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Analytical behaviour of CFST chord to CHS brace truss under flexural loading

Chao Hou [a], Lin-Hai Han [a,*], Ting-Min Mu [b], Shan-Hu He [a]

[a] Department of Civil Engineering, Tsinghua University, Beijing 100084, PR China
[b] Sichuan Province Transportation Department Highway Planning, Survey, Design and Research Institute, Chengdu 610041, PR China

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ABSTRACT

Concrete filled steel tubular truss (CFST truss for short) structures composed of CFST members as chords and steel tube members as braces are having expanded utilization in large-scale infrastructure constructions. In bridge structures, a concrete slab is usually provided on top of the CFST truss to form a hybrid CFST truss. Besides previous research work on the experimental performance of CFST and hybrid CFST trusses reported in the companion paper (Han et al., 2015), detailed analytical behaviour of such composite truss systems is needed. This paper thus presents a finite element analysis (FEA) modelling on CFST truss without concrete slab as well as hybrid CFST truss with concrete slab subjected to flexural loading, which is validated through reported test data. The FEA modelling is then used to perform analysis on typical failure modes, moment-deflection relations, stress developments, material interactions and the load transferring paths of the composite truss systems. Influences of important parameters on the flexural performance of the composite truss are also investigated, including chord types, existence of reinforced concrete (RC) slab, strength ratio between chords, cross-section profiles, etc. Finally, simplified methods for calculating the flexural strength of CFST and hybrid CFST trusses are recommended and validated.

1. Introduction

Concrete filled steel tubular (CFST) chord to steel tube brace truss (CFST truss for short) has proved to be a structural system with excellent architectural, structural and economical superiorities, since filling the chords of traditional circular hollow section (CHS) tubular truss with concrete can effectively enhance the strength, stiffness and even fatigue life of the tubular connections [17]. With existence of the concrete, the chords gain excellent axial capacity and the flexural behaviour of the whole truss is expected to improve as well. CFST truss systems are thus having expanded application as girders in large-scale structures to resist transverse loading. In these circumstances, it is common to add a reinforced concrete (RC) slab upon the top chords of the truss to form a hybrid CFST truss, a recent application of which is shown in Fig. 1, i.e., the Ganhaizi Bridge in China, with 1811 m in length. Schematic views of typical CFST truss without RC slab and hybrid CFST truss with RC slab are shown in Fig. 2(a) and (b), respectively. As can be deduced, the mechanical characteristic of a hybrid CFST truss enables it to take full advantage of the excellent compression capacity of the concrete slab as well as the tensile and flexure capacity of the CFST, it thus has increasing utilization in recent years.

In the past, many experimental and theoretical investigations have been conducted on the behaviour of CHS truss construction including the design of typical steel tube truss connections, such as Packer and Henderson [20], Wardenier et al. [22,23]. Moreover, advanced CHS truss system consisting of steel tube truss at the bottom and RC slab on the top has been put into use as floor systems since the 1970s. Corresponding experimental and numerical studies on the load-carrying capacity, load-transferring between the steel tube truss and the RC slab as well as the design method have been reported by Kravanja and Šilih [14], Mujagic et al. [18], Machacek and Cudejko [15], etc. However, when the chord members are filled with concrete in traditional CHS trusses, it could be deduced that with the enhancement of CFST chords and possible RC slabs on top, the failure modes and load transfer mechanism of these composite truss systems would vary and be significantly affected by the interaction of materials as well as the strength contrast between different components of the truss. Specific research investigations are thus needed on such new composite truss constructions.

Previously, the performance of individual CFST members under multiple conditions has been conducted all over the world [8]. The significant enhancement on the strength, stiffness and fatigue life of tubular joints in CFST trusses has also been presented by research work such

* Corresponding author.
E-mail address: lhhan@tsinghua.edu.cn (L.-H. Han).

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Nomenclature

A_c	cross-sectional area of concrete in the steel chord
A_s	cross-sectional area of the steel chord
b	gross width of truss section
b_f	width of the RC slab
b_i	effective width of truss section, i.e., distance between the centroids of two top chords
D	diameter of the steel tube
E_c	elastic modulus of concrete
E_s	elastic modulus of steel
f_{cu}	cube strength of concrete
f_c'	cylinder compression strength of concrete
f_y	yield strength of steel
f_u	tensile strength of steel
h	gross height of truss section
h_b	height of the RC slab
h_i	effective height of truss section, i.e., vertical distance between the centroid of the bottom chord and the centroid plane of the two top chords
k_M	flexural strength factor of the truss
L_0	effective span of the truss
M	bending moment
M_{ua}	analyzed flexural strength from FEA modelling
M_{uc}	calculated flexural strength from simplified formulae
M_{ue}	measured flexural strength from experimental testing
N_{ct}	ultimate compressive strength of the top chord
N_{cs}	ultimate compressive strength of the slab
N_{tb}	ultimate tensile strength of the bottom chord
N_{tt}	ultimate tensile strength of the top chord
P	transverse load
s	distance from a loading point of a truss to its closest support
t	thickness of the steel tube
β_c	chord strength ratio ($=N_{ct}/N_{tb}$)
ξ	confinement factor ($=A_s f_y/A_c f_{ck}$)
u_m	mid-span vertical deflection
ε	strain
θ	included angle between the diagonal brace and chord
ϕ	included angle between the braces in the cross-section of the truss
μ_s	Poisson's ratio of steel

