Thin-Walled Structures 116 (2017) 212–224

Contents lists available at ScienceDirect

Thin-Walled Structures

journal homepage: www.elsevier.com/locate/tws

Full length article

# Experiment on seismic performance of concrete filled steel tubular arch-rib under multi-shaking-tables

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ARTICLE INFO

*Keywords:*
CFST arch-rib model
Experiment
Multi-shaking-tables
Uniform and non-uniform excitation
Seismic performance

ABSTRACT

During the last two decades, a large number of concrete filled steel tubular (CFST) arch bridges had been built in China. However, the experiment on seismic performance of CFST structural arch rib was seldom conducted especially under spatial wave excitation. In order to understand the seismic behaviors of CFST arch bridges, a scaled 1:10 model of CFST arch-rib was constructed with fully compensative mass. The test was carried out uniform and non-uniform excitations under a Multi-shaking-tables array system in Fuzhou University, China. Artificial waves and several recorded ground motions were employed to identify the basically dynamic behavior and to evaluate the elastic and plastic seismic performance of this arch-rib model.

The testing results indicate that the seismic responses of CFST arch-rib are highly related to the predominant frequencies, ranges as well as peak magnitudes of input waves' spectrum. The testing results also show that the transverse seismic response is more distinct than that longitudinal response, and the bi-directional excitation has much larger responses than the single excitation. Furthermore, the non-uniform excitation has more significant effect than the uniform wave especially on the displacement responses. Therefore, the earthquake effect on the CFST arch bridge need necessary to take account of bi-directional excitation and non-uniform excitation.

In addition, the testing indicates that the CFST arch-rib structure has performed the nonlinear and plastic behavior especially under intensive excitations of El-centro wave and Hanshin wave. However, the natural frequencies or stiffness of the CFST arch-rib model don't have significant decrease and there is no distinct crack or damage on the steel surface because of the hooping effect on the core concrete. This indicates that the CFST arch-rib structure has a favorable seismic behavior and ductility.

## 1. Introduction

The main shortcomings for conventional large-span reinforced concrete arch bridge are its huge self-weight and difficult construction as well as poor ductility [1]. Compared to reinforced concrete arch bridge, concrete filled steel tubular (CFST) arch bridge is more convenient and lightweight in construction as well as high cost-efficiency of interaction between the steel tube and the core concrete [2].

Concrete filled steel tubular arch bridges have been widely used in China. The largest one is the Hechuan Yangtze River Bridge located in Sichuan province, Southwest of China, with clear span of 530 m.

A large number of static tests on mechanical behavior of CFST arch-rib model had been conducted to identify the basic static mechanical behavior and ultimate carrying-load capacity. The tests showed that CFST arch-rib had a reasonable mechanical performance and load-carrying capacity [3–5]. However, comprehensively seismic experiment on CFST arch structure under Shaking Tables had seldom been carried out especially under spatial excitations [6,7]. Previously, some researches mainly studied the basically dynamic behavior and mode analysis based on a practical CFST arch bridge [8–11]. Most recently, researchers have analyzed that the CFST arch bridge possesses a reasonable seismic performance [12–14,15]. Nevertheless, almost all of these analyses and results were gained by the finite element models (FEM) rather than based on the experiments [16,17]. Therefore, the experimental study on seismic performance of CFST arch bridge model under shaking tables is essential and significant.

This paper described a Multi-shaking-tables experiment on a scaled 1:10 CFST arch-rib model with fully slave mass that were conducted in Fuzhou University, Fujian Province, China. The testing CFST arch-rib

*Abbreviations:* AR, Acceleration response; CFST, Concrete filled steel tube; E1 & E2, Artificial waves for two level design; L-S, Left arch springing; MF, Magnification factor; PFP, Predominant frequency platform; PGA, Peak ground acceleration; R-S, Right arch springing

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http://dx.doi.org/10.1016/j.tws.2017.03.020
Received 14 November 2015; Received in revised form 1 March 2017; Accepted 14 March 2017

**Nomenclature**

| | |
|---|---|
| $l$ & $S_l$ | Quantity and scale of length (see Eq. (1)) |
| $\delta$ & $S_l$ | Quantity and scale of deformation (see Eq. (1)) |
| $E$ & $S_E$ | Quantity and scale of elastic modulus (see Eq. (1)) |
| $\sigma$&$S_\sigma$ | Quantity and scale of stress (see Eq. (1)) |
| $\varepsilon$&$S_\varepsilon$ | Quantity and scale of strain (see Eq. (1)) |
| $\rho$&$S_\rho$ | Quantity and scale of density (see Eq. (1)) |
| $\rho'$&$S_{\rho'}$ | Quantity and scale of density (see Eq. (3)) |
| $a$&$S_a$ | Quantity and scale of acceleration (see Eq. (1)) |
| $g$&$S_g$ | Quantity and scale of gravity acceleration (see Eq. (1)) |
| $P$&$S_P$ | Quantity and scale of load |
| $M$&$S_M$ | Quantity and scale of moment |
| $T$& $S_T$ | Quantity and scale of period (see Eq. (1)) |
| $\omega$&$S_\omega$ | Quantity and scale of natural circular frequency (see Eq. (1)) |
| $\zeta$ & $S_\xi$ | Quantity and scale of damp (see Eq. (1)) |
| $v$&$S_v$ | Quantity and scale of velocity (see Eq. (1)) |
| $k$&$S_k$ | Quantity and scale of stiffness |
| $m_m$&$S_{mm}$ | Quantity and scale of model mass |
| $m_a$&$S_{ma}$ | Quantity and scale of artificial mass |
| $A$ | Designed horizontal peak acceleration (see Eq. (2)) |
| $C_d$ | Adjustment factor of damp (see Eq. (2)) |
| $C_i$ | Seismic essentiality coefficient (see Eq. (2)) |
| $C_s$ | Field factor (see Eq. (2)) |
| $D$ | Time-history displacement (see Eq. (3)) |
| $D_1$ | Time-history displacement relative to side small table (see Eq. (3)) |
| $D_2$ | Time-history displacement relative to mid large table (see Eq. (4)) |
| $D_r$ | Relative peak displacement (see Eq. (4)) |
| $E_s$ | Young's modulus of steel |
| $E_c$ | Young's modulus of concrete |
| $f$ | Natural frequency of structure and sample frequency of input excitation |
| $f_{cu}$ | 28-day cubic strength of concrete |
| $f_s$ | Yield stress of steel |
| $f_u$ | Strength stress of steel |
| $L$ | Arch spans' length (see Fig. 5) |
| $H$ | Arch rise (see Fig. 5) |
| $S_{\max}$ | Predominant frequency platform (see Eq. (2)) |
| $t$ | Time |
| $T_g$ | Characteristic period (see Eq. (2)) |
| $\mu_c$ | Poisson's ratio of concrete |
| $\mu_s$ | Poisson's ration of steel |

