- Technical Paper -

# SEISMIC DAMAGE APPROACH OF A RC RIGID-FRAME ARCH BRIDGE AFFECTED BY WENCHUAN EARTHQUAKE, 2008

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#### ABSTRACT

Xiaoyudong Bridge, a rigid-frame arch bridge, received great damage in Wenchuan Earthquake, 2008. Based on the detailed field survey, failures of Span 1 were mainly caused by the surface fault, while Span 3 and 4 entirely collapsed, and Pier 3 titled about 7.5° mainly by the seismic effect. Pushover analyses were performed to evaluate the bearing capacity, and to approach the mechanisms of Span 4. Consequently, the reinforcement of mid-span may firstly yield at 0.40g. However, the support loss will cause failures occur earlier, which is considered to be the main reason of the collapse of Span 4. Keywords: rigid-frame arch bridge, failure mechanisms, pushover analysis

### 1. INTRODUCTION

Wenchuan Earthquake, which occurred in Sichuan Province, China, at 2:28 p.m. (Beijing time) on May 12<sup>th</sup>, 2008, had a magnitude of 8.0 by CEA (China Earthquake Administration) and 7.9 by USGS (US Geographical Survey)<sup>[1]</sup>. Authors conducted a detailed field-damage survey of Xiaoyudong Bridge on September 27th, 2009, which crossed Baishui River in Xiaoyudong Town. This bridge is a 189m long, 13.6m wide, 4 spans, rigid-frame arch bridge that was built in 1998. Rigid-frame arch bridge is a composite structural type of arch bridge and inclined rigid-frame bridge. According to reference [2], this type of bridge has been abundantly constructed in China since 1980s thanks to its advantages of construction, weight and appearance as well. Besides, the accumulative total span length of this type bridge is more than 15 thousand kilometers<sup>[2]</sup>. However, the research for the behavior of rigid-frame arch bridge under seismic effects, is still of great insufficiency.

As shown in Fig.1, based on the field survey, bridge structure, surface faults, as well as observed damage are presented. Then, pushover analyses for single span are performed to evaluate the bearing capacity of this type of bridge, and to approach the failure mechanisms of Span 4 after lost the support from abutment.

# 2. BRIDGE STRUCTURE AND DAMAGE CONDITION

#### 2.1 Bridge Structure

Due to the lack of design drawings of Xiaoyudong Bridge, the detailed dimensions and the reinforcement information have been assumed based on the results of field survey and referred from another rigid-frame arch bridge (Jinzhai No.6 Bridge<sup>[3]</sup>, Anhui, China), which has almost the same characteristics with Xiaoyudong Bridge, as the span length, the rise, the width-girder ratio and the design seismic fortification intensity of 7 degree. Here, as shown in Fig.2, the





Fig.2 Assumed length of spans before the earthquake based on the survey (unit: mm, from upstream)

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Fig.3 Dimensions of Xiaoyudong Bridge based on the survey (unit: mm)



Fig.4 Intensity scale and surface faults



Fig.5 Surface fault around Xiaoyudong Bridge

abutments, piers and spans were numbered from the left bank. Based on the data measured by measuring tape, Span 1 has a length of 42.35m, while Span 2 and 3 have the same length of 43.15m. Thus, considering the same length of Span 2 and 3, and no geographical limitation for piers and abutments, four spans are assumed to be symmetrical. As the river went through Span 4, and the girder collapsed into water, it was impossible to measure the girder of Span 4. Noticing the symmetry of the entire bridge, the length of Span 4 was assumed as same as Span 1 of 42.35m. The details of Span2 as examples are illustrated in Fig.3 that the arch leg (Point A) and the inclined leg (Point B) has 21° and 40° slope respectively. The arch frame is formed by two arch legs from the pile caps, and the girder in the middle span. This arch frame composes one single rigid-frame, together with two inclined legs, and the girders (Point C) at ends of deck. One span consists of five rigid-frames connected by crossing beam (Point D), arch slab (Point E), and extending slab (Point F). Four spans are supported by rubber bearings and connected by piers abutments. A pier consists of a reinforced concrete frame with two columns and a beam, upon which two decks were simply supported. The legs were connected to the pile cap supported by reinforced concrete piles.

# 2.2 Surface Fault Condition

According to Reference [4], there are two main surface faults after the earthquake: Beichuan-Yingxiu Fault (B-Y Fault in Fig.4), Guanxian-Jiangyou Fault (G-J Fault). Another fault named Xiaoyudong Fault (XYD Fault) connected these main two. Our object bridge Xiaoyudong Bridge (the triangle in Fig.4) is located between that two main surface faults and on this connecting Xiaoyudong Fault.

