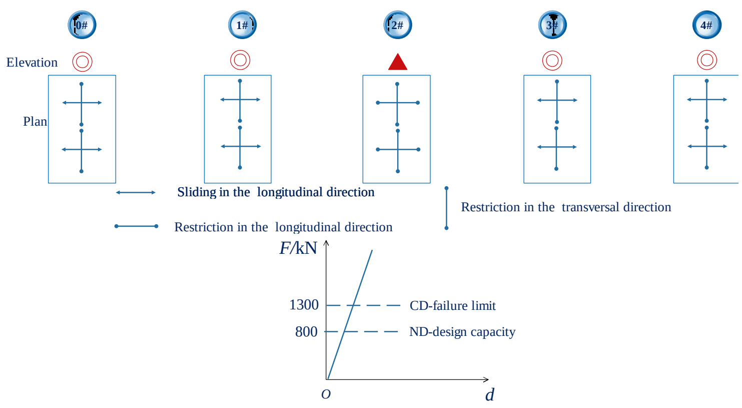


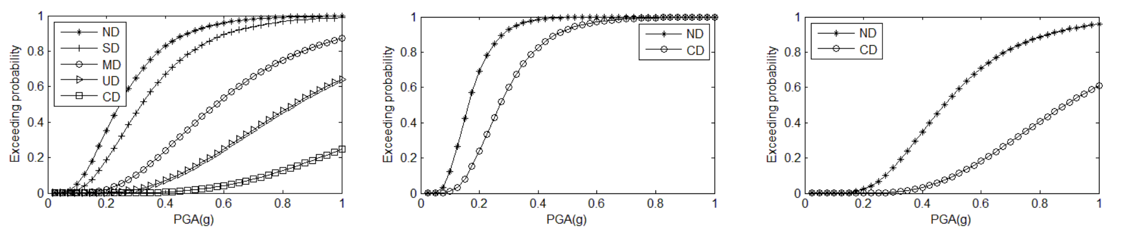
Figure 3. Finite element model of the bridge.

IDA results of the viaduct according to different DMs under transversal near-fault earthquake input are shown in Figure 4. Because the viaduct is a symmetrical structure, results of 1# and 3# piers are almost the same and the seismic damage of them is lower than 2# pier. ED state of 1# and 3# piers is reached at 1.0 g while 2# pier at 0.7 g. Transversal shear fragility of all bearings is reached more easily than plastic hinges of piers. Additionally, the sliding bearings at abutments reach the failure state at 0.3 g, which is lower than the bearings of 2# pier at 0.6 g.

Figure 4. IDA results for transversal near-fault ground motions.

3.2 Seismic Vulnerability Analysis

The seismic vulnerable curves of piers and bearings corresponding to each DM are shown in Figure 5. Probability distribution rules can be deduced from ND to CD according to PGA levels. Meanwhile it demonstrates the transversal shear vulnerability of bearings is higher than plastic hinges' failure of piers. For a certain level of transversal ground motions, the bearings at abutments are much easier to reach failure state, which may lead to the transversal restriction failure on the girder even unpredictable severe damage, for example girder falling in the traversal direction.



(a) Plastic hinge damage of 2# pier

(b) Shear damage of bearings on 0# abutment

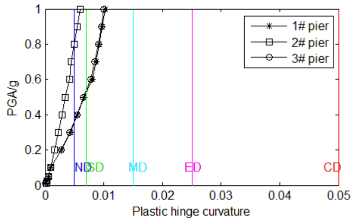
(c) Shear damage of bearings on 1# pier

Figure 5. Failure probability of piers and bearings under transversal seismic excitations.

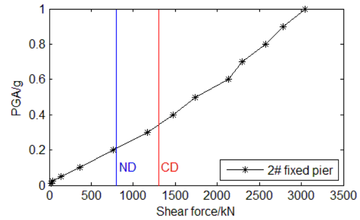
Under transversal earthquake excitations, damage of piers and bearings both may lead to seismic failure of a bridge system. So, it is necessary to evaluate the damage probability of the bridge system by the joint fragility probability method. The first-order reliability principle also called wide bounds method is adopted to evaluate the failure probability of the bridge system.

4 SEISMIC VULNERABILITY ANALYSIS FOR LONGITUDINAL GROUND MOTIONS

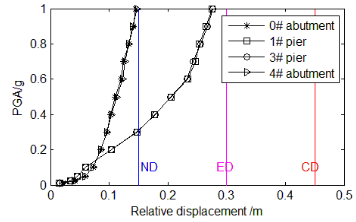
IDA results of the viaduct for longitudinal near-fault ground motions are shown in Figure 6. Considering the plastic hinge curvature, the seismic vulnerability of 1# and 3# piers is slightly higher than 2# fixed pier's. Compared with Figure 4, the seismic vulnerability of piers is higher than that under transversal excitations. When PGA reaches 1.0 g, the piers are damaged slightly under longitudinal excitations while may be damaged extremely in the transversal direction. Seismic vulnerability of the fixed bearing is higher than the plastic hinge of piers under longitudinal seismic excitations. The fixed bearing can reach the complete damage state at 0.3 g, indicating that its seismic vulnerability is higher than that under transversal excitations. The sliding bearings are hard to be destroyed because of the displacement restriction possibly by the pounding effect between abutments and the girder. Additionally, the pounding response is unable to generate the concrete damage of the girder or abutments.



