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Experimental investigation on seismic performance of rigid frame tied-arch bridge with split-piers

Ding Wensheng[1,2] Lü Zhitao[1] Liu Zhao[1] Zang Hua[1] Li Guoliang[1]

([1] School of Civil Engineering, Southeast University, Nanjing 210096, China)

([2] School of Construction and Safety Engineering, Shanghai Institute of Technology, Shanghai 200235, China)

Abstract: A novel seismic design method, namely split-pier seismic design, is proposed. A vertical gap and connect elements are set in split-piers. The lateral stiffness of piers is reduced by cracking of the connect elements under severe earthquake, and the seismic response of bridges is reduced by avoiding the site predominant periods. A model of tied-arch rigid frame bridge with split-piers was designed. Seismic performance was investigated by pseudo-static experimentation on the scale model. The failure process of split-piers, the hysteresis characteristic and the effect of split-piers on the superstructure are presented. Results show that the split-pier has better seismic performance than common ductile piers do.

Key words: seismic design; split-pier; pier; rigid frame tied-arch bridge; seismic performance

Nowadays, rigid frame tied-arch bridges have been widely constructed in China. They have become important parts of the lifeline in city traffic. And their seismic performance has been paid extensive attention to.

So far, most of the seismic designs for rigid frame tied-arch bridges have been carried out according to the ductility-based concept[1]. Usually, the goal of seismic resistance is achieved by the ductility design for the piers. This kind of bridge resists severe earthquake in two ways. One is that the plastic deformation of the concrete pier occurs to increase the displacement of structures and dissipate seismic energy with less carrying capacity decrease. The other is that the fundamental period of structure will be prolonged because of plastic hinges in piers, which reduces earthquake response. These ways achieve the goal that bridges will not collapse when suffering from a severe earthquake.

The piers designed in this method are the main load carrying and energy dissipation members. The piers must be damaged during dissipating seismic energy, which will weaken the performance of the piers. And it is difficult to retrofit. Moreover, the fundamental period of structure will be lengthened only after the use of plastic hinges in piers. Although plastic hinges will decrease the earthquake response, they cannot protect the structure before earthquake occurrence. That is to say, the plastic hinges do not reduce the damage done to the piers.

As for the long-span rigid frame tied-arch bridges located in the lifeline, ensuring the traffic function and the immediate retrofit capability after severe earthquake occurrence are of great significance[2]. So it is necessary for engineers and researchers to seek other more efficient and economical methods.

1 Concept of Split-Piers

Paulay et al. [3] presented a new kind of seismic pier, the split-pier, according to the philosophy of capacity design. The structure-control theory is adopted in the seismic design for the split-pier. The split-pier consists of two parts, as shown in Fig. 1. One is to carry design load. The other is to dissipate seismic energy. The main member carries the most of design load, while the subordinate one just carries a little. Under the design load, the split-pier behaves like a normal pier with large lateral stiffness. When suffering a severe earthquake, the subordinate member will crack. As a result, the whole pier will be split into two parts. The lateral stiffness of the structure will reduce. And the natural period of the pier will increase evidently. The seismic response of the structure will decrease. Some earthquake energy is dissipated by the damage of energy dissipation members. So the main members are protected and the designed goal for a rigid frame tied-arch bridge is achieved.

The concept of energy seems best to explain the structural response to a strong ground motion, and nu-

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Biographies: Ding Wensheng (1968—), male, graduate, associate professor; Lü Zhitao (corresponding author), male, professor, academician of Chinese Academy of Engineering, luzhitao@ seu. edu. cn.

