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COLUMN TEST OF CONCRETE-FILLED STEEL TUBES WITH REINFORCED LATTICE ANGLE

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ABSTRACT

Experimental investigation of concrete-filled steel tube columns with reinforced lattice angle was conducted in this study. The lattice angle was designed to reinforce the concrete-filled steel tube columns by increasing the percentage of steel cross-sectional area. Column specimens having different lengths ranged from 500mm to 3500mm were tested. The behavior and strengths of concrete-filled steel tube columns with lattice angle were investigated. In addition, concrete-filled steel tube columns having same size but without reinforced lattice angle were also tested for comparison. Material properties of the concrete and steel used in the test specimens were measured. A new design method was also proposed for the concrete-filled steel tube columns with reinforced lattice angle. It is shown the design predictions from the proposed method agree with test results well.

Keywords: Concrete-filled steel tube columns; Design; Experimental investigation; Reinforced lattice angle;

1. INTRODUCTION

Filled concrete composite members provide a solution to those members having large diameter to thickness ratio since the filled concrete could effectively enhance the local buckling resistance of the thin-walled steel tube (O’Shea and Bridge, 1997) (Uy, 2001a) (Ellobody, et al. 2006) (Han, et al. 2007). However, the requirement of steel to concrete cross-sectional area ratio may not be satisfied for such thin-walled concrete-filled steel tubes. I section or crossed I-section steel member has been used to reinforce the concrete filled steel tube by increasing the percentage of steel cross-sectional area (Wang, et al. 2004)(He and Xiao, 2006). However, I section or crossed I-section steel bone was different to be erected in some structures such as electric transmission line tower.

In this study, a lattice angle structure has been used to reinforce the concrete-filled steel tube. This kind of structural members has the engineering application in a 370m electric transmission line tower in Zhejiang province, China. The four main columns of the electric transmission line tower are concrete-filled steel tubes with reinforced lattice angle, as shown in Fig. 1. Compared with those

I section or crossed I-section steel members, the lattice angle has these advantages: 1) The angle could be connected to the inner wall of steel tube by short steel bars at spacing of meters so it is easy to be positioned; 2) The lattice angle could be used as scaffolding during the process of construction; 3) The steel cross-sectional area of lattice angle is far from the central axis of the column so that the moment of inertia could be maximized. However, the behavior and strength of this kind of composite member have not been studied. There is also a lack of knowledge about its structural behavior and corresponding design rules. Therefore, a test program on the thin-walled concrete-filled steel tube columns with reinforced lattice angle was conducted in this study.

Figure 1: An electric transmission line tower in Zhejiang Province

2. TEST PROGRAM

2.1. Test specimen

For casting the test specimens, the ends of the steel tubes were cut to specified lengths of 500mm, 1500mm, 2500mm and 3500mm. The insides surface of the tubes were wire brushed to remove any rust and loose debris present. The self-compacting concrete was cured without any vibration. During curing, a very small amount of longitudinal shrinkage occurred at the top of the column. High strength cement was used to fill this longitudinal gap before the welding of the top steel end plate.

A total of 14 concrete-filled steel tube specimens were tested. Due to the computer’s error, the displacement and strain data of specimen series having the diameter of 400mm were lost. Only the ultimate strengths and failure modes were record for specimen series having the diameter of 400mm. The measured cross-section dimensions and specimen length for each test specimen are shown in Table 1. Fig.2 shows the details of reinforced lattice angle. The L-500mm columns (columns having the length of 500mm) were design to study the local buckling of the single angle element inside the concrete-filled steel tubes. The test specimens are labeled such that the type of the specimen, diameter and length of specimen can be identified from the label. For example, the labels "CS300-500" and "CSB400-2500" define the specimens as follow:

- The first two or three letter indicate that the type of the specimen, where the prefix letter "CS" refers to concrete-filled steel tubes ("CSB" refers to concrete-filled steel tubes with lattice angle).
- The following three digits "300" or "400" indicate the diameter of the steel tubes in mm.
- The following three or four digits "500" or "2500" are the nominal length of the specimen in mm.

