TEST ON CIRCULAR STEEL TUBE CONFINED UHPC AND UHPFRC COLUMNS UNDER AXIAL LOADING

Hoang An Le (1) and Ekkehard Fehling (1)

(1) Institute of Structural Engineering, University of Kassel, Germany

Abstract

This paper presents the behavior of ultra high performance concrete with and without steel fibers (UHPC and UHPFRC) filled circular steel tube columns under axial loading on only concrete core. The experimental investigation was conducted with six columns having an outer diameter of 152.4 mm and steel thickness of 8.8 mm. These columns were divided into short columns with length of 600 mm and long columns with length of 1000 mm. The test results including load versus axial shortening curves, strength enhancement ratio, and ductility index were discussed in detail. In general, the confinement effect induced by steel tube provides an improvement in both strength and ductility for UHPC and UHPFRC. Test results demonstrated that the addition of steel fibers does not increase the strength enhancement for confined concrete, whereas the post-peak ductility can be considerably improved as compared to the columns without steel fibers. Furthermore, the presence of steel fibers reduces the localization of deformation of steel tube and the sudden drop of load right after the first peak load.

Résumé

Cet article présente le comportement de poteaux constitués de tubes d'acier circulaires remplis de béton à ultra-hautes performances sans fibres (BUHP) ou avec fibres métalliques (BFUP) sous chargement axial uniquement appliqué sur le cœur en béton. L'investigation expérimentale a été menée sur six poteaux d'un diamètre extérieur de 152.4 mm et d'une épaisseur d'acier de 8.8 mm. Les poteaux se divisaient en deux groupes, poteaux courts de 600 mm de long et poteaux longs de 1000 mm. L'analyse détaillée des résultats a porté sur les courbes chargement / raccourcissement axial, le taux d'augmentation de résistance et l'indice de ductilité. En général, l'effet de confinement provoqué par le tube en acier engendre une amélioration de ténacité et ductilité pour le BUHP comme pour le BFUP. Les résultats des tests ont montré que l'addition des fibres d'acier ne contribue pas à l'augmentation de résistance du béton confiné, mais que la ductilité post-pic peut être considérablement améliorée par rapport aux poteaux sans fibres d'acier. De plus, la présence de fibres d'aciers réduit la localisation de la déformation du tube d'acier et la chute brutale de la charge juste après le pic d'effort.

1. INTRODUCTION

It is well-understood that ultra high performance concrete (UHPC) with compressive strength higher than 150 MPa exhibits a brittle failure under compression, thus leading to a drawback for its utilization in construction, especially in seismically active regions. On the other hand, it is also established that lateral confinement of concrete results in a significant enhancement for its compressive strength and deformability. Therefore, steel tube confined UHPC columns (STC-UHPCCs) are capable of reducing the inherent brittleness of UHPC material as well as improving the load bearing capacity [14, 15]. The STC-UHPCCs refer as a form of UHPC filled steel tube columns (UHPC-FSTCs) under axial loading on only concrete core. In the past, there were several experimental studies on UHPC-FSTCs under two axial loading patterns including: on concrete core only and on entire section [4, 8, 9, 11, 12, 13]. These studies demonstrated that for the case of axial loading on entire section, no significant confinement effect is developed until reaching the peak load. The reason for this is that UHPC core is crushed before steel tube yields since in the elastic phase the Poisson's ratio of UHPC core is smaller than that of steel tube before. As a consequence, these authors suggested that the confinement effect should be neglected for UHPC-FSTCs under axial loading on entire section. However, Liew and Xiong (2012) [8] recommended that the tri-axial confinement effect reaches its maximum when only UHPC core is being loaded, thus improving both strength and ductility of UHPC-FSTCs. Likewise, Tue *et al.* (2004) [12] and Schneider (2006) [11] asserted that loading on UHPC core with thicker steel tube can generate sufficient confinement and impede the sudden load drop right after the peak load of UHPC-FSTCs. Based on these findings, in order to obtain more benefits of strength and ductility for UHPC columns, STC-UHPCCs should be further considered and examined.