model was subjected to uniform and non-uniform earthquake excitations at low intensity or high intensity to evaluate its elastic and plastic behaviors. The sine wave, and the recorded earthquakes of Taft wave, EL-centro wave, Hanshin wave as well as the artificial waves of E1 and E2 that established by the Guidelines Specification for Seismic Design of Highway Bridge, China [18], are utilized. Then, the basically findings were presented including the dynamic behavior of arch-rib, the seismic responses of acceleration, displacement and strain, et al. At last, comments and discussions are presented based on the damage and failure modes.

## 2. Prototype bridge

The prototype of Qunyi Bridge shown in Fig. 1(a), similar to the New Damen Ave. Bridge in Chicago City, locates at Fu-an County, Southeast China. It is a half-through CFST arch bridge with clear span and arch-rise of 46 m and 15.33 m, respectively. The total width of deck is 18 m, which includes the clear lane width of 9 m + 2 × 2.5 m, the footway of 2 × 1.75 m and so on.

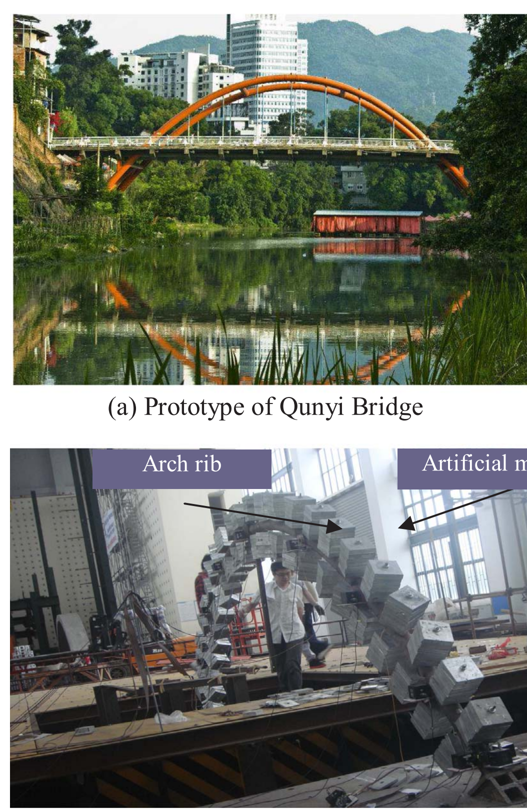
The main arch-ribs are composed of single steel tube and core concrete with outside diameter of 800 mm and thickness of 14 mm. The steel tube is Q345 that is similar to the A572 Grade 50 steel in the ASTM and core concrete is C30. The bridge has a gravity abutment located upon the enlarged rigid foundation to resist the reaction-force at arch springing. The ground site belongs to the Classification II that is similar to stiff soil conditions (Soil Type II) in AASHTO (2014), and its seismic intensity is VII according to Chinese Specification [18].

## 3. Model

### 3.1. Model design

The CFST arch-rib model was designed to be a scale of 1:10 that illustrated in Fig. 1. The arch-rib axis was the parabola that similar to prototype, and the corresponding clear span and rise were 4.6 m and 1.53 m, respectively. In order to implement the slave mass for compensating gravity weight due to reduced scale, total of 24 steel bars were perpendicularly welded on the model along the arch-rib axis with a spacing of 0.2 m. The steel plate with the size of 1.0 m × 1.0 m × 0.035 m were welded on each arch springing in order to fasten the model upon the Shaking-tables by high strength bolts.

The cross-section of the arch-rib model consisted of single tube and core concrete. According to the similarity law, the outer diameter and wall thickness of the steel tube were 80 mm and 1.4 mm. Nevertheless, they could not be available in steel tube market. Finally, the dimension of 76 mm × 3.8 mm was preferred instead of theoretical size. By the way, both of two cross-sections have the same relatively composite stiffness of $E_{sc}I_{sc}$ basically. That is to say the 76 mm × 3.8 mm tube has a




(a) Prototype of Qunyi Bridge

(b) Scaled model

**Fig. 1.** CFST arch-rib.