CIRCULAR UHPC-NSC COMPOSITE COLUMNS UNDER CONCENTRIC LOADING

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Abstract

This paper presents an experimental investigation on circular UHPC-NSC composite columns under concentric loading. The composite columns consisted of a precast spun NSC shell and a UHPC filled core. The spun NSC shell served both as the fire protection layer and a load-bearing element. Different amounts of steel fibers were added to the UHPC core, the amount and arrangement of the lateral reinforcement were also varied in order to investigate the influence of these parameters on the performance of the columns. In order to distinguish the load-bearing portion provided by the NSC shell, UHPC columns with the same geometry, material properties and ratio of lateral reinforcement as the corresponding UHPC core were tested and compared to the composite columns. Observations from the test program were discussed, providing preliminary information for the consideration of the application of this innovative structure.

Résumé

Cet article présente une étude expérimentale sur des poteaux circulaires mixtes BFUP-béton ordinaire sous chargement centré. Les poteaux sont constitués d'une coque préfabriquée en béton centrifugé remplie d'un noyau de BFUP. La coque en béton ordinaire sert à la fois de couche de protection contre l'incendie et d'élément porteur. Différentes quantités de fibres d'acier ont été ajoutées dans le BFUP du noyau, le taux et la disposition du ferraillage transversal ont également été modulés pour étudier l'influence de ces paramètres sur la performance des poteaux. Afin d'identifier la contribution à la reprise d'effort fournie par la coque en béton, des poteaux en BFUP avec la même géométrie, les même propriétés du matériau et le même taux de ferraillage transversal que le noyau BFUP ont été testés et comparés aux poteaux mixtes. Les observations issues de ces essais ont été analysées, fournissant des informations préliminaires pour envisager l'application de cette conception structurelle innovante.

1. INTRODUCTION

Having extremely high compressive strength, ultra-high performance concrete (UHPC) can be considered to apply in members subjected to axial compressive loading. In order to avoid brittle failure in compression, UHPC is normally combined with other materials in several kinds of composite structures such as UHPC filled steel tubes, fiber reinforced polymer (FRP) sheets or FRP wrapped UHPC columns. By the means of this, confinement effect can be obtained, that improves the performance of members in both terms of axial strength and ductility. By presence of a confinement in member, the addition of fibers can further improve the performance by controlling the cracking in UHPC at high loading. In the last decades, a large number of studies on composite structures with UHPC have been carried out, e.g. [1-3]. These studies are of significance, since most influencing parameters have been specified, both theoretically and in the experiments.

The structural performance of steel-UHPC or FRC-UHPC composite columns can, however, be significantly limited when requirements for the fire resistance of structure have to be considered. In the fire condition, a large outer part of the cross-section is ineffective toward the axial loading. In this case, a jacket made of normal-strength concrete (NSC) for the UHPC as usually used in construction steel-NSC composite columns can be considered. In normal design situation the NSC jacket and UHPC core act together by imposed loads, while only the UHPC core carries the imposed loads in the fire design situation. In contrary to conventional steel-NSC composite columns, where the profiled steel core can reach its compressive strength at the maximum loading by crushing of the NSC, attentions should be paid to considerable difference in the axial strain by reaching the compressive strength between UHPC and NSC in UHPC-NSC composite columns. Having the axial strain by reaching the compressive strength lower than that of UHPC, the NSC jacket can spall off before the stresses in the UHPC core reach the compressive strength. This limits the effectiveness of the UHPC strength and thus should be carefully investigated for a safe design of this kind of composite structure.

In an actual research program '*Substitution of steel by UHPC*' carried out at Graz University of Technology, extensive activities have been made in order to study and develop alternatives to steel construction in several types of structural members. A possible application to substitute structural steel in NSC-steel composite columns are composite UHPC-NSC columns. Thereby an UHPC core is cast in a spun NSC shell and serves as the single load-bearing element in the fire design situation. The NSC shell serves primarily as fire protection layer and secondly as load bearing element in normal design situation. Besides, it is used as formwork for the UHPC core.

This paper presents an experimental investigation on composite columns under concentric loading. In order to distinguish the load-bearing portion provided by the NSC shell and to determine the load-bearing capacity in fire situation, UHPC columns with the same geometry, material properties and ratio of lateral reinforcement as the corresponding UHPC core were tested and compared to the composite columns.

