

Effect of Steel Fiber on the Behavior of Circular Steel Tube Confined UHPC Columns Under Axial Loading

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Abstract. This paper is aimed at presenting an experimental investigation on a total of 12 circular ultra high performance (UHPC) concrete filled steel tube short and intermediate columns under axial loading on only the concrete core. The influence of steel fibers with 1% and 2% by volume was examined by means of some performance indices including the strength and strain enhancement index (*SI* and *SE*), the ductility index (*DI*) and the strength ratio (*SR*). It was found that the use of steel tube as a confinement method for UHPC columns provides a significant improvement in both terms of the strength and the ductility, thereby restricting the extremely brittle failure of UHPC. In addition, there is no noticeable influence of steel fibers on the strength and ductility of test columns. However, the presence of steel fibers affects to the failure mode and slightly increases the ductility of the intermediate columns.

Keywords: UHPC · Strength · Ductility · Steel tube · Steel fibers

1 Introduction

Ultra high performance concrete has recently considered as an attractive alternative to conventional concrete in some structural members subjected to compressive loading because of its extremely high compressive strength over 150 MPa. However, the inherent brittleness of UHPC accompanying with such high strength causes a disadvantage for its application (An and Fehling 2017a). Although steel fibers was added into plain UHPC to eliminating its inherent brittleness, the compressive ductility of UHPC is not well improved. Therefore, some confinement methods for UHPC in compression have been studied by means of several types of composite structures such as UHPC filled steel tube (UHPC-FST), fiber reinforced polymer (FRP) wrapped UHPC columns. Among the current confinement methods, the UHPC-FST columns have been proved to be an effective method of reducing the brittleness and increasing the strength of UHPC (An and Fehling 2016, 2017a, b). The circular UHPC-FST columns in both terms of loading on the entire section and on the concrete core only have been experimentally investigated by Tue et al. (2004), Schneider (2006), Liew and Xiong (2010, 2012), Xiong (2012). These authors reached the conclusions that,

the ductility and the strength of the circular UHPC-FST columns can be effectively improved by using steel fibers with at least 1% by volume, or applying the load only on the UHPC core, or using higher steel contribution ratio. Apart from the tests undertaken by these authors, the studies on UHPC-FST columns have been limited up to present. It has been documented that for high strength concrete filled steel tube (HSC-FST) columns, steel fibers are usually added to obtain more ductile behavior and to control the cracking in concrete at high stress. It was generally supposed by several studies that the addition of steel fibers is found to be an effective and economic method in comparison with increasing the thickness of steel tube in improving the post-peak behavior of HSC-FST columns (Xiong 2012). However, this recommendation should be justified by further studies on UHPC-FST columns.

Based on the issues highlighted, this paper presented an experimental investigation on 12 circular steel tube confined UHPC (STC-UHPC) columns. Herein, the STC-UHPC columns refer as a form of UHPC-FST columns subjected to the axial load on only concrete core. The composite behavior of circular STC-UHPC columns in pre-peak and post-peak stage is discussed. In addition, the effects of steel fibers with volume of 1% and 2% and the steel tube thickness on the strength and the ductility are also evaluated.

2 Experimental Investigation

2.1 Description of Test Specimens

A total of 12 circular STC-UHPC columns including 6 stub and 6 intermediate columns were tested under axial compression. The classification of the composite columns was in accordance with AIJ (2001) standard, in which the short column is defined as the length to diameter ratio (L/D) smaller than 4 and the intermediate column refers to L/D ratio ranging between 4 and 12. Details of test specimens are given in Table 1. Each specimen was labeled according to the steel fiber volume fraction (0%, 1%, 2%), steel tube thickness (8.8 mm, 6.3 mm), and steel tube length (600 mm and 1000 mm). For instance, for label SF2-t8.8-L600, the first letter SF2 represents 2% by volume of steel fibers, the middle letter t8.8 represents the steel tube thickness of 8.8 mm and the ending part L600 indicates the steel tube length of 600 mm.

2.2 Steel Tube and UHPC Materials

The mechanical properties of steel tube including the yield strength (f_y), and elastic modulus (E_s), as given in Table 1 were determined by tensile coupons tests in accordance with EN 10002-1.

The recipe of M3Q developed at University of Kassel (Schmidt et al. 2015) was adopted for producing UHPC in this study. It should be noted that the M3Q mix was designed to provide a very high self-compacting characteristic. Therefore, the necessity for compactness of concrete using external vibration was eliminated. This is favourable for the casting UHPC on site and provides a great convenience during the preparation of test specimens. The steel fibers with diameter d_f of 0.175 mm and length l_f of 13 mm

Table 1. Details of test specimens.

