CHINA TECHNICAL CODE FOR CFST ARCH BRIDGES

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SUMMARY

More than 400 Concrete Filled Steel Tube (CFST) arch bridges with a span no less than 50m have been built in China. Extensive practical experiences on CFST arch bridges have been accumulated from these bridge constructions. Meanwhile, extensive research activities have been performed and led to a series of profitable results. Based on the practical experiences and research results, the *China National Standard Technical Code for CFST Arch Bridges GB 50923-2013* was edited and published in November 11, 2013. The code deals with the design, construction and maintenance of CFST arch bridges. After a brief review of the code development of CFST arch bridges, this paper mainly draws a brief sketch of the *China National Standard Technical Code for CFST Arch Bridges GB 50923-2013*, focusing on the structural types and calculation methods for the ultimate load-carrying capacity of the CFST arch ribs.

Keywords: *Arch bridges, Concrete-filled steel tube (CFST), code, design, structure type, ultimate load-carrying capacity, China.*

1. INTRODUCTION

A Concrete Filled Steel Tube (CFST) member is benefit strengthening from the mutual mechanisms between the steel tube and the core concrete when it is subjected to compression, and hence the load-carrying capacity and ductility are improved. Therefore, CFST can be efficiently used in arch due to an arch is a compression dominent structure[1,2]. Since 1990, vast application of CFST arch bridges has been witnessed in China, which accumulates extensive practical experiences [3~5]. According an investigation, 423 CFST arch bridges with a main span no less than 50m have been built, up to January 2015 in China [6]. The current span record for a CFST arch bridge is held by the Hejiang Yangtze River No. 1 Bridge with a clear span of 518 m (calculation span of 530 m), which was opened to traffic in 2012 (Figure 1) [7].

Accompanying with the application, extensive research activities have been performed which lead to a series of profitable results [8~10]. Based on the rich engineering experience and fruitful research results, specifications on CFST Arch Bridges have been developing continuously since 1998. The China National Standard Technical Code for CFST Arch Bridges GB 50923-2013 [11] was edited and published in November 11, 2013, which deals with the design, construction and maintenance of CFST arch bridges.

Fig. 1. Hejiang Yangtze River No. 1 Bridge, China.

This paper mainly draws a brief sketch of the China National Standard Technical Code for CFST Arch Bridges GB 50923-2013, and focuses on the structural types and calculation methods for the ultimate load-carrying capacity of the CFST arch ribs.

2. CODIFICATION FOR CFST ARCH BRIDGES IN CHINA

There is no systematic national standard on bridges in China, instead there are two main professional standard systems for railway bridges and highway bridges respectively. The two systems are quite difference from the live load to the design philosophy, Load and Resistance Factor Design (LRFD) method for highway bridges and Allowable Stress Design (ASD) method for railway bridges. As for municipal bridges, they are closed to highway bridges, therefore there is only one general design code, and the codes for highway bridges are generally taken as codes or references in design and construction of municipal bridges.

The code system for design of highway bridges includes one general code, one for ground base and foundation, and other codes for bridges made of different construction materials, i.e., reinforced concrete and prestressed concrete bridges, masonry bridges and steel bridges. They are updated in recent years, and the renewed General Code for Design of Highway Bridge and Culverts JTG D60-2015 was issued in 2015. The code system for the highway bridge also includes codes for construction, quality control, rehabilitation and management, etc. Most of them have been translated into English Version and some into France Version in 2011 and published by the standards Press of China.

After some application of CFST arch bridges in China, corresponding requirements on them were appeared in Quality Inspection and Evaluation Standards for Highway Engineering JTJ 071-94 and JTJ 071-97, followed by the Technical Specifications for Construction of Highway Bridges and Culverts JTJ41-2000 and JTJ/T F50－2011. However, there was no a special specification for the CFST arch bridges. Due to continually application of CFST arch bridges in China since 1990 in the background of large scale infrastructure construction, code development of CFST arch bridges has been a great requirement in bridge engineering. In order to satisfy the requirement of engineering practice, two specifications on Highway CFST Arch Bridges (one for design and one for construction) were edited by Chongqing Communications Research and Design Institute (CCRDI), Fuzhou University, etc and submitted to the China Ministry of Transport to approval in 2004. But considering the basic design theory is not mature at that time, they have not been formally issued. At the same time, a research projects on the Research on Key Technology on Design, Construction and Maintenance of CFST Arch Bridges was founded by the Ministry of Transport. After the project finished, editing a Specifications for Design of Highway Concrete-filled Steel Tubular Arch Bridges was re-assigned by the Ministry of Transport to Sichuan Provincial Communications Planning & Design Institute, Fuzhou University, etc.. The specification was issued in 2015 with a code No. of JTG/T D65-06-2015[12].

