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INFLUENCE OF TIE BEAMS ON THE SEISMIC PERFORMANCE OF TWO-COLUMNED HIGH PIERS

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Two-columned high piers are widely used to continuous rigid frame bridges. The longitudinal flexural stiffness of high piers with height of over 40 m is generally smaller, so tie beams are usually set between two columns to decrease the calculating height of piers to improve the stability behavior. In addition, under the seismic action, tie beams generally yield before columns, forming the plastic hinge and dissipating seismic energy, which decreases the damage of piers. To study the seismic performance of two-columned high piers with tie beams, nonlinear static and quasi-static analysis of a typical two-columned high piers with height 45 m was conducted by two and three-dimensional finite element modeling techniques respectively. Factors of the longitudinal reinforcements and stirrups ratio of tie beams, the stiffness ratio of tie beams to columns and the number of tie beams on the seismic performance of high piers are all discussed. Analysis results show that the seismic performance two-columned high piers is effectively improved with increasing the number of tie beams and setting the stiffness ratio of tie beams to columns in a certain range, while there is little influence of the reinforcement ratio of tie beams. As a result, setting a reasonable number of tie beams is an effective way to improve the seismic performance of two-columned high piers.

Keywords: Continuous rigid frame bridge, Seismic performance, Hysteretic behavior, Seismic design.

1 INTRODUCTION

The western development strategy plays a key role in accelerating the highway construction in southwest and northwest of China. Because of the geologic condition in mountainous district, long-span continuous rigid frame bridges with two-columned high piers are often designed to span the deep ravines and big rivers. A preliminary survey shows that 40% of the total bridges in the west of China adopted the bridges with pier height exceeding 40 m (Liang and Li 2007). However, the guidelines of seismic design of highway bridges (Ministry of Transport of the People's Republic of China 2008) cannot be applied to bridges with high piers of more than 40 m.

Two-columned high piers which have a large slenderness ratio and small longitudinal stiffness are usually used in continuous rigid frame bridges (Qi *et al*. 2006, Yin and Yu 2012). The seismic performance is obviously different from bridges with lower height piers. Tie beams are usually set between two columns to guarantee the static mechanical characteristics of Two-columned high piers. Additionally, structural parameters and the number of tie beams all show certain influence on the seismic performance of two-columned high piers (Shen *et al.* 2013).

In this paper, nonlinear static and quasi-static analysis of a typical two-columned high piers with height 45 m was conducted by two- and three-dimensional finite element modeling techniques respectively analyzing to discuss the influence of longitudinal reinforcements and stirrups ratio of tie beams, the stiffness ratio of tie beams to columns and the number of tie beams on the seismic performance. Reasonable arrangement methods and suggestions in regard to tie beams were put forward for seismic design.

2 ENGINEERING SITUATION AND FINITE ELEMENT MODEL

A 540 m long multi-span (75 m + 3 m × 130 m + 75 m) continuous rigid frame bridge with box girder and four two-columned high piers are introduced, as shown in Figure 1. Each column of two-columned high piers shows rectangle section 1.2 m × 5.6 m, and distance between two columns is 4.8 m in the longitudinal direction. Concrete strength grade of the bridge is C50, and the longitudinal reinforcement and stirrup are respectively HRB335 and HPB300 grade steel (Ministry of Housing and Urban Rural Development of People's Republic of China 2010).

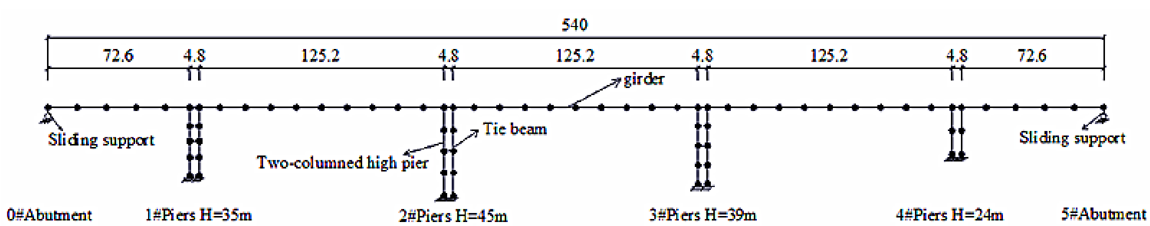
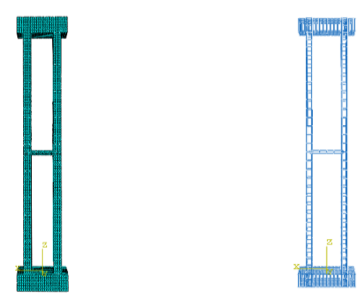