To the best knowledge of the authors, experimental studies on UHPC-FSTCs, in general, and STC-UHPCCs, in particular remain very limited. In addition, all current design codes for concrete filled steel tube columns (CFSTCs) may be applicable for normal strength concrete (NSC). Recently, Liew and Xiong (2015) [7] have presented an extended design guideline of Eurocode 4 (EC4, 2004) for CFSTCs using concrete with cylinder compressive strength up to 90 MPa, while Australia standard (AS, 2014) for CFSTCs in composite bridges and building allows the concrete cylinder compressive strengths up to 100 MPa. Hence, additional tests on UHPC-FSTCs under two types of loading patterns as discussed above should be conducted to investigate the suitability of design codes and to extend their applicability for the case of UHPC.

From the issues highlighted above, this paper aims at reporting on an experimental investigation into circular STC-UHPCCs on a total of 6 monotonically loaded short and long columns. The discussion on the testing processing, failure modes and the results of axial load versus axial shortening curve, strength and ductility enhancement will be presented.

2. EXPERIMENTAL STUDY

2.1 Details of Materials and Test Specimens

UHPC without steel fibers (UHPC) and UHPC with steel fibers of 1% by volume (UHPFRC-SF1%) and 2% by volume (UHPFRC-SF2%) was used in this study, following the recipe of M3Q which was developed at University of Kassel during the work on the priority program (SPP1182) of the German Research Foundation (Deutsche Forschungsgemeinschaft DFG) [10]. It should be noted that M3Q mix was designed to provide a very high self-compacting characteristic. The fine-grained UHPC and UHPFRC mix have a water-binder ratio of 0.21 and a maximum grain size of 0.5 mm. The details of the mix proportions are given in Table 1. The steel fibers with diameter d_f of 0.175 mm and length l_f of 13 mm were added to the UHPC mix in volume fraction of 1% and 2%. The mechanical properties of steel fibers are illustrated in Table 2.

Table 1: Composition of UHPC and UHPFRC mixes

Mix composition	Unit	Cast 1	Cast 2	Cast 3
		UHPC	UHPFRC-SF1%	UHPFRC-SF2%
Water	kg/m^3	187.98	187.98	187.98
CEM I 52.5R HS-NA	kg/m^3	795.4	795.4	795.4
Silica fume	kg/m^3	168.6	168.6	168.6
Superplasticizer Sika Viscorete 2810	kg/m^3	24.1	24.1	24.1
Ground Quartz W12	kg/m^3	198.4	198.4	198.4
Quartz sand 0.125/0.5	kg/m^3	971	971	971
Steel fibers	kg/m^3	-	79.31	160.25
Slump flow	mm	895/915	885/900	880/865

Table 2: Properties of steel fibers

Diameter d_f (mm)	Length l_f (mm)	Aspect ratio (l_f/d_f)	Density (g/cm^3)	Tensile strength (MPa)	Elastic Modulus (GPa)	Characteristics
0.175	13	13/0.175 = 74.29	7.8	2500	200	Smooth and brass coated surface

As a first series of experimental studies on circular STC-UHPCCs tested at the Laboratory of Structural Engineering Department of Kassel University, a total of 6 steel tubes (type of S355J2H) with an outer diameter (D) of 152.4 mm and a steel tube thickness (t) of 8.8 mm were manufactured for filling with UHPC. The height (L) of short columns and long columns were 600 mm and 1000 mm, respectively. Figures 1(a)-(b) show the formworks for filling UHPC into steel tubes, in which steel bars were used to connect the top wooden plate with the bottom wooden plate of European pallet, thereby holding the steel tube in place and preventing any movement during the casting process. Due to very high slump flow even with incorporation of steel fiber volume up to 2% (see Table 1), UHPC and UHPFRC mixes were directly and vertically poured into steel tubes without vibration (see Figure 1b). Figures 1(c)-(d) describe the test specimens and the top level of concrete after casting and hardening.

