

# Plastic hinge analysis of long-span rigid frame bridge

Zhongqiang Wang<sup>1</sup>, Tieyi Zhong<sup>\*</sup>, Zhenxu Li<sup>1</sup> and Weixiang Sun<sup>1</sup>

<sup>1</sup> School of Civil Engineering, Beijing Jiaotong University, Beijing, 100044, China

<sup>\*</sup>Tieyi Zhong's e-mail: tyzhong2012@163.com

**Abstract.** The formation and development of plastic hinge have a great influence on the seismic response of long-span rigid frame bridges. Therefore, it's especially important to study the development process of plastic hinges under ground motion. Based on the OpenSees software, the elastic-plastic finite element model of long-span rigid frame bridge is established, the influence of pier design parameters on plastic hinge is studied from the perspective of IDA analysis. Meanwhile, the advantages and disadvantages of lumped plastic hinge and distributed plastic hinge are discussed in two groups of bending failure pier of "Pseudo-static test on bridge pier of chengdu-lanzhou railway". The results show that the accuracy of distributed plastic hinge element simulation is higher than lumped plastic hinge; and with the increase of pier height and longitudinal reinforcement ratio, the PGA with plastic hinge in the section will increase for the first time.

## 1. Introduction

With the continuous construction of mountainous bridges, the rigid frame bridge has been widely used because of its long-span ability and beautiful shape[1]. However, there is no seismic design code for Long-Span Rigid Frame Bridge at present, under seismic action, both the top of piers and the bottom of piers are potential plastic zones for the rigid frame bridge[2]. Once damage occurs, the consequence will be serious. It is important to study the formation of plastic hinge and the law of development of plastic area of long-span rigid frame bridge for guiding the ductility design of rigid frame bridge.

Based on the finite element software such as SAP2000 and ANSYS, most scholars usually study the seismic resistance of rigid frame bridges by using the lumped plastic hinge model[3-5]. Compared with the distributed plastic hinge model, it can't study the plastic development law of rigid frame bridge, and the finite element software mentioned above can't consider distributed plastic hinge, but OpenSees can consider distributed plastic hinge for ductility seismic analysis. However, it's very complex to establish the model for the long-span rigid frame bridges with OpenSees software, which needs to solve the problem of large modeling workload. The paper takes a long-span rigid frame bridge as the research object, the influence of pier design parameters on plastic hinge is studied from the perspective of IDA analysis. Meanwhile, the advantages and disadvantages of lumped plastic hinge and distributed plastic hinge are discussed in two groups of bending failure pier of "Pseudo-static test on bridge pier of chengdu-lanzhou railway".

## 2. Establishing finite element model and selecting seismic waves

### 2.1. Engineering background

This paper takes the main bridge of a highway as the research object, the frame is a continue rigid frame and its spans of the main bridge is 70+5×120+70 meters. The main piers are double thin-walled



piers(S), with the center distance of 7.5m and section size of 6.5m×3.0m. The beam end adopts movable support, the main piers adopt C40 concrete, and the longitudinal reinforcement ratio is 1.2%. The seismic peak acceleration is 0.3g, the characteristic period of earthquake response spectrum is 0.45s, and the seismic fortification intensity is 8 degrees. Fig 1 is the layout of large span rigid frame bridge.



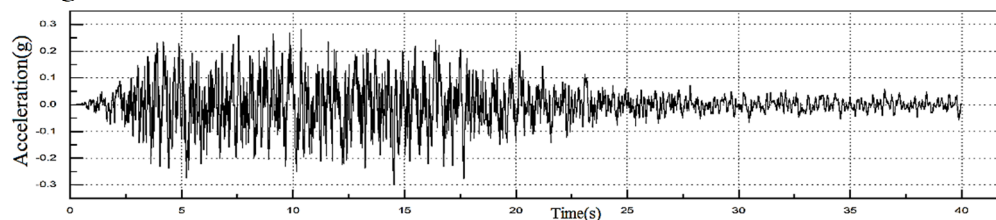
Figure 1. The layout of large span rigid frame bridge (cm)