In China, there are four levels for construction standards: national, professional (like highway, railway, and municipal bridges), local (provincial) as well as enterprise.

The first specification for CFST arch bridges in China is the Technical Specification of CFST Arch Bridges (DBJ/T13-136-2011) as a formal engineering construction standard of Fujian Province, China, which was issued to use on July 15, 2011[13]. The DBJ/T13-136-2011 specifies requirements on design, construction and maintenance of CFST arch bridges used in both highway and municipal areas. In order to be more easily understood of the design philosophy, four design examples have been given in the companion book published [14]. At the end of the same year, another local code, Code for Design of Highway CFST Arch Bridges (CQJTG/T D66-2011), was also issued as a Highway Specification of Chongqing [15].

The editing of a national code on CFST was started in 2011. There are 14 members in the editing board, come from university, design institute, research institute, construction company and maintenance unit. The editing board collected up data and investigated extensively on engineering practices on design, construction and maintenance of CFST arch bridges, performed specific research on creep, stiffness, initial stress and temperature effects, summarized the experiences. Based on these, a draft was edited taking reference on the existing standards and codes, especially the local code DBJ/T13-136-2011. Then it was revised several times on the comments and suggestions from many institutes and researchers collected by mails and meetings. This National standard--Technical code for CFST Arch Bridges (GB 50923-2013) was approved at the end of 2013 and was implemented since June 1st, 2014.

In order to facilitate the implementation based on an improved understanding of the code GB 50923-2013 by a great number of Chinese designers, constructors, field supervisors, researchers, teachers et al. the authors have published a book on "Design calculation method and application for concrete-filled steel tube arch bridges" based on the code[16]. A book on the details of design calculation with eight samples was also published in 2015 [17]. At the same time, the third edition of "Concrete-filled Steel Tube Arch bridges" [10] based on the GB 50923-2013 will also published soon.

3. ASIC DESCRIPTIONS OF THE NATIONAL STANDARD FOR CFST ARCH BRIDGES

3.1. Objects

The CFST arch bridge in this code is defined as a bridge whose main load resisting component(s) is the circular cross-section concrete-filled steel tube arch rib(s). In engineering practice, CFST can be of circular, square or the other cross sections. Due to their polar symmetry (in cross section), the resulting good mechanical performance and the easy fabrication (of the tube), circular CFST are most widely used, of which the theoretical development and practical applications are more innovative. Therefore, the code is specifically applied to bridges with circular CFST arch ribs as the main load resisting components.

The technical code for CFST arch bridges (GB 50923-2013) deals with the requirements arising from bridge engineering construction to ensure the design, construction and maintenance of CFST arch bridges in accordance with the requirements of safety and reliability, durability and usability, technical advancement, economy and rationality.

It is applicable to the design, construction and maintenance of municipal and highway CFST arch bridges. From the investigation, more than 80% of CFST arch bridges are used as highway bridge and municipal bridge and the bridge code system in highway and municipal are similar, so this code is served for highway and/or municipal CFST arch bridges [2][3][6].

As a code for a special bridge type, not only the requirements stipulated in the code, but also those in the current relevant ones of the nation shall be complied with in the process of the design, construction and maintenance of CFST arch bridges. The code is intended for the CFST arch ribs and the other special structural components in CFST arch bridges, such as the CFST arch ribs, hanger cables, tied cables, whereas the remaining structural components, such as the deck system, abutments and foundations which could be steel, reinforced concrete, prestressed concrete or masonry structures shall be in compliance with the relevant national standards for their design, construction and maintenance

3.2. Contents

The code comprises 14 chapters and supplementary provision explanation. The main technical contents include:

1. General Provision;
2. Terms and Symbols;
3. Materials;
4. Basic Requirements;
5. Calculation of the Ultimate Limit States in Persistent Situations;
6. Calculation of the Serviceability Limit States in Persistent Situations;
7. Structure and Detailing;
8. Fabrication of Steel Tube Arch Ribs;
9. Welding;
10. Anti-corrosion Coating;
11. Erection of Steel Tube Arch Ribs;
12. Filling of Concrete;
13. Construction of Other Parts;

14. Maintenance.

Further, it can be seen comprised of four sections, i.e., general section from Chapter 1 to 4; design section from Chapter 5 to 7; construction section from Chapter 8 to 13 and maintenance section only Chapter 13.