There were 3 batches of concrete mix corresponding with UHPC, UHPCFRC-SF1% and UHPCFRC-SF2% for 6 columns. The compressive strengths (f_c) and elastic modulus (E_c) were determined from three $\phi\,100\times200$ mm cylindrical specimens for each batch in accordance with the German standards DIN EN 12390-3:2009-07 [3] and DIN 1048-5 [2], respectively. Besides, the direct tension tests on 6 notches prisms of 40x40x80 mm to determine the fiber efficiency and 6 prisms without notches of 40x40x160 mm to determine the tensile strength (f_t) were carried out according to Leutbecher (2008) [6].

The details of circular STC-UHPCCs and concrete properties are presented in Table 3. The letters in the specimen names indicate volume fraction of steel fibers, steel tube thickness and the length of steel tube. For example, SF2-t8.8-L600 is the column constructed with 2% of steel fibers, steel tube thickness of 8.8 mm and steel tube height of 600 mm.

(a) (b) (c) (d)

Figure 1: Specimen fabrication

Table 3: Details of specimens

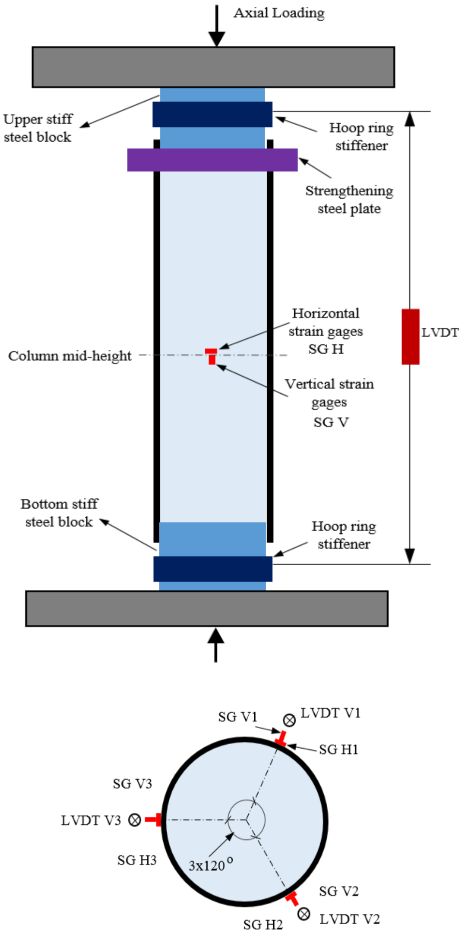
Mix	Specimen name	Steel fibers Vol. (%)	D x t (mm)	Length of columns L (mm)	Length of concrete core L_c (mm)	Compressive strength f_c (MPa)	Elastic modulus E_c (MPa)	Direct tensile strength f_t (MPa)
Cast 1	SF0-t8.8-L600	0	152.4 x 8.8	600	551.87	178.9	48370	7.1
	SF0-t8.8-L1000		152.4 x 8.8	1000	942.93			
Cast 2	SF1-t8.8-L600	1	152.4 x 8.8	600	559.67	195.5	49645	7.3
	SF1-t8.8-L1000		152.4 x 8.8	1000	951.27			
Cast 3	SF2-t8.8-L600	2	152.4 x 8.8	600	549.83	188.2	48421	8.5
	SF2-t8.8-L1000		152.4 x 8.8	1000	943.77			

2.2 Test Setup and Instrumentation

To monitor the longitudinal and hoop strain of the steel tube, six single-strain gauges were attached to the external surface at the mid-height of the steel tube and placed at 120° spacing around the steel tube perimeter. The axial shortening displacements between two stiff steel blocks were measured by three Linear Varying Displacement Transducers (LVDTs) which were placed between two hoop ring stiffeners at 120° apart. The LVDTs were equally spaced around the steel tube and coincident with the position of the strain gauges. The axial load was applied by a displacement control of hydraulic testing machine with a maximum capacity of 6300 kN. The axial compression test setup and instrumentation are shown in Figures 2(a)-(b).