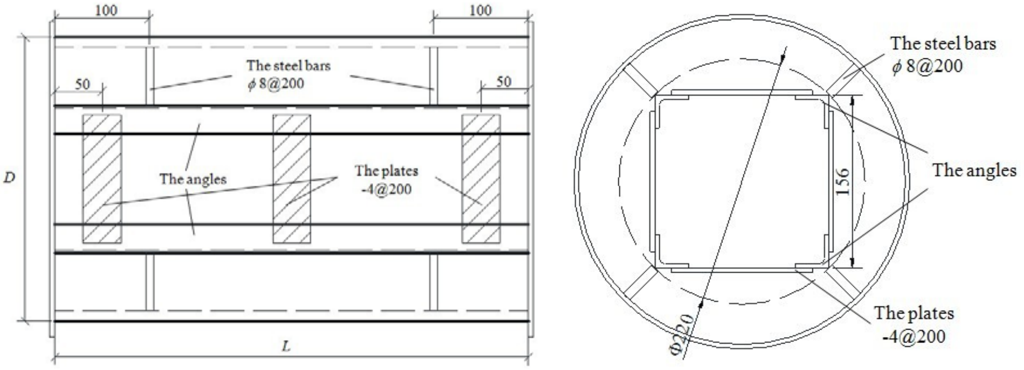

Figure 2: Details of test specimens with lattice angle

Table 1: Dimension of test specimens

Specimens	L	D	t	b_a	t_a	L_a	S_a	ρ	ϕ
				(mm)					
CS300-500	500	300	3.98	----	----	----	----	----	0.468
CSB300-500	500	300	3.97	30	3.01	500	200	0.100	0.473
CS300-1500	1500	300	4.06	----	----	----	----	----	0.468
CSB300-1500	1500	300	4.00	30	2.98	1500	200	0.100	0.473
CS300-2500	2500	300	4.03	----	----	----	----	----	0.468
CSB300-2500	2500	300	4.00	30	2.99	2500	200	0.100	0.473
CS300-3500	3500	300	3.97	----	----	----	----	----	0.468
CSB300-3500	3500	300	3.98	30	3.00	3500	200	0.100	0.473
CS400-500	500	400	3.96	----	----	----	----	----	0.335
CSB400-500	500	400	3.96	40	4.00	500	200	0.096	0.339
CS400-1500	1500	400	4.00	----	----	----	----	----	0.335
CSB400-1500	1500	400	4.04	40	3.98	1500	200	0.096	0.339
CS400-2500	2500	400	4.02	----	----	----	----	----	0.335
CSB400-2500	2500	400	3.97	40	3.98	2500	200	0.096	0.339

2.2. Test setup

The test set-up of the column tests is shown in Fig. 3. A 10000 kN hydraulic testing machine was used to apply axial compressive force to the column specimens. Two 20 mm thick steel end plates were welded to the ends of the specimen. Two spherical bearing were used at the upper and lower end supports (one spherical bearing on top and one plate bearing on bottom for 500mm columns). The spherical bearing was free to rotate in any direction. A small initial load of approximately 10% of design strength was applied on each specimen before testing to eliminate any possible gaps between bearing plates and end plates of the specimen. Two steel rings were place at the both ends of each column specimens to prevent the “elephant foot failure” (Uy, 2001b) (Young and Ellebody, 2006).

a) CS300-500 b) CSB300-1500

Figure 3: Test setup

Four LVDT transducers were also positioned on the top end plate of the specimen to measure the axial shortening of the column, as shown in Fig. 3. Displacement control was used to drive the hydraulic actuator at a constant speed of 1.0 mm/min for all test specimens. The use of displacement control allowed the tests to be continued into the post-ultimate range. A data acquisition system was used to record the applied load and the readings of the transducers at regular intervals during the tests. All specimens were loaded to failure.

3. MATERIAL TEST RESULTS

3.1. Steel

Tensile coupon tests were conducted to obtain the material properties of steel tube used in the test specimens. The coupons were taken from the steel tubes in the longitudinal direction belonging to the same batch as the column test specimens. The coupon dimensions conformed to the Australian Standard AS 1391 (1991) for the tensile testing of metals using 12.5 mm wide coupons. The coupons were also tested in accordance with the AS 1391 (1991) in a displacement controlled testing machine using friction grips. A calibrated extensometer of 50 mm gauge length was used to measure the longitudinal strain. A data acquisition system was used to record the load and the readings of strain at regular intervals during the tests. The material properties of the angle were provided by the supplier. The values of Young’s modulus (E_s), yield stress (F_y), ultimate tensile strength (F_u) based on a gauge length of 50 mm are shown in Table 2.

