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SEISMIC PERFORMANCE OF A CLASS OF LONG-SPAN HIGH-SPEED RAILWAY UPPER-DECK ARCH BRIDGE UNDER INTENSE EARTHQUAKE

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Abstract

A kind of innovative high-speed railways upper-deck arch bridge with stiff-frame of shaped steel and concrete-filled steel pipe and novel construction technology in the concrete rib was researched under intense earthquake. Seismic performance objectives were studied to quantify structural performance level corresponding to the fortification. The potential plastic hinge regions in the piers were identified by nonlinear time history analysis to discover the collapse status under intense earthquake. To figure out the seismic limit state of this bridge under different levels of earthquakes, applicability of the design parameters and structural behaviors were investigated comparatively. Seismic ductility and isolation design were studied respectively to balance the dilemma between driving comfort and seismic safety. The numerical results of the fragile sections suggest that this kind of bridge is much applicable on the railway across earthquake-prone area.

Keywords: seismic performance; upper-deck arch bridge; extra-intensity earthquake; ductile design; seismic isolation

1. Introduction

To satisfy the higher serviceability limits, stiffer structures, compared with conventional railway bridge, are preferred for the passenger dedicated line (Hu et al, 2014). Therefore, a large number of world-class arch bridges have been constructed along the railways in China. For the arch bridges coming across or near the earthquake-prone zone, the seismic performances should be researched to ensure their aseismic safety. When innovative structure is adopted in a bridge, further detail studies should be done to find its seismic applicability compared with conventional structural system. Here a long-span arch bridges, with rigid skeleton rib made up of concrete-filled steel cubes and shaped-steel braces as well as continuous rigid frame and T-type approaching spans, will be paid attention to .optimize its mechanical behaviors under isolation and ductile design.

In a ductile design, some members are permitted damage to prevent collapse of the capacity-protected members in a structure. However, seismic isolation usually leads to less damage (almost elastic) in the isolated structures than ductile design. To improve applicability of the arch bridge, the structural seismic demand is regularized by employing a mixed outlay of lead-plug rubber bearing and TFP (Becker and Mahin, 2013) in the isolation design. This can satisfy the requirement of three-level seismic performance objectives of railway engineering code (MR, 2009). What more important is that self-adaptive TFP will endow the isolate bridge with selectable and controllable seismic objectives corresponding to different seismic demands under different levels of possible earthquake.

2. Fortification criterion and ground motion of earthquake based on risk assessment

The seismic fortification requires that the bridge should be equipped with different seismic performances under different levels of earthquake. The piers and piles of the bridge concerned should be undamaged and remaining elastic under rare major earthquakes. The three exceedance probabilities in the seismic risk report of the bridge site are: frequent earthquake with 63% exceedance probability (PGA 0.05g), design earthquake with 10% exceedance probability (PGA 0.116g) and rare earthquake with 2% exceedance probability (PGA 0.2g) in 50 years. The input response spectra curves and the seismic ground motion history waves are represented in Figure 1 and Figure 2 respectively.

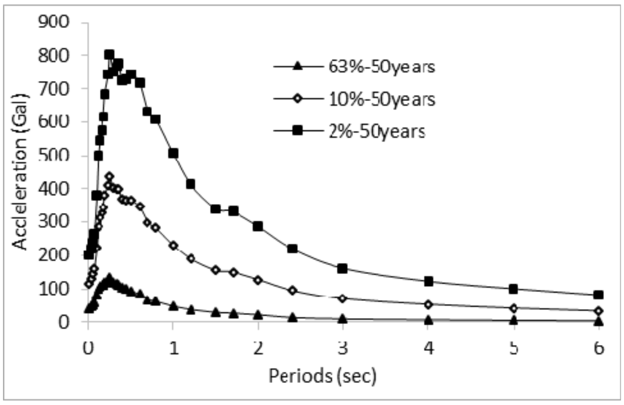
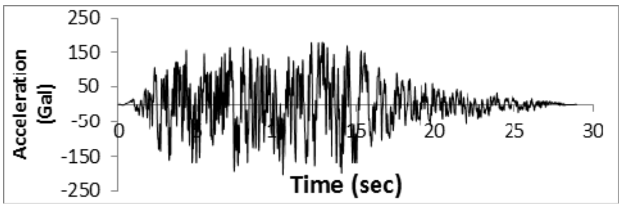
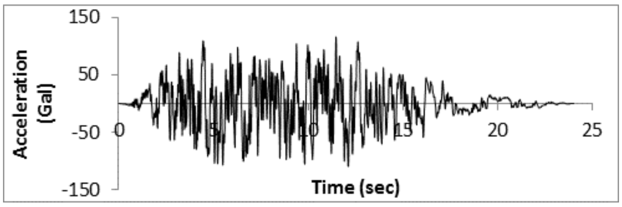


