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Seismic damage of highway bridges during the 2008 Wenchuan earthquake

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Abstract: Many highway bridges were severely damaged or completely collapsed during the 2008 Wenchuan earthquake. A field investigation was carried out in the strongly affected areas and over 320 bridges were examined. Damage to some representative highway bridges is briefly described and a preliminary analysis of the probable causes of the damage is presented in this paper. The most common damage included shear-flexural failure of the pier columns, expansion joint failure, shear key failure, and girder sliding in the transversal or longitudinal directions due to weak connections between girder and bearings. Lessons learned from this earthquake are described and recommendations related to the design of curved and skewed bridges, design of bearings and devices to prevent girder collapse, and ductility of bridge piers are presented. Suggestions for future seismic design and retrofitting techniques for bridges in moderate to severe earthquake areas are also proposed.

Keywords: Wenchuan earthquake; seismic damage; seismic design; highway bridge; field investigation

1 Introduction

At 14:28 (Beijing time) on Monday, May 12, 2008, a devastating earthquake with a magnitude of 8.0 on the Richter scale struck Wenchuan, Sichuan Province of China. It was the strongest earthquake to occur in China and the most costly natural disaster in the past 100 years. It caused great destruction to infrastructure systems; 24 highways, 161 state or provincial roads, and 8,618 county roads were affected, while 6,140 bridges and 156 tunnels were damaged. The total losses to the transportation system due to the earthquake were over 67 billion RMB, most of which consisted of damage to bridges (http://www.chinahighway.com/news/2008/260802.php, 2008-06-20).

Unlike the damage to buildings in earthquake affected regions, where a large number of injuries or deaths were caused directly by building collapse, bridge damage isolated the affected area by preventing the transport of lifeline supplies and denying access by rescuers. This generated an even larger impact to society. The severe damage to bridges and the difficulty in repairing or retrofitting them lengthened the rescue process to such an extent that many wounded people lost their lives due to the lack of access to medical care.

The investigation of earthquake damage to highway bridges in this event will provide valuable information for improving the criteria and specifications in existing seismic design codes for highway bridges. To this end, a large-scale 46-day field survey was carried out in the stricken areas, covering 18 cities or counties along the main central fault (Yingxiu-Beichuan fault), including Wenchuan County, Dujiangyang City, Pengzhou City, Guanghai City, Deyang City, Shifang City, Mianzhu City, Mianyang City, Jiangyou City, Anxian County, Beichuan County, Guangyuan City, Pingwu County, Qinchuan County, and Jiange County in Sichuan Province and Wenxian County in Gansu Province.

Among the 320 major bridges and other transportation facilities investigated, 46 bridges (about 14% of the total number of the damaged bridges) were severely damaged (traffic was interrupted due to failed bridge piers or falling beams), 128 bridges (39%) were moderately damaged (traffic control was imposed due to settlement, damaged bearings, and cracking of decks, beams, or piers), and 154 bridges (47%) had minor damaged or were intact (normal traffic was maintained with slight settlement, minor cracking, or minor

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horizontal movement).

According to the Chinese Specification of Earthquake Resistant Design for Highway Engineering (MCPRC, 1990), for a highway bridge designed to withstand the maximum earthquake intensity of IX, the basic design value of the peak ground acceleration (PGA) is 0.4 g. However, the observed maximum intensity in some regions in the Sichuan Province during the Wenchuan earthquake was nearly XI due to the large magnitude and shallow focal depth of the main earthquake source. The earthquake lasted for more than 90 seconds, and was followed by many aftershocks of M 6 or more. In the ground motion recordings from the main shock, there were 16 components with PGAs larger than 0.4 g, and seven were larger than 0.6 g, the largest being 0.98 g. The largest PGA recorded during the aftershock exceeded 0.3 g (Li *et al.*, 2008). Therefore, it was not surprising that many bridges designed according to the current code suffered severe damage or even collapsed during this earthquake.

