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Experimental Study on Self-Compacted Concrete-Filled Steel Tubular (CFST) Truss Girders

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ABSTACT

This paper studies the performance of steel tube truss girders filled with self-compacting concrete. Four concrete-filled steel tubular (CFST) truss girders specimens were tested. The first novelty in this research was using square tubes to manufacture truss girder. The main parameters were the bottom chord concrete compressive strength and reinforcing steel bar employment in the bottom chord (second novelty). One bar with a nominal diameter 16mm was used to reinforce the concrete in the bottom chord while keeping the concrete in the top chord without reinforcement. This paper shows the load-displacement curves at the mid-span, deflections along the span, peak loads, flexural strength, and failure shapes of the tested specimens. The design equation was used to predict the flexural strength of CFST truss specimens. Results show that the flexural strength was increased with the increase in the concrete strength from 29.23MPa to 48.41MPa by about 4.5% and was increased by about 10.27% when using reinforcing the concrete in the bottom chord.

1. Introduction

Concrete-filled steel tubular CFST truss girder is one of the most important inventions in civil engineering; generally, consist of concrete filled steel tube chords and hollow steel tube braces. The presence of concrete can delay or prevent local buckling of the steel tube. Meanwhile, the steel tube provides sufficient confinement for the concrete and therefore can increase the strength, stiffness, and ductility for tension, compression members, and then for joints. The infill concrete also provides a good resistant to seismic force by their good durability under cyclic loading. On the other hand, the steel tube works as formwork for casting concrete, which saving labor costs and construction cost and time [1-3].

CFST trusses have been extensively used in different types of structures. For instance, they have been used as girders in bridges, for example, in Ganhaizi Bridge, China, as shown in **Fig. 1.** They have also been used as girders in the roof system.

The CFST truss girder investigations have been started since 2000 by Zhang et al. [4]. Since then, various experimentally and theoretically studies have been carried to investigate the behaviour of CFST truss girders. Chen et al. [5], conducted three experimental work for Pratt type truss girders. The first specimen hollow steel tube was used in chords and braces. For the second specimen, the top chord was filled with concrete while the bottom chord and the braces were hollow. For the third specimen, the top and bottom chords were filled with concrete, while the braces were hollow. The tests indicated that the presence of infill-concrete in chords increased the strength and stiffness of CFST truss girders. Huang et al. [6] studied the effect of truss type on the behaviour of CFST truss girder. Three specimens were tested in this research, the first was Warren-vertical truss type (which has vertical braces along with diagonal braces), the second was Pratt truss, and the third was Warren Truss. The tests indicated that the Warren-vertical

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Nomenclature

A_{sc}	Cross-section area of the steel and concrete	$M_{exp.}$	Flexural strength obtained from experiments
A_s	Cross-section area of the steel	$M_{eq.}$	Flexural strength obtained from equation 1
A_c	Cross-section area of the infill concrete	P_u	Peak load obtained from experiments
B	Width of chords	C	Compressive strength of the top chord
t	Chord wall thickness	T	Tensile strength of the bottom chord
B_b	Width of braces	f_y	Steel yield stress
t_b	Brace wall thickness	f_u	Steel ultimate stress
H	Truss height	f_{cu}	Concrete cube compressive strength
h	Truss height centroidal distance between top and bottom chords	£	Confinement factor
M_u	Flexural strength	α	Steel ratio, $\alpha = A_s/A_c$

Figure 1: Ganhaizi Bridge, China.