(a) Plastic hinges of piers.



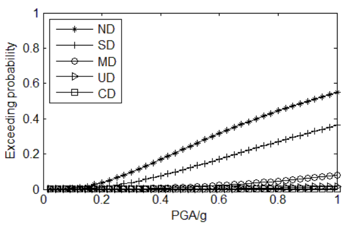
(b) Shear force of the fixed bearing.



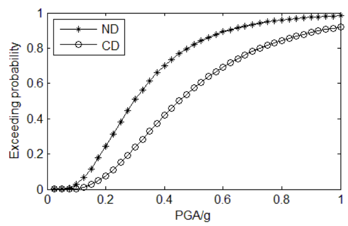
(c) Displacement of sliding bearings.

Figure 6. IDA results according to different DMs under the longitudinal seismic excitations.

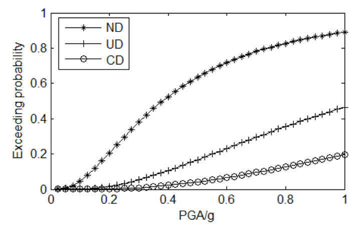
The seismic vulnerability curves of each member under longitudinal near-fault earthquake excitations are shown in Figure 7. It can be deduced that the shear failure vulnerability of the fixed bearing is higher than plastic hinges of piers. The failure probability of sliding bearings on piers is higher than that on abutments, and the failure probability of unfixed piers is higher than the fixed pier.



(a) Plastic hinge damage of 2# pier.

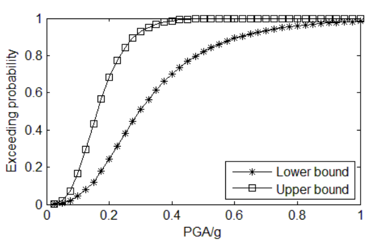


(b) Shear failure of the 2# fixed bearings.

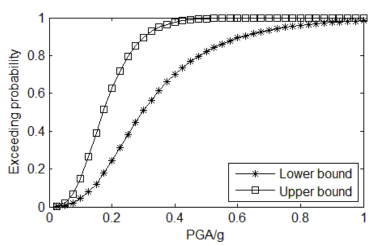


(c) Displacement of sliding bearings at 1# and 3# piers.

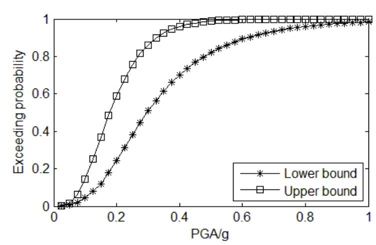
Figure 7. Failure probability of piers and bearings under longitudinal seismic excitations.



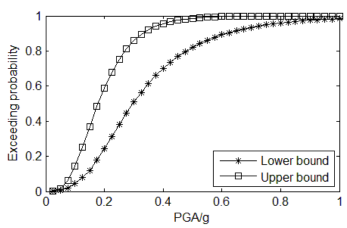
(a) No damage.



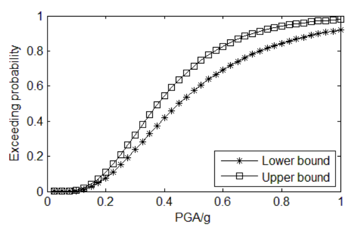
(b) Slight damage.



(c) Moderate damage.



(d) Ultimate damage.



(e) Complete damage.

Figure 8. Seismic vulnerability probability of the bridge system.

The failure probability of the bridge system is shown in Figure 8. Comparing with Figure 5 and Figure 7, it can be reflected that the seismic vulnerability probability of the bridge system under longitudinal seismic excitations is higher than that under transversal seismic excitations. Overall the seismic vulnerability of the viaduct in the longitudinal direction greatly depends on the shear failure of the fixed bearing.

5 CONCLUSIONS

(1) The seismic vulnerability under transversal earthquake inputs is higher than that under longitudinal seismic excitations. No matter the excitation directions, the probability of shear failure or the displacement failure of bearings is higher than that of plastic hinge of piers. The seismic vulnerability of the bridge system depends on the failure probability of bearings.

(2) Under longitudinal earthquake inputs, the plastic hinges' curvature of all piers and displacement response of all sliding bearings are small because of the pounding effect between abutments and the girder, but the shear force response of the fixed bearing

(3) Under transversal earthquake inputs, the seismic vulnerability of bearings' shear failure is much larger than that of piers' plastic hinge failure. As a result, the seismic vulnerability of the bearings on the abutments is the largest, secondly the fixed bearing, and the bearings on the other piers in the end.

(4) The bearings on the abutments are suitable for bi-direction sliding because of the rigid stiffness meanwhile the side restrainers are rigid enough to avoid pounding failure, which may lead to phenomenon of girder falling in transversal direction. All bearings of the bridge system should have preferable shear performance, which should be higher than that of piers.

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