This paper presents an overview of the field investigation and a preliminary analysis of the probable causes of the bridge damage. Many bridges are regarded as straightforward structural systems composed of superstructures, substructures, and foundations. However, the bridges damaged by this earthquake showed some complex failure modes. Even so, most of the damage modes can be traced to several sources. An overview of the causes of damage and collapse in this earthquake may offer new guidelines for bridge seismic design and considerations for improving code provisions.

2 Damage to RC girder bridges

The superstructures in the affected area were designed according to elastic theory and usually have more seismic resistance than other components of the bridge system. Therefore, the damage observed to the superstructure of RC girder bridges included, in most cases, damage due to the impact between girders at the expansion joints, and collapse of some of the main girders as a result of large relative movement between adjacent pier columns.

2.1 Unseating of bridge spans

Span failure was caused by unseating, which included pier tilting, insufficient seat width, and/or inadequate restraining force capacity. The relative movement was amplified if the motions of the adjacent piers were in the opposite directions. Figure 1(a) shows the collapse of the main girders of the Gaoyuan Bridge located at Hongkou, Dujiangyan City and Fig. 1(b) shows a similar case that occurred in the Miaoziping Bridge on the Duwen Highway. This bridge consisted of three-span continuous rigid frames and approach spans composed of 19×50 m spans simply supported girder with continuous bridge deck. The height of the pier columns exceeded 100 m. The collapse of the main girder was most likely caused by ground acceleration amplification due to the relatively flexible piers and large mass of the bridge deck, resulting in large inertia forces and considerable translational and rotational motions of the girders during the earthquake. The girder fell down after the shear key failed under the impact of the girder. Figure 1(c) shows the Naba Bridge of Pinwu County, which also suffered similar failure.

It was found that many collapsed bridges either had insufficient seat width or were located directly near a major fault rupture. The near-field effect was an essential cause of these failures. Most multispan simply-supported girder bridges have shorter fundamental periods (such as the Gaoyuan Bridge, Nanba Bridge and Longwei Bridge, whose fundamental periods were less than 1 s). Compared to far-field ground motions, there was significantly more displacement amplification for short-period inelastic bridges in the near field.

According to the Chinese Specification of Earthquake Resistant Design for Highway Engineering (MCPRC, 1990), the minimum seat width a defined as shown in Fig. 2 should satisfy:

$$a \geq 50 + L \quad \text{(cm)} \tag{1}$$

(a) Gaoyuan Bridge (VII/IX) (b) Miaoziping Bridge (VII/IX) (c) Nanba Bridge (VII/IX)

Fig.1 Girder failure of RC girder bridges (Note: for "A/B" in parenthesis, "A" denotes the specified intensity and "B" denotes the estimated intensity during the quake, and the same holds below)

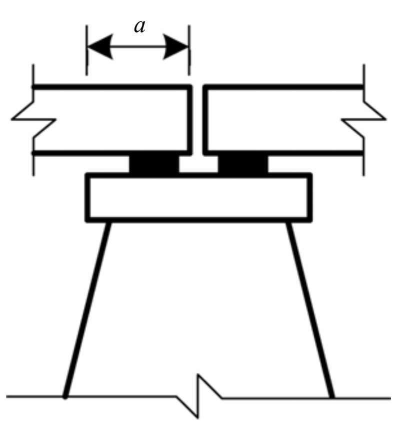


Fig. 2 Minimum seat width in Chinese specifications

where L: computational span length (in m).

In the Chinese Guidelines for Seismic Design of Highway Bridges (MCPRC, 2008) issued just after the Wenchuan earthquake, the a has been modified as

$$a \geq 70 + 0.5L \tag{2}$$

Note that in both the China Specifications/Guidelines, the influence of the seismic performance category, substructure height and angle of skew, etc., were not explicitly considered. For bridges with L= 40 m, both Eqs. (1) and (2) provide the same minimum seat width of a = 90 cm. In fact, the specification in Eq. (2) was given by the 1996 Japanese seismic design specifications of highway bridges revised in 1996 reflecting the destructive damage caused by the 1995 Hyogo-ken Nanbu earthquake (i.e., the Kobe earthquake) (Kawashima, 1997). Note that in addition to providing sufficient seat width and elastic padding between two adjacent girders to prevent failures of this type, it is recommended that strong hinge restraints be used to restrain relative motions in the longitudinal direction.