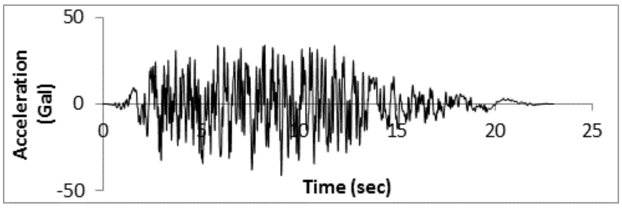
Fig.1 Response spectra accelerations with a 5% damping ratio



(a) Acceleration history with exceedance probability 2% in 50 years



(b) Acceleration history with exceedance probability 10% in 50 years



(c) Acceleration history with exceedance probability 63% in 50 years

Fig.2 Acceleration histories of ground motions

3. Overview of the bridge

The span layout of the railway arch bridge is 3×42m (continuous deck)+ (60.9m+104m+ 60.9m) (continuous rigid frame) + 4×39.5m (continuous deck) +4×39.5m (continuous deck)+(60.9m+60.9m) (T-type rigid frame)+ 43.7m (simply supported span)＝833.3m, we refer to Fig.3 below. The outlay of bearing type and the constraint direction is shown in Fig. 4. The decks above the arch rib are divided into two parts of continuous beam at the mid span. The main girder is made up of prestressed concrete box section with vertical webs: cf. Fig. 5. The height of girder and thickness of the bottom slab varies along the semi-cube parabolic curve with respect to the longitudinal direction of the bridge.

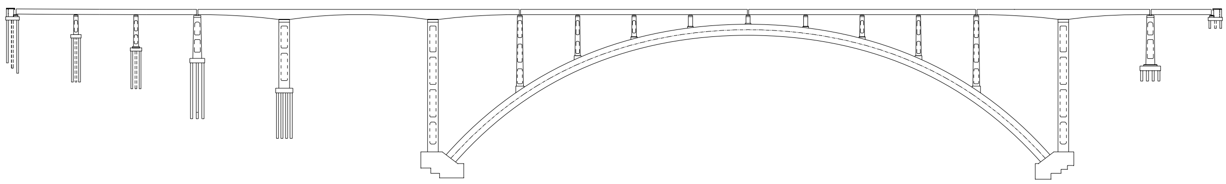
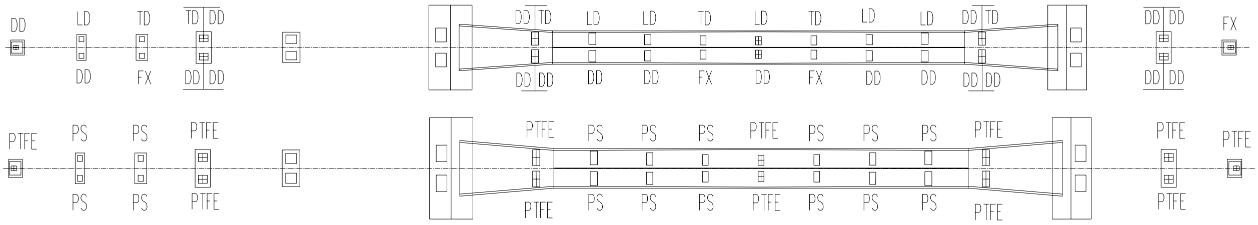


Fig.3 Elevation graph of the arch bridge



Where, DD denotes double-direction movable, LD longitudinal direction movable, TD transverse direction movable, FX fixed bearing, PEFE denotes Teflon sliding bearing movable, PS denotes spherical steel bearing.