4. STRUCTURES OF CFST ARCH BRIDGES

4.1. Main Structural Types

Various structure types, arch ribs and construction methods have been presented and applied. In GB 50923-2013, the CFST arch bridges are classified into five main types, i.e., deck (or true) arch, half-through true arch, through deck-stiffened arch, through rigid-frame tied arch and fly-bird-type arch (half-through tied rigid-frame arch) (Fig. 2).

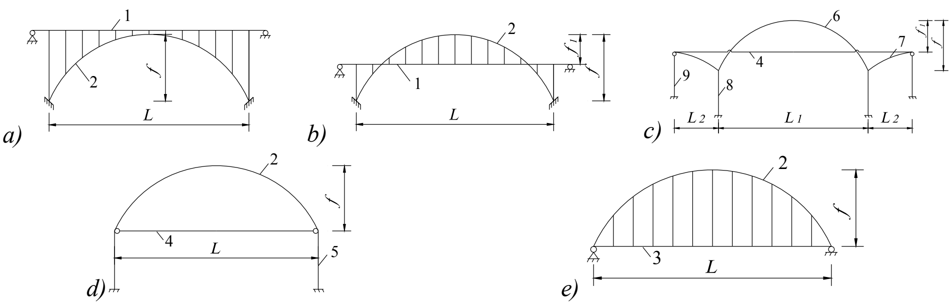


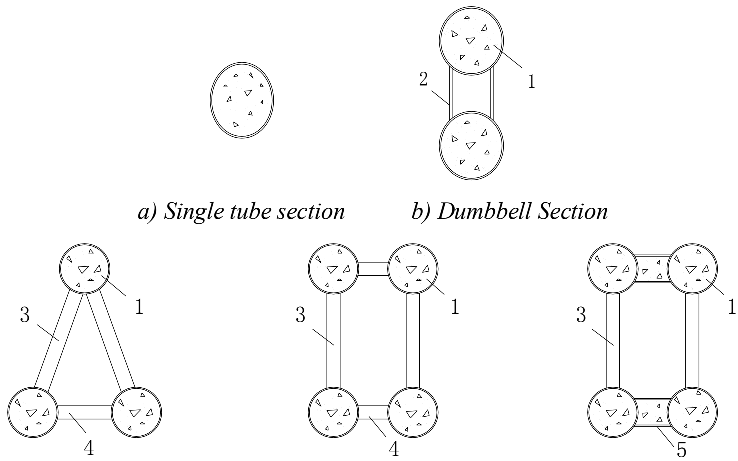
Fig. 2. *Main Structure Types of CFST Arches: a) Deck arch; b) Half-through arch; c) Rigid-frame tied half-through arch; d) Rigid-frame tied through arch; e) Arch and girder combined structure; Legend: 1 - Deck system; 2 - Arch rib; 3 - Tie girder; 4 - Tie bar; 5 - Pier; 6 - Main arch rib; 7 - Side arc rib; 8 - Main pier; 9 - Side pier.*

The structure types of deck (or true) arch, half-through true arch, through deck-stiffened arch are common ones in steel or concrete arch bridges, the main difference is the arch ribs are made of CFST. While the Rigid-frame tied half-through arch and Rigid-frame tied through arch are not common used in other kind arch bridges. In these two types, the arch ribs are fixed to the top of the piers (generally columns) at the arch springings to form a rigid frame structure with the piers, so the arch ribs can be erected by cantilver method like true arch bridges. Tie bars of high strength wires are prestressed to provide an active balance force against to the thrust forces of the arches induced by dead loads, which is the main part of thrust forces in an arch bridges, only remain a small part of thrust forces induced by live load to be carried by the rigid-frame structure. Thus they can be used in the bridge site with soft soil foundation as the arch and girder combined structure [18][19].

The rise-to-span ratio of CFST arch generally range between 1/3.5 and 1/6.0. 7.1.3 For rigid-frame tied half-through CFST arch bridges, the side span is usually 1/4.0~1/5.5 of the main span; the rise of the side span should be 1/3.5~1/4.5 of that of the main span; the rise-to-span ratio of the side span should be 1/1.1~1/2.0 of that of the main span.