2.2 Damage to expansion joints

Seismic waves may cause differential movement between the super- and substructures. Large differential movements may cause span failure due to unseating. Even with small differential movements, expansion joints may be either pushed against each other, causing a compression type of failure, or pulled apart, causing a tensile failure. In general, seismic deflections may be severely underestimated for structures located in near-field areas. Damage to superstructures was mostly due to pounding of adjacent segments at expansion joints. Expansion joints were commonly used to relieve the structural system from the internal forces generated by the change of environmental temperature. They were also the weak parts of the system and were easily damaged by large, instant or permanent deformation of the foundation. Figure 3 shows damage to expansion joints observed in this event.

2.3 Damage due to impact of girders

The impact damage occurred as a result of underestimating the maximum relative displacement between adjacent members. Figure 4(a) shows the impact damage to a viaduct in Mianzhu City. Damage of this type was more obvious in skew bridges, as the centerline of a skewed bridge is not perpendicular to the centerline of its piers. The collision of the deck with the abutment pier may induce rotations of the deck in the horizontal plane. The rotation of the deck may accumulate as the cyclic ground excitation continues. If the accumulated rotation is large enough, the bridge deck may lose support at corners with acute angles or even collapse. The rotation may also induce damage to the deck at corners with blunt angles as shown in Fig. 4 (b).

(a) Mawei River Bridge (VII/IX) (b) Lujiaoyan Bridge (VII/IX) (c) Mianyuan River Bridge (VII/VIII)

Fig. 3 Permanent deformations at expansions joints of bridges throughout the affected region

(a) Jinguan Viaduct (VII/IX)

(b) Xinding Skewed Bridge (VII/IX)

Fig. 4 Impact damage to bridge superstructure

2.4 Damage to bearings

Bearings, especially seismic isolation bearings, can protect the superstructure from damage by reducing its response to earthquake excitation. However, it was found that improperly installed bearings may instead cause more damage. Figures 5(a) and 5(b) show the failure of the bearings in the Longwei Bridge in Beichuan County and the Yinxu Minjiang Bridge, respectively. The failure was due to a lack of connections between the rubber bearings and adjacent components of the bridge structure. The bearings, therefore, are in a "floating" condition and cannot withstand the lateral or longitudinal relative movement between the pier cap and the deck, resulting in collapse of the deck. Figure 5(c) shows the shear failure of the bearing of Huilan Bridge in Mianzhu City. Figure 5(d) shows the maximum unrecoverable deformation of 15 cm of the bearing on the same bridge.

2.5 Damage to pier columns

Bridge pier column failure is also a common type of structural failure of bridges in earthquakes (Kawashima and Unjoh, 1997; Hsu and Fu, 2004). Single pier column is more vulnerable to failure than other components of bridge. As far as portal frame piers and multi-column piers, the bridge pier columns are usually weaker components in the system and strengthened by strong transversal beams with strong joints to make sure the plastic hinges occur in the columns instead of elsewhere (Priestley *et al.*, 1996). Therefore, the pier columns must have excellent ductility to withstand large deformations during an earthquake. This concept has been used in

(a) Longwei Bridge (VII/XI)

(b) Yinxu Minjiang Bridge (VII/X)

(c) Huilan viaduct (VII/IX)

(d) Huilan ramp Bridge (VII/IX)

Fig. 5 Bridge bearings damage in Wenchuan earthquake

both the design of new bridges and also in past designs. Moreover, good ductile performance for bending usually implies a considerably deformational capability and may prevent collapse of the entire structure during the earthquake.

The failure modes of RC pier columns observed in this survey can be divided into two categories, i.e., bending failure and bending-shear brittle damage. Figure 6 shows a pair of pier columns that have lost their concrete protective layers due to cyclic bending moment, indicating insufficient bending capacity. Figure 7 shows a pier column of the Jueyuan Bridge, which suffered bending-shear brittle damage at its middle height, leading to a crack throughout the entire section of the pier column. Another four spans of the bridge totally collapsed due to column bending failure.

