Study on Seismic Effect and Mechanism of TOBs in Girder Bridges with High Piers

Tianbo Peng[1, 2], *Yinhao Ni*[1, 2], *Li Liang*[1, 2]

1. State Key Laboratory of Disaster Reduction in Civil Engineering, Tongji University, Shanghai 200092, China

2. College of Civil Engineering, Tongji University, Shanghai 200092, China.

Abstract: Based on the concept of BRB (buckling-restrained brace), this paper proposes a new seismic device TOB (tension-only brace). TOBs can prevent plastic hinges from emerging in piers under moderate earthquakes, and mitigate the seismic damage of piers and substantially reduces the post-earthquake rehabilitation costs under strong earthquakes. In this paper, the concept development, geometry configurations and the mechanical characteristics of TOBs are introduced firstly. Then, an actual continuous girder bridge with high piers is simulated and its seismic responses are analyzed. To study the TOBs' influence on seismic responses of girder bridges, five models designed by different seismic methods are built. Simulation results show that TOBs remarkably reduce internal forces and displacements of bridges and the lateral cap beam displacement is reduced by nearly 15%. Lastly, the seismic mechanism of TOBs is discussed in terms of lateral stiffness, load path and energy dissipation, and the energy dissipation is the dominant one among the three factors.

Keywords: tension-only brace; girder bridge; high pier; seismic response

1 Introduction

With the constantly improvement of Chinese road facilities and the starting of Western Great Development, bridges constructed in southwest China are more and more. It is well known that Southwest China is mountainous, so bridges with high piers are built massively. According to statistics, bridges with over 40 meters high piers account for more than 40% of the total number of bridges in Southwest China, and the maximum pier height is up to 143m [1].

Along with the blossom of high pier bridges, their seismic performance has attracted more and more attention because of the high probability of earthquakes in Southwest China. Once bridges with high piers get damaged or even collapsed during earthquakes, the direct financial loss is several times than common bridges[2]. And due to the undeveloped transportation network, alternative traffic line is rare, which hampers the rescue after earthquakes and leads to an awful secondary disaster.

Recent research on seismic methods of bridges with high piers is insufficient. High piers are very massive and can even be heavier than the superstructure, and therefore a high pier has quite different mass distribution from a short pier. Unlike seismic responses of short pier bridges, seismic responses of high pier bridges are dominated by higher mode shapes other than lower mode shapes. Therefore, it's hard to simplify seismic responses of high pier bridges under earthquakes. According to the Chinese specification *Guidelines for Seismic Design of Highway Bridges,* high pier bridges with over 30 meters high piers are classified as irregular bridges, which means a special investigation on seismic capacity is needed [3]. There are two frequently used seismic design methods for common bridges: the seismic isolation design method and ductility design method. The seismic isolation design method usually extends the natural vibration period to reduce the energy input of earthquake and dissipate earthquake energy through seismic isolation devices. Chinese seismic specifications suggest bridge structures with a long natural period are not suitable for seismic isolation design. Usually, high pier bridges belong to flexible structures, which have a long natural vibration period. Therefore, the seismic isolation design method has few applications in bridges with high piers. On the other hand, the ductility design method is popular for seismic designs of high pier bridges. However, high pier bridges under the ductility design method may suffer seismic damage unavoidably, and post-earthquake rehabilitation is much harder in such mountainous areas.

In view of the problem above, this paper proposes a new seismic device, TOB (tension-only brace) based on the concept of BRB (buckling-restrained brace). BRBs can provide lateral constraints for steel core through a concrete casing, preventing the buckling under axial compression. It is proved that BRBs can dissipate energy under earthquakes, which means it can be used for seismic purpose [4~13]. BRBs have been used in Japan and USA since about 1990 [14]. Until now, BRBs are applied mostly in building structures, while less in bridge structures and none in high pier bridges [16]. For high pier bridges, very long BRBs are needed, which may cause the instability problem. Based on the concept of BRB, a new seismic device TOB is invented for seismic purpose of high pier bridges. In the following sections, the configuration and mechanic behaviors of TOBs are introduced firstly. Then a numerical analysis is conducted for a high pier bridge under transverse earthquakes. Differences between traditional seismic systems and systems with TOBs are studied. At last, the mechanism of seismic response reduction by TOBs is discussed. This paper establishes a sound foundation for further application of TOBs.

2 Concept development of TOBs

To avoid lateral buckling under uniaxial loading, BRB introduces a concrete casing. This casing confines the lateral deformation of the steel core in BRBs. Therefore, BRBs won't buckle and are able to yield under compressive loading. Because of the feature of yielding under both tensile and compressive loading, BRBs have the ability to deform back and forth and the load-displacement relation curves of BRBs usually consist of some hysteretic loops, which means the energy is dissipated. Therefore, BRBs can be used as additional dampers in structures to dissipate the seismic energy [19-21].

The length of BRB used in buildings is usually less than 10 meters, which is not enough to satisfy the need of bridges especially high pier bridges. Moreover, for a BRB with a length of more than 100 meters, the dead weight of concrete casing will be tremendous, which makes the application of BRBs in bridge structures not practical. This is the main reason why BRBs almost have no applications in high pier bridges.

To address the problem, a tension-only brace (TOB) is proposed. TOBs have a similar mechanical behaviors to BRBs under tensile loading, but turns to a zero-stiffness member to avoid buckling when subjected to compressive loading. This feature prevents TOBs from local buckling and overall buckling under compressive loading. Without the possibility of buckling, TOBs can be designed long enough theoretically and used for high pier bridges.

