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Torsional behavior of a new dumbbell-shaped concrete-filled steel tubes

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ABSTRACT

This paper presents the first study of its kind on the torsional moment behavior of a new dumbbell-shape concrete-filled steel tube (DCFST) system. Experiments were conducted to investigate the effect of the dimensions of the web connecting the two circular CFSTs, in terms of its width-to-diameter (b/D) and its minimum depth-to-diameter (h/D) ratios, on torsional strength (T_u). Torsion tests were also conducted on circular CFSTs (CCFSTs), on hollow tubes and on plain concrete, as control specimens. It was shown that T_u of DCFSTs ranged from 1.3 to 2.2 that of the CCFST, depending on (b/D) and (h/D) ratios. Increasing (b/D) from 0.31 to 0.54 resulted in only 7% increase in T_u. However, a further increase from 0.54 to 1.0 resulted in an additional 31% increase in T_u. The effect of (h/D) on T_u was more pronounced at higher (b/D) ratios. In general, increasing the web width appears to be more effective than web height. A rigorous nonlinear finite element model was developed and a simple mechanics-based design equation have been proposed to predict T_u of CCFSTs and DCFSTs and resulted in an average predicted-to-experimental T_u of 0.98.

1. Introduction

Concrete filled steel tubes (CFSTs) are being increasingly used in the construction of modern buildings and bridges. The system offers unique features, namely; excellent static and seismic resistance due to concrete confinement as well as rapid construction as the steel tube is essentially a stay-in-place structural form. When applied in buildings, circular and rectangle CFST sections are mostly used as columns. In bridges, CFST application in arch-type bridges is perhaps the most popular. In this application, there are three main configurations typically used for the main rib, namely; circular CFSTs (CCFSTs) (Fig. 1(a)), dumbbell-shape CFSTs (DCFSTs) (Fig. 1(b)) and trussed rib using several CCFSTs (Fig. 1(c)). The dumbbell-shape (DCFSTs) (Fig. 2(b)) in particular is relatively new and quite effective for large structures subjected to high level of thrust and moment. It offers a significantly higher in-plane moment of inertia than a single CCFST of the same cross-sectional area, enabling it to resist higher in-plane bending and thrust in the arch, while at the same time still benefits from the tremendous confinement offered by the two tubes.

The concept of CFST has been studied extensively over the past several decades, primarily under axial compression, bending and combined bending and axial compression, with most of the work focusing on circular CFSTs (e.g. [3,8,2] among many others). In fact, when used as a corner column of a building, a pier of a viaduct, or an arch rib with a transverse bracing, loading of the system could result in a complex set of loads and moments that involve significant torsional moment in the CFST member, which cannot be neglected. However, there are very limited studies on the behavior of CCFSTs under torsion and basically no studies at all on DCCFTs under torsion. Han and Zhong [5], Beck and Kiyomiya [1], and Han et al. [6] carried out tests on CFST members under pure torsion, while Gong [4] and Lee et al. [9] carried out combined axial compression and torsion tests on short CFST stubs while Xu et al. [11] and Zhou [12] carried out similar combined loading tests but on slender CFSTs. Again, all these studies focused on CCFSTs only with no attempts to address others sections such as DCFSTs.

This paper is part of a larger project involving the design and construction of an arch bridge with a DCFST rib, located in Zhengzhou City, Henan Province, China. The paper presents the first study ever conducted on the torsional moment behavior of dumbbell-shape CFSTs (DCFSTs) with emphasis on the geometric properties of the web connecting the two circular CFFTs. The study also investigates circular CFSTs (CCFSTs) with emphasis on understanding the individual contributions of the concrete core and steel tube, looking at tubes of different thicknesses. Additionally, the paper provides a rigorous finite element modeling of both systems, accounting for concrete non-

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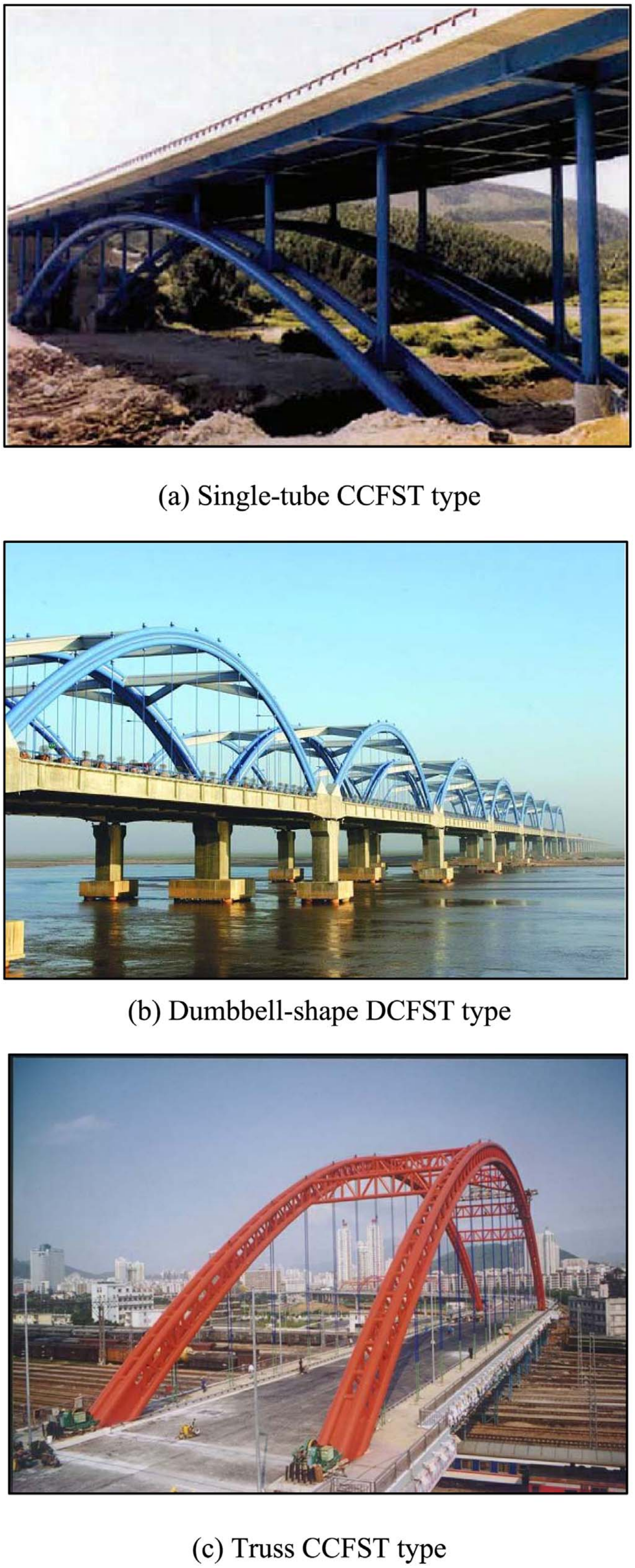

