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EXPERIMENTAL INVESTIGATION ON STRENGTHENING OF REINFORCED CONCRETE COLUMNS WITH CARBON CONCRETE COMPOSITE

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The application of textile reinforced concrete is well-approved technique for strengthening of reinforced concrete members. When using carbon fiber meshes and carbon fiber reinforced polymer bars as reinforcement, this material is called carbon concrete composite. Based on the outstanding properties of carbon fibers, carbon concrete composite is characterized by high bending and tensile strength, and good durability. Therefore, carbon concrete composite is increasingly applied as replacement for ordinary steel bar or steel mesh reinforced concrete. It is favorable building material for production of new buildings and for strengthening of existing reinforced concrete members. In the context of strengthening of existing reinforced concrete columns, it is a usual procedure to cover the member's surface with a thin layer of carbon concrete composite aiming on reduction of lateral strains of the core concrete when load is increasing. The result is an increased load-bearing capacity of the strengthened column. However, there is insufficient knowledge about the influence of curvature of the carbon meshes in circular cross-sections and in the corners of rectangular cross-sections on their load-bearing capacity. For this reason, an experimental program started to study the influence of curvature, number and type of mesh layers and specimen dimensions on structural behavior of strengthened columns under axial loading. As main outcome it can be stated that besides the curvature other parameters like yarn properties are of essential importance.

Keywords: Textile reinforced concrete, Carbon fibers, Yarn geometry, Influence of curvature.

1 INTRODUCTION

Reinforced concrete (RC) columns are important structural elements. Caused by deterioration or increased loads there is often a request for strengthening of existing RC columns. For this purpose, various techniques are available (Figure 1). The classical and mainly used method is the application of sprayed concrete leading to a substantial increase of the cross-section's dimensions. Furthermore, it is possible to arrange additional longitudinal steel bar or mesh reinforcement inside of the newly added parts of the section. The higher load-bearing capacity is mainly obtained with the increased cross-section and the additional longitudinal reinforcement.

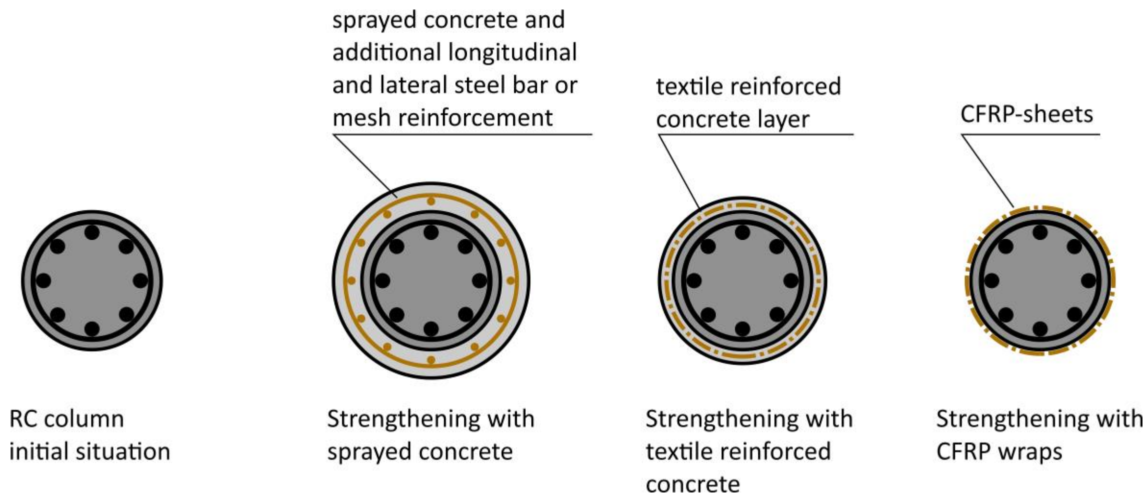


Figure 1. Possibilities for strengthening of reinforced concrete columns.