Fig.4 Outlay of bearings

Because the arch rib is one of the most important bearing components in the arch bridge. It may undergo yielding deformation under strong earthquake (Wakashima, 2000; Alvarez et al, 2012). Consequently, as one of the obvious structural properties, the box-section concrete rib is reinforced with stiff skeletons consisting of concrete-filled steel tubes and steel frames. This kind of structural design of arch rib will be helpful for the construction of the long-span concrete arch (Xie, 2012). The second outstanding characteristic is that adjacent parts of the main span are continuous stiff skeleton on the left and T-frame bridge on the right instead of continuous deck outlay as approaching spans: cf. Fig.3. The third characteristic is the construction method of the arch rib which is constructed in the sequence illustrated in Fig.5. This build order will be helpful to decrease the effect of creep and shrink and unify the stress on the box section of the rib (Xie, 2012).

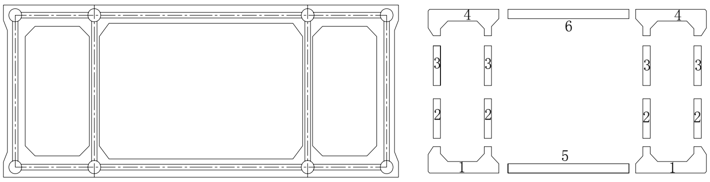


Fig.5 Section and construction sequence number of the arch rib

The main part of the piers is made up of double columns with a thin-walled rectangular box section. The foundation is designed as cast-in-place drilled piles with diameter from 1.25m to 2.50m. Fig. 4 and Fig. 6 show us part details of the structure.

4 Ductile design process

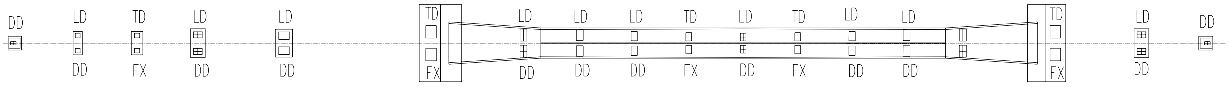
The conventional seismic design procedure was employed to make usage of ductile behavior to remain integrity of structural system at the cost of damages of predicted structural member. It is generally neither practical nor desirable to provide for plastic hinge formation in superstructure, and hence column hinges are typically chosen as the site for inelastic deformation. To ensure that ductile inelastic flexural response is achieved, it is essential that nonductile deformation should be inhibited. Therefore, it is necessary to ensure adequate margin of strength between brittle failure modes and designated ductile modes of deformation. Here, adequate transverse reinforcements are provided in the region of potential plastic hinge to ensure that the nonductile failure modes occur much later than ductile deformation.

In order to guarantee minimum loss and keep ductile response, the design should satisfy the performance demand of seismic fortification, and adequately consider possible structural damages under the earthquake beyond fortification. Accordingly, the positions and order of yielding members are required by different strength levels. Through optimal design, the structure is guaranteed adequate ductile deformation capacity, requisite deformation and dissipative capacity.

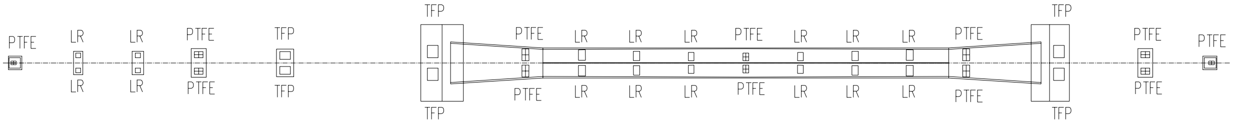
5 Analysis on isolated system

To reduce the inconsistent in-plane responses caused by structural irregularity the different height and stiffness of the piers, some effective measures should be adopted to regularize the structural properties. The most practical method is to weaken the stiffness of the joint between the ribs and the piers, such as dissipative bearings on the top of the piers. By this way, the effective stiffness and expected displacements of different piers are more similar to each other. Simultaneously, the seismic responses are reduced greatly by isolation device’s weakening the coupling effects between the superstructure and substructure via the fundamental period elongation and the energy dissipation function (Naeim and Kelly, 1999). Hereby, the continuous rigid-frame and T-frame spans are modified to continuous girder system with the same geometric size as their original outlay. The lead-plug rubber bearings are adopted on the intermediate piers of continuous deck spans. The triple friction pendulum bearings are laid on the intermediate piers of original stiff-frame and T-frame spans to optimize the seismic responses of a railway arch bridge (see Fig.7). The steel spherical bearings are located on the transfer piers. This outlay of bearings is helpful to realize regular seismic design of the structure and optimization of structural performance.