2. EXPERIMENTAL PROGRAM

2.1 Specimens

UHPC columns

Three series with thirteen UHPC columns having different arrangements of the lateral reinforcement were tested. The column diameter and height were 200 mm and 1000 mm, respectively. Two steel tube rings of 100 mm length were embedded at the column ends to avoid failure in these areas. The tested area had thus a length of 800 mm (Fig. 1).

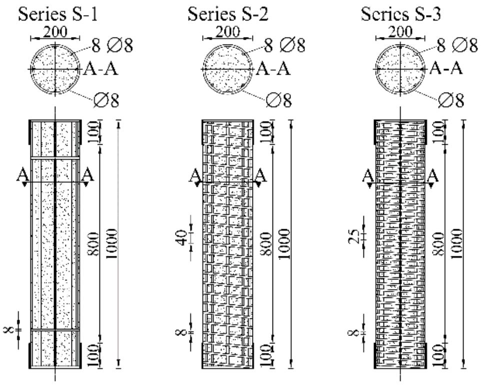

Figure 1. Specimen details of UHPC columns

The test series S-1 consisted of three UHPC columns without lateral reinforcement and with different fiber volume fractions. For the high laterally reinforced series S-2 and S-3, the lateral reinforcement was preliminarily chosen by a non-linear FE analysis using a micro-plane model [4-6]. Each of this two series consisted of 5 specimens. The reinforcement was positioned at the column surface, at the same position of that of composite columns. The longitudinal reinforcement was kept constant for all specimens. Investigated parameters were the load-bearing capacity, the ductility for different lateral reinforcement ratios and fiber amounts. Tab. 1 summarizes the specimen properties for UHPC columns. These include the longitudinal reinforcement ratio ρ_s, lateral reinforcement ratio ρ_{sh}, spacing of spirals s, compressive strength f_c, and fiber volume fraction ρ_f.

UHPC-NSC composite columns

Based on the preliminary observations from the first part with UHPC columns, three series of composite UHPC-NSC columns were designed for the second part, as illustrated in Fig. 2. The composite column diameter and height were 300 mm and 1000 mm, respectively. The UHPC-core diameter was equal to the diameter of UHPC columns, of 200 mm.

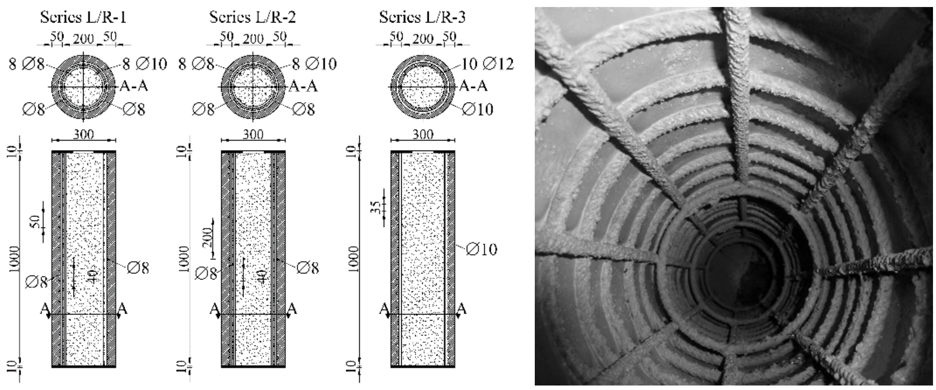

Figure 2. UHPC-NSC composite column series, core reinforcement

Two series L/R-1 and L/R-2, had the same lateral reinforcement ratios in the UHPC core and different ratios in the NSC cover. The series L/R-3 had lateral reinforcement only in NSC cover. The ratio in NSC cover was nearly the same as for whole composite column from series L/R-1. The longitudinal reinforcement ratio was the same for all three series. For three columns of each series, the UHPC-core was filled in the laboratory (denoted as L in the specimen notation), the other three columns were filled in a prefabricated plant (denoted as R in the specimen notation). The fiber volume fraction was 0.50% for all specimen. Details of the composite columns are presented in Tab. 2.

Investigated parameters were the load-bearing capacity, the ductility for different lateral reinforcement ratios and ductility for same lateral reinforcement ratios but different reinforcement positions.