Besides, based on Reference [5] and [1], as shown in Fig.5, a surface fault went through the right dyke at about 70m upstream (Point A). This fault displacement extended to downstream along the right dyke and crossed the road at 10m (Point B) and 50m (Point C) behind A1. On the other hand, no obvious trace of surface fault has been found at the left dyke.

# 2.3 Observed Damage

To confirm the influence of the surface faults, detailed field survey of the span length has been done by using both the electrical total station and the measuring tape (shown in Fig.6). The method is illustrated in Fig.7. We measured the length of Span 3 as 43.15m by measuring tape and assumed the length of Span 4 as 42.35m as mentioned in Chapter 2.1. Thus, the original distance between P2 and A2 (length of Span 3 and 4) before the earthquake was predicted as 85.50m. On the other hand, the actual distance between P2 and A2 was observed again by using electrical total station. Therefore, the change of span length was got as -0.252m (=85.248- 85.500). Thus, the average length change of Span 3 and 4 is about 12.6cm, which is





relative small and might not have great influence to the failure. By same procedures, the changes of span length were also got as -0.052m for Span 2, which is ignorable, and -0.347m for Span 1,. Thus, it can be inferred that, the surface fault mainly effected on Span 1.

For the detailed damage conditions, as shown in Fig.8, Span 1 moved about 75cm downwards at middle span (Point A) and there was great collision between the girder and A1 (Point B) probably due to the surface fault mentioned, which consequently caused the girder moved about 50cm into A1, and the shear failure of side wall (Point C). Because the settlement of A1, the arch legs collided with the revetment next to A1 (Point D), great shear failures occurred to the bottom of arch legs (Point E) and the top of inclined legs (Point F). Besides, some cracks occurred to the bottom of the legs (Point G) on Pier 1. For Span 2, damages are relatively slight that the middle span moved about 10cm upwards and some cracks have been observed at the bottoms of both inclined legs and arch legs. Pier 3 tilted averagely 7.5 ° toward A2 (8.08 ° from up stream, 6.85 ° from down stream of the bridge). The piles under it suffered great damage due to this tilt. Span 3 and Span 4 collapsed entirely, while the arch legs and inclined legs on them failed as well. Besides, there are shear failure on the side wall of A2, and a permanent displacement of the support about 20cm in the backsoil side.

# 3. EVALUATION OF BEARING CAPACITY

#### 3.1 Analytical Model

The model has been made for Span 2 where damage was few, to evaluate the bearing capacity (using the definition that failure to less than three parts on the rigid-frame arch). As shown in Fig.9, on the transversal direction of the bridge, noticing five arch frames were arranged together to form one span, here select one single arch frame, included the arch slab, to establish the 2-dimensional model. A horizontal spring



Fig.7 Method of measuring



Fig.8 Damage of Span 1 (from downstream)



Fig.9 Model for single span

and a rotational spring are used at the bottom of each footing, ignoring the vertical displacement, according to former analyses. Besides, for the springs between the girders and the piers, one shear resisting spring, and one vertical spring which is only able to support the compression are in use for each side. Additionally, axial forces under only dead load are used to calculate the tri-linear M- $\Phi$  relationship based on References [6]. Noticing greater sectional area and greater amount of reinforcement, rigid element is set to the following parts: footings, the beam on the top of the piers and joints between legs and girder.

#### 3.2 Analytical Result

As illustrated in Fig.10, as the horizontal load growing up to 0.40g (g: value of gravity), the tensile reinforcement at middle span (Point A) will yield due to negative moment, then this cross section reaches at the ultimate stage at 0.62g. Because the negative failures happen relatively early, the positive flexural moments do not develop greatly in elements at middle. For the inclined legs, the first yield of tensile rebars occurs to the left bottom (Point B) at 0.47g horizontal load. The same point will reach at the ultimate stage as

the load increase by 0.01g. Then the yield of tensile rebars and the ultimate stage will happen to the right bottom of the inclined leg (Point C) after the horizontal load becomes greater than 0.53g. For the arch legs, the damage will happen to the left bottom at first among all parts: cracks occur at 0.29g, yield of reinforcement at 0.93g. Under 0.62g horizontal load, when is the ultimate stage of middle span, the vertical displacement about 3.1cm happens to the point of middle span.

Consequently, as being defined in 3.1, noticing the failure of middle span (Point A), and both bottoms of the inclined legs (Point B and C), the bearing capacity is considered to be 0.53g.

# 4. DAMAGE APPROACH

The enormous damage that occurred to Span 3 and 4 drew our attention. To find possible mechanisms of failure, the detailed damage condition is summarized and an approach analysis is done as following.