The comparative numerical results between the seismic ductile and isolation design illustrate that seismic demands decrease apparently. The section size and reinforcement needed are reduced substantially compared with ductile design. The dissipative weak connection between the piers and the deck is preferred for this type of long-span bridge, justifying modified structural design layout of the original scheme.



Where, DD denotes double-direction movable, LD longitudinal direction movable, TD transverse direction movable, FX fixed bearing.



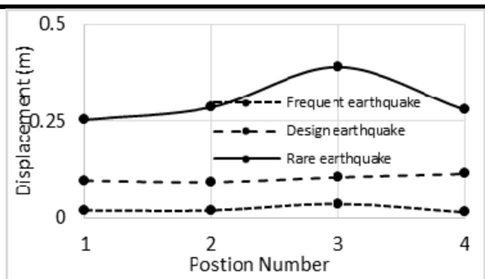
Where, PEFE denotes Teflon sliding bearing movable, LR denotes lead-plug rubber bearing, TFP denotes triple friction pendulum.

Fig.7 Outlay of isolation bearings

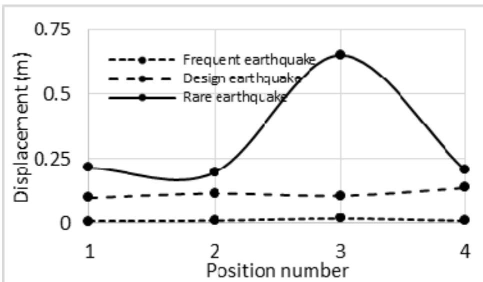
It could be observed that the great difference among different level of displacements (see Figure 8(a) and Figure 8(b)) of bearings (output positions see Table 1). To ensure seismic train-running comfort and safety, some effective measures should be made to limit displacement demand of operational period or mid-small earthquake. Fortunately, the TFP devices are naturally endowed with self-adaptive ability with different design parameters. The adaptability of TFP device renders multi-level shift capacity with three separate pendulum mechanism. The above numerical results show regularization of seismic requirement due to the TFP device. The output position of seismic demand of piers in Fig is shown in Tab.1.

Table 1 No. of output key sections of the structural components

Output position	No. of section
Lowest hollow section of No. 4 pier	1
Lowest hollow section of No. 5 pier	2
Lowest hollow section of No. 1 pier above rib	3
Lowest hollow section of No. 4 pier above rib	4
Foot of rib	5



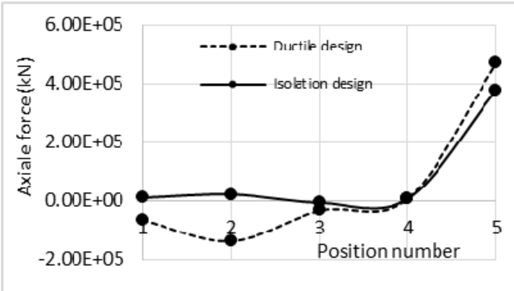
(a) Longitudinal shift demands of bearings



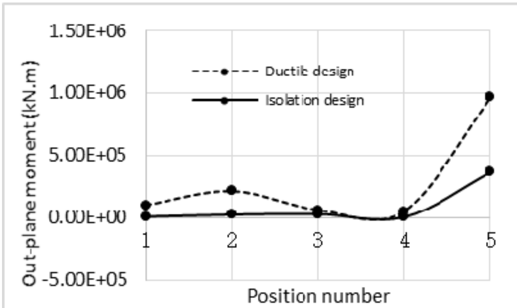
(b) Transverse shift demands of bearings

Fig.8 Seismic shift demands of four positions under different level of earthquake