2.2 Materials

A coarse grain UHPC mixture with maximum grain size of 8 mm was developed for the UHPC core. The target compressive strength f_c was 180 MPa after 28 days, without heat treatment and without self-compacting properties. The Young's modulus was of 54000 MPa. Shrinkage rate was about 0.45‰. In addition, the flowability and plastic viscosity properties was optimized for the tested columns. The brass-plated micro steel fibers with tensile strength of approximately 3000 MPa and the fiber factor *l/d* (length to diameter-ratio) of 75 were used.

For the NSC shell from prefabricated plant, commercial spun concrete with strength class C 50/60 was used. The NSC had a compressive strength f_c of 80 MPa on the composite columns testing date which was 56 days. Despite double normative age the strength class of shell concrete was clearly exceeded. Reinforcing steel with characteristic yielding limit of 550 MPa was used for longitudinal and lateral reinforcement.

2.3 Test set-up and measurements

The columns were tested under concentric loading by a rigid frame with a 10 MN actuator. For the displacement measurement of UHPC columns, two LVDTs with a basis of 1000 mm were arranged at opposite sides. In addition, six strain transducers with measurement basis of 200 mm were arranged at three positions over the height of columns. In cross-section, these transducers were also arranged at opposite sides, whose axis was perpendicular to that of the LVDTs. By the means of this, the uncontrolled eccentricity could be analyzed. Nine strain gauges were attached on spiral reinforcement at three levels, in order to quantify reinforcement yielding. Testing configuration for the UHPC columns is presented in Fig. 3 (left). For the UHPC-NSC composite columns, besides the four LVDTs for longitudinal displacement measurement and a control local strain transducer, three strain transducers clamp rings were arranged in order to determine the lateral displacement in quarter height planes (Fig. 3).

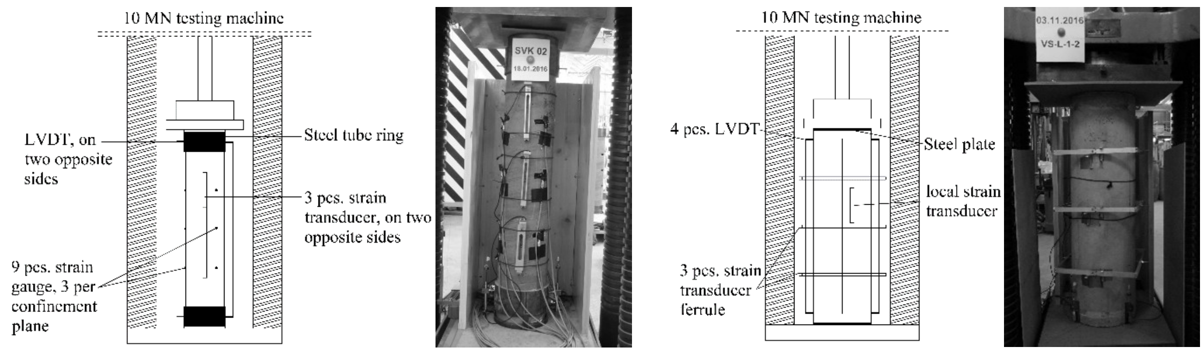

Figure 3. Test configuration for the UHPC columns (left) and the UHPC-NSC composite columns (right)

2.4 Experimental results

UHPC columns

Failure of series S-1 was extremely brittle and without warning. The failure characterized by formation of an inclined shear plane and buckling of longitudinal reinforcement. No influence of the fiber amount was observed. For series S-2 and S-3, the failure was relatively ductile. On the cover concrete several cracks appeared before the peak load was reached. After the peak load, the stress of specimens from series S-2 with wider spiral spacing decreased more rapidly than for series S-3. The damage zone was primarily localized on spiral reinforcement planes spreading afterwards through formation of inclined shear plane and splitting by low stresses. No spalling of concrete cover was observed in series S-2 and S-3. The yielding of lateral reinforcement before peak load point was observed. Regarding fiber amount, there was also no difference in the maximum loads for these two series. The series S-1 and S-2 reached nearly the same values of mean maximum force. The values of mean uncontrolled eccentricity were also almost equal for the series S-1 and S-2. The series S-3 had higher values of mean maximum force at lower mean uncontrolled eccentricity values. The variation of maximum force test results was inferior to 5% for all three series. Tab. 1 summarizes the key experimental results, it includes maximum load N_{exp} and their mean value of each series N_{UHPC}, and the uncontrolled eccentricity e_0.