Specimens	Fiber vol. (%)	D × t (mm)	L (mm)	L_c (mm)	f_c (MPa)	E_c (GPa)	f_y (MPa)	E_s (GPa)
SF0-t8.8-L600	0	152.4 × 8.8	600	551.87	178.9	48.37	392.6	197.7
SF0-t8.8-L1000		152.4 × 8.8	1000	942.93				
SF1-t8.8-L600	1	152.4 × 8.8	600	559.67	195.5	49.65	392.6	197.7
SF1-t8.8-L1000		152.4 × 8.8	1000	951.27				
SF2-t8.8-L600	2	152.4 × 8.8	600	549.83	188.2	48.42	392.6	197.7
SF2-t8.8-L1000		152.4 × 8.8	1000	943.77				
SF0-t6.3-L600	0	152.4 × 6.3	600	553.00	178.9	48.37	373.4	201.4
SF0-6.3-L1000		152.4 × 6.3	1000	949.70				
SF1-t6.3-L600	1	152.4 × 6.3	600	554.70	195.5	49.65	373.4	201.4
SF1-t6.3-L1000		152.4 × 6.3	1000	951.30				
SF2-t6.3-L600	2	152.4 × 6.3	600	552.70	188.2	48.42	373.4	201.4
SF2-t6.3-L1000		152.4 × 6.3	1000	950.50				

were added to the UHPC mix in volume fraction of 1% and 2% (see Fig. 1a). The average slump flow is about 800–850 mm, indicating an excellent flowability even with the use of steel fibers up to 2% by volume as shown in Fig. 1(b), (c). The compressive strengths f_c and elastic modulus E_c as given in Table 1 were determined from 3 cylindrical specimens of 100 × 200 mm for each batch in accordance with DIN EN 12390-3:2009-07.



Fig. 1. Steel fibers and fresh UHPC mixture.

2.3 Fabrication of Test Specimens and Test Setup

A formwork was designed to hold the steel tube in place and to prevent any movement during the casting process as depicted in Fig. 2(c). Due to very high self-compacting characteristic of UHPC mixture even with incorporation of steel fibers with volume up to 2%, the concrete mixture was vertically poured into steel tube without any additional vibration. For installation of the upper stiff steel blocks and the symmetry of the columns, the concrete was filled up to a level which is roughly 25 mm lower than the

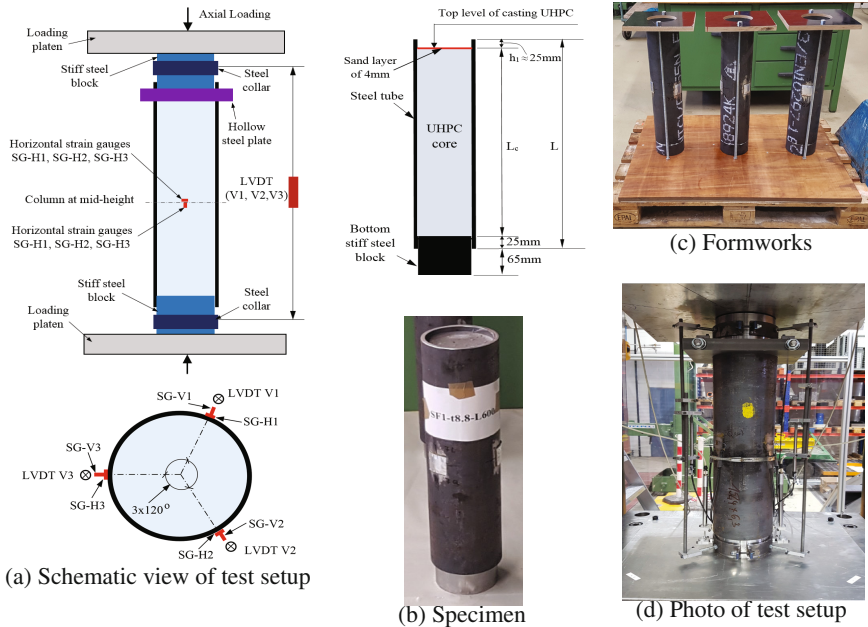


Fig. 2. Schematic view and photos of specimen and test setup.

top end of the steel tube as demonstrated in Fig. 2(b). Once the casting was complete, all specimens were cured at ambient temperature in the laboratory. The height of concrete core (L_c) and steel tube (L) were carefully measured and given in Table 1.