as Packer [19], Makino et al. [16], Feng and Young [3] and Qian et al. [21]. In terms of the overall flexural behaviour of CFST trusses, limited work could be found up to now. Kawano and Sakino [13] studied the seismic resistance of CFST truss under cyclic lateral load based on test data of two specimens, Fong et al. [4] detected a 29% increase in maximum load when the chords of hollow truss are filled with concrete. Both studies found that the infilled concrete in chords could benefit the behaviour of the whole truss.

In recent years, the authors have conducted and reported some research work related to the application of CFST in truss structures. Han et al. [7] and Hou et al. [12] investigated the experimental and theoretical behaviour of CFST member under tension and local bearing when acting as the main chords in trusses or bridges, respectively. Hou and Han [11] studied the behaviour of typical composite K-joints. Studies on the performance of members and connections help lay a foundation for further research on the corresponding structural systems. Moreover, the authors reported studies on the flexural behaviour of curved truss in arch bridges [24], as well as the experimental observation of both CFST and hybrid CFST truss subjected to flexural loading [9]. In the latter, six CFST trusses without RC slabs, four hybrid CFST trusses with RC slabs and two reference CHS trusses were transversely loaded, the effects of shear span ratio, truss profile and RC slab are studied. However, detailed analytical behaviour of CFST truss and hybrid CFST truss has rarely been conducted yet. For the widely grown application of composite CFST truss systems, the scope of experimental work needs to be extended since the testing on truss segments is costly and the data that could be obtained through testing are always limited. The corresponding moment-deflection relations as well as the interaction between materials need to be demonstrated through effective numerical studies, whilst the ranges of parameters should be expanded.

This paper thus presents a preliminary study on the performance and design of such composite trusses. The objectives are threefold: (1) to present a finite element analysis (FEA) modelling on CFST truss and hybrid CFST truss subjected to transverse flexural loading, which is verified against reported experimental data in Han et al. [9]. (2) To conduct analysis on the typical failure modes, moment-deflection relations, material interactions of such composite trusses and to investigate the corresponding load-transfer mechanism. (3) To extend the testing scope and to study the influencing of significant parameters, based on which the design methodologies for practical composite trusses are recommended and evaluated.

2. Finite element analysis (FEA) modelling

2.1. General description of the FEA modelling

A numerical model to account for the flexural behaviour of composite truss is established using the finite element analysis (FEA) package ABAQUS. Schematic views of the FEA modelling for CFST truss and hybrid CFST truss are shown in Fig. 3(a) and (b), respectively. The modelling is a further development of the analysis used for simulating curved CFST truss presented in Xu et al. [24] as well as that for typical K-joint in composite truss presented in Hou and Han [11].

2.1.1. Material properties

In this simulation, the proper selection of concrete constitutive model is a critical issue, since the concrete in chord members is under the passive confinement from the chord tube, with enhanced compressive strength and ductility, whilst the slab concrete in hybrid truss remains unconfined. Concrete damaged plasticity (CDP) models in ABAQUS are used to define the material behaviour of concrete in different components, with the value assignments for significant parameters the same as those adopted in Hou and Han [11], such as the dilation angle and the flow potential eccentricity. For slab concrete without confinement, the stress (σ)-strain (ε) relation suggested in GB 50010-2010 [5] is adopted, which consists a nonlinear ascent stage up to the ultimate strength, followed by a descent stage for both compression and tension envelopes. For the confined concrete within chords, the constitutive model proposed by Han et al. [6] considering the confinement features is adopted. Schematic diagrams of the σ-ε relations for both types of concrete are shown in Fig. 4. For the tension stiffening of chord concrete, fracture energy based approach suggested by Hillerborg et al. [10] was successfully adopted in the simulation of CFST members in tension [7], which is also employed in the current modelling.

For chord and brace tubes, elastic-plastic model is used to describe the uniaxial behaviour of steel. The five-stage stress-strain model presented in Han et al. [6] is adopted in this analysis, as shown in Fig. 4(a), where the solid line and dash line stand for the simulative and actual constitutive curves of the steel. In Fig. 4(a), f_p, f_y and f_u stand for the elastic proportional strength, the yield strength and the tensile strength of the steel, detailed formulae of the curve can be found in Han et al. [6]. This model has been used in the modelling of CFST structural members and systems under multiple loading conditions, with reasonable results achieved. The initial modulus of elasticity (E_s) and Poisson's ratio (μ_s) are set as 206,000 N/mm^2 and 0.3, respectively.