4.2. Rib Section Types

The cross section type of CFST arch rib shall be determined according to arch span, width of bridge, vehicle load level and so on. The arch rib may adopt single tube, dumbbell section or truss types (see Figure 3). From the engineering practice, the single tube rib is generally used for the bridge with a span smaller than 80m, dumbbell section for the bridge with a span smaller than 150m. Truss type is widely used in large span CFST arch bridges, from 120m to the longest one with a span to 500 m.



a) Single tube section *b) Dumbbell Section*

c) Three-chord truss section *d) Four-chord truss section* *e) Horizontal dumbbell truss*

Fig. 3. *CFST rib section types; 1- Chord; 2 - Web plate; 3 - Web truss; 4 - Horizontal connection bar; 5 - Horizontal connection plate.*

The wall thickness of steel tubes shall not be less than 8mm. The D/t generally is in the range of 35~100 times ($235/f_y$), in which f_y is the Characteristic Strength of steel. The confinement coefficient ξ_0 of CFST should not be less than 0.60. The sectional steel ratio ρ_c should be in the range of 0.04-0.20. The ξ_0 and ρ_c is calculated according to formulae (1) and (2).

$$\xi_0 = \frac{A_s f_s}{A_c f_{cd}} \tag{1}$$

$$\rho_c = A_s / A_c \tag{2}$$

where ξ_0 – Design confinement coefficient of CFST.

ρ_c – Sectional steel ratio of CFST.

A_s – Sectional area of steel tube.

A_c – Sectional area of concrete core.

f_s − Design tensile, compressive and flexural strength of steel.

f_{cd} − Design compressive strength of concrete.

For uniform cross section dumbbell or truss CFST bridge ribs spanning no larger than 300m, the section height, H, may be calculated according to the empirical equation, Eq. (3), and the horizontal central distance of four-chord ribs may be 0.40H~0.75H. If a non-uniform section is adopted, the section heights of four-chord ribs at crown and springs may be 0.8 and 1.4~1.5 times of those determined by Eq. (3).

$$H = k_1 k_2 \left[0.2 \left(\frac{l_{01}}{100} \right)^2 + \frac{l_{01}}{100} + 1.2 \right] \tag{3}$$

where: H − Height of arch rib section (m);

l_{01} − Net span of arch (m);

k_1 − Load level coefficient: 1.0 for Class I highway or Class A city roadway; 0.9 for Class II highway or Class B city roadway;

k_2 − Driveway coefficient: 0.9 for 2 or 3 lanes; 1.0 for 4 lanes and 1.1 for 6 lanes.

5. DESIGN CALCULATION

The code GB 50923-2013 adopts the limit states design concept based on the probability theory. Partial safety factors are used in design calculation. According to the code, CFST arch bridges shall be designed according to the following two limit states:

1) Ultimate Limit State (ULS): The state that the CFST arch bridge or any of its components reaches the maximum load capacity or the deformation/displacement no longer fits for loading.

2) Serviceability Limit State (SLS): The state that the CFST arch bridge or any of its components reaches certain functionality or durability limit.

5.1. Resistance of a single CFST member in axial compression

The resistance of a CFST member in axial compression, N0, is the basic formula of the calculation of the ultimate load-carrying capacity of CFST arch. Extensive experiments on it have been carried out worldwide. Various calculation methods have been presented and adopted in various design codes. The calculations can be categorized as with or without considering the effects of confinement of steel tube on the concrete. All the Chinese codes have considered the effects of confinement. Based on an extensive study of the different calculation methods by authors, it is concluded that all the existing methods, which are based on a large number of experimental findings, tend to lead the similar results. The method as indicated by Eq. (4) which is adopted in code GB 50923-2013 has the advantages of simple format and vast range of applicability based on different choices of the parameters.

$$N_0 = k_3(1.14 + 1.02\xi_0)(1 + \rho_c) f_{cd} A_c \tag{4}$$

where: N_s − Design composite compressive force;

N_0 − Design composite compressive resistance of circular CFST section;

ξ_0 − Design confinement coefficient;

ρ_c − Sectional steel ratio;

f_{cd} − Design compressive strength of concrete;

k_3 − Conversion coefficient of design compressive strength.

In terms of mechanical properties, the main advantages of CFST structures stem from the confinement to the concrete core from the steel tube and the resistance to the lateral deflection of the steel tube due to the concrete core. In order to guarantee that these advantages of CFST structures can be taken, the steel tube and the concrete core must be closely in contact. However, massive engineering practices have indicated that debonding may occur at the interface between the steel tube and the concrete core and will reduce the compressive resistance of the CFST member. The thickness of debonding space at the location of debonding is usually even and of small amplitude, which mostly occurs at the cross sections of the crown and seldom occurs at the cross sections of spring. For quality inspection of in-filled concrete core, the item 12.3.2 of the code has proposed "If the debonding (angle) ratio is greater than 20% or the debonding gap exceeds 3mm, drilling hole grouting shall be done to ensure the compactness." In design calculation, assuming the debonding (angle) ratio is less than 20% or the debonding gap does not exceed 3mm, debonding reduction factor, K_t, is introduced to consider the debonding influence to the compressive resistance [20].