When used in engineering practice, TOBs can be linked between cap beams and bearing platforms. A TOB is usually hinged at both ends and contains a damper, which consists of a hydraulic rod, a piston, a cylinder, a check valve, a differential pressure valve and two tubes as shown in Figure 2.1. One end of the hydraulic rod is connected with the shaft of the TOB, and the other one is connected with a piston inserted into the cylinder. The piston divides the cylinder into two chambers. Two tubes are used outside the cylinder to join the two chambers. A check valve is installed between the two chambers with one tube, and a differential pressure valve is installed between the two chambers with the other tube. The check valve permits flowing in one direction only, such as from the right chamber to the left one as shown.

When the TOB is in tension, the hydraulic rod goes outwards, and the left chamber becomes smaller in volume while the right one becomes larger contributing to the tendency that hydraulic oil flows from the left chamber to the right. However, the check valve stops the oil flow in this direction, resulting in the pressure difference between the two sides of the piston. The pressure difference brings the restoring force of the TOB. When the pressure difference reaches differential pressure valve’s threshold value, the differential pressure valve switch is turned on to preventing the growing pressure. The piston would move with a constant tensile load and a certain energy would be dissipated.

When the TOB is in compression, the hydraulic rod goes inwards, and the check valve permits the oil flow from right chamber to the left one smoothly. Thus, there is no pressure difference on the piston and the piston would move without a compressive load or with a very small compressive load.

According to the description above, the constitutive model of restoring force of a TOB is shown in Figure 2.2. Under tensile loading, the restoring force is directly proportional to the tensile deformation until the yield strength. The yield strength depends on the differential pressure valve and the area of the piston. The restoring force will not increase after yielding. Under compression loading, the restoring force is close to zero no matter how much the compression deformation is. Different from traditional dampers, hysteretic loops of a TOB only exist in the half region where the restoring force is tensile.

