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Experimental study on confining-strengthening, confining-stiffening, and fractal cracking of circular concrete filled steel tubes under axial tension

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ABSTRACT

This paper studies the mechanical behavior of the circular concrete filled steel tubes (CCFTs) under axial tension. A group of three CCFTs with different steel ratios and in-filled concrete diameters are tested and compared with hollow steel tubes (HTs). Based on the experimental results in the present and previous studies, three key issues of CCFTs under tension, i.e. the *confining-strengthening effect*, the *confining-stiffening effect*, and the *tension-stiffening effect*, are studied at both the stress-resultant level (i.e., force-displacement relationship) and stress levels (i.e., stress-strain relationship). Due to the tendency of the shrinking and slipping of the steel tube in relation to the infilled concrete, the confining contact stress and bonding shear stress, in the vertical and tangential direction respectively, are distributed in the interface between the steel and concrete, which results in the confining and bonding effect of the CCFTs. At the stress-resultant level, the test results demonstrate that the strength and stiffness of CCFTs are average 10% and 29% larger than those of HTs, respectively. The strength increase is contributed by the confining-strengthening effect, and the stiffness enhancement is a combined result of the confining-stiffening and tension-stiffening effects. At the stress-strain level, the measured strains show that the steel tube of the CCFT is in the state of the bi-axial tensile stress state because of the difference of the Poisson's ratio between steel tube and infilled concrete, which contributes to the confining-strengthening and confining-stiffening effects of the CCFTs. In addition, a *fractal cracking* phenomenon of the core concrete of tensile CCFTs is observed and discussed.

1. Introduction

Well-designed steel-concrete composite structure components, like the composite beams, concrete filled steel tubes (CFTs), and steel plate-concrete composite walls, are well known for highlighting the synergistic behavior of their constituent materials, including the high compressive strength, high cross-sectional stiffness, and strong fire resistance associated with the concrete, and the high tensile strength, high strength-to-weight ratio, and large ductility associated with the steel [1–8]. Composite members also take advantage of the interaction of their constituent materials, including the confining effect of CFTs in compression, therefore often achieving larger strength-to-weight ratios than comparable reinforced concrete (RC) or steel members [9,10]. As a result, CFTs have become commonly used as columns in tall buildings and bridge towers in the last several decades. CFTs typically comprise either circular concrete-filled steel tubes (CCFTs) or rectangular concrete-filled steel tubes (RCFTs); this paper specifically addresses the axial tensile behavior of CCFTs.

Although the CCFT components are especially effective when subjected to compression, they may be subjected to tension in some engineering applications, as shown in Fig. 1. CCFT truss girders are used in large-span continuous girder bridges (Fig. 1a), rigid frame bridges (Fig. 1b), deck systems in suspension bridges (Fig. 1c), roof structures (Fig. 1d), and transfer girder structures in buildings (Fig. 1e) because the concrete fill can improve the strength, stiffness, stability and fatigue resistance of the steel tube. The lower CCFT chord in the sagging moment region and the upper CCFT chord in the hogging moment region are under tension, while CCFT components in a CCFT lattice pier, tower (Fig. 1c) or perimeter column system (Fig. 1f) also may be subjected to tension during a severe earthquake [11–13].

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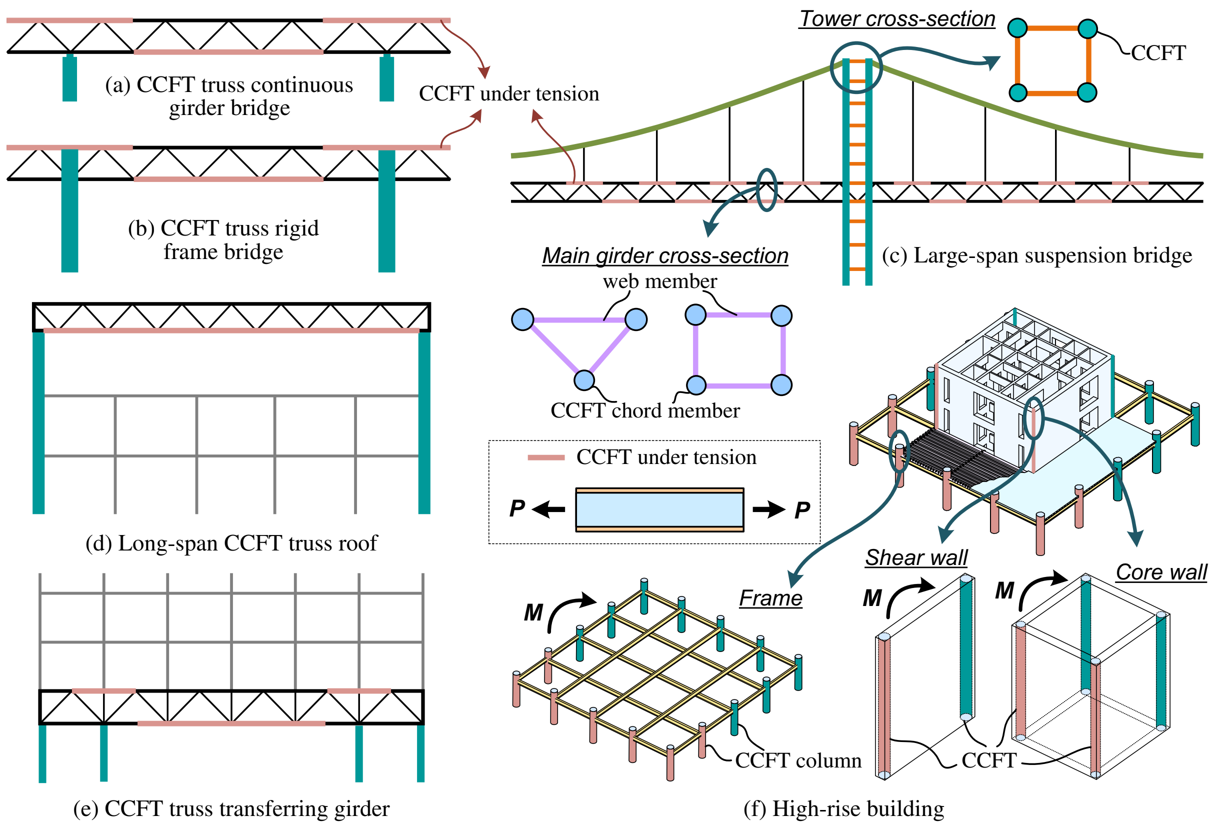