Fig. 1. Three main configurations of CFST arch bridges. (a) Single-tube CCFST type. (b) Dumbbell-shape DCFST type. (c) Truss CCFST type.

linearity and steel plasticity, to predict the full response in torsion. A simple mechanics-based design equation is proposed for the torsional capacity of both CCFSTs and DCFSTs.

2. Bridge description

The Yellow River Second Highway Bridge, located in Zhengzhou City, Henan Province, China, is a dumbbell-shaped CFST (DCFST) arch bridge design (Figs. 1(b) and 2). The bridge has eight spans, each is 100 m long between the centers of the piers, giving a 95.5 m span of each individual arch, with a rise-to-span ratio of 1:4.5. The bridge is of the rigid-frame tied-arch type with a through arch configuration. Rigid-frame tied-arch system is different from common arch-girder systems, in several aspects:the arch ribs are fixed to the piers to form a rigid frame, and high strength prestressed strands are employed as horizontal ties to produce tension forces that balance the thrust of the arch ribs. These horizontal ties are not bonded to the deck system and do not take part in resisting any stresses in the deck.

The superstructure of the bridge consists of a primary load-bearing system consisting of two parallel DCFST arches, a lateral bracing configuration connecting the two arches, and a floor system. The cross-section of each arch rib is a 2.4 m deep DCFST (Fig. 2(b)) comprising two 1000 mm diameter circular CFST with a 16 mm thick steel tube and 16 mm thick web plates stiffened by 16 mm thickness plates forming an H-shape web. There are 32 main suspenders vertically attached to the arch rib and the floor system, each of them consists of 91 zinc surface-plated 7 mm diameter high-strength steel wires. The floor system consists of 250 mm thick concrete slab supported directly on prestressed concrete box girders with height of 2.75 m and width of 2 m. The DCFST rib of the arch has strong in-plane stiffness but a relatively weak out-of-plane stiffness. As such, I-shape transverse bracing is used at mid-span and K-shape transverse bracing is used near quarter-span points between the two arch ribs (Figs. 1(b) and 2(a)) to enhance stability against out-of-plane bucking. Under transverse out of plane loading, torsional moments are generated in the arch rib.

3. Experimental investigation

An experimental study was carried out on CCFST of two different tube thicknesses and DCFST specimens with webs of different widths and heights. Also, control plain concrete and hollow steel tubes were tested in torsion to understand the contribution of individual components. The following is a brief summary of the program:

3.1. Test specimens and parameters

A total of ten, 950 mm long specimens were tested as shown in Table 1. Specimen C-0 is a 100 mm diameter control plain concrete specimen. Specimens ST-4 and ST-6 are control hollow steel tubes of 108 mm outer diameter and 4 and 6 mm wall thickness, respectively. CCFST-4 and CCFST-6 are circular concrete-filled tubes identical to ST-4 and ST6. The steel reinforcement ratio, ρ (ratio of cross-sectional areas of steel tube and concrete core) and reinforcement index, ω (which is ρ normalized with respect to the ratio of steel yield stress and concrete compressive strength) of CCFST-4 are 0.148 and 0.71, respectively, and of CCFST-6 are 0.222 and 1.066, respectively. DCFST-25-40, DCFST-50-40 and DCFST-100-40 are dumbbell-shape sections using the ST-4 tube and having a constant web height, defined here as the minimum clear distance between the tubes, h, (see Fig. 3(b)) of 40 mm but with varying web widths, measured from the inside of web plates, b, (see Fig. 3(b)) of 25, 50 and 100 mm, respectively. DCFST-50-70 and DCFST-100-70 are also dumbbell-shape sections using the ST-4 tube and having a constant web height (h) of 70 mm and web widths (b) of 50 and 100 mm, respectively. In the DCFST specimens, the web space was also filled with concrete.

3.2. Materials

The steel tubes used for the construction of the CFST specimens