Figure 1. Linear 2-D model of the whole bridge (units in meters).

Linear 2-D model of the bridge was established to obtain axial force at the top of piers as shown in Figure 1. Nonlinear quasi-static analysis of 2# pier was conducted by three-dimensional finite element modeling technique, as shown in Figure 2. Kent-Park model is adopted to the compressive stress-stain relation of concrete, as shown in Figure 3, and the tensile stress-strain relationship (GB 50010-2010)(Ministry of Housing and Urban Rural Development of People's Republic of China 2010) is shown in the following Eq. (1) and Figure 4.



(a) Solid element of concrete. (b) Truss element of steel bars.

Figure 2. Three-dimensional finite element model.

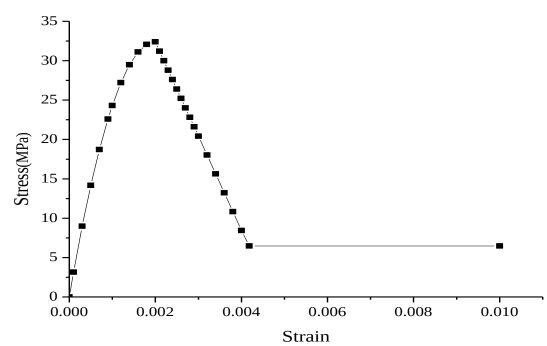


Figure 3. Compressive stress-stain relationship of concrete.

$$\begin{cases} x \le 1 \quad \sigma = f_t \times \left[1.2 \times x - 0.2 \times (x)^6\right] \\ x > 1 \quad \sigma = f_t \times \left[\dfrac{x}{0.312 \times f_t^{\,2} \times (x-1)^{1.7} + x}\right] \\ x = \varepsilon / \varepsilon_p \end{cases} \tag{1}$$

Where f_t and ε_p are characteristic value of axial tensile strength and peak tensile strain of concrete, respectively. The ideal elastic bilinear model is used for the tensile stress-strain relationship of steel bars. The elements of C3D8R and T3D2 are used respectively for concrete and steel bars. The horizontal reciprocating low cycle displacement load with variable amplitude is applied on the pier top in the longitudinal directions shown in Figure 5.

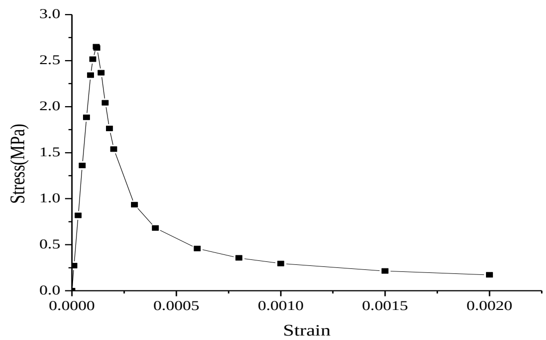


Figure 4. Tensile stress-strain relationship of concrete.

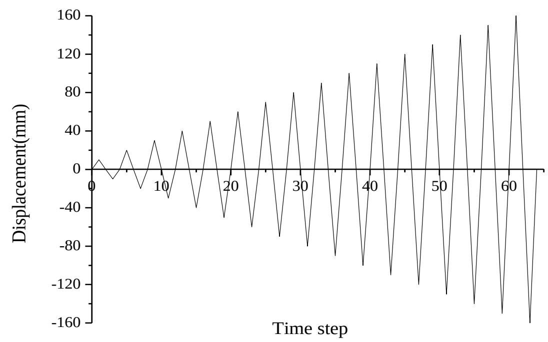


Figure 5. Longitudinal displacement loading.