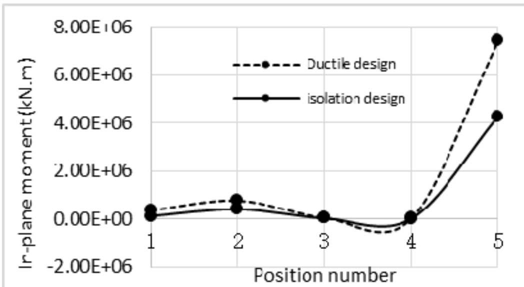
According to the results in Fig. 9(a), the isolation design decreased the internal force demand of the foot section of the arch rib, the tensile forces of pier 4 and 5 were turned into pressure ones. At the same time, the moment demand of these sections were also reduced obviously from Fig 9(b) and Fig. 9(c). That means the isolation design are effective to migrate the earthquake responses. The similar conclusions could also be obtained from the results in Fig. 8 and Fig.9 14 and Fig. 15.



(a) Axial forces demands



(b) In-plane ductile and isolation moment demands



(c) Out-plane ductile and isolation moment demands

Fig.9 Seismic internal force demands of key sections under rare earthquake

When the displacement demands of the girder are concerned, we give these results of the key positions of the bridge (see Table 2). The comparative displacements of Fig. 10 and Fig 11 show that the shift demands of the girder are amplified by the isolators. However, those of arch crown are decreased due to isolation design. The output position of seismic demand of girder in Fig.10 and Fig.11 is shown in Tab.2.

Table 2 Displacement output positions of girder

Position number	Output positions
1	Top of left joint pier

2	Left of main girder
3	Medium of main span
4	Right end of main girder
5	Top of right joint pier
6	Arch crown

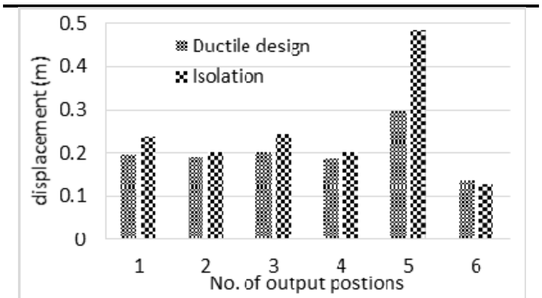


Fig. 10 Longitudinal displacement demand of girder under rare earthquake (Unit: m)

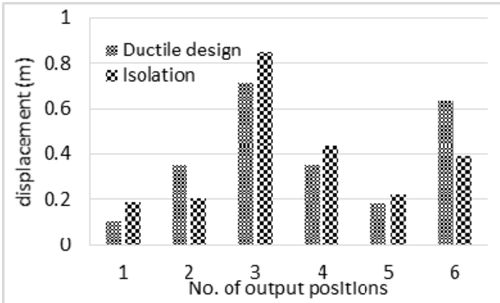


Fig. 11 Lateral displacement demand of girder under rare earthquake (Unit: m)

Comparative results from Fig. 7 to Fig.11 show that isolation design endows the arch bridge with much seismic applicability than the ductile method. It means that stiff approaching spans appear poor seismic performance. However continuous beam spans exhibit excellent anti-earthquake behavior.

6 Conclusions

1. The continuous girder design is more excellent than the continuous rigid frame approach layout for this arch bridge under rare earthquake. However, the final structural layout should balance the dilemma between the seismic safety and train running comfort for the railway bridge.
2. The original design of piers and columns above the arch rib should be strengthened to offer sufficient capacity to satisfy the demand of the potential ductile components under rare earthquake.
3. The flexural performances of key sections are investigated in the course of seismic design. However, other performances such as the shearing capacity of members and the displacement of bearings should also receive much attention. The different performance objectives should be optimized to ensure rational seismic structural response in accordance with the requirements in safety, functionality cost and even aesthetics.
4. Comparative numerical results from ductile and isolation design show that mixed layout of isolators endow the system with much excellent performance than the ductile design scheme. The lead-plug rubber bearings and TFP devices optimize the seismic properties of the railway arch bridge substantially. This features calculable and controllable bearing displacements by changing the stiffness and damping of the system.
5. Although the isolators are excellent to regularize the internal force demands under earthquake, the large seismic displacement should be considered for long-span railway bridge. In fact, excessively large shift,

especially the lateral displacement of girder, caused by earthquake may be much trouble to handle for train-running safety and comfort in design process.

Acknowledgements

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