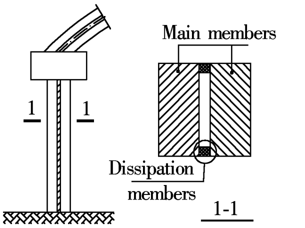

Fig. 1 Schematic of split-pier

merous studies on the energy concept have been carried out[4-7]. So an energy-based split-pier design aims at resisting energy input to structure by earthquake. The energy equation[8] is as follows:

$$E_K + E_D + E_S + E_P + E_H = E_I \quad (1)$$

where E_I is the input energy to structure by earthquake; E_K is the kinetic energy; E_S is the elastic strain energy; E_D is the viscous damping energy; E_P is the energy dissipated by irrecoverable deformation of the concrete; E_H is the energy dissipated by the hysteretic behavior of plastic hinges.

The aims of the split-pier resisting different levels of the earthquake load are as follows:

When the earthquake level is frequent,

$$\left.\begin{array}{l} E_P^m + E_P^d + E_H^m + E_H^d = 0 \\ E_D > E_I^f \end{array}\right\} \quad (2)$$

When the earthquake level is designed,

$$\left.\begin{array}{l} E_H^m = 0 \\ E_D + E_P^m + E_H^d + E_P^d > E_I^d \end{array}\right\} \quad (3)$$

When the earthquake level is severe,

$$E_D + E_P^m + E_H^m + E_P^d + E_H^d > E_I^r \quad (4)$$

where E_I^f, E_I^d and E_I^r are the input energy in structure by earthquake at frequent level, designed level and severe level, respectively; E_P^m and E_P^d are the energy dissipated by irrecoverable deformation of main member and dissipated member, respectively; E_H^m and E_H^d are the energy dissipated by the hysteretic behavior of plastic hinges in main member and in dissipated member, respectively.

Two models are tested to make a study on the seismic performance of rigid frame tied-arch bridge with split-piers.

2 Test Design and Loading History

The prototype of the model is the 80 m rigid frame tied-arch bridge in Shenzhen, China. According to the similarity theory of experiment, it is not necessary for the model to be strictly similar to the prototype in the case of proving the theory[9]. The similarity ratio of the model is 1 : 20. To avoid the differences between material characteristics caused by the too small specimen sections, all the pier sections and arch sections are amplified following the rule that the model and the prototype have the same flexural stiffness ratio between arch rib and pier. The main similarity relationships are listed in Tab. 1. To be a typical one, all the parameters are selected in the normal range, as shown in Fig. 2.

Tab. 1 Main similarity relationships

Similarity factors	Geometry		Material characteristics	Strain σ	Stress ε	Displacement D
	L_s, H_p, f_a	$E_a I_a / E_p I_p$	E, G, μ			
Theoretical	1/20	1	1	1	1	1/20
Adopted	1/20	1	1	1	1	1/20

Notes: L_s is the span of the rigid frame tied-arch bridge, H_p is the height of the piers, f_a is the rise of the arch, E_a is the elasticity modulus of the arch rib, E_p is the elasticity modulus of the piers, I_a is the inertia moment of the piers, I_p is the inertia moment of the arch rib.