Prior to testing, the top surface of concrete core was capped using a very thin layer of sand (about 4 mm) to ensure even load distribution from the upper stiff steel block to the concrete core and to provide uniform stress distribution during the testing (see Figure 1d). To avoid premature local failure at the top region of any column due to lateral pressure on the steel tube due to the sand, a steel plate was produced and used to confine the column at the top position.

Axial load was applied at a constant displacement rate of 0.01 mm/s up to the ultimate load. This process was found to be continued well beyond the attainment of ultimate load. When the performance of post-peak branch was fully observed at the axial displacement of about 15 mm, the displacement rate was increased up to 0.05 mm/s. The testing was continued until the axial displacement reached a value of 20 mm. The duration of loading for each test ranged between 25 and 30 minutes.



(a) Sketch of Test setup (b) Photo of Test setup

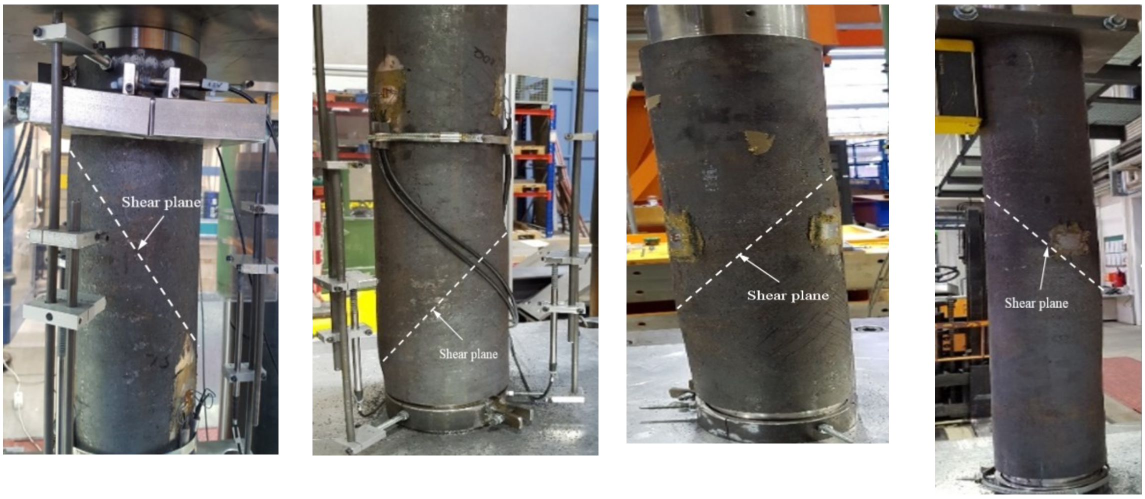
Figure 2: Test setup and instrumentation

3. TEST RESULTS AND DISCUSSION

3.1 Test observations and failure mode

The values recorded from three LVDTs were observed to be quite similar during testing process, thus indicating the proper action of the sand layer. In contradiction to the behavior of unconfined UHPC and UHPFRC cylinder under compression test, there was no loud cracking/crushing noise emanating from the concrete core around the peak load for all columns. When the load reached the ultimate load, oblique slip lines appeared on the outer walls of the steel tubes and expanded along the length of steel tube beyond the ultimate load. After testing, two small bulges were observed at opposite side of the columns. It can be inferred from these observations that the failure of the columns is associated with a shear failure of the concrete core and the steel tube provided a restraint to restrict the slip movement along the shear plane. Therefore, all columns exhibited a softening behavior due to the shear failure. However, the ductility and the residual strength could be increased due to the utilization of comparatively thick steel tubes of 8.8 mm, resulting in small bulges of steel tube. This phenomenon is supported and explained by some previous studies for high strength concrete confined by steel tube columns [1, 5, 13].