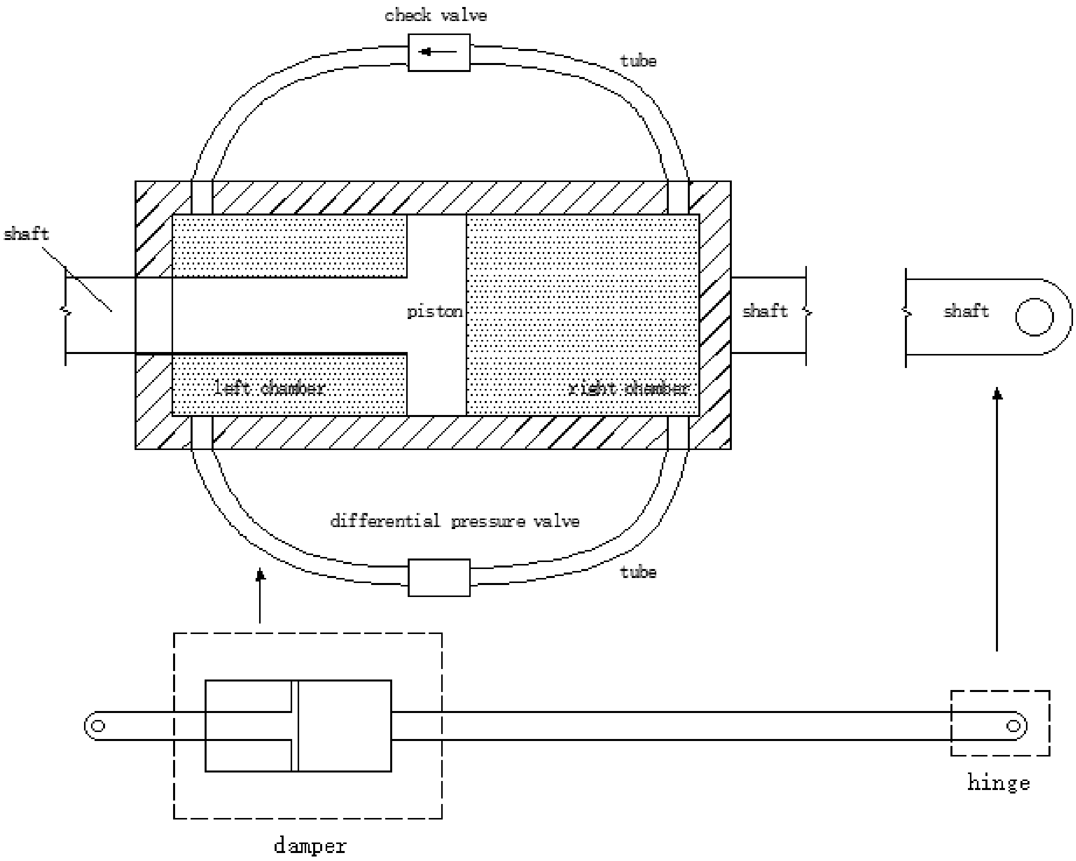

Figure 2.1 An illustration of a TOB

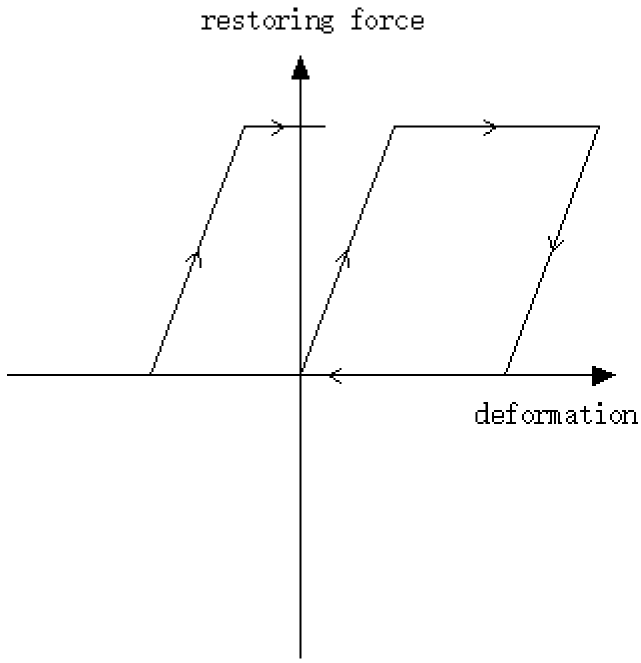

Figure 2.2 The constitutive model of the damper of a TOB

3 Numerical Simulation Analysis

3.1 Background Project

The example is a four-span simply supported bridge with a uniform girder. There are 4 beams in each span, and each beam weighs 200 tons respectively. The pier is composed of the cap beam, columns and the bearing platform. The cap beam's cross section is approximately a 2.2m×2.4m rectangle. Moreover, below the cap beam are two circular columns with a diameter of 2.0m and a height of 45m. The distance between columns is 7.05m. The materials of the cap beam and columns are both C30 concrete. The bearing platform can be thought as a 11.6m×6.0m×2.5m cuboid. Rebars in columns are extended and inserted into the bearing platform and the cap beam. Six piles are designed below the bearing platform and the diameter and the length of each pile are 1.8m and 24m. The proportionality coefficient of soil is 30000kN/m^4.

SAP2000, a software developed by Berkeley is used to compute the seismic response. The cap beam and columns can be simulated using frame elements. Suppose the cap beam keeps elastic while plastic hinges may appear at ends of columns during earthquakes. The moment-rotation curve is considered as a bilinear constitutive relation. In addition, the yield bending moment is calculated from the stress-strain curve of confined concrete proposed by Mander [22]. In view of the time consumption of nonlinear analysis, the girder is regarded as a rigid body and the mass value will be lumped on the top of the pier. The bearing platform is simulated as a rigid body. Six-degree springs will be applied below the bearing platform to simulate the pile-soil interaction. The stiffness of soil springs is determined by "m-method". TOBs are simulated by a multilinear plastic link element in kinematic hysteresis theory [23][23].