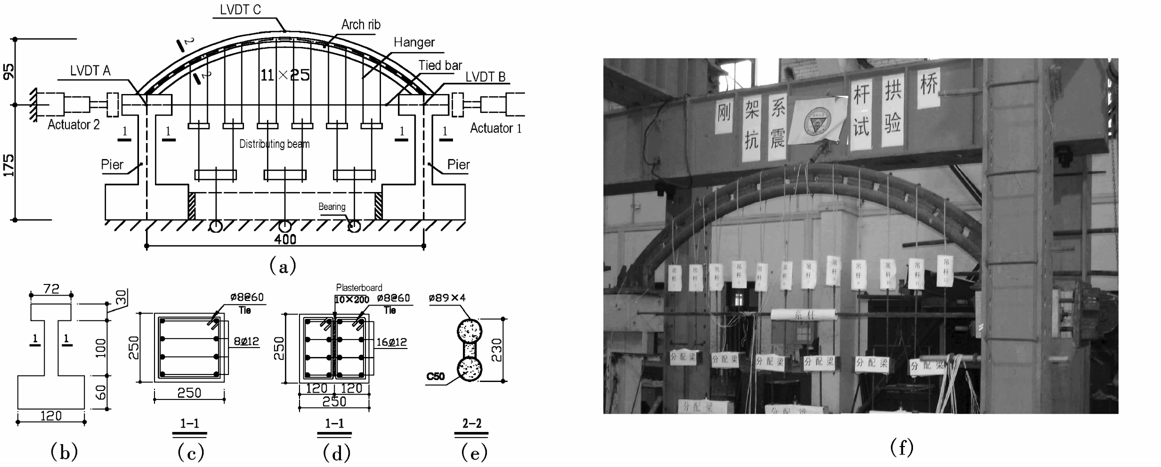

Fig. 2 Test setup and details of test specimens. (a) Schematic test setup(cm); (b) Elevation(cm); (c) Cross section 1-1 of common piers (mm); (d) Cross section 1-1 of split-piers (mm); (e) Cross section 2-2 (mm); (f) Picture of test setup

According to the principles mentioned above, one model with common piers and one model with split-piers were designed respectively.

The concrete strength of the piers is about 40 MPa. Each section of the arch rib is dumbbell shaped with two Φ89 × 4 pipes filled with concrete. The strength of filled concrete is about 57 MPa. The arch feet and piers are jointed rigidly. The measured parameters of the material are listed in Tab. 2.

Tab. 2 Material properties MPa

Compression strength of concrete		Strength of reinforcement				Compressive ultimate strength of CFST
		Φ8		Φ12		
C30	C50	f_y	f_u	f_y	f_u	
40.3	56.7	298.4	426.5	373.9	531.6	123.4

The lateral loading equipment comprised two servo-actuators of MTS. The two servo-actuators supplied the lateral force or displacement toward the same direction to the model according to the input in the control system. The loading history included force control and displacement control, as shown in Fig. 3. To eliminate the gap between the servo-actuators and models, two external displacement sensors were applied, which were placed at the top of the two piers. The sampling frequency of the sensors was 20 Hz.

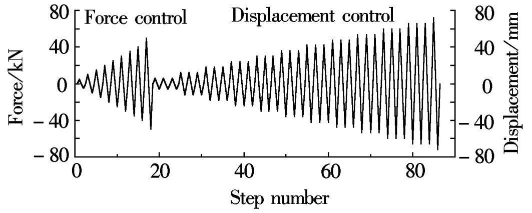

Fig. 3 Cyclic loading history

The vertical load was applied by three high strength steel wires through the slots in the anchor beam. The load was distributed by nine distributing beams to the arch through twelve hangers.

The strain of the reinforcements and ties were monitored during the experiment, as well as the moment of the arch rib and the distribution of concrete strain at pier ends.

The experiment was carried out in the structure laboratory of Southeast University.

3 Results and Analyses

3.1 Loading process of split-piers

The whole test process of split-piers consists of elastic integral phase, integral phase with transverse cracks, double-shaft splitting phase, self-working phase of double shafts, plastic hinges occurrence phase and failure phase, as shown in Fig. 4.