The load was applied on the concrete core only by means of two upper and bottom steel blocks which have a height of 90 mm and a diameter smaller than that of UHPC core. 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. To avoid premature local failure due to lateral pressure on the steel tube induced by the sand, a steel plate was produced and used to confine the column at the position of sand layer.

To monitor the longitudinal and the hoop strain of the steel tube, six unidirectional 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. Each columns was instrumented with three strain gauges (SG-V1, SG-V2, SG-V3) installed in the longitudinal direction and three strain gauges (SG-H1, SG-H2, SG-H3) installed in the transverse direction. Axial shortening displacements of the specimens were recorded using three Linear Varying Displacement Transducers (LVDTs - V1, V2, and V3), which were mounted on circular steel collars. These three LVDTs were also located at 120° apart and coincident with the position of the strain gauges. The test setup is described in Fig. 2(a) and (d). All column specimens were tested under uniaxial compression using a 6300 kN capacity computer-controlled universal compression testing machine. 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 displacements of LVDTs of about 15 mm, the displacement rate was increased up to 0.05 mm/s. The testing was continued until the axial displacements of LVDTs reached a value of 20 mm. The duration of loading for each test ranged between 25 and 30 min.

3 Test Results and Discussions

3.1 Failure Mode

Figure 3 shows the typical failure modes for the columns. The local deformation along the shear plane failure of concrete core was the typical failure mode for all specimens. It was observed that after reaching the ultimate load, oblique slip lines appeared on the outer walls of the steel tube and subsequently expanded along the length of steel tube, this indicates the appearance of shear failure. For the short columns, the shear plane predominantly occurred within the haft length of the specimens. For the intermediate columns, the shear plane of concrete core for the columns using steel fibers occurred near the mid-height region of the specimens, while the columns without steel fibers experienced a shear plane near the bottom region of the specimens. It is mentioned that the shear failure causes a steep descending branch in the load versus axial strain curves.

The measured axial load versus axial strain responses of all specimens are depicted in Fig. 4(a–d). The axial displacement of specimens was calculated by subtracting the elastic displacement of steel blocks from the average displacement recorded from three LVDTs. The axial strain of specimens was subsequently calculated from this axial displacement divided by the length of concrete core (L_c). Generally, the load-strain curves of all specimens are notably close in the ascending portion.

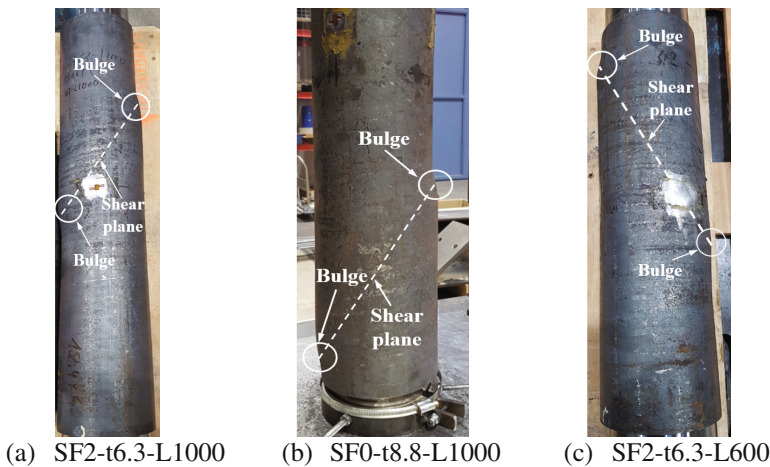


Fig. 3. Typical failure modes of the columns.

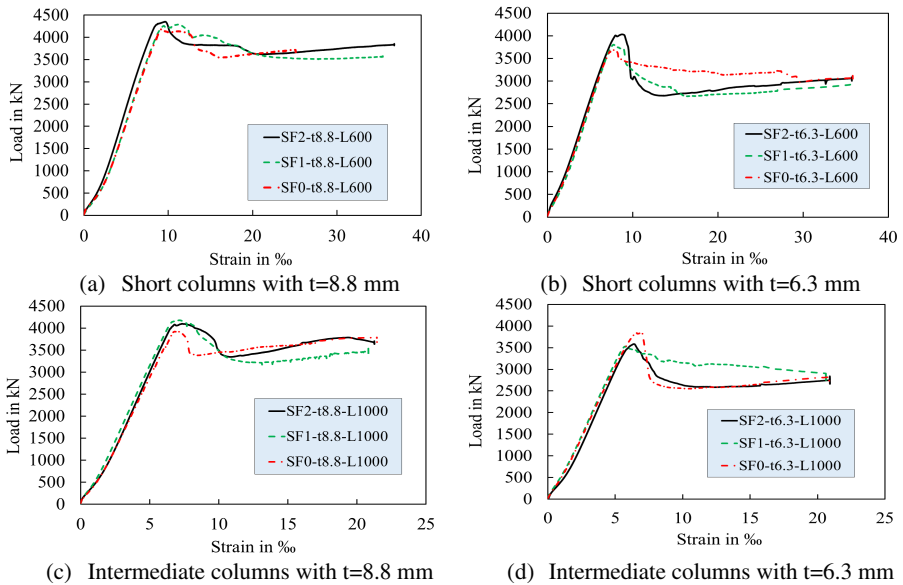


Fig. 4. Load versus axial strain response of test specimens.