2.6 Damage to retaining block /shear key

Damage to retaining block/shear key is another common mode of damage to bridges in this earthquake. Figure 8(a) shows the damage to the retaining block at a position where the superstructure changed from T-beams to plates. The retaining blocks in Figs. 8(c) and 8(d) are 15 cm wide and were reinforced with 6Φ14 rebar. It is clear that these blocks did not have enough strength and reinforcement to resist lateral force. Therefore, it is important that retaining blocks/shear keys be strong, ductile, and wide enough to resist the imposed force and prevent the beams from falling.

2.7 Damage to beam cap and juncture

As shown in Fig. 9, the beam cap of the Longwei Bridge was cracked by a combined effect of gravity and earthquake related inertia forces. The crack initiated from the connection zone between the beam and the cap, and penetrated throughout the entire transversal beam almost vertically as a result of strong shear force induced by the earthquake. The crack width was as large as 6 mm, implying insufficient shear reinforcement. Figure 10 shows juncture damage of the Beihua Bridge, where the column and beam joints and the lateral braces were damaged as a result of strong shear force during the earthquake. The crack width was as large as 50 mm, also implying insufficient shear reinforcement. This failure indicated that the design of the column and beam junctures had at least two deficiencies: (1) insufficient shear capacity, especially in the column-beam juncture and (2) insufficient anchorage of rebar at the column end and improper design of the joint connecting the column and the lateral braces.

2.8 Damage to abutments

The rotation of the abutment and the excessive settlement of the foundation under the abutment are common modes of abutment damage. Figure 11(a) shows the settlement of the foundation under the abutment of the Shoujiang Bridge in Duwen Highway. The soil pressure in the longitudinal direction increased considerably as a result of the vertical ground acceleration, pushing the walls of the abutment to the water side. The impact on the abutment by the main girders generated larger passive soil pressure on the abutment, which pushed the lower part of the wall further towards the water side. Large settlement occurred when the lower part of the retaining wall was displaced towards the water, and consequently, cracks on the retaining wall developed because the top of the abutment was restrained by the superstructure. Figures 11(b) and 11(c) show inclined cracks in the abutment of the Duwen Highway and horizontal cracks in the abutment of the Gangou Bridge in Dujiangyan City, respectively. Damage observed to abutments of the bridges in this earthquake suggest that the abutment back wall, backfill, and approach slabs should be carefully designed and constructed to prevent collapse.

3 Damage to curved RC bridges

A curved bridge has a complex configuration. Under earthquake shaking, it may experience additional

Fig. 6 Bending damage of pier of Baihua Bridge (VII/XI)

Fig. 7 Bending-shear damage of pier of Jueyuan Bridge (VII/X)

(a) A viaduct in Duwen Highway (VII/IX)

(b) Lujiaoyan Bridge (VII/IX)

(c) Mawei River on Wuxin Road (VII/IX)

(d) Lonwei Bridge (VII/XI)

Fig. 8 Bridge retaining block failure

Fig. 9 Beam cap cracking of Longwei Bridge (VII/XI)

Fig. 10 Juncture damage of Beihua Bridge (VII/XI)

bending moment due to the eccentricity of the mass center. It may also exhibit asymmetrical responses as a result of the combined effect of vertical and horizontal ground motions, making curved bridges more vulnerable to extensive damage and possible collapse. Figure 12 shows the collapse of the curved part of the Baihua Bridge. The Baihua Bridge was constructed in 2004 and is located at state route 213, about 2 km from Yingxiu Town, the epicenter of the main central fault (Yingxiu-Beichuan Fault). The total length of the bridge is 495.55 m. The substructure was supported by twin-column piers connected by lateral braces, and the piers were about 20–30 m high. The common types of component failures observed for the Baihua Bridge include shear-flexural failure of the pier columns, expansion joint failure, shear key failure, juncture damage, lateral braces between