Table 1: Specimen properties and test results of UHPC columns

Series	column	ρ_s [%]	ρ_{sh} [%]	s [mm]	f_c [kN]	ρ_f [%]	e_0 [mm]	N_{exp} [kN]	$N_{UHPC,exp}$ [kN]	$N_{UHPC,exp}/N_{pred}$
S-1	SVK 1	1.29	0.39		181	0.50	5.1	5001	4860	0.97
	SVK 4	1.29	0.39		183	0.75	6.8	5065		
	SVK 13	1.29	0.39		181	0.50	11.8	4513		
S-2	SVK 3	1.29	2.46	40	181	0.50	3.7	4940	4769	0.95
	SVK 6	1.29	2.46	40	183	0.75	9.5	4668		
	SVK 7	1.29	2.46	40	183	0.75	6.1	4757		
	SVK 8	1.29	2.46	40	181	0.50	9.2	4886		
	SVK 9	1.29	2.46	40	181	0.50	9.8	4592		
S-3	SVK 2	1.29	3.94	25	181	0.50	11.5	4720	5188	1.03
	SVK 5	1.29	3.94	25	183	0.75	6.3	5218		
	SVK 10	1.29	3.94	25	181	0.50	3.0	5407		
	SVK 11	1.29	3.94	25	181	0.50	2.5	5340		
	SVK 12	1.29	3.94	25	183	0.75	4.4	5257		

UHPC-NSC composite columns

Failure of all three series was very ductile. At the peak load, numerous cracks on NSC cover were observed. The failure of UHPC-NSC composite columns occurred with the spalling of NSC cover. After the peak load was reached, the stress of specimens decreased until load-bearing capacity of UHPC core was reached. The specimens cast in laboratory and prefabricated plant had very similar maximum loads for all three series. The series L/R-1 reached lowest load-bearing capacity and longitudinal strain values followed from series L/R-2. The series L/R-3 had almost same values for longitudinal strain but a highest load-bearing capacity. The axial strain reached at maximum force for composite UHPC-NSC columns corresponded to axial strain of NSC jacket by reaching the compressive strength of NSC with variation of axial strain under 10% for all tested composite columns. The variation of maximum force results is averaged 5% or less for all series. Tab. 2 summarizes the key experimental results.

Typical failure pattern is given for two tested UHPC-NSC composite columns in Fig. 4. with typical spalling of NSC-cover. On the left side spalling up to lateral reinforcement and at the right side locally spreading to UHPC core.

Figure 4. Failure of two tested UHPC-NSC composite columns

Table 2: Specimen properties and test results of the UHPC-NSC composite columns

Series	column	ρ_s [%]	ρ_{sh} [%]	s_{cover} [mm]	s_{core} [mm]	$f_{c,UHPC}$ [kN]	ε_{cc} [‰]	ε_l [‰]	N_{exp} [kN]	$N_{comp,exp}$ [kN]	$N_{comp,exp}/N_{pred}$
L-1	VSL-1-1	1.46	3.56	50	40	178	2.01	0.91	6672	6734	0.86
	VSL-1-2	1.46	3.56	50	40	178	2.05	0.95	7017		
	VSL-1-3	1.46	3.56	50	40	178	1.97	0.57	6512		
L-2	VSL-2-1	1.46	2.70	200	40	178	2.71	0.89	7614	7239	0.92
	VSL-2-2	1.46	2.70	200	40	178	2.18	0.70	6890		
	VSL-2-3	1.46	2.70	200	40	178	2.41	0.85	7215		
L-3	VSL-3-1	1.60	3.33	35		178	1.97	0.58	7294	7500	0.94
	VSL-3-2	1.60	3.33	35		178	2.08	0.56	7127		
	VSL-3-3	1.60	3.33	35		178	2.30	0.63	8080		
R-1	VSR-1-1	1.46	3.56	50	40	176	2.02	0.56	6394	6679	0.85
	VSR-1-2	1.46	3.56	50	40	176	2.01	0.64	6647		
	VSR-1-3	1.46	3.56	50	40	176	2.31	0.91	6998		
R-2	VSR-2-1	1.60	2.70	200	40	176	2.54	0.82	7222	7089	0.90
	VSR-2-2	1.60	2.70	200	40	176	2.25	0.70	6894		
	VSR-2-3	1.60	2.70	200	40	176	2.38	0.89	7151		
R-3	VSR-3-1	1.60	3.33	35		176	2.32	0.54	7086	7514	0.95
	VSR-3-2	1.60	3.33	35		176	2.49	0.68	8017		
	VSR-3-3	1.60	3.33	35		176	2.05	0.57	7440		