### 2.2. Finite Element Model

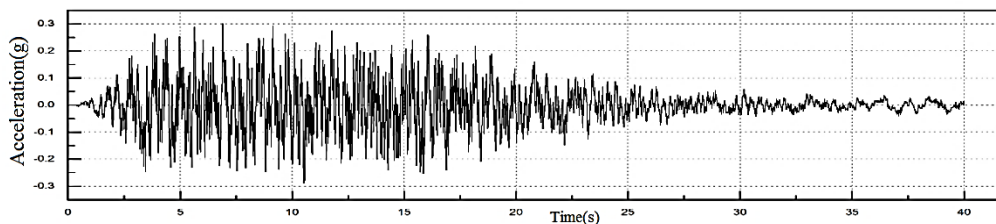
In this paper, concrete and steel materials are simulated respectively by using concrete02 and steel02, and bridge piers are simulated by using beam-column element based on displacement. The finite element model of distributed plastic hinge is established by considering geometrical and material non-linearity. In order to solve the problem that the finite element calculation model of the distributed plastic hinge of the long-span rigid frame bridge is too complicated to be solved by OpenSees software, this paper compiled the program of building fiber cross-section pier based on Python language. This program realizes the combination of material-section-element, and can quickly establish the finite element analysis model of rigid frame bridge in the form of equal section, variable section, solid or hollow pier.

### 2.3. Select and input ground motion

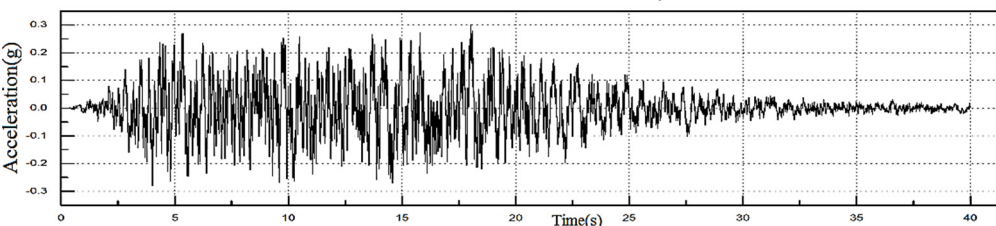
Three artificial waves are selected to study the seismic performance of long-span rigid frame bridge, as shown in Figure 2.



(a) 01 Seismic wave time history curve



(b) 02 Seismic wave time history curve



(c) 03 Seismic wave time history curve

Figure 2. The seismic wave time history curve

### 3. Lumped plastic hinge unit and distributed plastic hinge unit

Most scholars usually study the seismic resistance of rigid frame bridges by using the lumped plastic hinge model at present. It is considered that the middle area of the pier is generally elastic and is calculated according to the calculation formula of equivalent plastic hinge length of the regulation and stipulation, The corresponding length of plastic hinge is set in the potential plastic area such as the bottom and top of the pier, and elastic beam-column elements are still used in the middle of the pier. However, there are still problems in using the lumped plastic hinge model, which mainly includes two aspects: one is the calculation of the length of equivalent plastic hinge; the other is the accuracy of using elastic element in areas outside plastic hinge.

#### 3.1. Calculation of equivalent plastic hinge length

At present, Chinese aseismic bylaw for highway bridges stipulated, for calculating the equivalent length of plastic hinge generally adopt empirical formula. In addition, foreign scholars also use empirical formulas to calculate the length of equivalent plastic hinge, such as Mander, Priestley and Berry, and respectively propose different calculation formulas. In this paper, two groups of bending failure piers are selected from "Pseudo-static test on bridge pier of chengdu-lanzhou railway ", and the length of equivalent plastic hinge is calculated by different formulas. The bridge pier parameters are shown in Table 1, and the calculation results are shown in Table 2.

