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SHAKING TABLE TEST STUDY ON SEISMIC PERFORMANCE OF CONCRETE ARCH BRIDGE WITH STEEL WEB

Huihui Yuan(1), Qingxiong Wu(2) , Baochun Chen(3)

(1) *Assistant Researcher, College of Civil Engineering, Fuzhou University, yuanhh@fzu.edu.cn*
(2) *Professor, College of Civil Engineering, Fuzhou University, wuqingx@fzu.edu.cn*
(3) *Professor, College of Civil Engineering, Fuzhou University, baochunchen@fzu.edu.cn*

Abstract

Concrete arch bridge with steel web plate is a new type of composite bridge, of which the main arch ring consists of concrete top plate, bottom plate, and corrugated or plane steel web. This new structure has advantages of light-weight, convenient construction, and consequentially, extending the span of concrete arch bridge. In this study, three concrete arch model experiments in scale 1:14.5, including one conventional reinforced concrete (RC) arch model based on a practical project and two trial designed concrete arch models with corrugated steel web (CSW) and plane steel web (PSW), have been carried out to investigate the natural modes and seismic response by the Earthquake Simulation Triple Shaking Tables System at Fuzhou University. The first order natural frequencies of the arch models in the in-plane and out-plane directions were reduced by replacing the RC web with CSW and PSW webs due to the loss of the integral rigidity of the arch models; Under the transverse seismic excitations, the RC-CSW arch model presented the largest displacement response and out-plane acceleration magnification coefficients among the three arch models; Under the longitudinal seismic excitations, RC-CSW and RC-PSW arch models showed slightly larger displacement responses and in-plane acceleration magnification coefficients than those of RC arch model; As the PGA of longitudinal seismic excitations increased, a large number of cracks gradually occurred in the arch springing of RC arch model whereas the RC-CSW and RC-PSW models were still in elastic working stage. The maximum strain of RC arch model was approximately 1.5 times larger than the other two models. It is believed that the replacement of RC web with CSW or PSW can reduce the internal force of arch bridge.

Keywords: shaking table test, concrete arch bridge, steel web

1. Introduction

Concrete arch bridge with steel web plate refers to a new kind of composite structure, in which the conventional solid concrete webs of the cross section of RC arch rib are replaced by the corrugated steel web (CSW) or plane steel web (PSW) without significantly modifying the existing concrete roofs and floors. In comparison with the conventional RC arch bridge, these two types of composite arch ribs have several advantages such as less deadweight, more convenient construction, lower cost and shorter construction period. In the previous studies [1] of trial-design on the Lingdou Bridge, a 160m-span concrete arch bridge in Fujian Province, China, the replacement of concrete webs with steel webs can effectively reduce the deadweight by approximately 30%, and consequently decrease the internal force to some extent.

A linear seismic analysis of a RC arch bridge with CSW [2], whose span is 420m and rise of arc 80m, subjected to tri-directional ground motions was carried out by the FE software, ANSYS. The effect of vertical ground motions on the RC arch bridge with CSW was discussed by comparing the seismic responses from the tri-directional ground motions with those of the bi-directional (transversal and longitudinal directions) ground motions. The analytical results indicated that, under the vertical ground motion, the composite cross section of arch rib with CSW showed better seismic performance than conventional RC cross section. Using the nonlinear FE program developed by the author, *NL_Beam 3D* [3], two 3D FE models for the Lingdou Bridge respectively with CSW and PSW were established [4] to investigate the natural vibration characteristics and nonlinear seismic response characteristics under tri-directional ground motions.

However, the previous studies are still confined to the theoretical analysis by using FE software, and the validity and accuracy of these FE models have not been verified by experiments, especially the actual seismic responses of the new types of composite arch bridges during large earthquakes are not clear. At present, the shaking table simulation test is an effective way to obtain the actual dynamic responses of structures, especially for the long span bridges.