3. DISCUSSION OF THE TEST RESULTS

The mean values of the maximum load of the UHPC columns were compared with the predicted load-bearing capacity using the following expression:

$$N_{UHPC} = f_{co,UHPC} \cdot A_c + f_{ys} \cdot A_s \qquad (1)$$

where $f_{co,UHPC} = 0.85 f_{c,UHPC}$ is the in-place compressive strength of UHPC, A_c is the cross-sectional area of columns, f_{ys} and A_s are the yield limit and total area of the longitudinal reinforcement, respectively.

Results of the comparison between the experimental and predicted maximum load (N_{exp}/N_{pred}) using Eq. (1) for each series are presented in Tab 1. The mean value of uncontrolled eccentricity was calculated from the measured longitudinal deformations, at 7.7 mm for series S-1, 7.9 mm for series S-2 and 5.5 mm for series S-3. The comparison shows that with the ratio of the lateral reinforcement of 2.46%, the spirals did not contribute to the load-bearing capacity of the columns. The series S-1 had slightly higher load-bearing capacity as series S-2 by almost the same values of uncontrolled eccentricity. The effect of spirals on the load-bearing capacity can only be observed by relatively high reinforcement ratio, at approx. 4,0% in series S-3. Considering the possible confinement effect for this series, an expression for estimating the maximum load proposed by Mander et al. [7] can be used:

$$N_{cc,UHPC} = (f_{co,UHPC} + 4.1\, K_e \cdot \rho_{sh} \cdot f_{yh}) \cdot A_{cc} + f_{ys} \cdot A_s \quad (2)$$

where K_e confinement effectiveness coefficient [7], A_{cc} is area of concrete core. The $N_{UHPC,exp}/N_{pred}$-ratio using Eq. (2) for this series becomes only 0.82. Similar results can be obtained by some other confinement models, e.g. [8-10], also when the steel fibers are considered, e.g. [11]. Since existing confinement models are normally developed for normal or high-strength concrete columns, refined models for the evaluation of possible confinement effect in UHPC columns tied by reinforcing steel are of necessary.

For the second part of experimental investigation regarding mean values of maximum force following equations analog Eq. (1) were used:

$$N_{COMP} = f_{co,NSC} \cdot A_{c,NSC} + f_{co,UHPC} \cdot A_{c,UHPC} + f_{ys} \cdot A_s \quad (3)$$

where $f_{co,NSC}$ is the in-place compressive strength of unconfined NSC, $A_{c,NSC}$ is the cross-sectional area of NSC and $A_{c,UHPC}$ is the cross-sectional area of UHPC, respectively. Results of the comparison between the experimental and predicted maximum load ($N_{comp,exp}/N_{pred}$) using Eq. (3) for each series are presented in Tab 2. Despite higher lateral reinforcement ratio had series L/R-1 lower load-bearing capacity than series L/R-2. The series L/R-3 reached highest load-bearing capacity. After experimental investigation all tested specimens were sliced in order to examine the composite column cross-section. Smaller material imperfections were observed for some specimens of the series L/R-1. Obviously the two layers of longitudinal and two layers of lateral reinforcement were too closely and tight to each other in NSC-cover area so that local problems regarding concrete distribution and consolidation occurred during casting process.

The observed longitudinal strains at failure shown in Tab. 2 are significantly lower than the ultimate strain of UHPC (of approx. 3.5). However, the observed maximum load of the composite columns was higher than the calculated load level when the stresses of the UHPC core are estimated using these strains. This implies the effectiveness of UHPC-NSC composite action over the single contributions of each material.

4. CONCLUSION

In this paper, an experimental investigation on UHPC and NSC-UHPC composite columns under concentric loading was presented. The experiments show that for UHPC columns the effect of fibers and lateral reinforcement is insignificant. The estimation using existing confinement models can lead to unsafe design. For the NSC-UHPC composite columns, total load-bearing capacity is higher than UHPC columns as a result of the NSC contribution. This composite action can be considered in the normal design situation, however a reduction factor for UHPC must be considered for the early spalling of NSC cover. While UHPC core can be considered for the fire design situation.

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