5.2. Resistance of long CFST columns in eccentrically compression

For dumbbell shaped and truss (or laced) CFST stub columns, the axial compressive ultimate load-carrying capacity is the sum of the strength of the CFST chords and the connection steel web plates in the cross-section.

The ultimate load-carrying capacity of a short CFST column subjected to eccentrically compression is the product of the ultimate load-carrying capacity of the short CFST column subjected to axial compression and a reduction factor of eccentricity ratio φe, which depends on the type of cross section used.

Researches on single-tube, dumbbell shape and multi-tube section CFST slender columns have shown that the two main parameters affecting the stability strength are the slenderness ratio and the eccentricity ratio, and their influences are basically independent when the slenderness ratio is limited in a certain range. Therefore the global strength reduction factor can be expressed as the product of the eccentricity reduction factor φe and the stability factor φl, which considers the material properties of the column and the shear effect of the lacing bars or battens in the laced columns [21-24]. The formula for calculation of the stability coefficients are uniform for the single tube, dumbbell and trussed CFST columns. By using converted slenderness ratios for the three different CFST columns, the effects of material properties on the stability coefficients are taken into account. The converted slenderness ratios of laced CFST columns adopts the form as a product of relative parameters, which is more reasonable[25-26].

5.3. Ultimate load-carrying capacity and stability of CFST arch

A number of investigators have studied theoretically the simplified method to estimate the critical loads of arches. The equivalent beam-column method is one of the most commonly used methods. After a research on equivalent beam-column method to estimate in-plane critical loads of parabolic fixed steel arches [27], the authors conducted a further study on CFST arches and showed this method is also suitable to be used in CFST arch [28]. This method is adopted by this code to predict the ultimate load-carrying capacity of CFST arch, in which an arch rib is treated as a simple beam-column with an equivalent effective length. The equivalent effective length is the product of the arc length of the arch and a coefficient, α, which is 0.36 for hingeless arches, 0.54 for two-hinge arches and 0.58 for three-hinge arches.

The forces, both compression and bending moment, acting at the section of quarter span of the arch rib is taken as the forces acted on the two ends of the equivalent beam-column, and the in-plane stability strength of the arch rib can be checked by the method given before.

In construction, the steel tube arch is always erected and closed before the concrete filling into the tube to form a CFST arch, so the steel tube in the CFST arch is preloaded and this preloading will influence the stability load-carrying capacity of the CFST column. A series of comparative experiments were carried out for the preloading and a uniform format prediction method was developed [29]. In stability resistance calculation of CFST arches, when preloading effect is considered, the axial compressive design load resistance of CFST cross section is adjusted by a preloading reduction factor K_p in GB 50923-2013.

Arch rib is a structure under compression forces needs to be checked by means of stability calculation. With respect to the direction of instability, the stability problems of arch rib can be categorized as in-plane instability and out-of-plane instability (a spatial problem); or with respect to the types of instability, they can be categorized as limit point instability and bifurcation instability. In-plane instability of the CFST arch ribs are mainly limit point instability, which is considered as an equivalent CFST beam/column member for its global stability calculation in the current code as described in the last section.

Since out-of-plane loadings are much smaller in comparison to the in-plane loadings, for the CFST arch ribs its spatial instability is almost a bifurcation instability problem. It is stipulated in the code that the spatial stability of CFST arch ribs shall be calculated and the eigenvalue of elastic stability shall not be less than 4.0.

6. LAST REMARKS

More than 400 CFST arch bridges have been built in China and the increasing trend of both number and span for the construction of CFST arch bridges is continued. Now, a CFST deck arch bridge with a main span of 430m in a railway from Sichuan to Tibet is under construction, a CFST deck arch bridge in Guizhou Province in the expressway has been designed and will soon be constructed, a CFST fly-bird-type arch bridges in Hechuan City of Sichuan Province is under design.

The China national standard--the *Technical Code for Concrete Filled Steel Tube Arch Bridges* (GB 50923-2013) was issued in 2013, which highly concentrated the rich engineering practices and extensive research works on CFST arch bridges in China and constitutes the most important document and guideline for design, construction and maintenance of such a kind bridge.

According to China relative requirements, a code or specification could be revised after five years application, so the comments are collected and research on some remains problems of CFST arch bridges are also continually conducted for the revising of the code in 2018. At the same time, the authors are translating the *Technical Code for CFST Arch Bridges* (GB 50923-2013) into English edition, and are plan to write an English book on CFST arch bridges in the near future.

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