CFST truss girder had better performance, followed by the Pratt truss and then the Warren Truss. Xu et al. [7] tested the behaviour of eight curved CFST trusses. The tested specimens included four curved CFST trusses, two straight CFST trusses, and two curved hollow steel tube trusses. Han et al. [8] showed the development and applications of CFST members. On the comparison between CFST members with steel and reinforced concrete RC members, the load carrying capacity of CFST member was higher than the summation of a load of steel and RC members. Han et al. [9] tested ten CFST trusses girders (Warren truss). They studied the effect of shear span to depth ratio, infill concrete, slab concrete and the angle between chords and diagonal braces. These studies denoted that the strength and stiffness of CFST trusses significantly increased when compared to hollow steel tube trusses and the CFST trusses had two types of failure modes; tensile fracture of bottom chord and shear failure. Zhou et al. [10] studied the performance of CFST truss girders Warren truss type. Four circular section specimens were tested; hollow steel section chords (CH), concrete-filled top chord (CT), concrete- filled bottom chord (CB) and concrete-filled bottom and top cord (CA). The research indicated that the best load carrying capacity obtained from specimen CA and was 180kN, while the maximum load obtained from specimens CH, CB, and CT were 85, 92.2, and 145kN, respectively.

In the last years, the behaviour of the CFST truss girder was investigated by Wenjin et al. in 2012 [11]. Welded joints of circular hollow steel and CFST truss girder were studied. The presence of core concrete in the top and bottom chords increased the joint rigidity and the strength of the whole truss. The governing failure mode was the punching shear failure. In 2017, Huang et al. [12] studied the behaviour of pre-stressed CFST truss girder. High strength strands were used to get on pre-stressed CFST truss girder. Five specimens were tested to study the performance of shear span to depth ratio and pre-stress level. The results indicated that the strength and stiffness of the pre-stress CFST truss girders were increased by increasing the ratios of shear span to depth and pre-stress level. The failure mode was a tensile fracture of the bottom chord when the shear span to depth ratios increased. On the other hand, the joint shear failure was the dominant failure mode if the latter ratios decreased. In 2018, Huang et al. [13] investigated the behaviour of Warren-vertical truss girders experimentally and numerically using finite element analyses (FEA). The test results indicated that the CFST had two failure modes, tensile fracture of the bottom chord (flexural dominated) and shear failure in the joint (shear dominated). CFST trusses must be designed as a flexural dominated, so the author put some point (i) the compression strength concrete in a top chord not less than 1.1% from that in the bottom chord, (ii) shear span to depth ratio ≥ 4.8, (iii) brace to chord ratio ≥ 0.8

The truss load carrying capacity mainly depends on the strength of the bottom chord (in the case the sections of the top and bottom chords were the same), this is due to the lack of concrete effect in the tensile area compared to the compression zone. Therefore, many researchers have tried to strengthen the tensile properties. Studies have shown that the increase of the compressive strength will improve the properties of the tensile members, but affect the ductility of the truss. So in this study, the strengthening the bottom chord by adding a conventional steel reinforcement bar embedded in the concrete core in the bottom chord was investigated. The self-compacting concrete was employed in this study for being suitable in such types of structures.

2. Experimental work

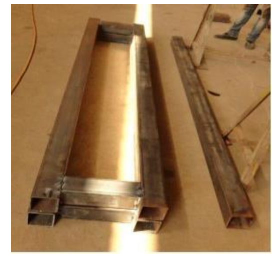
Four CFST truss girders (Warren-vertical truss) were tested. The test parameters were; the bottom chord reinforcement and concrete compressive strength, as shown in **Table 1**. The designation used in **Table 1** to describe each specimen: the first part (R0) indicates that there is no reinforcing steel bar embedded in the bottom chord, (R1) denotes the bottom chord reinforced by one steel bar with diameter 16mm, the second part (T) indicates the concrete grade at top chord, the third part (B) indicates the grade of concrete at the bottom chord. The concrete grade describes the concrete cube compression strength in MPa at 28 days.

The dimensions of all specimens were kept same: the length was 2660 mm, truss height was 500 mm, chord width (B) was 100mm, the wall thickness of the chord (t) was 3.8mm, brace width (B_b) was 80mm, thickness wall of brace (t_b) was 2.8mm and the angle between the chord and inclined braces was 54° as shown in **Fig. 2.**. The width and wall thickness for the first and last braces were increased to 100mm and 3.8mm, respectively, because these braces carried extra forces from supports so the diameter and wall thickness increased to avoid the local buckling.