Therefore, in order to investigate the actual seismic responses of the concrete arch bridges with steel webs, three reduced-scale arch models, the RC, RC-CSW, and RC-PSW arch models, were firstly designed and manufactured according to the previous trial design. Then two types of strong seismic excitations, T111 and T211, recommended in the JRA Design Specification for Highway Bridges [5, 6], were selected and input in the shaking table tests, which were carried out in Fujian Provincial Key Lab of Structures. Finally, the differences and connections of dynamic characteristics among the three arch modes were discussed, aiming at providing reference for the seismic design and analysis of RC arch bridges with steel webs in China.

2. Experimental Program

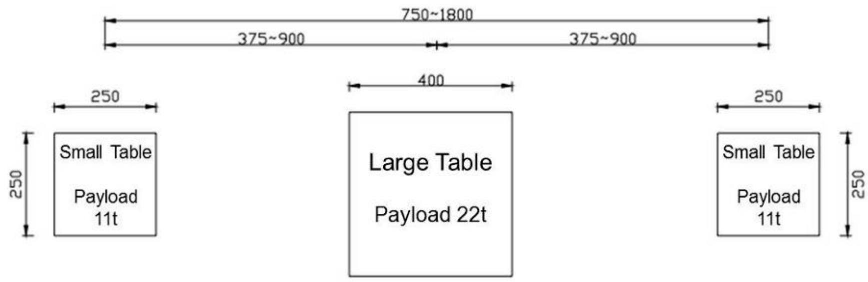
2.1 Experimental Facility

In order to truly reflect the actual seismic responses of three different arch-bridge models under strong earthquakes, as shown in Fig. 1, the Earthquake Simulation Triple Shaking Tables System (hereafter referred to as shaking-table system) in Fuzhou University is adopted in this study.

The shaking-table system consists of three shaking tables, among which the middle one is a fixed-position 4m×4m vibration table and a movable 2.5m×2.5m vibration table on each side, and all the three tables are able to move simultaneously in two horizontal directions. The three tables along a straight line are located in a foundation pit having the dimensions 11m by 32m. The minimum distance between the centers of fixed-position and movable tables is 3.75m; while the maximum distance is 9m (see Fig. 1b)).

The basic performance parameters of the shaking-table system are listed in Table 1. The vibration freedom degrees of this system are horizontal X, Y, and Yaw rotation. The maximum acceleration value of the three tables under full payload is 1.5g in horizontal direction X and 1.2g in horizontal direction Y, respectively. The working frequency range of the shaking-table system is between 0.1Hz and 50Hz. This means that most actual ground motions can be effectively simulated by this system.

(a) Photo of triple shaking tables



(b) Arrangement plane view of shaking table system (unit: cm)

Fig. 1 – Earthquake Simulation Triple Shaking Tables System

Table 1 – Basic performance parameters of the shaking-table system

Technical Parameters	Fixed-position Table	Movable Table
Table Size	4m×4m	2.5m×2.5m
Table Mass	10t	5.5t
Full Payload	22t	11t
Maximum Overturning Moment	600kN*m	220kN*m
Maximum Eccentricity Moment	110kN*m	50kN*m
Maximum Eccentricity	0.5m	
Maximum Displacement of Actuator	±250mm	
Vibration Freedom Degree	Horizontal X, Y and Yaw rotation	
Maximum Acceleration under Full Payload	1.5g for X and 1.2g for Y	
Vibration Wave	Periodic wave, random wave, earthquake wave	
Control Mode	Digital Control	

Considering the existing situation of experimental equipment, the dimensions and weight of the test models cannot exceed the bearing capacities of the shaking-table system, and the maximum span of model should be less than 20m. In this study, the arch models are fixed on the two moveable tables to achieve long span as far as possible. Besides, the weight of the test models are advised to be less than 80% of bearing capacity of vibration tables, i.e. 17.6t, due to the sum of maximal capacity of two movable tables, to keep stable performance of the test system. Therefore, according to the above requirements, the weight of the three arch models including structure deadweight and compensation weight is designed to be 13.3t when the clear span is chosen as 11m.