3 INFLUENCE OF STRUCTURAL PARAMETERS OF TIE BEAM

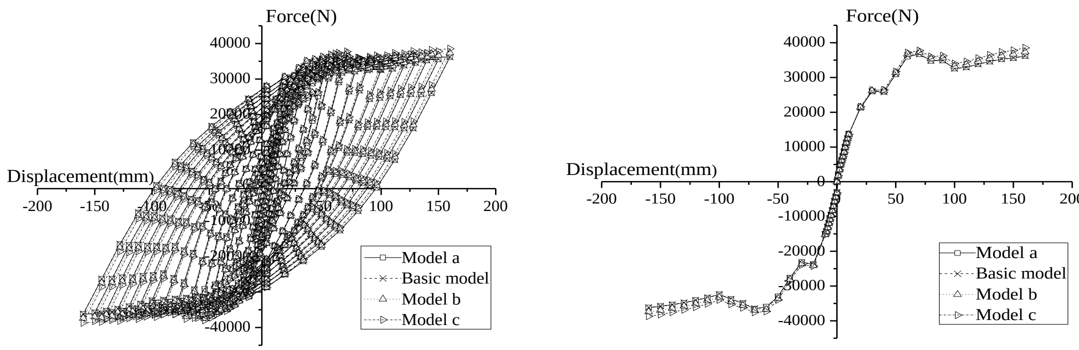
Although there is no clear specification for the design of tie-beams, section size and reinforcements ratio of them are generally designed in accordance with experience. To study influences of tie beams on the seismic performance of two-columns, factors of the longitudinal reinforcements and stirrups ratio of tie beams, the stiffness ratio of tie beams to columns and the number of tie beams are all considered. The stiffness ratio of tie beams to columns is shown in Eq. (2), and the influence of longitudinal reinforcement ratio and stirrup ratio in the concrete is neglected. E_{cb} and E_{cp} are the elastic modulus of concrete beams and piers respectively. I_b and I_p represent the inertia moment respectively. The specific related values are shown in Table 1. The tie beam is located at half of the columns, and its original section size is 5.6 m × 0.8m.

$$r = \frac{E_b I_b}{E_p I_p} \tag{2}$$

By changing the structural parameters of the tie beam, the force-displacement curves are shown in Figure 6, 7, and 8. Comparing between Figure 6 and Figure 7, it can be concluded that the influence of the longitudinal reinforcement and stirrup ratio of the tie beam on the seismic performance of two-columned high piers is not significant when one tie beam is set. It can be seen from Figure 8 that the stiffness ratio of tie beam to column has little effect on the seismic energy dissipation when the pier is in elastic stage. After it develops into the plastic stage, the displacement at the top of the pier is the smallest when the stiffness ratio is 0.36, which is beneficial for the protection of the superstructure of the bridge.

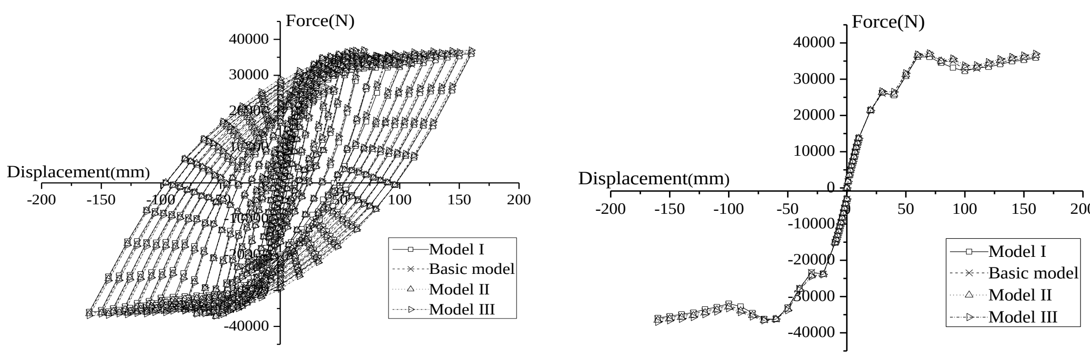
Table 1. Structural parameters of tie beam.