The typical failure modes of test specimens with and without internal steel fibers are presented in Figure 3. The local deformation of the steel tube wall in the specimens SF0-t8.8-L600 and SF0-t8.8-L1000 were found to be near the top and the bottom of column, respectively. On the contrary, the local deformation occurred near the mid-height in the columns using steel fibers. The comparison of failure modes between columns with and without steel fiber stated that the steel fibers formed bridges across the crack of the concrete core, leading to a distribution of load to whole column length. Moreover, the outward bulges in the columns without fiber is more pronounced than those of the columns containing steel fibers, which can be attributed to the contribution of the steel fibers together with the steel tube in delaying and minimizing the localized deformation.



(a) SF0-t8.8-L600 (b) SF0-t8.8-L1000 (c) SF2-t8.8-L600 (d) SF2-t8.8-L1000

Figure 3: Failure modes after testing

3.2 Axial load versus axial shortening response

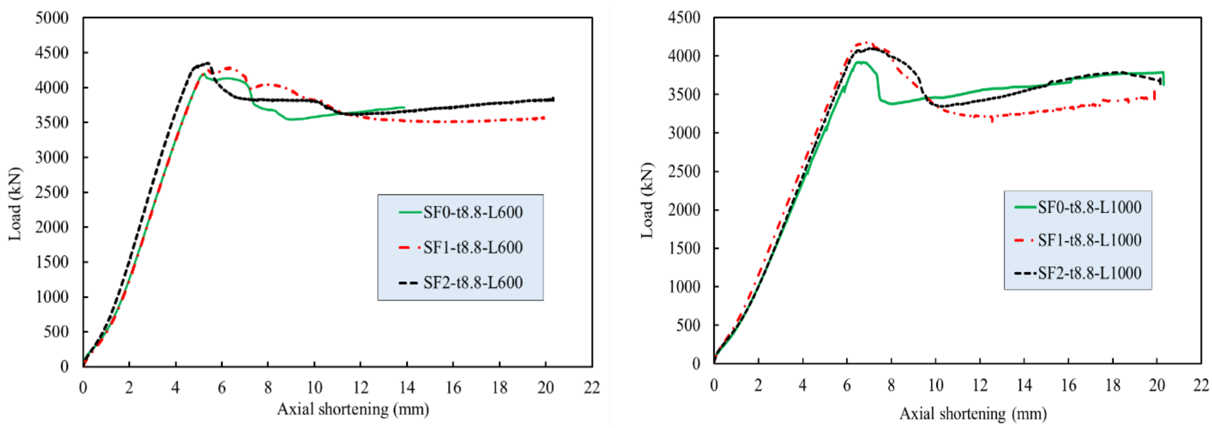
The structural behaviors of confined UHPC and UHPFRC are represented in Figure 4 by the relations between the axial load and the shortening displacement. In addition, the mean values of longitudinal and hoop strain recorded from strain gauges at mid-height of steel tube were plotted against axial loads as illustrated in Figure 5. It can be observed from these figures that all columns behaved in a similar manner in the ascending branch of the loading response, performing an almost linear and a short plastic stage until the first peak load (N_u), then followed by a decrease of load until the second peak load (N_{res}) at which a slight recovery of strength developed.

The initial stage of loading is linear and quite similar to unconfined UHPC and UHPFRC. At this stage, although the load is applied on the concrete core only, the steel tube carries the load together with the concrete core through the interfacial bond between two materials. The axial load transfer from the concrete core to the steel tube for all columns was confirmed by the value of strain gauges which measured the longitudinal strain of steel as seen in Figure 5.

The second stage corresponds to a plastic behavior when the applied load is close to the ultimate load. The bond at the interface of steel – concrete might be broken because of the occurrence of relative slip, thus the load is mainly sustained by concrete core while the steel tube shares less load. Therefore, the load versus shortening curve becomes softer. Otherwise, at the second stage, the lateral dilation of concrete core is quickly increased, which in turn activates the confinement effect of steel tube. It can be evident from Figure 5 that the values of hoop strains measured from strain gauges at this stage start increasing, thus indicating the activation of confinement effect. At the maximum load, the concrete core is crushed and its strength degrades rapidly, thus the third stage is marked by a gradual load decrease in cases with UHPFRC core due to the incorporation of steel fibers and a sudden load drop for the case of a UHPC core due to its extremely brittleness. After obtaining the second peak load, the final stage is regarded as a strength recovery by an ascending branch. This behavior may be attributed to the fact that, the larger confining stress and the hardening effect of steel tube are, a better compensation of the strain-softening of concrete core is achieved, leading to an increase in axial load again. The slope of the ascending branch in the post-peak stage is dependent on the confining level.