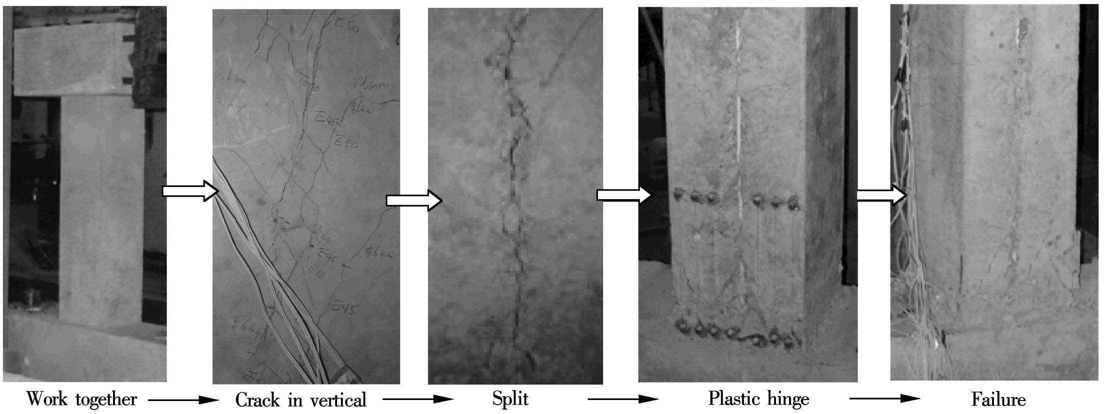

Fig. 4 Failure process of the split-pier

At the initial stage of the test, the piers were in the elastic integral working phase. When the lateral load increased to 30 kN, transverse bending cracks occurred at the bottoms of the piers and the piers came into the integral phase with transverse cracks. When the lateral load rose to 40 kN, inclined short cracks appeared from the bottom to the top along the axes of the piers, which were about 45° to the axes. At this time, the load-displacement curves of the piers mostly remained linear. While the lateral load reached 50 kN, the inclined short cracks increased numerously and they interlaced. In this stage, the split-piers split into double shafts and the piers came into the self-working phase of double shafts. The concrete between shafts was used as energy dissipating members and worked with the whole structure.

During the stage of displacement control, when the displacement was 6 mm, transverse cracks almost appeared. The concrete along the axes began to crumble. When the displacement was 12 mm, the concrete along the axes spalled badly and quit working. The width of the cracks increased obviously and the lateral load was about 74 kN. The width of cracks increased as the displacement of the piers increased. When the displacement reached 18 mm, the lateral load-carrying capacity of the piers reached a maximum of about 76 kN and the plastic hinge of each shaft occurred. When the displacement reached 60 mm, the lateral load was about 67 kN and the reduction of lateral load-carrying capacity of piers did not exceed 15% of the maximum. When the displacement reached 66 mm, the load-carrying capacity decreased rapidly. After one circle with the displacement of 72 mm, the piers failed completely and the test finished.

3.2 Strain of end-concrete of split-piers

To find out the strain changing of end-concrete of the split-piers, the splitting load and the forming of plastic hinges, Handholding strain gauges were used to measure the strain of the end-concrete of the split-piers. The layout of measuring spots is shown in Fig. 5.

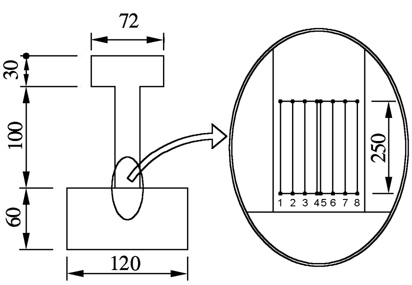

Fig. 5 Details of measuring points on split-piers (unit: cm)

The strain of concrete and the longitudinal reinforcement at the bottom of the split-pier is shown in Fig. 6. It illustrates that the shafts functioned wholly before vertical crack occurrence and the section deformation at cracks turned after vertical crack occurrence. After cracks finally occurred, the original pier section was divided into two substantive parts and they deformed independently.

3.3 Moment in the arch rib

The changes of the moment in the arch rib represented the superstructure's reaction along splitting and plastic hinges' occurrence. The changes of curvature of the arch rib section were monitored at arch foot, quarter span and mid span during the test.

The changes of moment at arch foot and quarter span are shown in Fig. 7. It is clear that the moment in the arch changed gently.