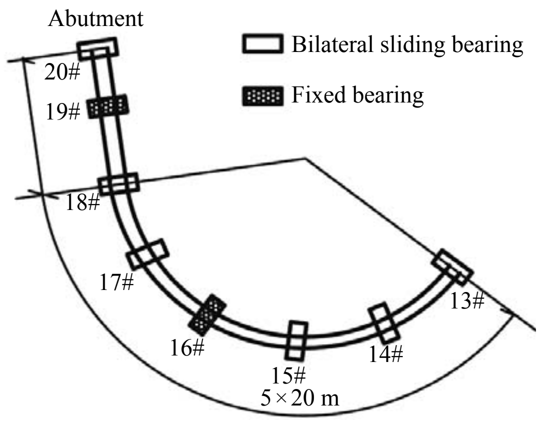
(a) Abutment collapse and broken deck on one-side of the Shoujiang Bridge (VII/IX)

(b) Bridge in Duwen Highway (VII/IX)

(c) Gangou Bridge (VII/IX)

Fig. 11 Abutment damage of RC bridge in Wenchuan earthquake

(a) Collapse of Baihua Bridge



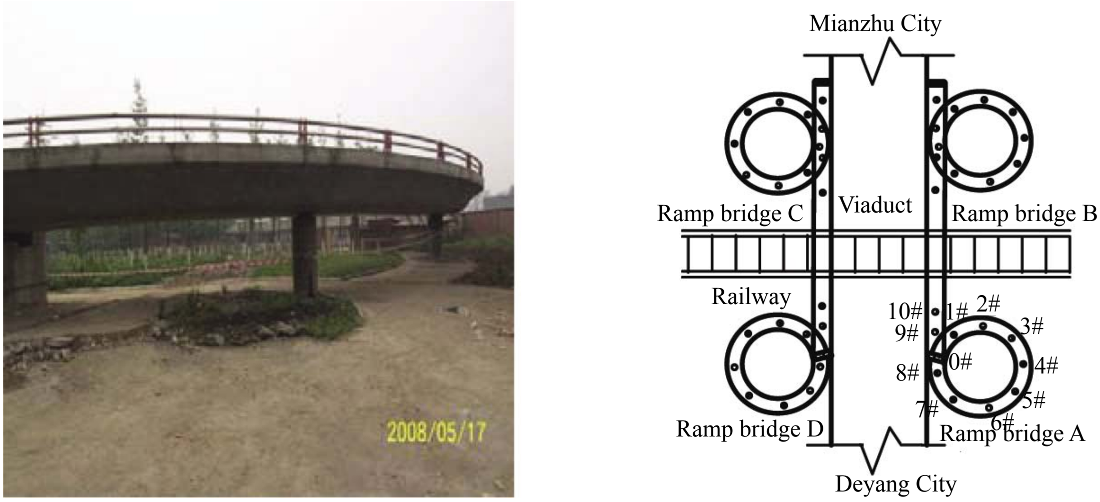
(b) Plane view of Baihua Bridge

Fig. 12 Collapse of curved segment of Baihua Bridge (VII/XI)

twin-column piers failure, rubber bearings failure. The possible causes of bridge collapse are summarized as follows: (1) the bridge is about 2 km from the epicenter of the main central fault, and a sub-fault passed through near the bridge so the fault effect was an important factor in the collapse of the bridge; (2) insufficient support length of the transversal beam and lack of longitudinal and vertical displacement restraints; (3) displacement of the piles due to the settlement of the newly deposited soil, amplified by the long pier columns; (4) excessive ground motion that displaced the curved girder from the bearing at the outer side of the curve, resulting in the collapse of the superstructure, initiating from the side towards the Yingxiu Town; (5) insufficient loops in the plastic hinge to provide necessary shear capacity; (6) improper design of the joint connecting the column and the transversal beam; and (7) complex dynamic behavior of the curved bridge in a complex mountainous region. Curved bridges with high pier columns usually exhibit complex dynamic behaviors when subjected to vertical and horizontal ground motions simultaneously. The eccentricity of the mass center may cause more problems by generating additional bending moments and torsional effect.