3.2 Load Versus Axial Strain Response

It is evident from the Fig. 4(a–d) that all columns exhibit an almost linear ascending part and a shortly plastic stage until reaching the ultimate load, then followed by a sudden loss of load until reaching the second peak load, at which a slight recovery stage of the strength or a virtually horizontal branch develops. Although the load is applied only on the concrete core, the steel tube carries the load together with the concrete core during the ascending part. This can be confirmed by the values of longitudinal strain gauges. After reaching the ultimate load, the softening branch is marked by a sudden drop of load, which is caused by the brittle nature of UHPC. Beyond the sudden drop of load, the larger expansion of the concrete core leads to a contact with the outer steel tube. In this stage, the significant confinement provided by the steel tube effectively prevents the shear failure of the concrete core, thus improves the ductility. The larger confining stress and the hardening effect of steel tube compensate the strength degradation of concrete, thus causing a strength recovery.

Considering the comparison of the load – axial strain responses between the columns with steel thickness of 8.8 mm and 6.3 mm, the thicker steel tube results in a more gradual loss of load capacity right after the peak load as compared to that of thinner one. With respect to the influence of steel fiber, it is evident from the Fig. 4 that there is no significant improvement of the ductility in the post-peak domain in the short columns using the steel fibers as compared to the columns without steel fibers, whereas the inclusion of steel fibers was found to delay the abrupt drop of load at the peak load in the intermediate columns.

3.3 Evaluation of Test Results

The strength ratio (SR) introduced by Han et al. (2005) as expressed by Eq. (1) provides a quantitative measure of the strength enhancement arising from the composite action in STC-UHPC columns:

$$SR = \frac{N_u}{A_c \cdot f_c} \quad (1)$$

where N_u is the ultimate load obtained from the experimental test, A_c is the cross-sectional area of the concrete core, and f_c is the concrete cylinder strength.

The ductility of the specimens is assessed by means of the ductility index DI which is defined by Eq. (2):

$$DI = \frac{\varepsilon_{85\%}}{\varepsilon_u} \quad (2)$$

in which $\varepsilon_{85\%}$ is the axial strain when the load decreased to 85% of the ultimate load, and ε_u is equal to the axial strain at the ultimate load.

To evaluate the load-carrying capacity of the composite section (N_u), relative to the sum of the strengths of the individual components, the strength enhancement index SI is adopted as follow:

$$SI = \frac{N_u}{A_s f_y + A_c f_c} \quad (3)$$

The strain enhancement is also assessed in terms of the strain enhancement index SE which is given by the follow equation:

$$SE = \frac{\varepsilon_{cc}}{\varepsilon_{co}} \quad (4)$$

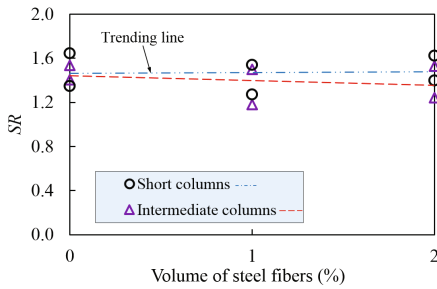
where ε_{cc} is the strain at the ultimate load of composite specimens and ε_{co} is the strain at the ultimate load of concrete cylinders. The strain ε_{co} was taken as 4.2‰ in this study as a results of suggestion by Schmidt et al. (2015).

The experimental results of N_u , SR , DI , SI , SE are listed in Table 2. Figure 5(a–d) present a graphical comparison of the influence of steel fiber volume on these values.