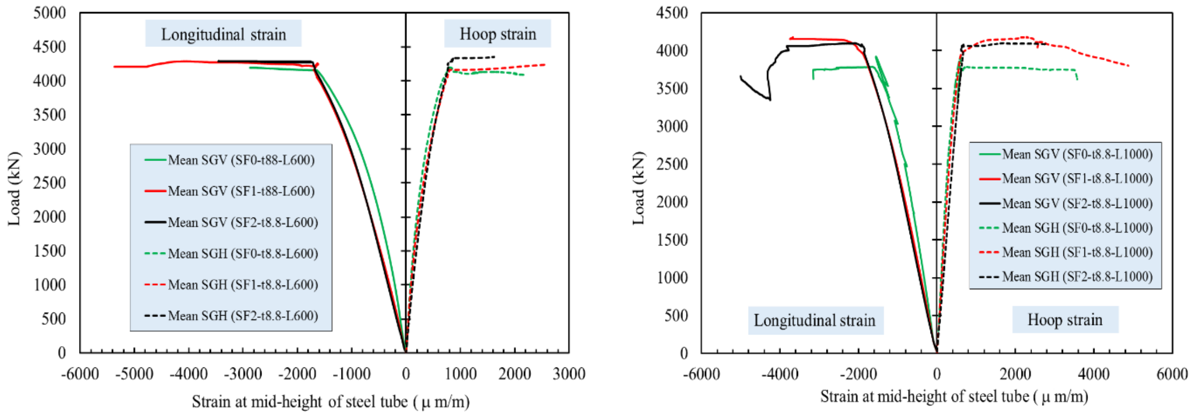
Among short columns, a more pronounced plastic behavior before the first peak load was found in the columns using steel fibers. Generally, the decrease of load in descending branch was gradual for all short columns and the residual strength ratio (N_{res}/N_u) was about 0.83-0.88. The specimens SF0-t8.8-L600 (without steel fibers) exhibited a sudden drop of load soon after the first peak load but the amount of load decrease was extremely small. Afterwards, a horizontal plateau of load-shortening curve was developed before the load dropped again. With respect to the short columns using steel fibers, the specimen SF2-t8.8-L600 presented a steeper drop of load compared to the short specimens SF1-t8.8-L600.

For long columns, it can be clearly seen in Figure 4(b) that after the maximum load was reached, the specimens SF0-t8.8-L1000 (without steel fibers) performed a sudden and a steep drop of load of about 15%, while there was a gradual decrease in the gradient of the descending branch in both specimens SF1-t8.8-L1000 and SF2-t8.8-L1000 with the ratio N_{res}/N_u of 0.78 and 0.82, respectively.



(a) Short columns (b) Long columns

Figure 4: Axial load versus shortening curves



(a) Short columns (b) Long columns

Figure 5: Axial load versus longitudinal and hoop strain of steel tube

3.3 Strength enhancement and ductility

The confinement effect on the unconfined concrete strength is quantified by means of the strength enhancement ratio, which is defined as the ratio f_{cc}/f_c of the confined strength (f_{cc}) to the unconfined concrete strength (f_c). The confined strength f_{cc} can be calculated by the following equation:

$$f_{cc} = \frac{N_u}{A_c} \tag{1}$$

where N_u is the ultimate load (the first peak load) and A_c is the cross section area of the concrete core.

The ductility index (*DI*) defined in Eq. (2) is introduced by numerous studies so as to evaluate the ability of circular STC-UHPCCs to withstand a large plastic deformation without a significant loss of load bearing capacity.

$$DI = \frac{\Delta_{85\%}}{\Delta_u} \tag{2}$$

in which $\Delta_{85\%}$ is the axial shortening when the load decreased to 85% of the ultimate load, and Δ_u is equal to the axial shortening at the ultimate load.