Another strengthening method is the confinement of existing RC columns by carbon fiber reinforced polymer (CFRP) sheets (Matthys *et al*. 2005). By the confinement, increase of lateral concrete strains is reduced when axial load on column is rising. This effect results in a higher load-bearing capacity. There is no increase of concrete section's dimension. Just some space for the arrangement of the CFRP wrap is needed, see Kaeseberg *et al*. (2018) and Kaeseberg *et al*. (2019).

A third possibility for strengthening of RC columns is the application of textile reinforced concrete (Ombres 2014). By the arrangement of textile reinforced concrete, the cross-section is slightly increased. As well as CFRP sheets, the textile reinforcement causes a reduction of lateral concrete strains resulting in a three-dimensional stress distribution in the confined concrete and, therefore, a higher load-bearing capacity of the concrete in longitudinal direction. Therefore, the strengthening effect is caused by a combination of the increased cross-section and the confinement of the core concrete.

2 CARBON CONCRETE COMPOSITE FOR STRENGTHENING OF RC COLUMNS

Non-metallic reinforcements are in the focus of many research activities (Kaeseberg *et al*. 2017). Today, there is a good experience with textile reinforced concrete where meshes of glass, polymeric and other fibers are applied as reinforcement. The recent development is the application of carbon meshes in combination with carbon fiber reinforced polymer bars resulting in a new structural material called carbon concrete composite. Carbon reinforcement is resistant to corrosion, and therefore concrete cover can be minimized. Based on the outstanding mechanical properties of carbon fibers (Table 1), the usage of carbon reinforcement, combined with high-performance concrete, enables very thin cross sections of structural concrete members.

Nowadays, the number of applications of carbon concrete composite is strongly increasing in Germany, especially in precast concrete industry and for strengthening purposes. However, there is still a considerable research demand, especially in the context of load-bearing behavior of the carbon reinforcement if it is arranged not straight but curved as it is done when strengthening a RC column (Holschemacher *et al*. 2018). The paper reports about an experimental program performed in the context of strengthening of RC columns with carbon concrete composite. Main target was the investigation of how radius of curvature in the corner of rectangular sections influences the efficiency of carbon concrete composite confinement.

Table 1. Mechanical properties of typical fiber materials (Holschemacher *et al*. 2017).

Materials	**Density** (g/cm^3)	**Modulus of elasticity** (N/mm^2)	**Tensile strength** (N/mm^2)	**Ultimate strain** (%)
Steel fibers	7.85	160-210	0.3-3	1-10
Polypropylene fibers	0.9	1.3-10	0.2-0.4	5-15
Alkali-resistant glass fibers	2.68-2.70	72-80	1.5-3.7	1.5-3.6
Basalt fibers	2.6-2.8	90-110	4.8	<4.0
Aramid fibers	1.44	30-130	0.6-2.9	1.8-4.4
Carbon fibers	1.8	240-600	3.0-5.0	0.5-2.5

3 EXPERIMENTAL INVESTIGATIONS

3.1 Test Program

At the beginning of the reported experimental investigations, there has already an existing database with results of previous tests on circular concrete columns strengthened with carbon concrete composite (Holschemacher *et al*. 2018). To enhance this database and to get new information about the influence of corner radius in rectangular sections, additional tests were performed with the variation of the following parameters:

- Application of two commercially available carbon concrete composite strengthening systems.
- Investigation of five different specimen geometries.

One test series performed for each of the two carbon concrete composite strengthening systems. The following specimens were tested in each of the both series (Figure 2):

- 3 non-strengthened specimens, side length of 150 mm, corner radius of 62.5 mm
- 9 strengthened specimens with square-shaped sections and side length of 150 mm, the corner radius did vary (R = 25 mm, R = 37.5 mm and R = 55 mm)
- 3 strengthened specimens with circular cross-section and a diameter of 150 mm.

The height of the specimens with circular cross-section was 300 mm and 350 mm, and 350 mm in all other cases.