Parameters	Basic model	Model number									
		a	**b**	**c**	**I**	**II**	**III**	**A**	**B**	**C**	**D**
Section height(m)	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.85	0.90	0.95	1.00
Stiffness ratio of tie beams to columns *r*	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.36	0.42	0.50	0.58
Reinforcement ratio（%）	1.65	1.04	2.45	3.53	1.65	1.65	1.65	1.65	1.65	1.65	1.65
Stirrup ratio（%）	0.43	0.43	0.43	0.43	0.25	0.65	0.91	0.43	0.43	0.43	0.43



(a) Hysteretic curves. (b) Skeleton curves.

Figure 6. Influence of longitudinal reinforcement ratio.

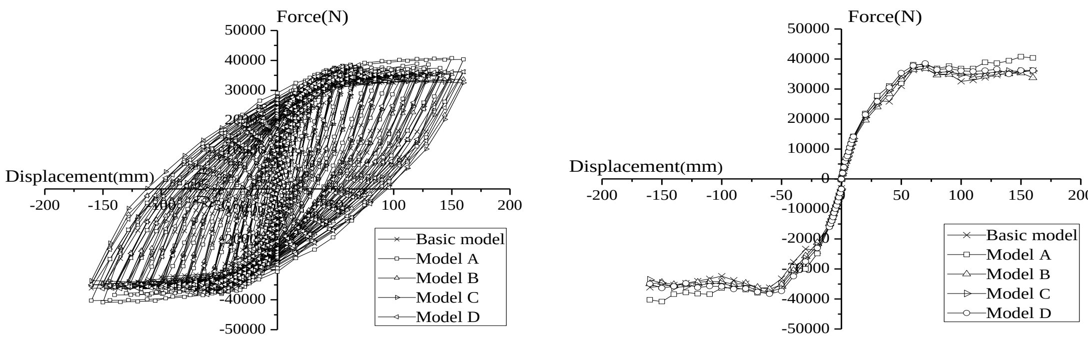


(a) Hysteretic curves. (b) Skeleton curves.

Figure 7. Influence of stirrup ratio.

4 INFLUENCE OF THE NUMBER OF TIE BEAMS

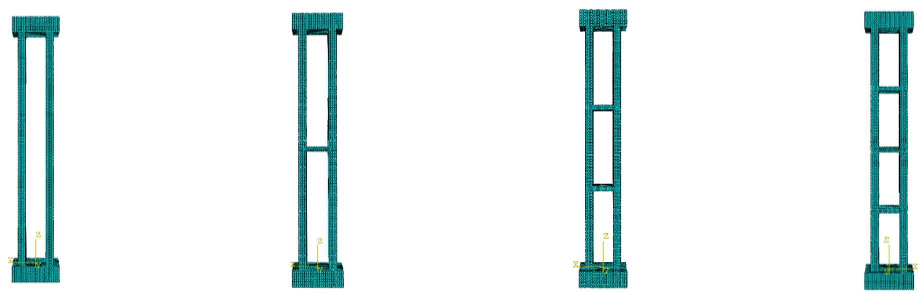
The number of tie beams may affect the location, quantity and sequence of the emergence of plastic hinges on two-columned high piers. Based on the engineering practice, tie beams are set on the basis of height of piers. The finite element model is conducted here and the number of tie beams is varied from 0 to 3 in the model and uniformly distributed along the pier, as shown in Figure 9. The force-displacement curves at the top of the pier are shown in Figure 10.



(a) Hysteretic curves.

(b) Skeleton curves.

Figure 8. Influence of the stiffness ratio of tie beams to columns.