2.2 Test Specimens

2.2.1 Model 1 - RC Arch

In this study, the RC arch model is fabricated according to the aforementioned Lingdou Bridge, a 160m-span concrete arch bridge locate in Fujian Province, China. The RC arch model has an 11m-long clear span and a 2.75m-high arch rise, as shown in Fig. 2, which means the reduced-scale of the test model to the actual bridge is 1: 14.5 in longitudinal direction.

The cross section of the arch rib of the RC arch model is shown in Fig. 3(a). The sectional dimension of the RC arch model is 80cm×32cm, and the thickness of floor and roof concrete-plates is 7cm. For the concrete web, the height is 18cm and the thickness is 3.5cm. The diaphragm adopts 5cm-thick concrete plate at interval of 50cm. Symmetrical distribution of reinforcement is chosen for the arch rib, where 9 ϕ10mm longitudinal steel bars are both set in floor and roof plates and the reinforcement ratio is 1.26%. 2 ϕ10mm and 2 ϕ6mm longitudinal steel bars are both arranged in the webs; the stirrup uses ϕ6mm steel bars at interval of 15cm. The overview of the RC arch model fixed on the shaking tables is shown in Fig. 3(b).

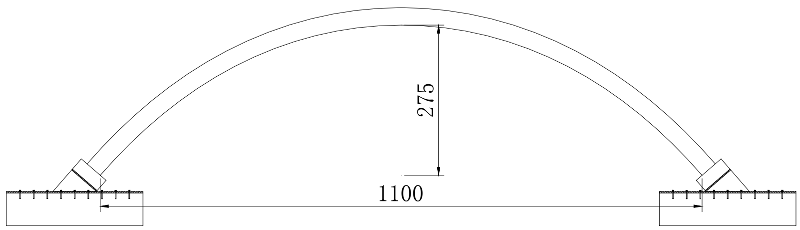
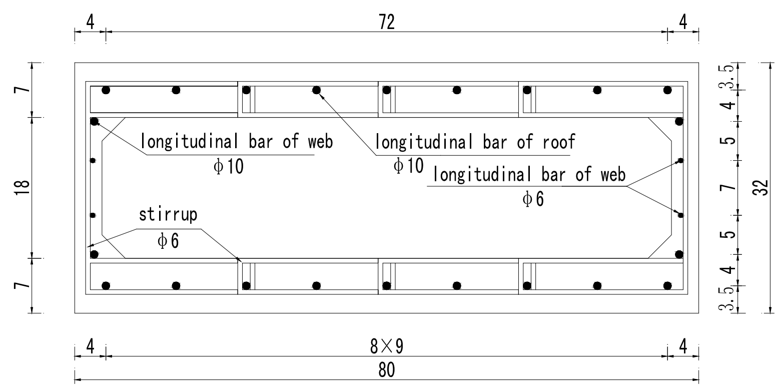


Fig. 2 – Schematic illustration of elevation arrangement for RC arch model (unit: cm)



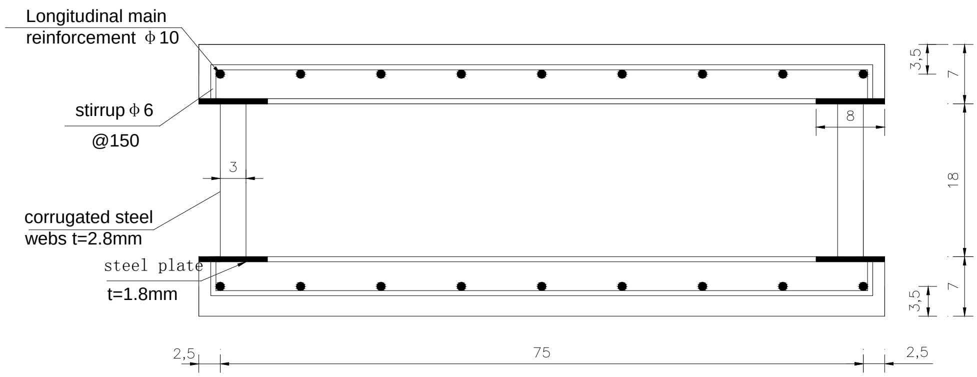
(a) Cross section of RC arch model (unit: cm)