After specimen fabrication, the specimens were placed vertically and filled with self consolidation concrete. After that the specimens stored in the laboratory for 28 days for testing as shown in **Fig. 3.**. The steel properties measured according to ASTM 370-05a[14] as shown in **Table 2**. The type of concrete used in this study was self-compacting concrete (SCC), and the mix proportions of SCC were given in **Table 3.** The fresh concrete tests were presented in **Table 4**, while the average cube strength (fcu) were 29.23 MPa and 48.41MPa, respectively. The concrete properties measured according to European Guidelines [15].

Table 1. Specimen details.

Specimen ID.	f_{cu} (MPa)		H (mm)	B (mm)	t (mm)	B_b (mm)	t_b (mm)
	Top chord	Bottom chord					
R0T50B30	50	30	500	100	3.8	80	2.8
R0T50B50	50	50	500	100	3.8	80	2.8
R1T50B30	50	30	500	100	3.8	80	2.8
R1T50B50	50	50	500	100	3.8	80	2.8



(a)Position the chords

(b)Complete welding

(c)Specimens paint

(d)Cast concrete

Figure 3: Fabrication and cast of the test specimens.

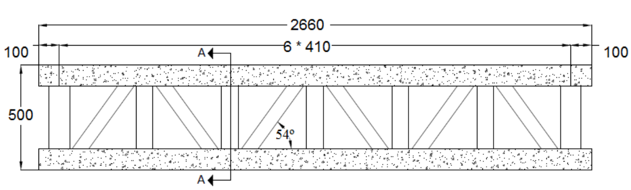
3. Test results

3.1. Ultimate load and mid-span deflection

All specimens were tested using a 3-point load configuration. The load was applied by a hydraulic jack machine with a capacity of 1000 kN and measured by a load cell. Two lateral supports were provided on each side to supply stability to the specimen. Three linear variable displacement transducers (LVDTs) were used to measure the vertical deflection, as shown in **Fig. 4.**

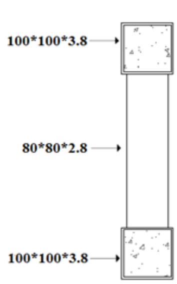
Table 2, The steel properties.

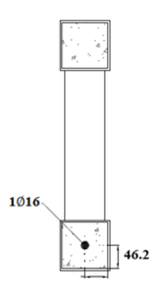
Member	f_y (MPa)	f_u (MPa)
Top and bottom chord	335	371.24
Brace	390	437.59
Steel bar 16mm	480	545.54



(a)Elevation view of the truss girder

Section A-A





(b)Without reinforcement (c)With reinforcement

Figure 2: Specimens details.

Table 3, Concrete mix proportions.

Mix type	C30	C50
Cement (kg/m^3)	300	450
Sand (kg/m^3)	670	670
Gravel (kg/m^3)	730	730
Limestone powder (kg/m^3)	110	90
SP %	1	1.5
Water (kg/m^3)	210	189
w/c ratio	0.7	0.42
f_{cu} at 28-day	29.23	48.41

Table 4, Fresh concrete test results.

Test ID.	C30	C50	Specification
Slump Flow (mm)	760	730	(600 – 800) mm
T50 Slump (Sec)	3	3.5	(2 – 5) Sec
L Box	0.9	0.85	(0.8 – 1)
V Funnel (Sec)	9.4	10.1	(8 – 12) Sec