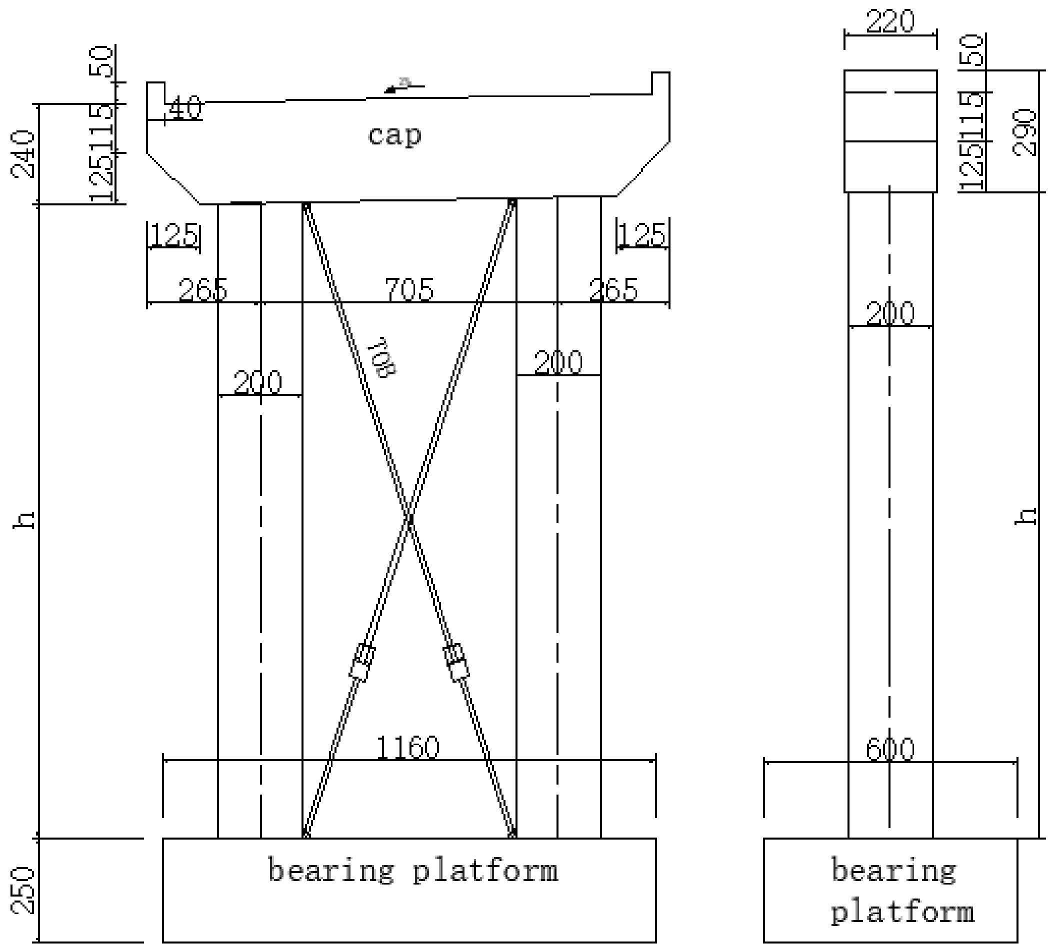

Figure 3.1 the Geometry of the pier

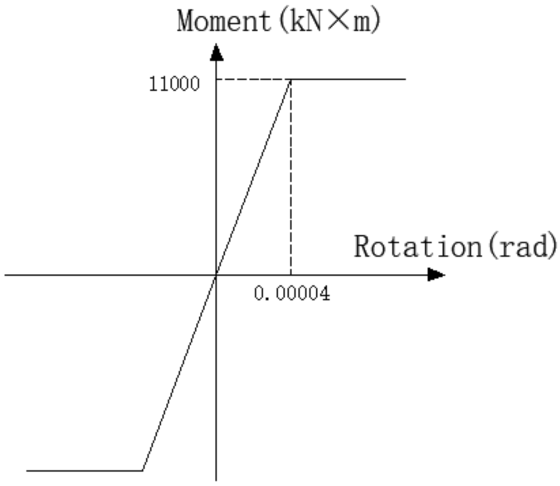

Figure 3.2 the moment-rotation curve for plastic hinges

3.2 Ground Motion Input

Artificial seismic waves fitting response spectra in the Chinese seismic specification are chosen as input ground motions . The peak acceleration of basis ground motion at the bridge site is 0.15g, the soil conditions belong to site class II, the characteristic period is 0.45s and the seismic fortification criterion is class B. According to *Guidelines for Seismic Design of Highway Bridges*, 14 horizontal acceleration waves under E1 and E2 earthquake actions are generated. The first 7 waves stand for E1 earthquake action whose return period is 50 years. Their peak accelerations are about 75gal. The last 7 waves stand for E2 earthquake action whose return period is 475 years. Their peak accelerations are about 250gal. Figure 3. shows the comparison between response spectra of artificial waves and target response spectra, and the 14 waves are shown in Figure 3..

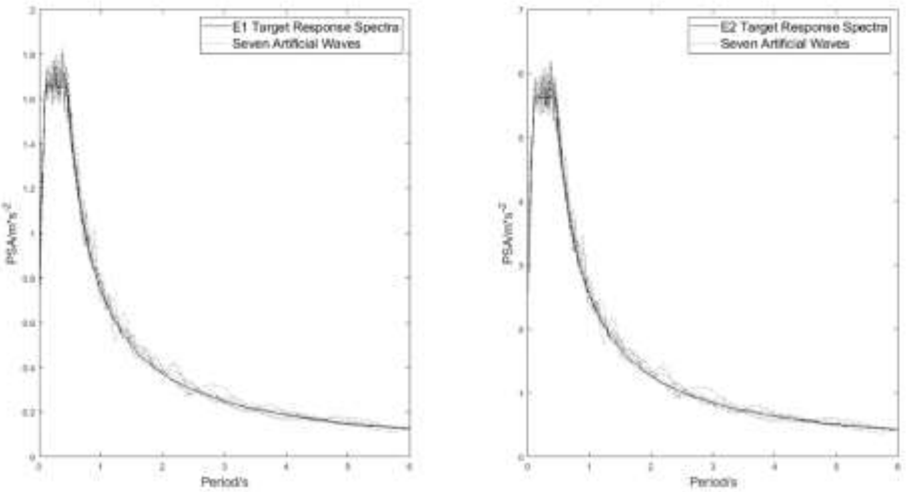

Figure 3.3 the comparison between response spectra of artificial waves and target response spectra