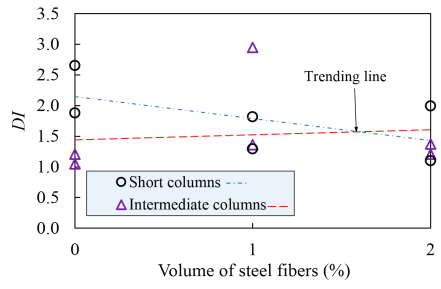
Based on the results of Table 2 and Fig. 5, there is no significant difference in the values of all indices between the columns using steel fibers with 1% and 2% by volume. In general, the values of all indices were higher with the columns using thicker steel thickness. As the steel fibers are used, there is no noticeable increase in the values of SR and SI of the short columns, while the intermediate columns exhibit a slight decrease in the values of SR and SI . It can be seen from the values of SI , the ultimate load in each specimen is close to the sum of the strengths of the UHPC core and the steel tube. Besides, it is worth noting that with the use of steel fibers, the values of DI tend to considerably decrease in the short columns, while they perform a slight increase in the intermediate columns. Regarding the values of SE , the intermediate columns

Table 2. The experimental results of N_u , SR , DI , SI and SE .

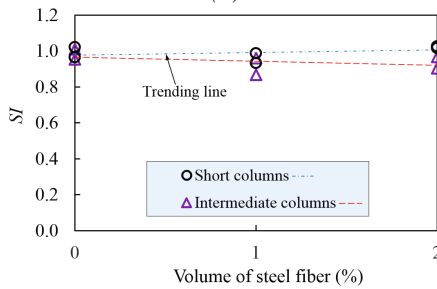
Type of columns	Specimens	L_c/D	Steel fiber vol. (%)	N_u (kN)	SR	DI	SI	SE
Short columns	SF0-t6.3-L600	3.63	0	3692.81	1.35	2.65	0.97	1.87
	SF1-t6.3-L600	3.64	1	3807.97	1.27	1.29	0.93	1.84
	SF2-t6.3-L600	3.63	2	4033.01	1.40	1.10	1.02	2.08
	SF0-t8.8-L600	3.62	0	4200.84	1.65	1.88	1.02	2.21
	SF1-t8.8-L600	3.67	1	4288.54	1.54	1.81	0.99	2.65
	SF2-t8.8-L600	3.61	2	4354.06	1.62	2.00	1.03	2.29
Intermediate columns	SF0-t6.3-L1000	6.19	0	3861.14	1.41	1.05	1.01	1.66
	SF1-t6.3-L1000	6.24	1	3535.31	1.18	2.95	0.87	1.40
	SF2-t6.3-L1000	6.19	2	3584.70	1.24	1.21	0.90	1.52
	SF0-t8.8-L1000	6.23	0	3919.86	1.54	1.21	0.95	1.65
	SF1-t8.8-L1000	6.24	1	4178.66	1.50	1.36	0.96	1.71
	SF2-t8.8-L1000	6.24	2	4099.03	1.53	1.38	0.98	1.75



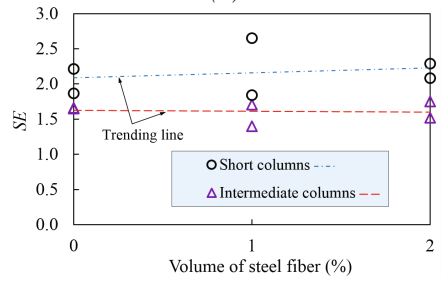
(a) SR



(b) DI



(c) SI



(d) SE

Fig. 5. Experimental results of SR , DI , SI , SE .

have smaller values than that of short columns. There is also no significant increase in the values of SE for the columns using steel fibers as compared to three companions without steel fibers. On the basis of the comparisons of the four indices between the cases of using steel fibers and without steel fibers, it is briefly concluded that the effect of steel fibers is insignificant even that in some cases, steel fibers have some adverse effects. This is attributed to the fact the presence of inner steel fibers reduces the amount of micro-cracking under compression, thereby decreasing the lateral dilation of concrete core and leading to the lower confinement effect. However, the ductility was slightly enhanced by the presence of steel fibers in the intermediate columns.

4 Conclusions

In this paper, an experimental investigation on the circular STC-UHPC columns under axial loading was presented. Based on the test results and analyses, some conclusions can be drawn as follows:

- The use of steel tube as a confinement method for UHPC columns exhibits a significant improvement in both terms of the strength and the ductility. The brittleness of UHPC can be rather well restricted.
- The ultimate load of the specimens was found to be close to the sum of the strengths of the UHPC core and the steel tube, regardless the steel fiber content. Hence, the circular STC-UHPC columns can fully exploit the contribution of two materials.
- In general, the effect of steel fibers on the strength and ductility enhancement was found to be insignificant owing to the lower confinement effect induced by lower dilation of concrete core. However, in the intermediate columns, the presence of steel fibers affect to the failure mode and slightly enhances the ductility. Hence, it would make more sense to use UHPC without steel fibers in combination with thicker steel thickness for this type of columns.

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

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