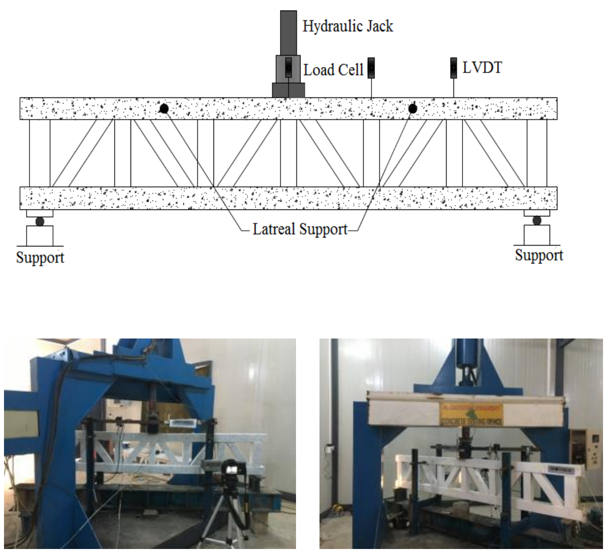


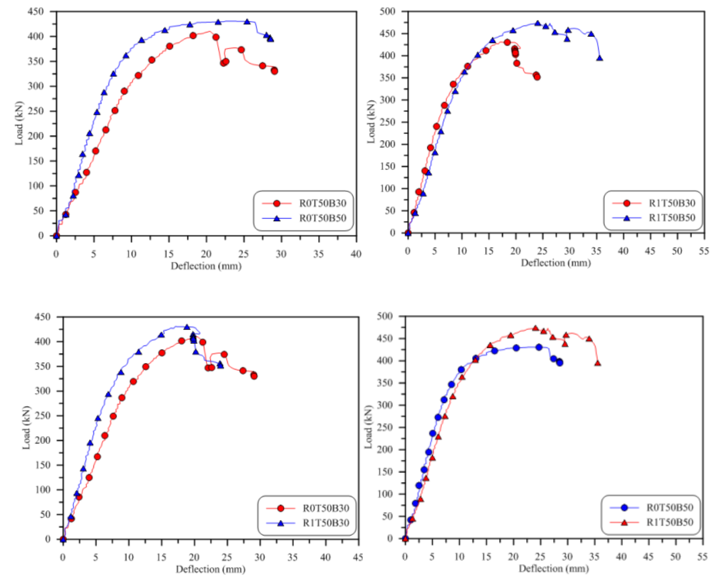
Figure 4: Test set up.

Fig. 5. shows the load-deflection curves at mid-span for the test specimens. The behaviour of test specimens is similar, and is summarized as follows; the load mid-span deflection remained linear when the applied load was less than 0.75Pu (Pu is the peak load). After that, the steel tube in the bottom chord gained hardening, and the top chord yielded at approximately 0.9Pu. The peak load (Pu) and flexural strength (Mu) gained from tests is summarized in **Table 5**. The results were divided into two parts; the concrete compressive effect and steel reinforcement presence in the bottom chord. The results indicated that the concrete grade has a little effect on the strength. Flexural strength of specimen R0T50B50 was increased by about 4.55% as compared to specimen R0T50B30, and the strength of specimen R1T50B50 as compared to R1T50B30 was increased by about 10.34%. The effect of the presence of steel reinforcement was more effective with high compressive strength. Steel works to increase the ductility for such specimens. The flexural strength of specimens R1T50B30 and R1T50B50 as compared to specimens R0T50B30 and R0T50B50 were increased by about 4.92% and 10.27% respectively, **Fig. 6.** shows the variation of the peak load due to the effect of the concrete compressive strength and the effect of the reinforced concrete in the bottom chord. In the plastic stage, the deformities became high and affected the joints where one of the joints failed in the welding area completely due to tension loads, while some of these joints suffered from buckling due to compression loads. Some of the failure modes are shown in **Fig. 7.** The use of steel bars embedded in the bottom chord showed an improvement in load resistance as indicated, but this improvement in the results could have been obtained by increasing the wall thickness of the steel tube and may have a better effect when using bigger sections.

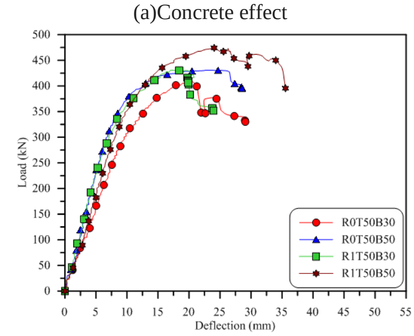
Table 5, Peak load and flexural strength.