The test results of strength enhancement ratio f_{cc}/f_c, ductility index *DI* and the residual load (the second peak load N_{res}) are given in Table 4. As evident in this table, there was no increase in strength enhancement in the columns with internal steel fibers compared to the columns without steel fibers. In addition, the increase in steel fiber volume from 1% to 2% did not significantly increase the strength enhancement. The provision of steel fibers only slightly increased the unconfined strength of concrete cylinder as compared to the case of no steel fibers. As noted in some previous studies [1, 5], higher unconfined concrete strength results in lower confined concrete strength for CFSTCs because lower concrete strength can generate larger lateral deformation leading to stronger restraint by steel tube and, thus, a higher confinement effect. Therefore, in this test series, there were no significant differences in the strength enhancement ratio between the columns using steel fibers up to 2% by volume and the columns without steel fibers.

With regard to the ductility of columns, it can be seen from Table 4 that the columns using steel fibers had higher ductility index compared to the columns without steel fibers. In addition, the ductility index in columns using 2% by volume of steel fibers is slightly higher than that in the columns using 1% by volume of steel fibers. This proves that the columns with incorporation of steel fibers perform more ductile in the post-peak stage in comparison to the columns without steel fibers.

The comparison between short and long columns shows that due to the effect of higher slenderness ratio, the strength enhancement ratio as well as the ductility index of long columns were obviously lower than those of short columns. Besides, the ratio N_{res}/N_u demonstrated in Table 4 was higher than 0.78 and there is no significant variation of these ratios among columns. It is suggested by Liew *et al.* (2014) [9] that to ensure a safe design for CFSTCs, the residual resistance should be at least equal to 70% of the designed ultimate resistance, which means that the ratio N_{res}/N_u should not be lower than 0.7. Consequently, with the use of steel tube thickness of 8.8 mm, all the columns in this study are satisfactory with this suggestion.

Table 4: Test results of strength enhancement, residual strength and ductility index

Specimen ID	Fiber Vol. (%)	N_u (kN)	Unconfined strength f_c (MPa)	Confined strength f_{cc} (MPa)	Strength enhancement f_{cc}/f_c	N_{res} (kN)	N_{res}/N_u	*Ductility index DI*
SF0-t8.8-L600	0	4200.84	178.9	292.95	1.64	3551.44	0.85	1.65
SF0-t8.8-L1000		3919.86		274.80	1.54	3564.04	0.85	1.20
SF1-t8.8-L600	1	4288.54	195.5	300.65	1.53	3831.41	0.83	1.80
SF1-t8.8-L1000		4178.66		292.95	1.50	3331.88	0.78	1.36
SF2-t8.8-L600	2	4356.04	188.2	305.24	1.62	3239.96	0.88	1.97
SF2-t8.8-L1000		4099.03		287.36	1.53	3352.36	0.82	1.40

4. CONCLUSION

This paper has presented the results of an experimental study on the axial compressive behavior of circular steel tube confined UHPC and UHPFRC columns. Based on the discussion and the results as shown in this study, the following conclusions can be drawn:

- The confinement effect induced by steel tube can result in a good improvement in both strength and ductility for UHPC and UHPFRC. As compared to the columns without steel fibers, the columns with steel fibers do not increase the strength enhancement, whereas the ductility, particularly in the long columns can be considerably enhanced. However, additional improvement for ductility and strength was limited when increasing the volume of steel fibers from 1% to 2%.
- The presence of steel fibers can minimize the localization of deformation of steel tube because they also provide a resistance together with steel tube to the shear failure of concrete core. Furthermore, steel fibers can restrict the sudden drop of load which was observed for the columns without steel fibers in this study and normally occurs with unconfined UHPC and UHPFRC cylinder in compression test.

Further tests with various steel tube thicknesses are being conducted for the clarity of this conclusion.