(b) Overview of RC arch model

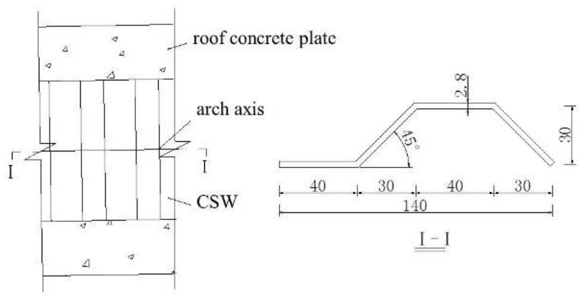
Fig. 3 – RC arch model

2.2.2 Model 2 - RC-CSW Arch

For comparison, the RC-CSW arch model (see Fig. 4(a)) adopts the same clear span, arch rise, sectional dimensions, and main reinforcement configuration as RC arch model. Instead of the RC web, the RC-CSW arch model adopts the corrugated steel web, of which the detailed dimensions can be found in Fig. 4(b). The RC-CSW arch model is divided into 4 arch segments; each segment is approximately 3.25m long and consists of corrugated steel web, steel connector and diaphragm. The arch segments were firstly prefabricated in the factory, then transported to the lab for assemabling. The overview of the RC-CSW arch model fixed on the shaking tables is shown in Fig. 4(c).



(a) Cross section of RC-CSW arch model (unit: cm)



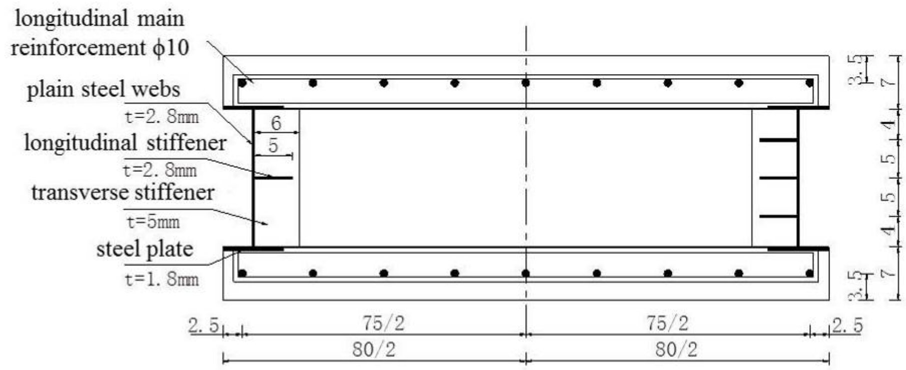
(b) Dimensions of corrugated steel web (unit: mm)

(c) Overview of RC-CSW arch model

Fig. 4 – RC-CSW arch model

2.2.3 Model 3 - RC-PSW Arch

For comparison, the RC-PSW arch model also adopts the same clear span, arch rise, sectional dimensions, and main reinforcement configuration as RC arch model. Instead of the RC web or CSW web, the RC-PSW arch model adopts the plane steel web, of which the thickness is 2.8mm, as shown in Fig. 5(a). In order to avoid the local buckling of the plane steel web, longitudinal and transverse stiffeners are placed on the steel web. Along the arch axis, one longitudinal stiffener is setup for normal cross section, while three longitudinal stiffeners for the cross sections around the arch spring; the width of each longitudinal stiffener is 50mm, and the thickness is 2.8mm. Besides, there is one transverse stiffener, of which the width is 60mm and the thickness is 5mm, welded on the web between every two diaphragms. The overview of the RC-PSW arch model is shown in Fig. 5(b).