Specimen name	P_u(kN)	M_u(kN.m)*
R0T50B30	252.295	410.236
R0T50B50	264.88	430.71
R1T50B30	264.72	430.44
R1T50B50	292.09	474.945

*calculated ($M_u = PL/4$)

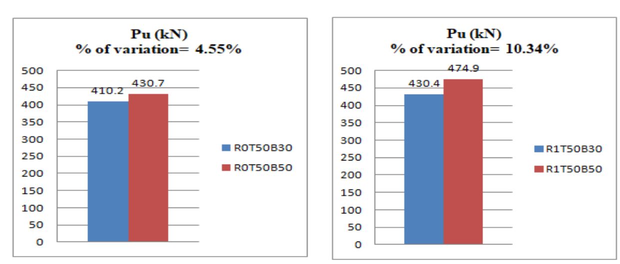


(a)Concrete effect

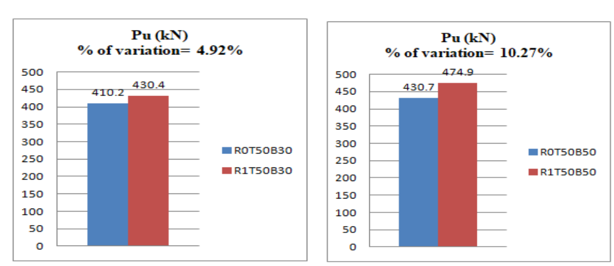


(b)Reinforcement effect

Figure 5: Load mid-span deflection.



(a)Concrete effect.



(b)Reinforcement effect

Figure 6: Peak load variation ratio.

3.2. The deflections profile

Deflections profile is shown in **Fig. 8.** . Due to symmetry the deflections in the second half of the truss equal to the deflections in the first half. These deflections compared with half-sine curves represented as a dashed line. It is clear that when the load was less than 0.75Pu the half sine curves and the deflections along the span of CFST specimens are almost the same. When the applied load exceeded the 0.75Pu, half sine curves didn't coincide with those obtained from the tests except at mid-span, because that the steel tube yielding and fracture result in the deflections to focus at the middle. These results are similar to those found by Xu et al.[7] and Huang et al.[13].

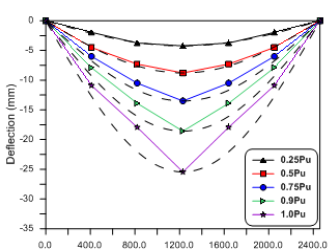
(a)Joint failure.

(b) Joint failure.

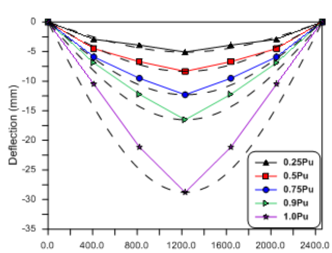
(c)Weld fracture.

(d)Braces buckling.

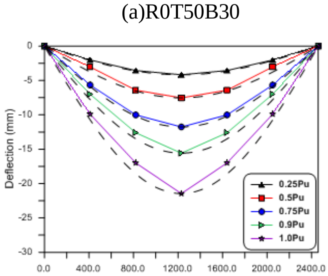
Figure 7: Modes of failure.



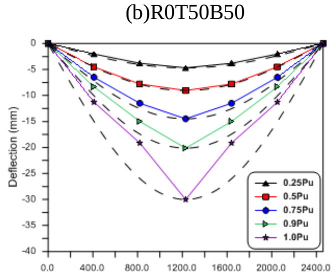
(a)R0T50B30



(b)R0T50B50



(c)R1T50B30



(d)R1T50B50

Figure 8: Deflection along the span at different load levels.