The ramp bridge of the Huilan interchange was constructed in 2004 and located in Mianzhu City. It consists of a viaduct and four twisted ramp bridges as shown in Fig. 13. The viaduct is approximate 318 m long and 38 m wide. The substructure of the ramp bridges consisted of curved continuous box-girders, and the planar projection was circular. The radius of the ramp bridges was about 20 m, the height of the box-girder was 1.4 m, and the top and bottom widths of the box-girder were about 4 m and 2.2 m, respectively. The eight circular pier columns were circumferentially distributed evenly and the pier columns were about 1.8 m to 7.2 m high.

Some piers were fixed at their top to the box girder, i.e., the curved ramp, while others were connected to the superstructure via rubber bearings. The tops of the fixed piers were damaged during the earthquake since they experienced larger earthquake loads. The failures of 2# and 4# piers are shown in Fig.14, where the diameter of the pier columns was 800 mm, the circumference of the pier columns was reinforced with 20Φ25 rebar, and the ratio of longitudinal reinforcement was 1.95%. The hoop rebar distance of the pier column was about 100 mm to



(a) Ramp bridge of Huilan interchange (b) Plane view of Huilan Bridge

Fig. 13 Ramp bridge of the Huilan interchange (VII /IX)

(a) Failure of 2# pier of ramp bridge A (b) Failure of 4# pier of ramp bridge A

Fig. 14 Pier damage to Huilan interchange ramp bridge (VII/IX)

200 mm with Φ12, and the corresponding volume ratio was about 0.26% to 0.56%. No region was found where the hoop rebars of the volume ratio were less than 0.3% and spacing was not more than 100 mm as specified by JTJ 004-89 (MCPRC, 1990). The JTG/T B02-01-2008 (MCPRC, 2008) requires the minimum volume ratio of transverse reinforcement in the potential plastic hinge region to be at least 0.4%. This may be one of the major causes of damage to the fixed piers at their top. The damage took a compression-shear mode, with steep diagonal cracks and an expanded core of concrete. Two lateral ties failed in tension while the longitudinal rebar did not yield. Under the cyclic action of the vertical earthquake load, the concrete of the piers was smashed, losing vertical loading capacity. Therefore, to prevent this type of failure, more lateral ties should be used in future designs.

4 Damage to RC arch bridges

RC arch bridges have been widely adopted in the western mountainous area of China. The majority of these bridges survived the earthquake, with only a small percentage of failures. Figure 15 shows the collapsed Xiaoyudong Bridge, which was a RC frame arch bridge. The collapse of the bridge was due to the combined effect of the displacement of the fault near the bridge, liquefaction of the soil and insufficient reinforcement (Φ6@200) to resist the shear forces during the earthquake. The possible causes of its collapse are summarized as follows: (1) large topographical changes such as motion of the fault due to the strong earthquake; (2) large/uneven settlement of the foundation due to liquefaction of the soil; and (3) large internal forces or deformations that exceeded the capacity of the structural members.

Figure 16 shows a two-span half-through RC arch bridge in Anxian County. The inclined struts were cracked with a maximum crack width of 8 mm as shown in Fig. 16 (b). Cracks also appeared in the main arch and had a maximum width of 5 mm.

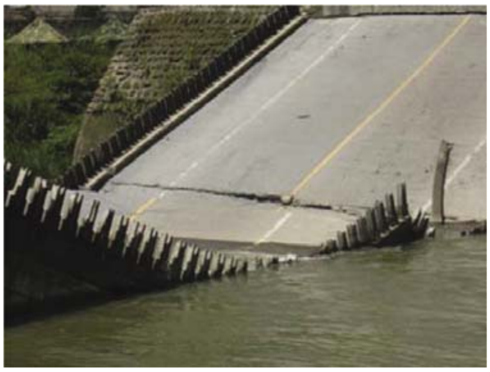
Figure 17 shows the collapsed Jingtianba Bridge in Qingchuan County. This bridge was built in 1999, and very lightly reinforced. The major reason for the collapse of the bridge was its poor design and construction quality. Other similar bridges in the near region did not suffer damage during the earthquake.