3.4 Comparison of hysteresis curves

The hysteresis curve synthetically reflects the seismic performance and ductility of structures. The hysteresis curves of the pier top were obtained from the test, as shown in Fig. 8. This figure shows that the hysteresis curve of the common pier falls sharply past its maximum and pinches obviously in anaphase. The

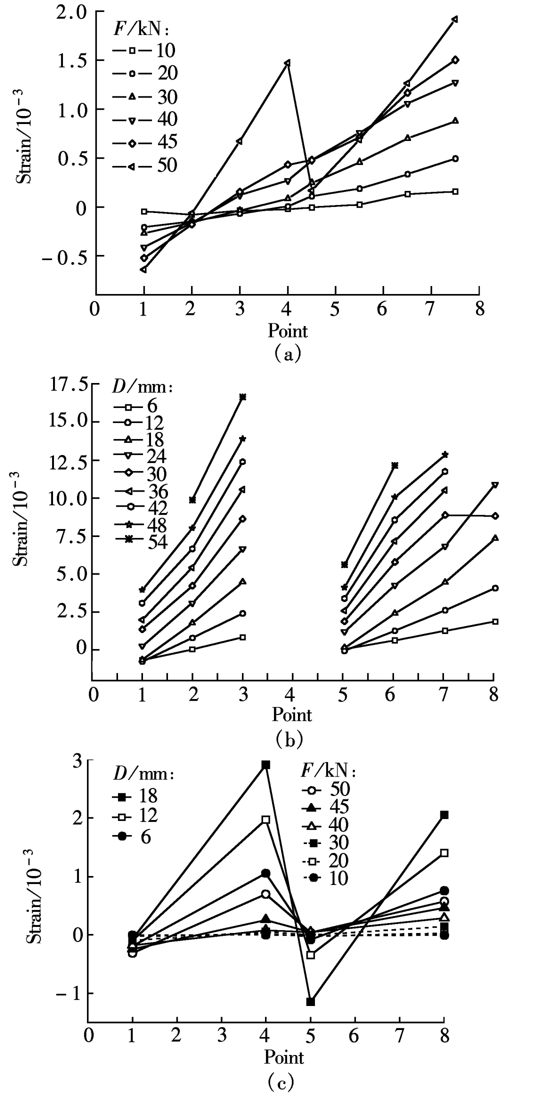

Fig. 6 Distribution of strain of the split-piers. (a) Before splitting; (b) After splitting; (c) Strain of longitudinal reinforcement

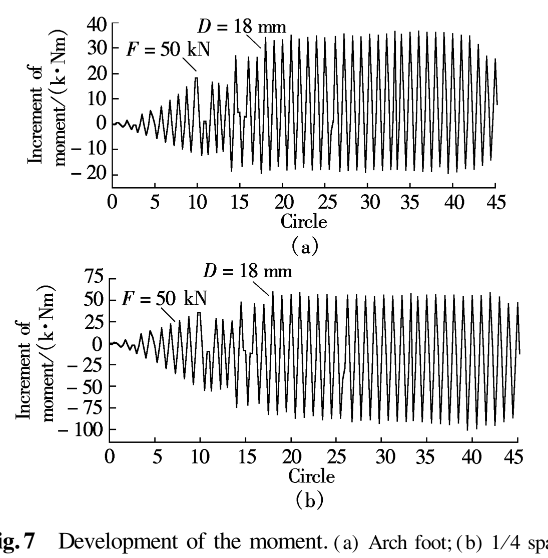

Fig. 7 Development of the moment. (a) Arch foot; (b) 1/4 span

hysteresis curve of the split-pier expresses its good ductility. The displacement can reach 60 mm with almost uniform carrying capacity. In addition, the hysteresis curve of split-pier is full, which indicates that the structure has good energy dissipation behavior.