ACKNOWLEDGEMENTS

The work presented in this paper was supported by Vietnamese Government for PhD scholarship and Institute of Structural Engineering – University of Kassel for the project of UHPC confined by circular steel tube columns. The first author also wishes to thank the assistance of Dr.-Ing. Jenny Thiemicke, Dipl.-Ing. Beniamino Faion, Dr.-Ing. Thomas Hahn, Mr. Klaus Trost, Mr. Hendrik Mattfeld, M.Sc. Paul Lorenz who actively participated during the tests.

REFERENCES

[1] De Oliveira, W.L.A., De Nardin, S., De Cresce El Debs, A.L.H. and El Debs, M.K., 'Evaluation of passive confinement in CFT columns', *J. Constructional Steel Research*, **66**(4), 2010, 487-495.
[2] DIN 1048-5:1991-06, Prüfverfahren für Beton, Teil 5: Festbeton, gesondert hergestellte Probekörper. Normenausschuss für Bauwesen (NABau) im DIN Deutsches Institut für Norming e.V., Beuth Verlag GmBH, Berlin, 1991.
[3] DIN EN 12390-3:2009-7, Testing hardened concrete-Part 3: Compressive strength of test specimens, German version EN 12390-3:2009, Beuth Verlag, Berlin.
[4] Guler, S., Aydogan, M. and Copur, A., 'Axial Capacity and Ductility of Circular UHPC-filled Steel Tube Columns', Magazine of Concrete Research, February, 2013.
[5] Johansson M., 'The efficiency of passive confinement in CFT columns', *Steel and Compos. Struct, Int. J*, **2**(5), 2002, 379-396.
[6] Leutbecher T, 'Rissbildung und Zugtragverhalten von mit Fasern und Stabstahl bewehrtem Ultrahochfesten Beton (UHPC)'. Ph.D. Dissertation, Heft 9, kassel university press GmbH, University of Kassel, Germany, 2008. [In German].
[7] Liew, J.Y.R. and Xiong, M.X., 'Design Guide For Concrete Filled Tubular Members With High Strength Materials to Eurocode 4', *Research Publishing*, Blk 12 Lorong Bakar Batu, 349568 Singapore, 2015.
[8] Liew, J.Y.R. and Xiong, D.X., 'Ultra-high strength concrete filled composite columns for multi-storey building construction'. *Adv. Struct. Eng.*, 15(9), 2012, 1487-1503.
[9] Liew, J.Y.R., Xiong, M.X. and Xiong, D.X., 'Design of high strength concrete filled tubular columns for tall buildings', *International Journal of High-Rise Building*, 3(3), 2014, 215-221.
[10] Schmidt, M., Fehling, E., Fröhlich, S. and Thiemicke, J., 'Sustainable Building with Ultra-High Performance Concrete, Results of the German Priority Programme 1182 funded by Deutsche Forschungsgemeinschaft (DFG)', No. 22, 2015, kassel university press GmbH, Germany
[11] Schneider, H., 'Zum Tragverhalten kurzer, umschnürter, kreisförmiger, Druckglieder aus ungefasertem UHFB'. Doctoral Dissertation, 2006, University of Leipzig.
[12] Tue, N.V., Schneider, H., Simsch, G. and Schmidt, D., 'Bearing Capacity of Stub columns made of NSC, HSC and UHPC confined by a Steel Tube', in Proceeding of 1st International Symposium on Ultra High Performance Concrete, kassel university press, Kassel, March 2004, pp. 339-350.
[13] Xiong, D.X., 'Structural behaviour of concrete filled steel tube with high strength materials', Ph.D. Dissertation, 2012, National University of Singapore, Singapore.
[14] An, L.H. and Fehling, E., 'Numerical analysis of circular steel tube confined UHPC stub columns', *Computer and Concrete*, 19(3), 2017: 263-273. *DOI: 10.12989/cac.2017.19.3.263*
[15] An, L.H. and Fehling, E., 'Analysis of circular steel tube confined UHPC stub columns', *Steel and Composite Structures*, 23(6), 2017: 669-682. *DOI: 10.12989/scs.2017.23.6.669*.