Figure 18 shows the Miaoba Bridge in Dujiangyan City. The rib of the main arch and the vertical strut were severely damaged. Note that this bridge had been retrofitted before the earthquake using FRP to strengthen the main arch. It seemed that the retrofitting did not help enhance the seismic resistance of the bridge.

(a) An overview

(b) Close up of the failed bridge and liquefaction about the piers

(c) Fault near the bridge, showing a ground surface sank 1.2 m



(d) Lateral-shift of the deck of about 30 cm

Fig. 15 Collapse of Xiaoyudong Bridge (VII/X)

(a) An overview

(b) Bottom struts crack

Fig. 16 Damage to the Anzhou RC arch bridge (VII/IX)

(a) An overview of the collasped bridge

(b) Reinforcement was lacking

Fig. 17 Collapse of Jintianba Bridge (VII/VIII)

(a) Overview of the Miaoba Bridge

(b) Detail of Miaoba Bridge damage

Fig. 18 Miaoba Bridge (VII/XI)

5 Damage to masonry arch bridges

Masonry arch bridges are very common in the county road system in the western mountainous area of China. The majority of these structures survived the earthquake, and resumed carrying traffic loads soon after the event. Only a few masonry arch bridges failed during the earthquake. Figure 19 (a) shows the collapse of Yingxin Bridge in Shifang City. The ventro-arch of the Guantong Bridge in Shifang City was severely damaged as shown in Fig. 19 (b); furthermore, major cracking of its main arch shoulder and footing occurred. The major reason masonry arch bridges survived the earthquake is that they have relatively short spans, were well constructed, and in particular, were founded on a rigid base.

(a) Collapsed Yingxin arch stone bridge (VII/IX)

(b) Ventro-arch damage (VII/IX)

Fig.19 Damage to masonry arch bridges

6 Summary of lessons learned

The 2008 Wenchuan earthquake provided an opportunity to learn from a detailed survey of the failures so that future bridges can be better designed and built in mountainous, earthquake prone areas in the future. Some lessons learned are as follows:

(1) Capacity design procedures, ductile details and generous seat widths are necessary to prevent catastrophic collapse during large earthquakes.

(2) Important structures must be designed to a higher level of performance than provided by current specifications, if full service is to be maintained after a large earthquake. Multi-level performance criteria and corresponding design strategies are necessary for important bridges.

(3) Premature failures of some bearings appear to have reduced the seismic loads of their supporting substructures by uncoupling the superstructure from its supports. This fuse-like action may have saved a number of spans from collapse and columns from failure in shear and flexure.

(4) Seismic isolation can minimize the damage caused by earthquakes, so there is a need to design better damping devices and isolation bearings to decouple energy and motion for use in areas of high seismicity.

(5) Skewed bridges are susceptible to in-plane rotation, leading to large displacements at their supports and possible unseating of girders in acute corners.

7 Conclusions and suggestions

The 2008 Wenchuan earthquake caused widespread and catastrophic damage to highway bridges. A 46-day field investigation was conducted by the authors in the affected area and over 320 bridges were examined. In this paper, damage to different types of bridges, including RC girder bridges, curved RC bridges, RC arch bridges, and masonry arch bridges, are described. A preliminary analysis was carried out, with particular emphasis on RC girder bridges, for which damage features of the major members of the bridge are provided and discussed.

In general, most of the damage and collapse of bridges observed in this survey was caused by inappropriate design and/ or large ground movement induced by the nearby fault strip. Typical damage modes included shear-flexural failures in nonductile reinforced concrete columns, unseated girders due to bearing failures, and gross foundation movements due to liquefaction. In addition, some pounding between spans occurred and approach fills behind abutment walls were unsettled. Some special structures also suffered typical damage, such as excessive rotation of a skew bridge on pin-ended columns.

Rubber bearing technology seemed to be effective in mitigating seismic hazards to bridges in regions of high seismicity. They have great potential for use in both new construction and retrofitting. However, they can also cause undesired overly large displacements to occur. More research on both isolation bearings and displacement control is needed.

As stated earlier in this paper, an overview of the causes of damage and collapse in this earthquake may offer new guidelines for bridge design and further considerations for improving code provisions.

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