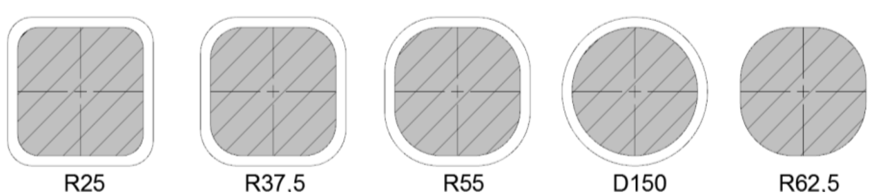


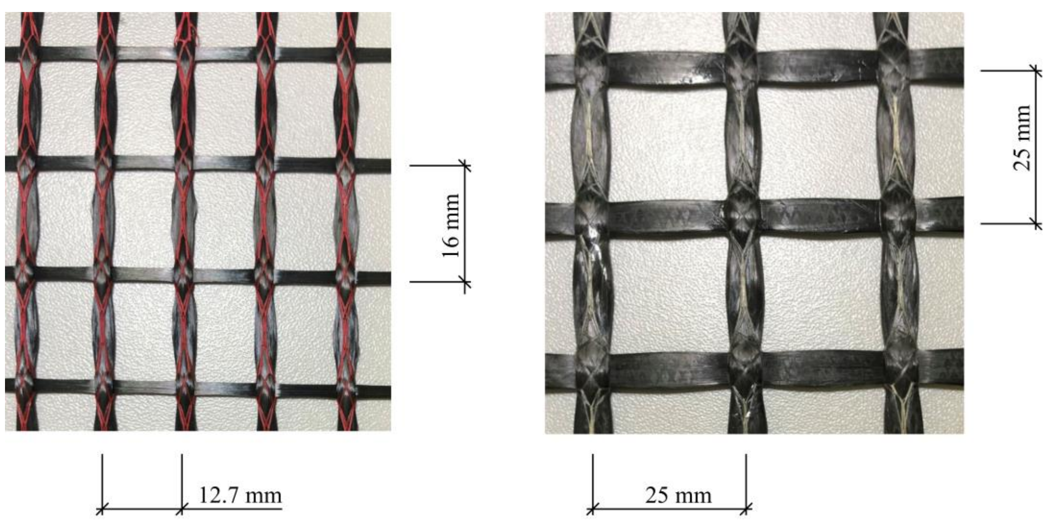
Figure 2. Specimen sections.

For the production of the core concrete, cement CEM II/A-LL 32-5 and natural aggregate with a maximum grain size of 16 mm were used. To reduce variations of the water/cement-ratio the aggregates were dried before mixing the concrete. Additional additives and admixtures were not used.

In a laminating procedure, the carbon concrete composite strengthening systems were applied at the surface of the core concrete. The properties of the two systems are summarized in Table 2. Their differences were the structure of the textile mesh, the used fine grading concrete and the number of textile reinforcement layers. Both of the applied textile meshes are illustrated in Figure 3.

Table 2. Properties of the applied carbon concrete composite systems.

Properties	**Carbon concrete composite system 1**		**Carbon concrete composite system 2**	
	Longitudinal direction	Lateral direction	Longitudinal direction	Lateral direction
Area of carbon fiber reinforcement (mm^2/m)	140	28	142	142
Tensile strength of the yarn (N/mm^2)	1,980	2,940	4,000	4,000
Yarn spacing (mm)	12.7	16.0	25.0	25.
Number of textile reinforcement layers	3		2	
Fine grading concrete compressive strength (N/mm^2)	≥ 50		≥ 80	
Fresh concrete density in (kg/m^3)	2,100		2,150	
Depth of the strengthening layer (mm)	15		15	



Textile mesh for carbon concrete composite strengthening system 1

Textile mesh for carbon concrete composite strengthening system 2

Figure 3. Applied textile meshes.

3.2 Test Procedure

Longitudinal strains using strain gauges and lateral deformations with linear variable differential transformers (LVDT) in the half height of the specimen were measured during the tests. The strain gauges were arranged at the surface of the core concrete and the LVDTs at the surface of the strengthened specimen. Additionally, total specimen deformations in longitudinal direction with LVDTs and loads were recorded.

The load was applied with a deformation-controlled universal testing machine. Load is increased with a deformation rate of 0.01 mm/s.