Table 2: Material properties of steel used in test specimens

Specimen	E_s (GPa)	F_y (MPa)	F_u (MPa)
Angle 30×3 mm	204	298	427
Angle 40×4 mm	205	290	420

Tube 300×4 mm	206	264	435
Tube 400×4 mm	205	255	417

3.2. Self compacting concrete

The concrete mix was designed for compressive cube strength (f_{cu}) at 28 days of approximately 40 MPa. The compressive strength (f_{cu}) and elastic modulus (E_c) obtained on 150-mm cubes at 28 days were 47 MPa and 37420 MPa, respectively. Concrete were taken out from the specimens belonging to the same batched as the column test specimens. It is shown that the self-compacting concrete filled the steel tubes well and there is no obvious void.

4. COLUMN TEST RESULTS

The measured axial load versus axial deformation responses based on the LVDT readings of test specimens are shown in Fig. 4. Table 3 lists the ultimate strengths and failure modes of test specimens. The lattice angle and concrete core was taken out from the failed specimens, as shown in Fig. 5. The angle shows large yielding deformation but no obvious local buckling for CSB300-500 specimen. The lattice angle taken out from specimen CSB300-2500 shows overall buckling but there is no single angle element's buckling deformation.

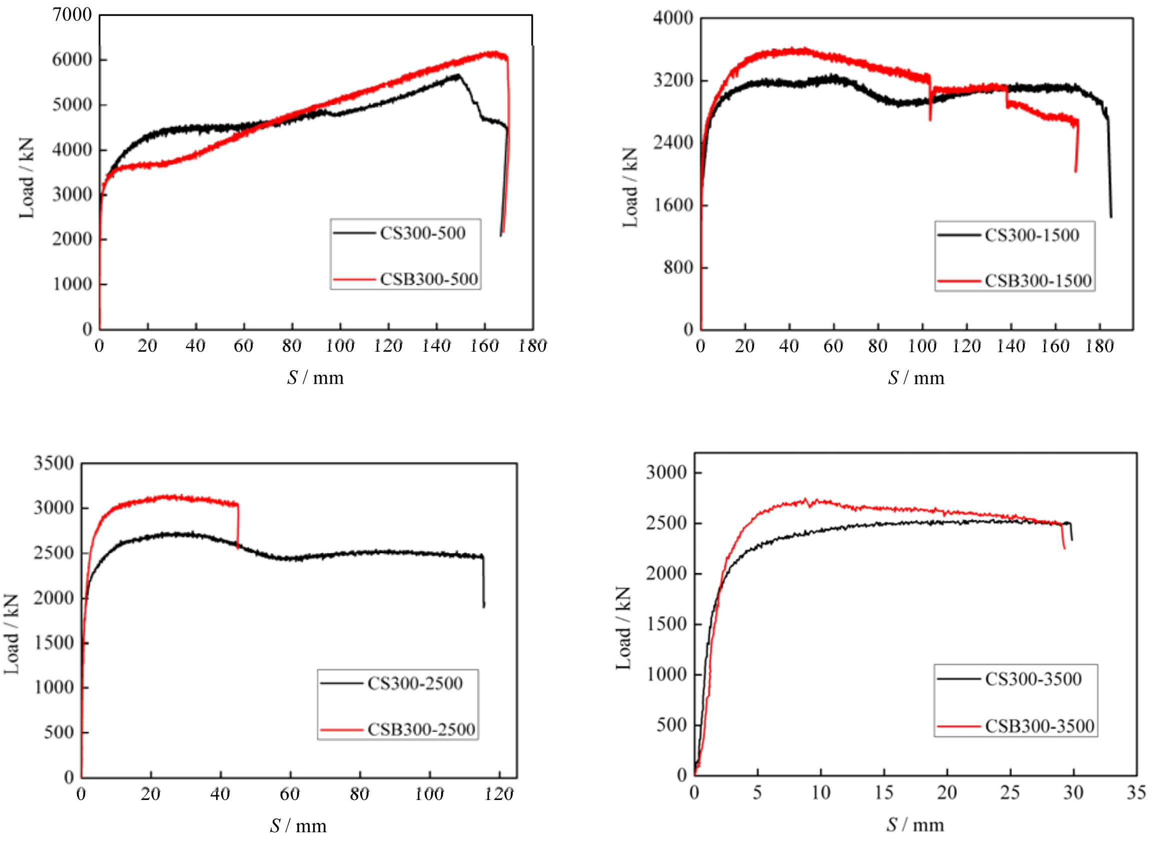

Figure 4: Load versus axial shortening curves

Table 2: Ultimate strengths and failure modes of test specimens

Specimens	$P_{\text{u-test}}$ (kN)	Failure mode
CS300-500	5680	Steel Yielding & Concrete Crush
CSB300-500	6194	Steel Yielding & Concrete Crush
CS300-1500	3280	Shear Failure
CSB300-1500	3626	Shear Failure
CS300-2500	2751	Overall buckling
CSB300-2500	3150	Shear Failure
CS300-3500	2547	Overall buckling
CSB300-3500	2751	Overall buckling
CS400-500	7711	Steel Yielding & Concrete Crush
CSB400-500	8588	Steel Yielding & Concrete Crush
CS400-1500	4562	Shear Failure
CSB400-1500	4696	Shear Failure
CS400-2500	4486	Shear Failure
CSB400-2500	4614	Shear Failure