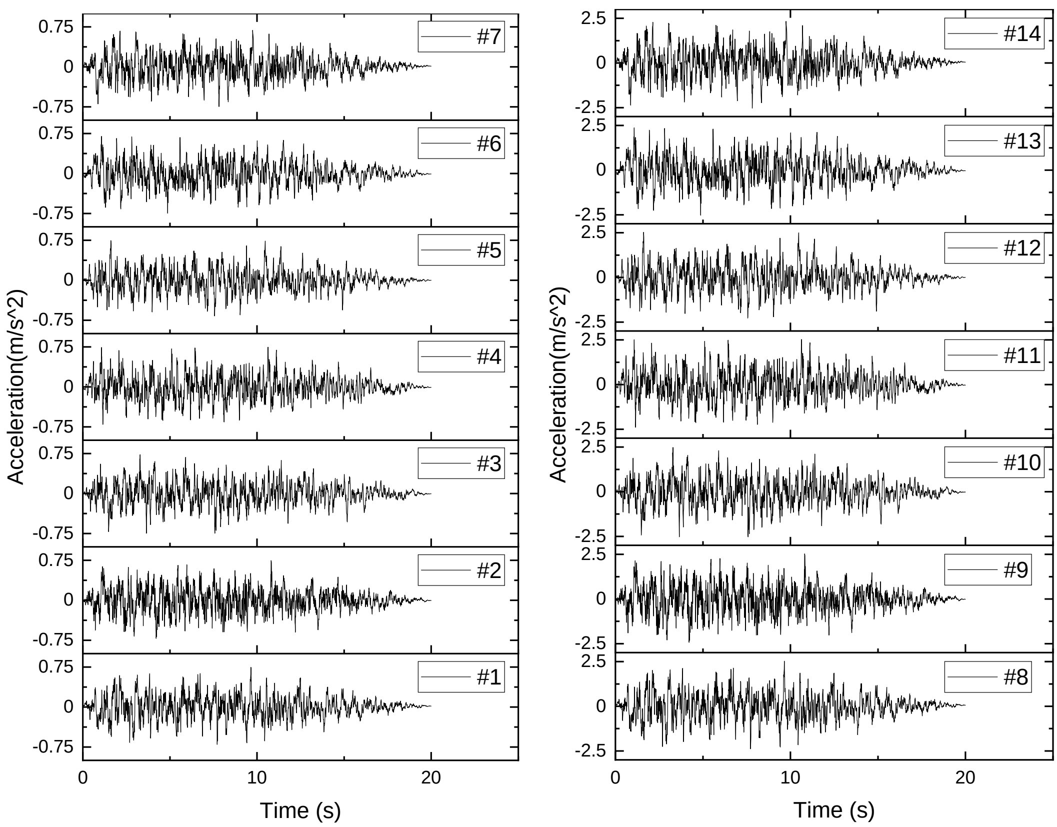

Figure 3.4 the 14 artificial earthquake waves

3.3 Five Analysis Models

To compare the ductility design method and seismic isolation seismic design method in high pier bridges, three different models are built:

Model A: This model stands for linear elastic pier model which means bending strength of piers are infinite and piers are always elastic during earthquakes. The girder and the cap beam are linked by fixed constraints. This model is only for contrast purpose.

Model B: This model stands for ductile pier model which means plastic hinges may appear at the columns' ends during earthquakes. The girder and the cap beam are linked by fixed constraints. This model corresponds to a bridge designed by the ductility design method.

Model C: In this model the bending strength of piers is supposed to be infinite and keep elastic during earthquakes. The girder and the cap beam are linked by lead rubber bearing whose type is 670mm×670mm×217mm rectangular. The pre-yield stiffness, yield strength and the post-yield stiffness of this bearing are 10800kN/m, 216kN and 1700kN/m, respectively. This model corresponds to a bridge designed by the seismic isolation design method.

To study TOBs' influence on the seismic responses of the bridges, another two models are built:

Model D: Based on Model B, two TOBs are installed across each other between the cap beam and the bearing platform.

Model E: Based on Model C, two TOBs are installed across each other between the cap beam and the bearing platform.

In Model D and Model E, the pre-yield stiffness and yield strength of the TOB are 40000kN/m and 650kN, respectively.

Fourteen analysis cases corresponding to 14 artificial waves are set up in each model. The input direction of earthquake is transverse, and damping ratio is set to be 5%.

4 Seismic Effect and Mechanism Analysis of TOBs

Based on the seismic damage investigation of high pier bridges, the bending moment, shear force, rotation at the columns' ends, the lateral displacement of the cap beam are chosen as the key responses to represent the seismic performance of the bridge structure. The mean values of 7 maximum values of these key responses during 7 artificial waves are list in

Table 4.1. The following conclusions can be drawn:

According to the comparison between Model A and Model B, the seismic responses under E1 earthquake actions are the same because the bridge does not yield. Under E2 earthquake actions, plastic hinges may appear at columns' ends. Therefore, the bending moment and shear force at the columns' ends decrease a lot, the displacement decreases a little, although the rotation at the columns' ends increases almost twofold.

According to the comparison between Model A and Model C, it's easy to find that seismic isolation bearings cannot greatly reduce seismic responses of high pier bridges. Under E2 earthquake actions, the lateral displacement of the cap beam, rotation, bending moment and shear force at columns' ends decrease by 7.8%、90.9%、9.0%、8.2%. In other words, isolating super structure by seismic isolation bearings has little effect on seismic responses of high pier bridges. Generally, seismic isolation bearings can isolate the superstructure from the pier and reduce the inertia force transferred from the superstructure to the pier. However, for high piers, the internal force at columns' bottoms mostly results from the high pier itself. So isolating superstructure is not an efficient way to reduce the seismic responses of high pier bridges. Moreover, this agrees with the dominant view that seismic isolation bearings are not suitable for seismic performance of high pier bridges [24].

According to the comparison between Model B and Model D, TOBs dramatically reduce the seismic responses of high pier bridges with ductility design method under both E1 and E2 earthquake actions. The reductions of the lateral cap beam displacement, rotation, bending moment and shear force at columns' ends are 13%, 14%, 14% and 15% under E1 earthquake actions. In addition, they are 15%, 56%, 0.2% and 6.5% under E2 earthquake actions. The E2 earthquake actions are so intense that TOBs cannot prevent the pier from yielding. The bending moments in Model B and Model D under E2 earthquake actions both reach the yielding strength 11000kNm. In addition, the bending moment nearly remains unchanged after yielding. Therefore, the bending moments and shear force at columns' bottoms change slightly. However, TOBs reduce the deformation of high pier bridges greatly under earthquakes, especially under E2 earthquake actions. The reduction of rotation at columns' bottoms is up to 52%. It means TOBs are reliable for the seismic purpose of high pier bridges with the ductility design method. TOBs can reduce the deformation of high pier bridges largely and mitigate the damage in high pier bridges efficiently.