3.3 Test Results

In previous investigations, the carbon concrete composite systems were tested under uniaxial tension to get reference values for their tensile strength (Holschemacher *et al*. 2018). The mean values of the first cracking tensile strength were

- Carbon concrete composite system 1: f_{tm} = 2.12 N/mm^2
- Carbon concrete composite system 2: f_{tm} = 1.76 N/mm^2.

The strengthened specimens were characterized by a ductile load-bearing behavior. Typical stress-stain relationships are stated in Figure 4. If the compressive stress in the core concrete is close to its compressive strength, an essential increase of lateral strains in the core concrete is visible. The result is the activation of the confinement effect of the textile reinforcement leading to an increase of the bearable load. In the carbon concrete composite strengthening layer, longitudinal cracks will occur whereby particularly wide cracks are concentrated in the corners of the rectangular cross-sections. At the end, the specimens failed by fiber rupture or delamination of the carbon concrete composite layer. Typical crack patterns of failed specimen are shown in Figure 5.

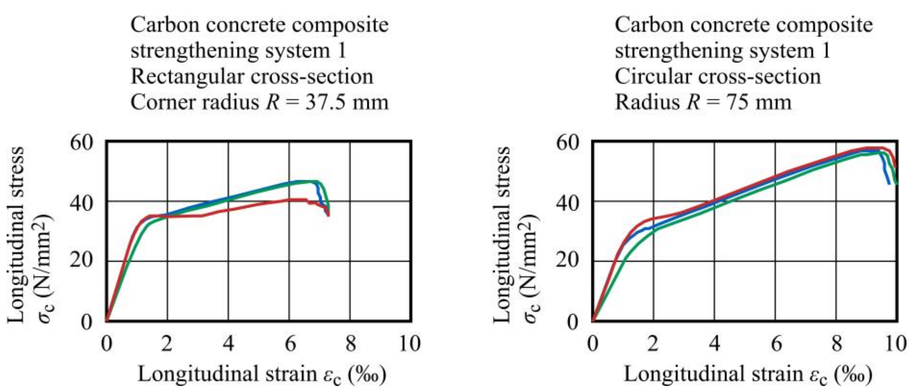


Figure 4. Typical stress-strain curves of tested specimens.

One of the main outcomes of the investigations is the fact that there is a clear dependence of the corner radius on the ultimate load of strengthened specimens f_{cc} (Table 3). It can be explained by the influence of geometry on the three-dimensional stress state inside of the specimens and the sensitivity of the carbon fibers to lateral pressure in curved regions. Another interesting finding consists in the different efficiency of the applied carbon concrete composite systems. System no. 2, where a carbon yarn with larger diameter was used, resulted in lower strengthening effects. This circumstance is comprehensible because with increasing yarn size the bond behavior is unfavorably affected.

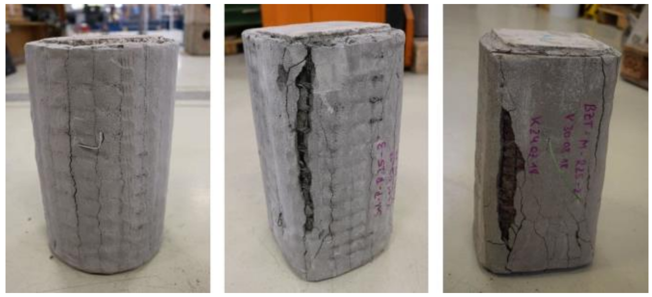


Figure 5. Typical crack pattern of tested specimens.

Table 3. Influence of corner radius on ultimate strength f_{cc} (N/mm^2).

Radius (mm)	**Carbon concrete composite system 1**	**Carbon concrete composite system 2**
25	39.5	30.1
37.5	44.2	34.4
55	49.0	38.6
150	56.7	40.5

4 CONCLUSIONS

The evaluation of test results indicates a significant dependence of the corner radius on the ultimate load of strengthened specimen with rectangular cross-section. With rising corner radius, the load-bearing capacity is essentially increasing. By the application of two different carbon concrete composite strengthening systems, it was obvious that the yarn geometry is of major importance on the bond performance and, consequently, on the exploitation of the theoretical tensile strength. This affects the performance of the strengthening system. An analytic model will be developed considering the mentioned effects in another study and it will be published in a following publication.

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