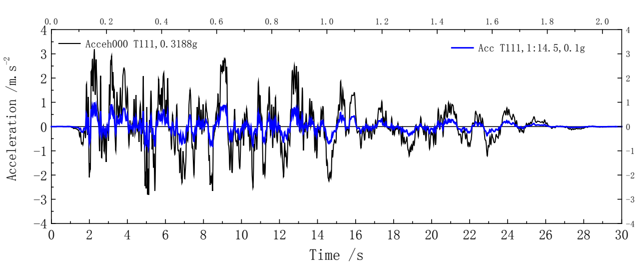
(a) Cross section of RC-PSW arch model (unit: cm)

(b) Overview of RC-PSW arch model

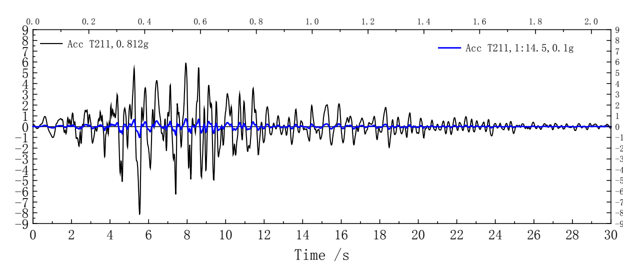
Fig. 5 – RC-PSW arch model

2.3 Input Ground Motions

As shown in Figure 6, the input ground motions named T111 and T211 for shaking table test are recommended standard seismic waves of Ground Type I, i.e. hard foundation, according to the Specification for Highway Bridges in Japan [5]. The ground motion T111 is a plate-boundary-type (Type I) seismic excitation, while T211 is a inland-direct-type seismic excitation. The peak ground accelerations (PGA) of T111 and T211 waves are 0.319g and 0.812g, respectively. Due to the reduced-scale effect, the duration of input seismic waves will be compressed to 1/14.5 of the original duration when carrying out the shaking table test.



(a) Seismic wave T111

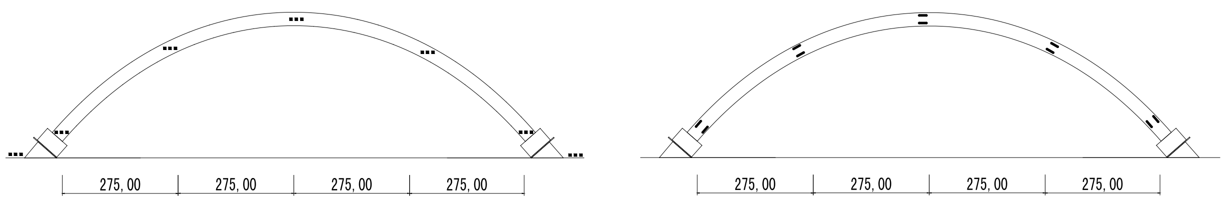


(b) Seismic wave T211

Fig. 6 – Time history curve of input ground motions

2.4 Measure Point Arrangement

As shown in Fig. 7(a), there are a total of 21 acceleration sensors for 7 measure points arranged on every arch model, i.e. three acceleration sensors for longitudinal, transverse, and vertical directions at each measure point. The measure points include two on the shaking tables, two on the arch springing sections, two on the cross sections at 1/4 clear span, and one on the arch vault section. For strain measurement, there are 5 measure points for each arch model, including two on the arch springing sections, two on the cross sections at 1/4 clear span, and one on the arch vault section, as shown in Fig. 7(b). For each measure point, both two strain gauges for steel and concrete are placed. In addition, in order to obtain the longitudinal and transverse dynamic displacement, there is one bilateral dynamic-displacement measure point set on the arch vault bottom section.



(a) Acceleration measure point (b) Strain measure point

Fig. 7 – Measure point arrangement (unit: cm)

3. Results and Discussion

3.1 Natural Vibration Test

The white noise tests are firstly carried out to obtain the basic dynamic performance of three arch models. Through the spectrum analysis of arch models' acceleration response signal, both the first-order natural frequencies of in-plane and out-plane are obtained, which are listed in Table 2.

The first-order frequencies of three arch models in the out-plane direction are respectively 4.9Hz (Model 1), 4.4Hz (Model 2), and 4.0 Hz (Model 3). The first-order frequencies in the in-plane direction are respectively 10.7Hz (Model 1), 10.5Hz (Model 2), and 8.7 Hz (Model 3).It is clearly seen from the Table 2 that the in-plane and out-plane natural frequencies of the arch models are reduced by replacing the RC web with CSW and PSW webs, which means the loss of the integral rigidity of the arch models. When using the CSW, the natural frequencies of the Model 2 are slightly less than those of Model 1, -10.2% for out-plane and -1.8% for in-plane frequencies; however, when using the PSW, the decreased ranges are up to -18.4% for out-plane and -18.7% for in-plane frequencies.