Fig. 1. CCFTs under tension in engineering practices.

So far, compared with the large amount of both experimental and numerical studies on the compressive behavior of CCFTs [14–17], few researches has been carried out for the tensile behavior of CCFTs [18–20]. Moreover, all the existing design codes (AIJ 2008 [21]; AISC 2005 [22]; CEN 2004 [23]) suggest the CCFTs under axial tension should be treated as hollow tubes both in design and analysis, assuming that the concrete fill possesses small tensile strength and thus has slight influence on both the tensile strength and stiffness of the CCFTs. However, experimental results reported by Pan and Zhong [18] demonstrate that the concrete fill enhances the tensile strength of hollow tubes by approximately 10%. Experimental results reported by Han et al. [19] show that the tensile strengths of the CCFTs are larger than the hollow tubes by 9.0–13.5% according to their different steel ratios. A review of the experimental results of the tests of Pan and Zhong [18] and Han et al. [19] also indicates that the effective tensile stiffness of CCFTs are generally larger than the hollow tubes by 12% to 31%. As explained by Han et al. [19] that the larger stiffness of CCFTs when compared with the reference hollow tubes may be a result of the tension-stiffening effect, the effective stiffness of CCFTs suggested be calculated as $E_sA_s + 0.1E_cA_c$, where E_s and E_c are the elastic modulus of steel and concrete, respectively; and A_s and A_c are the cross-sectional of steel and concrete, respectively. However, this equation does not reflect the *confining-stiffening effect* and include the discussion about the cracking behavior.

Therefore, the study of the present paper is specifically focused on the strength and stiffness enhancement of CCFTs under axial tension compared to hollow tubes. A set of CCFT and hollow tube specimens were tested under axial tensile loading, where both the macroscopic force-displacement curves and the strain distribution and cracking behavior in the micro level are measured. Based on these experimental results and available tests reported in the literature, the three key issues influencing the mechanical performance of CCFTs under tension, i.e. the *confining-strengthening effect*, the *confining-stiffening effect*, and the *tension-stiffening effect*, are studied and two important ratios for the enhancements of the tensile strength and effective stiffness, i.e. the strengthening ratio $\alpha_{strength}$ and the stiffening ratio $\alpha_{stiffness}$, are determined and summarized. In this work, the measured ratios of the transverse to the longitudinal steel strain $\left|\frac{\varepsilon_{s,t}}{\varepsilon_{s,l}}\right|$ both along the specimen and through the cross-section, and the distributions of the longitudinal steel strain $\varepsilon_{s,l}$ are used to demonstrate these three effects of CCFTs under tension.

2. Theoretical analysis

A schematic diagram showing the strain and stress state of the concrete and steel tube of the CCFT member under uniaxial tensile loading is illustrated in Fig. 2. It is indicated that due to the tendency of the shrinking and slipping of the steel tube in relation to the infilled concrete, the confining contact stress and bonding shear stress, in the vertical and tangential direction respectively, are distributed in the interface between the steel and concrete, which results in the confining and bonding effect of the CCFTs.

This confinement effect is caused by the difference of the Poisson's ratio between steel tube and infilled concrete, which makes the concrete core act as a brace to resist the transverse shrinkage tendency of the outer steel tube under longitudinal tensile load, thus results in the bi-axial tensile stress state of the steel tube as shown in Fig. 2. Correspondingly, the infilled concrete in the uncracked region is in a state of triaxial stress due to the confining of the outer steel tube. The bonding-sliding behavior is similar to the well-known tension-stiffening effect of a RC member subjected to tension [26], which is a result of the capability of the intact con-