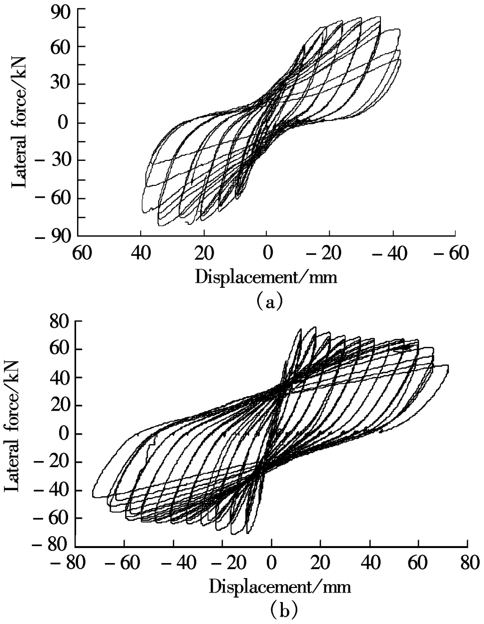

Fig. 8 Hysteresis curves of piers. (a) Common pier; (b) Split pier

4 Conclusions

1) When suffering lateral force, the failure processes of the split-pier, which is designed following the concept of structure control, are as follows: First, the main members and the dissipate members work together as a whole at elastic stages. Secondly, the dissipate members split and quit working. The main members almost maintain an elastic stage and the lateral stiffness of the split-pier decreases at the same time. Then, plastic hinges occur in the main member. Finally the main members fail.

2) The hysteresis curve of the split-pier is full after entering into its plasticity, which indicates that the deformation capacity and seismic performance of rigid frame tied-arch bridges with split-piers are superior to those of tied arch bridges with common ductile piers.

3) The superstructure reacts gently and the moment of arch rib almost remains unchanged after split-pier splitting and entering into its plasticity.

References

[1] Houser G W. Behaviour of structures during earthquakes [J]. *Journal of the Mechanics Engineering* (*ASCE*), 1959, **85**(4): 109 − 129.

[2] SEAOC Vision 2000 Committee. Performance-based seismic engineering [R]. Sacramento, California, USA: Structural Engineering Association of California, 1995.

[3] Paulay T, Prisestley M J N. *Seismic design of reinforced concrete and masonry buildings*[M]. New York: John Wiley & Sons, 1992. 24 − 26.

[4] Dargush G F, Sant R S. Evolutionary aseismic design and retrofit of structures with passive energy dissipation[J]. *Earthquake Engineering and Structural Dynamics*, 2005, **34**(13): 1601 − 1626.

[5] Manfredi Gaetano. Evaluation of seismic energy demand [J]. *Earthquake Engineering and Structural Dynamics*, 2001, **30**(4): 485 − 499.

[6] Akbas B, Shen J, Hao H. Energy approach in performance-based seismic design of steel moment resisting frames for the basic safety objective [J]. *Structural Design of Tall Buildings*, 2001, **10**(3): 179 − 217.

[7] Leelataviwat Sutat, Goel Subhash C, Stojadinovi Boidar. Energy-based seismic design of structures using yield mechanism and target drift[J]. *Journal of Structural Engineering* (*ASCE*), 2002, **128**(8): 1046 − 1054.

[8] Uang C M, Bertero V V. Evaluation of seismic energy in structures [J]. *Earthquake Engineering and Structural Dynamics*, 1990, **19**(1): 77 − 90.

[9] Zhu Bolong. *Structure seismic test* [M]. Beijing: Earthquake Press, 1989, 8 − 13. (in Chinese)

采用被动分肢墩的刚架系杆拱桥抗震性能试验研究

丁文胜[1,2] 吕志涛[1] 刘 钊[1] 臧 华[1] 李国亮[1]

([1] 东南大学土木工程学院,南京 210096)
([2] 上海应用技术学院土木建筑与安全工程学院,上海 200235)

摘要:为了提高刚架系杆拱桥的抗震性能,提出了一种新型抗震墩柱——被动分肢墩的抗震设计概念. 即在墩柱中设置竖缝和连接件,利用连接件在罕遇地震下的破坏,降低墩柱抗侧刚度,避开场地卓越周期,减小结构的地震反应. 以实桥为原型,设计了采用被动分肢墩的刚架系杆拱桥比例模型,进行了该模型拟静力试验研究. 介绍了被动分肢墩的试验破坏过程,滞回特性以及对上部拱肋的影响,试验结果表明:与普通延性抗震墩柱相比,被动分肢墩具有良好的抗震性能.

关键词:抗震设计; 被动分肢墩; 墩柱; 刚架系杆拱桥; 抗震性能

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