Table 2 – First-order natural frequencies of three arch models (unit: Hz)

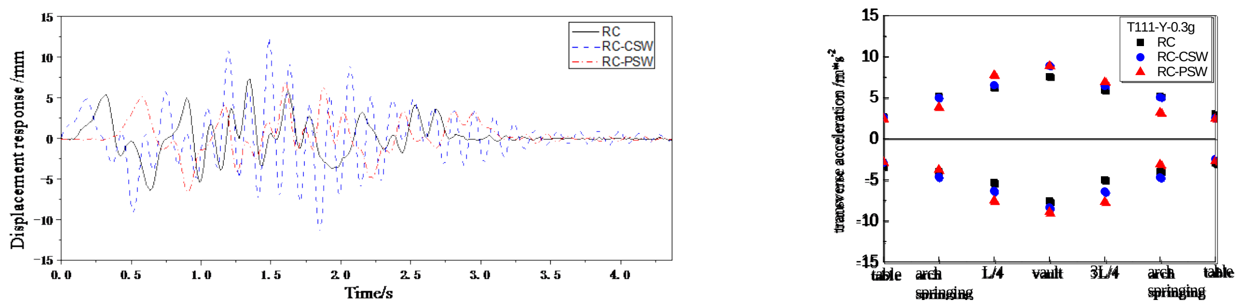
Model types	Out-plane frequency	In-plane frequency
Model 1 (RC arch)	4.9	10.7
Model 2 (RC-CSW arch)	4.4	10.5
Model 3 (RC-PSW arch)	4.0	8.7

3.2 Shaking Table Test

When the peak acceleration of longitudinal seismic wave reaches 0.5g or transverse seismic wave reaches 0.39g, the overturning moment of shaking table exceeds permissible value; in order to ensure the security of equipment, the test has to be terminated.

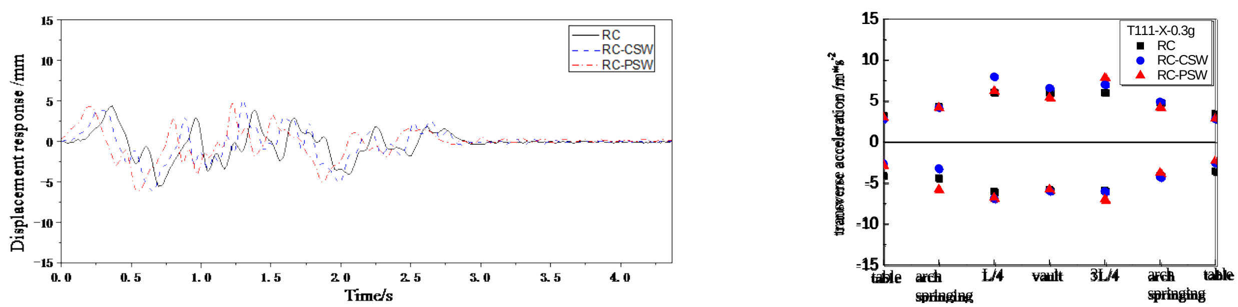
Under transverse seismic excitations, all of the seismic responses of three arch models increase as the PGA of input ground motions increase. To better understand the differences of seismic performance of three models, the seismic responses of the models under the same transverse seismic excitation T111 with PGA=0.3g are compared in Fig. 8, where plots (a) and (b) respectively compare the displacement response time-history curve and maximum acceleration response. In comparison with the RC arch model, the RC-CSW arch model shows about 80% larger transverse displacement, whereas the RC-PSW arch model presents 5% less displacement response. It is possible that the largest displacement response of Model 2 is due to the minimal transverse stiffness of CSW and the inherent characteristics of input ground motions [6]. The out-plane acceleration magnification coefficients of RC, RC-CSW, and RC-PSW arch models are 2.25, 3.04, and 3.15, respectively, which indicates that RC arch bridge exhibits the best integrality.