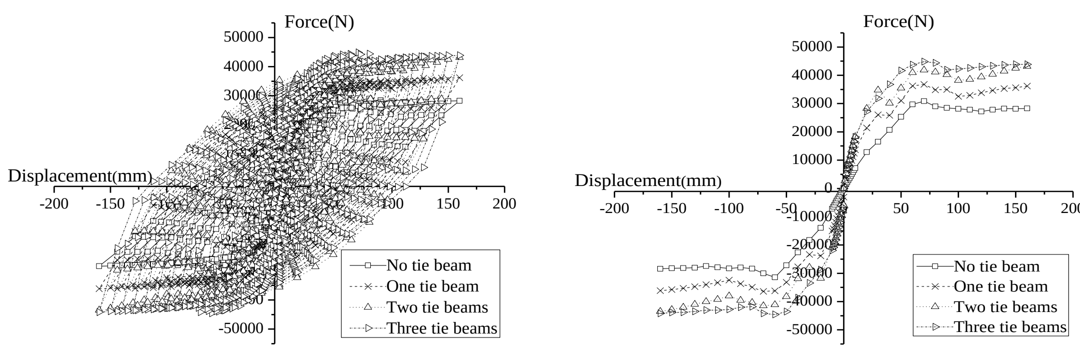
(a) Model without tie beam.

(b) Model with one tie beam.

(c) Model with two tie beams.

(d) Model with three tie beams.

Figure 9. Position(s) of the tie beam(s)



(a) Hysteretic curves.

(b) Skeleton curves.

Figure 10. Influence of the number of tie beams.

The horizontal displacement is 70 mm corresponding meanwhile the maximum force reaches, as shown in Figure 10. The dissipated energy of one hysteretic loop corresponding with the displacement variation along 0 mm - 70 mm - -70 mm - 0 mm is calculated and shown in Figure 11. In addition, a two-dimensional finite element model of a two-columned high pier is also established here to obtain the capacity curve by nonlinear pushover analysis. The base shear-displacement curves are shown in Figure 12.

Comparing Figure 10, 11, and 12, it can be concluded that the results between two and three-dimensional models are different, but the error is small and can be ignored. Meanwhile, the displacement at the top of pier decreases along with the increase of the number of tie beams, and conversely the seismic force enlarges, which improves the seismic performance of the two-columned piers.

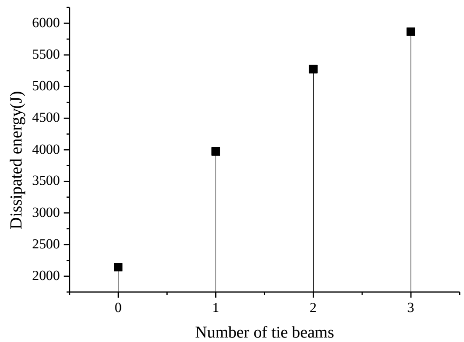


Figure 11. Dissipated energy of a hysteretic loop.

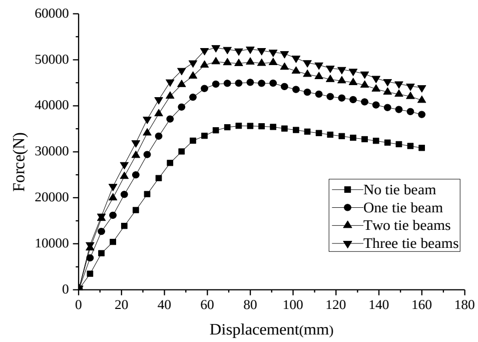


Figure 12. Base shear-displacement curves.

5 CONCLUSION

From the analysis of the two-columned high piers carried out the following conclusions have been reached:

- The number of the tie beams has great influence on the hysteretic behavior of two-columned high piers. As the number increase, the seismic performance can be improved effectively.
- The structural parameters of tie beams show small influence on the seismic performance of two-columned high piers. The stiffness ratio of tie beams to columns varying between 0.30 and 0.42 is suggested in seismic design of two-columned high piers.

Acknowledgments

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