According to the comparison between Model C and Model E, TOBs can reduce the seismic responses of high pier bridges under both E1 and E2 earthquake actions to a certain extent. The reductions of the lateral cap beam displacement, rotation, bending moment and shear force at columns' bottoms are 12%, 14%, 14% and 12% under E1 earthquake actions. In addition, they are 19%, 19%, 19% and 14% under E2 earthquake actions. It means TOBs can reduce both internal forces and deformations to a certain extent for high pier bridges with the seismic isolation design method.

Table 4.1 Key responses under E1 and E2 earthquake actions

Model	Displacement of the cap beam /m		Rotation /rad		Bending Moment /kN*m		Shear force /kN	
	E1	E2	E1	E2	E1	E2	E1	E2
A	0.0621	0.2108	1.78E-05	6.06E-04	4832	16414	258	877
B	0.0621	0.1985	1.78E-05	1.60E-03	4832	11050	258	724
C	0.0596	0.1944	1.67E-05	5.51E-05	4515	14933	244	805
D	0.0540	0.1687	1.53E-05	7.07E-04	4145	11030	220	677
E	0.0524	0.1571	1.43E-05	4.48E-05	3889	12139	214	696

The mechanism of TOBs' seismic effect can be discussed in the following three aspects:

Firstly, the TOB has a certain axial tensile stiffness, and can increase the total lateral stiffness of the bridge structure. Then the natural vibration period of the bridge decreases accordingly. The fundamental period of most high pier bridges is located in the descending part of the response spectra. The decrease of the natural vibration period may result in the increase of input energy under earthquakes. Comparing the PSD (power spectral density) of the lateral cap beam displacements in Model B and Model D as shown in Figure 4.1, the frequency corresponding to the maximum PSD grows higher after the introduction of TOBs. The lateral stiffness contributed by TOBs is related to their axial tensile stiffnesses and horizontal angles. However, compared to the lateral stiffness of piers, the lateral stiffness contributed by TOBs is relatively small. Besides, TOBs' axial stiffness changes to zero under compressive loading. So the change of the total lateral stiffness is not the main reason to reduce seismic responses.

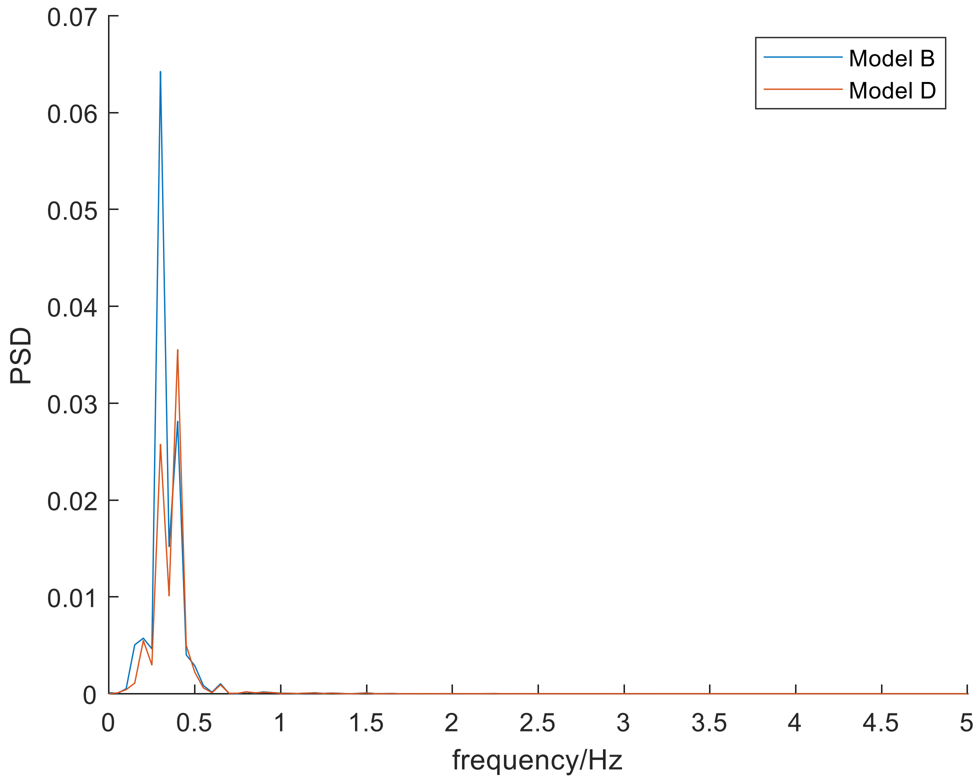

Figure 4.1 the PSD of the lateral cap beam displacement(under artificial wave 14)

Secondly, the introduction of TOBs can change the load path of the inertia force of girders. Without TOBs, the inertia force of girders is transferred to the foundation through bearings, the cap beam and columns in sequence. The introduction of TOB separates the inertia force on columns into two parts. The first part is still transferred through columns while the second one is transferred through TOBs. As a consequence, the internal force and deformation of piers are reduced. However because of the relatively smaller TOBs' axial stiffness compared with the lateral stiffness of piers, the seismic effect of changing load path is very limited.