Similar to the case of transverse seismic excitations, all of the seismic responses of arch models under longitudinal seismic excitations increase as the PGA of input ground motions increase. Fig. 9 compares the seismic responses of the three models under the same longitudinal seismic excitation T111 with PGA=0.3g. It can be observed from Fig. 9(a) that the difference in longitudinal displacement response among three arch models is not as large as that in transverse displacement response; both the maximum displacement responses of RC-CSW and RC-PSW arch models are about 11% larger than that of RC arch model. This is because the difference of in-plane rigidity among three models is not significant as shown in Table 2. The in-plane acceleration magnification coefficients of RC, RC-CSW, and RC-PSW arch models are 1.47, 2.34, and 1.92 respectively, which represents the similar variation.



(a) Displacement time-history curve (b) Maximum acceleration

Fig. 8 – Comparison of seismic response among three models under transverse seismic excitation (PGA=0.3g)



(a) Displacement time-history curve (b) Maximum acceleration

Fig. 9 – Comparison of seismic response among three models under longitudinal seismic excitation (PGA=0.3g)

The maximum concrete strain at different cross sections under longitudinal seismic excitation with PGA=0.5g are compared among three arch models, as illustrated in Fig. 10, it can be found that the largest concrete strain occurs at the arch springing, and the maximum strain of RC arch model is approximately 1.44 and 1.58 times larger than values of RC-CSW and RC-PSW arch models, respectively. At the same time, a large number of cracks can be obviously found in the arch springing of RC arch model (see Fig. 11) whereas for the RC-CSW and RC-PSW models they are still in elastic working stage. It is believed that under the same longitudinal seismic excitation the internal force of RC arch model is largest among three models, in other words, the replacement of RC web with CSW or PSW can reduce the internal force of arch bridge. On the other side, when the PGA of transverse seismic excitations reaches 0.39g, all the cross sections of three arch models still remain in the elastic working stage.

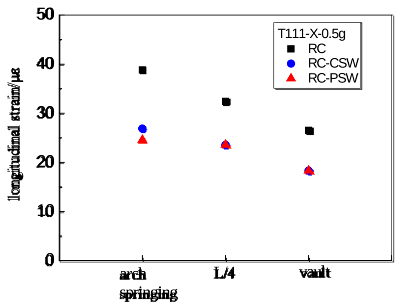


Fig. 10 – Comparison of concrete strain under longitudinal seismic excitation (PGA=0.5g)

Figure 11 – Cracks in the arch springing of RC arch model

4. Conclusions

Three reduced-scale arch models with different web types (RC, CSW, and PSW) have been tested on the shaking-table system in Fuzhou University. The main conclusions of this study can be summarized as follows:

(1) The first order natural frequencies of the arch models in the in-plane and out-plane directions were reduced by replacing the RC web with CSW and PSW webs due to the loss of the integral rigidity of the arch models.

(2) Under the transverse seismic excitations, the RC-CSW arch model presented the largest displacment response among the three arch models; The out-plane acceleration magnification coefficients of RC, RC-CSW, and RC-PSW arch models were 2.25, 3.04, and 3.15, respectively, which indicates that RC arch model had the best integrality; Until the end of the test (PGA=0.39g), all the cross sections of three arch models still remained in the elastic working stage.

(3) Under the longitudinal seismic excitations, RC-CSW and RC-PSW arch models showed slightly larger displacement responses than that of RC arch model; The in-plane acceleration magnification coefficients of RC, RC-CSW, and RC-PSW arch models were 1.47, 2.34, and 1.92, respectively; As the PGA of longitudinal seismic excitations increased, a large number of cracks gradually occurred in the arch springing of RC arch model whereas the RC-CSW and RC-PSW models were still in elastic working stage.

(4) The maximum strain of RC arch model was approximately 1.44 and 1.58 times larger than values of RC-CSW and RC-PSW arch models, respectively. It is believed that the replacement of RC web with CSW or PSW can reduce the internal force of arch bridge.

5. References

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