4. Predicted design equation

CFST truss girders have three possible failure shapes, local buckling of the top chord, tensile fracture of the bottom chord, and joint failure. CFST trusses girders must be designed as flexural dominated (tensile fracture of the bottom chord) because they had better ductility due to the good tensile behaviour of CFST members. Meanwhile, CFST truss girders designed as a joint failure had less ductility. The proposed flexural strength determined from the following equation[9].

$$M = \text{Min.}(C\ ,\ T) * d \tag{1}$$

where d is the centroid distance between the bottom and top chords, C compressive strength of top chord, and T tensile strength of bottom chord. The compressive strength of the top chord (C) and the tensile strength of the bottom chord (T) can be predicted by the following equations. These equations were suggested by Han et al. [16, 17].

$$C = \sum(1.14 + 1.02£)\, f_{cu} A_{sc} \tag{2}$$

$$T = \sum(1.1 - 0.4\alpha)\, f_y A_s \tag{3}$$

where £ = $f_y A_s / f_{cu} A_c$ is the confinement factor, f_{cu} is the concrete strength, A_{sc} is the cross section area of steel and concrete, α = A_s/A_c is the steel ratio, A_s is the cross section area of the steel tube bottom chord, A_c is the cross section area of the concrete, and f_y is the steel tube bottom chord yield strength. The Summation symbol (∑) was proposed by the author, which is used when there is more than one type of steel section.
The predicted design equations were used to propose the flexural strength of the four specimens tested in this paper and compared to previous research. **Fig. 9.** shows the comparison results, the horizontal and vertical axis represents the flexural strength obtained from the tests ($M_{exp.}$) and from Han equation ($M_{eq.1}$), respectively. **Table 6** shows the test specimen flexural strength obtained from the experimental test and Han equation and compared with other research results. Han equation considered equations that give acceptable results to estimate the flexural strength of CFST member within 20%. However, there are some observations on these equations;

(i) Han proposed these equations when tested column subjected to direct axial tension, so the strain was uniform on the section, meanwhile, the strain in the CFST truss girders was linear and that caused the defect especially when the cross-section of the chords was large,

(ii) Han equations did not take into account the presence of any additional section within the original section, as in this search adding a steel bar in the concrete of the bottom chord.

5. Conclusion

This research studied the performance of CFST truss girders. Four CFST truss girders were tested experimentally. The test parameters were the concrete grade of the bottom chord and embedded steel reinforced bar of the bottom chord.

The tests indicate that the increase of concrete compressive strength increases the strength of the CFST trusses. Using the reinforcement in the bottom chord of specimens, R1T50B30 and R1T50B50 increased the flexural strength by about 4.92% and 10.27%, respectively.

Proposed design equations were used to predict the flexural strength of the CFST truss girders which give acceptable results within 20%, but this equation must be modified to take into consideration the existence of additional sections within the original section for example the presence of steel reinforcement.

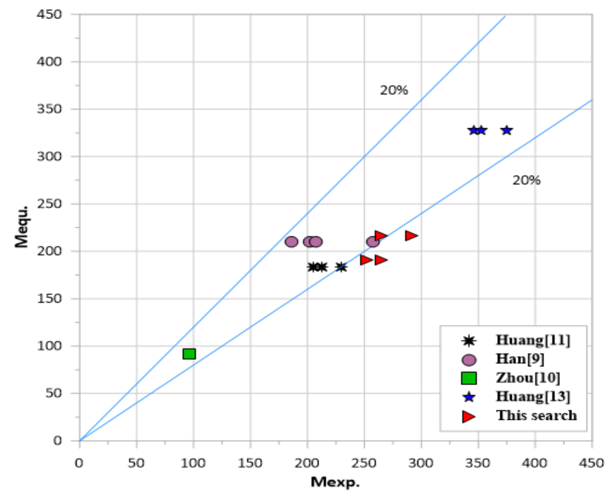


Figure 9: Comparison of the flexural strength obtained from the test and Eq. (1).

Table 6, Peak load and flexural strength.