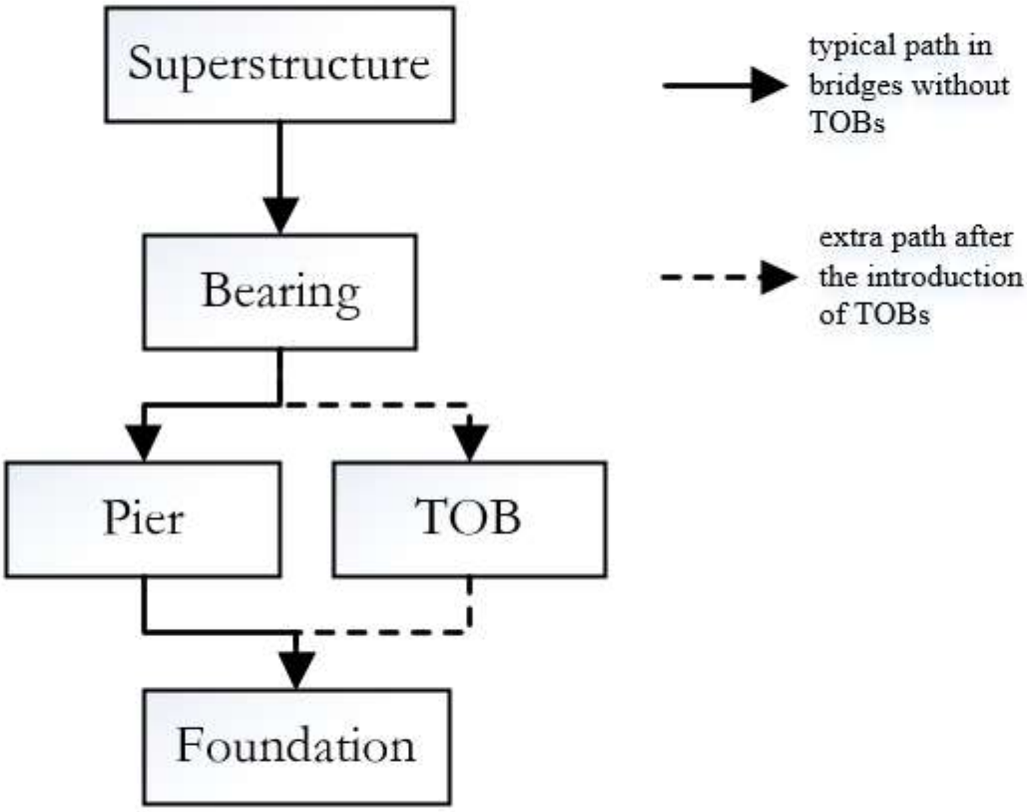

Figure 4.2 the load path in high pier bridges with TOBs

Thirdly, like BRBs, TOBs have the ability to dissipate energy. According to the numerical simulation results, the accumulative hysteretic energy of the whole bridge structure is substantially increased after the introduction of TOBs. The average increase of 7 artificial earthquake waves under E2 earthquake actions is up to 37.4% as shown in Figure 4.3. TOBs provide a new device for high pier bridges to dissipate seismic energy. TOBs can accelerate the process of energy dissipation during earthquakes and protect the whole bridge structure from accumulating too much energy that may lead to the collapse of bridges. And this is the most important reason on the seismic mechanism of TOBs.

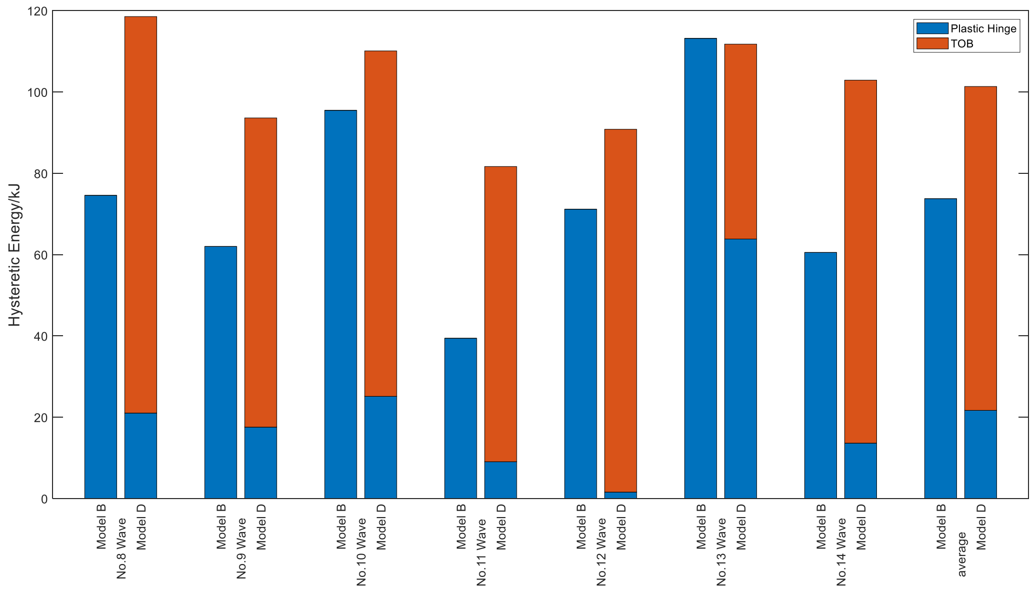

Figure 4.3 the accumulative hysteretic energy of Model B and Model D

5 Conclusion

Aimed at seismic resistance of high pier bridges, this paper proposes a new seismic device TOB. Via the numerical simulation of the seismic responses of an actual high pier bridge, the following conclusions are drawn:

(1) A check valve and a differential pressure valve are used to develop a new seismic device TOB. TOBs have a similar mechanical behaviors to BRBs under tensile loading, but turns to a zero-stiffness member to avoid buckling when subjected to compressive loading.