Table 1. Bridge Pier Parameters

Model number	Section size (mm)	Effective height (mm)	Axial pressure (kN)	Main bar diameter (mm)	Concrete (MPa)	Reinforcement (MPa)
A1	710×600	2200	120	16	26.8	400
A2	846×446	1200	240	8	26.8	400

Table 2. Comparison of equivalent plastic hinge length

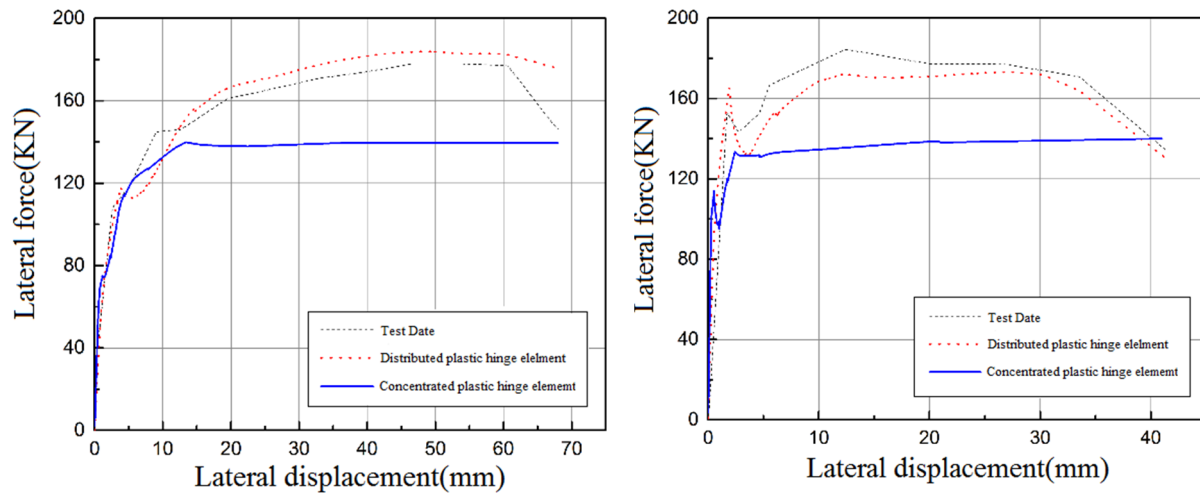
Model number	Chinese Code(mm)	Mander (mm)	Priestley park(mm)	Berry(mm)
A1	317	260	190	103
A2	166	163	234	122

According to Table 2, the equivalent plastic hinge length calculated by different formulas differs greatly. For pier A1 and pier A2, the calculation results of different formulas are quite different. Among them, the plastic hinge length calculated by the Chinese standard for the A1 pier is about 1.7 times that calculated by Priestley's formula.

In conclusion, at present, the calculation formulas of equivalent plastic hinge length at home and abroad are based on empirical fitting, and the calculation results of the same pier are dispersed very much. Therefore, by using the model of lumped plastic hinge, the calculation results may produce great influence because of the length error of the plastic hinge.

#### 3.2. Comparison of test data

In order to compare the advantages and disadvantages of the two models of lumped plastic hinge and distributed plastic hinge, the lumped plastic hinge units and distributed plastic hinge units were respectively used to calculate and compare with the test results. The parameters of the two sets of piers are shown in Table 1. Pushover method[6-8] was used to analyze the quasi-static analysis of the pier, and the calculated skeleton curve was compared with the test skeleton curve. The plastic hinge length in the lumped plastic hinge model is calculated by the Chinese aseismic code. The comparison results are shown in Figure 3.



(a) A1 pier comparison result

(b) A2 pier comparison result

Figure 3. Comparison of the skeleton curves of two models

It can be seen from Figure 3 that the skeleton curve of the distributed plastic hinge model of the three piers agrees well with the skeleton curve of the test results, the bottom reaction of the piers with lumped plastic hinge model tends to be stable when it increases to a certain extent, and there is no strengthening stage. Therefore, although the calculation time of distributed plastic hinge model is longer, the accuracy of calculation is much better than that of centralized plastic hinge model. At the same time, distributed plastic hinge model is inclined to safety. In this paper, it is suggested that the lumped plastic hinge model can be used to qualitative analysis and calculation of structure in order to save calculation time. But when the precision requirement is high, the distributed plastic hinge model should be used to the structure calculation. In conclusion, when study the seismic performance of long-span rigid frame bridge, the pier is calculated by using a more accurate distributed plastic hinge model.