#### 4.1 Detailed Damage Condition of Span 4

As shown in Fig.11, for A2, there is a 20cm permanent displacement of the support into backsoil



Fig.11 Detailed damage of Span 4 (from downstream)



Fig.12 Sequence of failure based on approach analysis

(Point A) due to the collision between the girder and A2, and thus shear failure on the side wall (Point B). It should be noticed that at the joints of the girder and the arch legs, different types of failure occurred to left and right. On the left (see from downstream, Point C shown in Fig.11), by the negative moment, failure occurred because the reinforcement on the upside of girder resisted tension while the downside concrete resisted compression, which suggests that the girder of the left end might fell down before the failure of middle span. Differred from left, the girder on the right (Point D) was pulled by positive moment to separate from the joint, which caused the extensive crack at the joint.

#### 4.2 Approaching Analysis and Result

Considering the phenomenon that backwards movement occurred to the support on the top of the abutment, the possibility might be great for the girder on A2 to drop down after lost the support from the abutment. Further, the difference of the joint failure between left and right also suggests the failure occurred to two sides of Span 4 at different time, that the right side (from upstream) probably drop first.

Therefore, a new pushover analysis is performed to approach the mechanisms of Span 4. Compared with the former one, the right support is removed in the new analysis to simulate the girder at the right side loses the support of A2 and the span was modified as 42.35m of Span 4. Horizontal load is also pushed from right to left, to simulate the seismic effect.

The analytical result is explained in Fig.12. As shown in Fig.12(a), due to the loss of support, the top of the right inclined leg (Point A) and the girder next to the right joint with the arch leg (Point C) will reach their ultimate stages, while reinforcement will yield at the bottom of the right inclined leg (Point B) under only dead load. Besides, the failure will happen to the other points much earlier as well compared with that in the standard case in Chapter 3. As illustrated in Fig.13, (a) shows the responding curvature of point at the left of middle span (Point D), from which we can see that the curvature will reaches at  $\Phi_{vD}$  (yield curvature of Section D) at 0.17g horizontal load (0.40g in the standard case). Similarly, at the top of right arch leg, the curvature will reaches at  $\Phi_{vE}$  (yield curvature of Section E) under 0.59g horizontal load (no yield until 1.0g in the standard case). Because of the collision after the girder and the drop of the inclined leg at the right side, the actual failure to the right arch leg probably



occur even earlier than 0.59g. By using the definition of the bearing capacity as well, the failures of right inclined leg (Point A and B), right side of the girder (Point C) and the middle span (Point D) will cause the entire stability to lose. Therefore, the failure is likely to happen to Span 4 around 0.17g horizontal load as lost the support from the abutment, which is much earlier than the bearing capacity of 0.53g mentioned in Chap3.

#### 4.3 Failure Mechanisms of Span 4

According to the detailed damage condition mentioned in Chapter 4.1 and the approaching analysis conducted in Chapter 4.2, the possible failure mechanisms of Span 4 has been summarized and illustrated in Fig.14 (view from upstream).

As step 1 which is illustrated in Fig. 14(a) and details in Fig.15, the longitudinally movement of the deck of Span 4 due to the earthquake effect, as well as the movement of foundation, led to the collision between the deck of Span 4 and A2. Because of the weakness of A2 against collision, that caused the parapet and the pavement on A2 slid about 20cm into the backsoil together with the deck, and also caused the



Fig.14 Failure mechanisms of Span 4 (from upstream)

shear failure at the side wall of A2 (shown in Fig.15(a.2)). Then, the girder moved on reversal direction. As shown in Fig.15(a.3), once the displacement of girder towards left became greater than 20cm, Span 4 lost the support from A2. Thus, based on the analytical result, the inclined legs and the girder on the right side received greater applied load, which caused the damage occurred to them (Fig.14(b)). Then, failure happened to middle span soon. Shown in Fig.14(c), as the pier and inclined leg still supported the girder on the left but failures already occurred to the right half span, the support at left and the drop at right formed greater positive moment and pulled the girder to separate from the left joint with the arch leg. Thus, the left half also failed and the entire span collapsed into the water. Consequently, Pier 3 was pushed to tilt by the force from Span 3, which caused the enormous chain failure of Span 3.

# 5. CONCLUSIONS

- (1) A1 and the deck of Span 1 were damaged enormously by the collision, and Span 1 was shortened by about 35cm. Noticed there is only an ignorable length change of Span 2 about 5cm, it can be inferred that the influence of the surface fault was relatively limited to Span 1.
- (2) By the pushover analysis for single span without support movement (Span 2 for instance), the bearing capacity is thought to be 0.53g horizontal load, till when the reinforcement will yield at the cross sections of middle span, and the bottoms of both the right and the left inclined legs.
- (3) As Span 4, if the girder loss the support, damage

### Fig.15 Details of step 1

will occur to left inclined leg and girder immediately and to middle span as early as 0.17g horizontal load. This is thought to be the main reason of the entire failure of Span 4, and consequently failures of Pier 3 and Span 3.

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