Tested by	Specimen name	Tube section	h (mm)	A_s (mm^2)	A_c (mm^2)	Steel properties (MPa) f_y	f_u	Flexural strength (kN.m) $M_{exp.}$	$M_{equ.}$
Huang et al.[11]	W2	circular	399	1006	11450	428	533	181.01	182.94
	AW2							230.04	
	P2							205.02	
	AP2							212.4	
Han et al.[9]	T8	circular	375	1733	13714	316	454	202.2	209.8
	T8S							207	
	T6							170.1	
Zhou et al. [10].	CA	circular	400	628	7238	342	660	96.75	91.52
Huang et al.[13]	H5C50C30	circular	500	1479.5	6687	438	534	346.3	327.77
	H5C50C50							352.1	
	H5C70C70							374.4	
Present study	R0T50B30	square	400	1375	8538	350	371.24	252.3	190.8
	R0T50B50							264.8	
	R1T50B30			1575	8338			264.7	216.33
	R1T50B50							292.1	

REFERENCES

[1] Z. Lai, A.H. Varma, K. Zhang, Noncompact and slender rectangular CFT members: Experimental database, analysis, and design, Journal of Constructional Steel Research, 101 (2014) 455-468.

[2] Z. Lai, A.H. Varma, Noncompact and slender circular CFT members: Experimental database, analysis, and design, Journal of Constructional Steel Research, 106 (2015) 220-233.

[3] Z. Lai, A.H. Varma, L.G. Griffis, Analysis and design of noncompact and slender CFT beam-columns, Journal of Structural Engineering, 142(1) (2015) 04015097.

[4] L.Z. Zhang L, Cheng M., Concrete-filled steel tube truss girders, Beijing, China (Press in Chinese): China Communications Press, (2000).

[5] H.W. Chen B, Experimental research on ultimate load carrying capacity of truss girders made with circular tubes (press in Chinese). J Build Struct, (2007).

[6] C.B. Huang W, Research on influence of web member on mechanical behavior of CFST truss girders (Press in Chinese). J Build Struct (2009).

[7] W. Xu, L.-H. Han, Z. Tao, Flexural behaviour of curved concrete filled steel tubular trusses, Journal of constructional steel research, 93 (2014) 119-134.

[8] L.-H. Han, W. Li, R. Bjorhovde, Developments and advanced applications of concrete-filled steel tubular (CFST) structures: Members, Journal of Constructional Steel Research, 100 (2014) 211-228.

[9] L.-H. Han, W. Xu, S.-H. He, Z. Tao, Flexural behaviour of concrete filled steel tubular (CFST) chord to hollow tubular brace truss: experiments, Journal of Constructional Steel Research, 109 (2015) 137-151.

[10] W. Zhou, Y. Chen, K. Wang, S. Han, F.P. Galarza, Experimental research on circular concrete filled stainless steel tubular truss, Thin-Walled Structures, 117 (2017) 224-238.

[11] W. Huang, L. Fenu, B. Chen, J. Liu, B. Briseghella, Resistance of Welded Joints of Concrete Filled Steel Tubular Truss Girders, in: 10th International Conference on Advances in Steel Concrete Composite and Hybrid Structure (ASCCS 2012), Research Publishing, 2012.

[12] W. Huang, Z. Lai, B. Chen, P. Yao, Experimental behavior and analysis of prestressed concrete-filled steel tube (CFT) truss girders, Engineering Structures, 152 (2017) 607-618.

[13] W. Huang, Z. Lai, B. Chen, Z. Xie, A.H. Varma, Concrete-filled steel tube

(CFT) truss girders: Experimental tests, analysis, and design, Engineering Structures, 156 (2018) 118-129.

[14] A.D. 370-05a, "Test Methods and Definitions for Mechanical Testing of Steel Products", , American Society for Testing and Material, (2001 Annual Book of ASTM Standards,).

[15] The European Guidelines for Self-Compacting Concrete Specification, Production and Use, (May 2005).

[16] L.-H. Han, G.-H. Yao, X.-L. Zhao, Tests and calculations for hollow structural steel (HSS) stub columns filled with self-consolidating concrete (SCC), Journal of Constructional Steel Research, 61(9) (2005) 1241-1269.

[17] L.-H. Han, S.-H. He, F.-Y. Liao, Performance and calculations of concrete filled steel tubes (CFST) under axial tension, Journal of Constructional Steel Research, 67(11) (2011) 1699-1709.