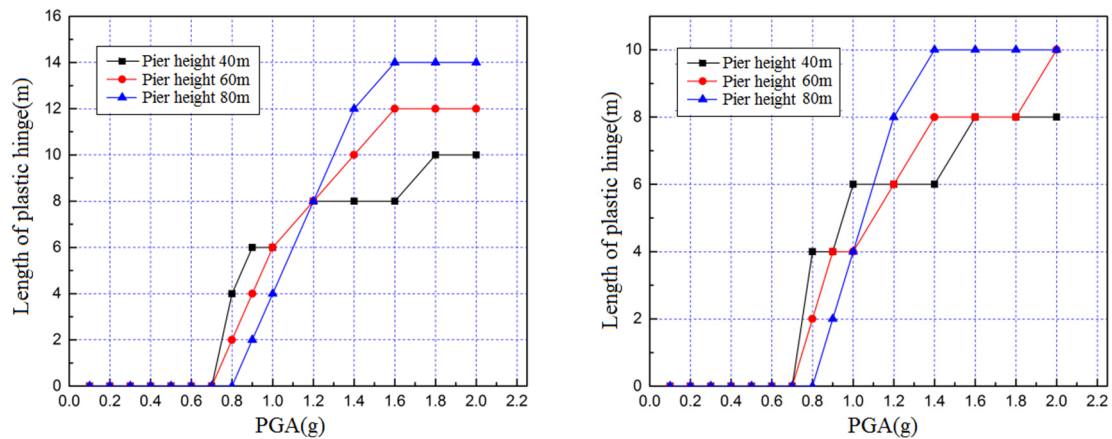
#### 4. Influence of Pier Parameters on Plastic Hinge

As the height of the long-span rigid frame bridge continues to increase, it is very important to fully grasp the seismic response law. In order to study the influence of pier design parameters on the seismic response of long-span rigid frame bridges, this section studies the seismic performance of long-span rigid frame bridges under the loading of seismic waves from the perspective of pier height and longitudinal reinforcement. Due to space limitations, only the seismic response results under the first wave are taken as an example.

##### 4.1. Pier height impact analysis

In order to study the influence of the variation of pier height on the seismic performance of long-span rigid frame bridges, the pier heights were set to 40m, 60m and 80m respectively. Based on IDA analysis method, the influence of pier height on seismic response of long-span rigid frame bridge is studied.

The finite element model of the rigid frame bridge has a length of 2 m per pier unit. Once the steel bar strain in the unit reaches 0.002, it is determined that the unit has yielded and a plastic hinge is produced, which the length of is 2m. Figure 4 shows the variation of the plastic zone length at the top and the bottom of the pier with the PGA under three conditions.



(a) Pier top plastic zone length under 01 ground motion

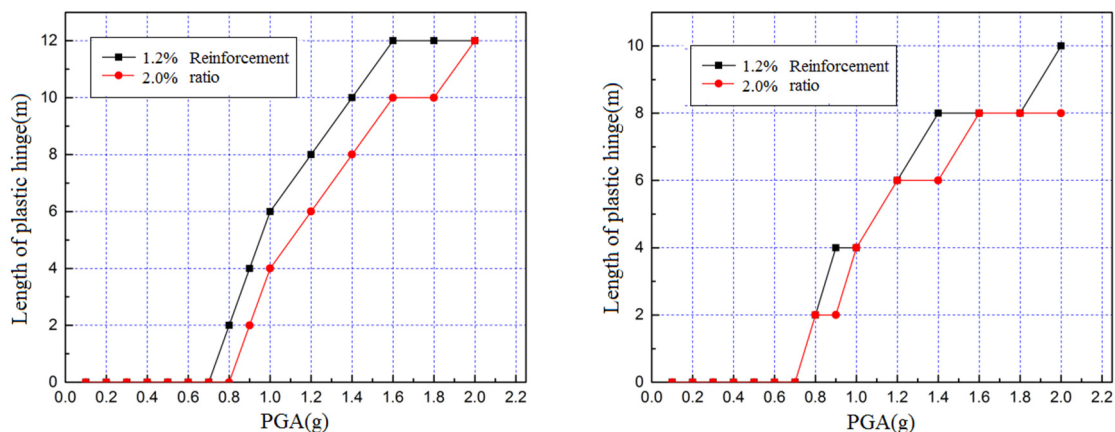
(b) Pier bottom plastic zone length under 01 ground motion