(2) TOBs can reduce displacements and internal forces of high pier bridges under both E1 and E2 earthquake actions. Therefore, the cost of post-earthquake rehabilitation for high pier bridges is reduced accordingly.

(3) The introduction of TOB changes the lateral stiffness, load path and energy dissipation of high pier bridges. Among them, the change of energy dissipation is the dominant one.

Conflict of Interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

Acknowledgments

This work was supported partly by the Ministry of Science and Technology of China, Grant No. SLDRCE19-B-21 and the National Natural Science Foundation of China (No. 51278372 and No. 51878489).

Reference

[1] Zhi-Yao Liang. Study on Seismic Design Theory of Irregular Girder Bridges with High Piers [D].Tongji University,2007.

[2] LUO Xiao-yu,CHEN Ai-rong,WU Huai-yi,CHANG Cheng.Value Engineering Study on High Pier of T-Beam Bridges in Mountain Area[J].China Journal of Highway and Transpost,2013,26(05):115-120.

[3] Guidelines for Seismic Design of Highway Bridges[S].Beijing：China communications press,2008.

[4] Tsai K C , Hsiao P C . Pseudo-Dynamic test of a full：cale CFT/BRB frame—Part II: Seismic performance of buckling - restrained braces and connections[J]. Earthquake Engineering & Structural Dynamics, 2008, 37(7):1099-1115.

[5] Gao E X , Wang Y G . Seismic Performance Study on Buckling-Restrained Brace[J]. Applied Mechanics and Materials, 2013, 353-356:2101-2104.

[6] Wang Jingfeng, Gao Xiang, Li Beibei, Qian Liping, Zuo Jinzhou. Seismic performance tests and analysis of connections between buckling restrained braces and steel frame [J/OL].China Civil Engineering Journal:1-9[2019-04-27].https://doi.org/10.15951/j.tmgcxb.20190422.001.

[7] Feng Yulong, Wu Jing, Chong Xun, Meng Shaoping. Damage concentration effect analysis of buckling-restrained braced frames after yielding of the braces [J/OL].China Civil Engineering Journal:1-10[2019-04-27].https://doi.org/10.15951/j.tmgcxb.20190116.001.

[8] FELLOW J, et al. Damage-controlled structures. I: preliminary design methodology for seismically active regions[J]. J Struct Eng 1997. 123:423.

[9] Vargas R, Bruneau M. Analytical response and design of buildings with metallic structural fuses. I[J]. J Struct Eng 2009;135:386.

[10] Vargas R, Bruneau M. Experimental response of buildings designed with metallic structural fuses. II[J]. J Struct Eng 2009;135:394.

[11] El-Bahey S, Bruneau M. Buckling restrained braces as structural fuses for the seismic

retrofit of reinforced concrete bridge bents [J]. Engineering Structures, 2011, 33(3): 1052-1061.

[12] Lanning, J., Benzoni, G., and Uang, C. M. The feasibility of using buckling-restrained braces for long-span bridges, a case study[R]. Tech. Rep. CA12-2149, Caltrans, Sacramento, CA,2011.

[13] Carden, L., Itani, A. P. E., and Buckle, F. I. Seismic performance of steel girder bridges with ductile cross frames using buckling-restrained braces[J]. J. Struct. Eng., 10.1061/(ASCE) 0733-9445 (2006) 132:3(338), 338–345.

[14] Guo Yanlin,Liu Jian-bin,Cai Yiyan,DengKe. Structural Energy Dissipation and Seismic Mitigation Method and Buckling-restrained Brace [J]. Building Strucure, 2005(8):18-23.

[15] XIAONE WEI, MICHEL BRUNEAU. Case Study on Applications of Structural Fuses in Bridge Bents[J]. Journal of Bridge Engineering, 2016, 21(7): 5016004.1-15.

[16] Shi Yan, Wang Dongsheng,Han Jianping. Displacement-based design method for bridge bents with buckling-restrained braces (BRBs) [J].CHINA CIVIL ENGINEERING JOURNAL,2017,50(07):62-68+128.

[17] XIAONE WEI, MICHEL BRUNEAU. Resilient Bridges: Replaceable Structural Fuses for Post-Earthquake Accelerated Service, Phase I: Analytical Investigation[R]. New York: Department of Civil, Structural and Environmental Engineering, 2013.

[18] Usami T, Lu Zhizhao, Ge Hanbin. A seismic upgrading for steel arch bridges using bucking-restrained braces [J]. Earthquake Engineering and Structure Dybanics, 2005, 34(4): 471-496.

[19] Sabelli R , Mahin S , Chang C . Seismic demands on steel braced frame buildings with buckling-restrained braces[J]. Engineering Structures, 2003, 25(5):655-666.

[20] Takeuchi T , Ida M , Yamada S , et al. Estimation of Cumulative Deformation Capacity of Buckling Restrained Braces[J]. Journal of Structural Engineering, 2008, 134(5):822-831.

[21] López, W. A., and Sabelli, R. Steel tips report: Seismic design of buckling-restrained braced frames[R]. Structural Steel Educational Council, Lafayette, CA, 2004

[22] Mander J A B , Priestley M J N. Theoretical Stress-Strain Model for Confined Concrete[J]. Journal of Structural Engineering, 1988, 114(8):1804-1826.

[23] Malvern, Lawrence E. Introduction to the Mechanics of a Continuous Medium. No. Monograph. 1969.

[24] YE Aijun, GUAN Zhongguo. Seismic Design of Bridges(3rd edition)[M]. 2017.