a) CSB300-500 b) CSB300-3500

Figure 5: Lattice angle taken from the tested specimen

5. DESIGN METHOD

The ultimate strengths of test specimens are compared with the design predictions. Due to the end constraint effect, the ultimate strengths of L-500mm specimens are not used in the comparison. Ultimate strengths of specimen series having the diameters of 400mm were used in the comparison. In the proposed design method, the strength of concrete-filled steel tubes with lattice angle is considered to be the sum of two parts, namely the strength of concrete-filled steel tub and the strength of lattice angle, as shown in Eq. (1). A coefficient (Φ_{sr}) considering the interaction between the steel section reinforced ratio and the slenderness ratio is also proposed. The strength of concrete-filled steel tube ($P_{\text{u-CFT}}$) is calculated according to the AISC Standard (2010). The strength of lattice angle ($P_{\text{u-sr}}$) is calculated using Eq. (2). The global bulking and local bucking of single angle element are not considered since there is no single angle element buckling according to the test results. The global buckling of lattice angle structure is still considered, as shown in Eq. (3). Table 5 shows the comparison of the ultimate strengths of test specimens with the proposed method's predictions. The average value of P_{u} /$P_{\text{u-test}}$ is 1.01 with the corresponding COV of 0.084. It is shown that the proposed method generally predicted the specimen with lattice angle well.

$$P_{\text{u}} = P_{\text{u-CFT}} + \Phi_{\text{sr}} P_{\text{u-sr}} \tag{1}$$

$$P_{\text{u-sr}} = F_{\text{cr}} A_{\text{g}} \tag{2}$$

when $\lambda \le 35$, $\Phi_{\text{sr}} = 1 + \rho$, when $\lambda > 35$, $\Phi_{\text{sr}} = 1$;

F_{cr} is the critical stress determined as Eq. (4).

When $F_{\text{y-sr}} / F_{\text{e}} \le 2.25$, $F_{\text{cr}} = (0.658^{F_{\text{y-sr}}/F_{\text{cr}}})F_{\text{y-sr}}$ (3)

When $F_{\text{y-sr}} / F_{\text{e}} > 2.25$, $F_{\text{cr}} = 0.877 F_{\text{e}}$

Where $F_{\text{e}} = \pi^2 E_{\text{sr}} / (L_0 / r_{\text{sr}})^2$;

L_0 / r_{sr} is slenderness ratio of lattice angle member acting as a unit in the buckling direction being considered.

Table 5 The comparison of ultimate strengths obtained from test results with proposed design predications

Specimen	P_{u} kN	$P_{\text{u-test}}$ kN	$P_{\text{u}}/P_{\text{u-test}}$
CS300-1500	2922	3280	0.89
CS300-2500	2830	2751	1.03
CS300-3500	2697	2547	1.06
CS400-1500	4810	4562	1.05
CS400-2500	4718	4486	1.05
CSB300-1500	3125	3626	0.86
CSB300-2500	3023	3150	0.96
CSB300-3500	2859	2751	1.04
CSB400-1500	5155	4696	1.10
CSB400-2500	5045	4614	1.09
		Mean	1.01
		COV	0.084

6. CONCLUSIONS

An innovative structural element of concrete-filled steel tube with reinforced lattice angle was studied in this paper. Column tests on concrete-filled steel tube with and without lattice angle were carried out. Load displacement curves were obtained. It is shown that the reinforced lattice angle could effectively enhance the strength of concrete-filled steel tubes. However the effect of reinforced lattice angle on axial stiffness of specimens is small. Also there is no obvious enhancement on ductile for specimens with lattice angle. Design method was proposed for the concrete-filled steel tube columns with reinforced lattice angle. It is shown that the proposed design method is able to predict the strength of concrete-filled steel tubes reinforced with lattice angle with reasonable accuracy.

7. ACKNOWLEDGMENTS

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