Figure 4. Plastic hinge length curves with PGA

As can be seen from Figure 4, in the case of a single pier, the PGA of the plastic joint for the first time is the same. In the initial stage of plastic hinge development, for a 40m rigid frame bridge, the length of the plastic hinge is basically larger than the rigid frame bridge with a height of 60m and 80m. With the increase of the height of the pier, the length of the plastic hinge is reduced. However, with the increasing range of plastic hinges, the length of plastic piers of piers and piers with a pier height of 40m is obviously smaller than that of piers with a height of 60m and 80m, and with the increase of pier height, the range of plastic hinges is also increasing.

#### 4.2. Longitudinal reinforcement rate impact analysis

Figure 5 shows that with the increase of PGA, the development of the plastic zone length of the rigid frame bridges with different longitudinal reinforcements under the action of the bridge to ground motion.



(a) Pier top plastic zone length under 01 ground motion

(b) Pier bottom plastic zone length under 01 ground motion

Figure 5. Plastic hinge length curves with PGA

From the development of the plastic zone length between the top of the pier and the bottom of the pier, the influence of the longitudinal reinforcement ratio on the plastic zone of the pier top and the bottom of the pier is basically the same under ground motion. The PGA of the first plastic joint of the bottom and the top of the rigid frame pier with a longitudinal reinforcement ratio of 1.2% is more than

2.0%. That is, the increase of the longitudinal reinforcement ratio increases the PGA of the plastic hinge for the first time at the top of the pier and the bottom of the pier.

## 5. Conclusions

Based on OpenSees software, the finite element model of long-span rigid frame bridge is established. From the analysis of IDA, the influence of the variation of pier height and longitudinal reinforcement on the seismic performance of long-span rigid frame bridge is analyzed. The conclusions are as follows:

- (1) The accuracy of the simulation of plastic hinge unit is higher than that of concentrated plastic hinge unit, and the calculation result of distributed plastic hinge unit is safe. It is recommended to use distributed plastic hinge unit for seismic analysis of long-span rigid frame bridge.
- (2) The increase of pier height increases the PGA of plastic joint for the first time in section, and with the increase of PGA, the change of pier height has a great influence on the development of plastic zone length.
- (3) The increase of the longitudinal reinforcement ratio increases the PGA of the plastic joint for the first time at the top and the bottom of the pier.

## Acknowledgments

This study is sponsored by the Science & Technology Research Development Project of China Railway (Grant No.2015G002-B).

## References

- [1] Zhong, Y. W., Chen, S. X., & Rui, L. I. (2015). Study on influences of foundation on rigid frame continuous girders with a-type super high pier. *Railway Standard Design*.
- [2] Choe, D. E., Gardoni, P., & Rosowsky, D. (2007). Closed-form fragility estimates, parameter sensitivity, and bayesian updating for rc columns. *Journal of Engineering Mechanics*, 133(7), 833-843.
- [3] LiLi, PengYuancheng, LongXiaohong, & LiaoPing. (2005). Nonlinear stability analysis of long span continuous rigid frame bridge with thin wall high piers. *Journal of China University of Geosciences*, 16(1), 72-78.
- [4] Song, D, (2007) Research on elastoplastic seismic response analysis method of high-rise long-span continuous rigid frame bridge.
- [5] Xia,XS. (2012) Research on seismic design method of railway high pier.
- [6] Appliedtechnologycouncil. (1996). *ATC-40 Seismic evaluation and retrofit of concrete buildings. Volume 2, Appendices*. Seismic Safety Commission.
- [7] Council, A. T., Rojahn, C., Moehle, J., Hamburger, R., Krawinkler, H., & Whittaker, A., et al. (1997). Nehrps commentary on the guidelines for the seismic rehabilitation of buildings.
- [8] Krawinkler, H., & Seneviratna, G. D. P. K. (1998). Pros and cons of a pushover analysis of seismic performance evaluation. *Engineering Structures*, 20(4), 452-464.