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EFFECT OF SUBSTRATE PREPARATION ON THE LOAD-BEARING BEHAVIOR OF CFRP-CONFINED RC COLUMNS

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The confinement of reinforced concrete (RC) columns with fiber reinforced polymer (FRP) jackets is an effective measure for the strengthening and retrofitting of existing structures. The jacket withstands the increasing lateral strains of the axially loaded column causing a three-dimensional stress state inside the concrete. In the result, a higher concrete compressive strength can be achieved. So far, extensive international research on FRP-confined concrete has been conducted, but there are still some open issues regarding the influence of different parameters on the load-bearing behavior. This paper is focusing on the effect of the substrate preparation on the maximum concrete strength and stress-strain behavior. Therefore, an experimental study of carbon fiber reinforced polymer (CFRP) confined concrete cylinders with various substrate conditions and preparation methods is presented. The results are compared with previous investigations and assessed accordingly. Furthermore, recommendations regarding the substrate preparation by current national codes and guidelines are specified and considered critically.

Keywords: Columns, Concrete, Confinement, Retrofitting, Fiber reinforced polymers.

1 INTRODUCTION

The confinement of reinforced concrete (RC) columns using fiber reinforced polymers (FRPs) can be seen as an effective alternative to conventional strengthening methods like shotcrete. The confinement enables an increase of the load bearing capacity without affecting the cross-sectional dimensions as well as the dead weight significantly. FRP confinement of RC columns has been widely investigated by a great number of international research programs so far. The results lead to various design models as well as codes and design guidelines (Kaeseberg *et al.* 2019). However, there are still uncertainties regarding the influence of different parameters on the load bearing behavior of confined concrete. The substrate preparation prior to the strengthening process constitutes one of these parameters. The different codes and guidelines demand varying requirements for the preparation process of the concrete surface. Many guidelines, including the Canadian standard CSA S806 (2012), the Italian guide CNR-DT 200 R1 (2014), the German guideline DAfStb-RiLi VBgB (2012), etc., do not differentiate between different applications of FRP for the strengthening of concrete structures regarding the requirements for substrate preparation. Whereas the American guideline ACI 440.2R (2017) is the only one which divides the range of applications in “bond-critical” applications, such as flexural or shear strengthening of beams, slabs or walls, and “contact-critical” applications, such as the confinement of columns with lower requirements for the substrate preparation. In consideration of the high costs of different preparation methods like sandblasting or grinding, including expensive protective measures against dust and noise, the preparation requirements for the strengthening of RC columns with FRP can be decisive for the methods' economic efficiency.

Further investigations on the influence of the concrete's surface condition and therefore on the influence of the interfacial bond between the concrete and the jacket on the load bearing behavior of FRP-confined concrete lead to contrasting results. Li (2006), Mirmiran *et al.* (1998), and Shahawy *et al.* (2000) determined no significant effect in their experimental results. However, Deb and Bhattacharyya (2010) as well as Matthys *et al.* (1999) found a direct effect on the compressive strength and the ultimate strain. The experimental studies on eccentrically loaded, FRP-confined RC circular columns by Jiang *et al.* (2019) furthermore showed only an insignificant influence on the global load-displacement response. The carried out test programs only considered the conditions "bond" or rather "no bond" between the concrete and the FRP jacket. For the determination of the effect of different gradations of bond conditions in dependence of the preparation method, an experimental program containing 21 Carbon(C)-FRP-confined concrete cylinders has been carried out.

2 EXPERIMENTAL INVESTIGATIONS

2.1 Experimental Program

The experimental investigations focus on the effect of different surface conditions of the specimens before the application of the CFRP strengthening system. Therefore, confined concrete cylinders with a diameter of 150 mm and a height of 300 mm with different concrete mixtures (S1, S2), various substrate conditions (P, U, S, Pa) and preparation methods have been conceptualized. Table 1 shows the experimental program containing the surface condition as well as the preparation method.

Table 1. Experimental program.

Series	No. of specimens	Substrate condition	Preparation method
S1-P	3	Prepared	Grinding until aggregates >4 mm can be seen according to DAfStb-RiLi VBgB (2012)
S1-U	3	Unprepared	No preparation after stripping (no water storage, no cleaning of the surface)
S1-S	3	Separated with lubricating layer	No substrate preparation, application of two plies of plastic foil with a lubricant (petrolatum) in between
S2-P	3	Prepared	Grinding until aggregates >4 mm can be seen according to DAfStb-RiLi VBgB (2012)
S2-U	3	Unprepared	No preparation after stripping (no water storage, no cleaning of the surface)
S2-S	3	Separated	No substrate preparation, application of one ply of plastic foil
S2-Pa	3	Painted	Cleaning of the concrete surface, application of synth. dispersion paint: 1. Application of an acrylic primer 2. Application of an intermediate and top coat of paint 3. Application of a renovation coat of paint

2.2 Materials

The concrete cylinders of the two main series (S1, S2) were produced using different concrete mixtures. Each series was made of concrete of the same batch. Both series used CEM II/A-LL 32.5 cement according to EN 197-1, natural aggregates with a maximum grain size of 16 mm and powdered limestone. Series S2 additionally contained fly ash. The average compressive strength of series S1 was 23.16 MPa. The concrete mixture was designed to correlate with columns that typically require retrofitting (low-strength concrete). The mixture of series S2 was designed to meet the requirements of a widely used normal strength concrete with an average compressive strength of 44.94 MPa. After stripping, the top and bottom of the cylinders were grinded plane and parallel to assure uniform load distribution. Curing has been carried out using plastic foils rather than water storage for all specimens.

The FRP-system used for strengthening contained unidirectional carbon fiber fabric sheets and a high-strength, high-modulus impregnating epoxy resin. The mechanical properties of the laminate are shown in Table 2.

Table 2. Mechanical properties of the used CFRP-system as given by the manufacturer.

Mechanical property	**Average value**	**Characteristic Value**
Laminate nominal thickness	0.167 mm	
Laminate tensile strength	4,300 MPa	3,850 MPa
Laminate tensile modulus of elasticity	225 GPa	210 GPa
Laminate elongation at break	Strain 1.91 %	

The CFRP-system was applied using the dry application method according to the manufacturer specifications.

2.3 Test Procedure

The specimens were tested under axial compression using a servo-hydraulic press with a 6,000 MPa load carrying capacity. The testing machine was set to a deformation-controlled mode with a rate of 0.01 mm/s. The axial displacements were measured using linear variable differential transformers (LVDTs). Lateral strains of the CFRP jacket were measured using strain gages bonded on mid-height of the specimens. Additionally, series S1 contained longitudinal strain gauges to measure axial strains.

2.4 Test Results

The results of the tests are summarized in Table 3. Using the same FRP system, the reduction factor k_ε, which reflects the ratio of the rupture strains of FRP-confined concrete to those obtained from flat coupon tests according to Lam and Teng (2003), has been determined to $k_\varepsilon = 0.84$ as an average over all tested specimens. Figure 1 to Figure 3 show the stress-strain behavior of the tested specimens including the strains of the concrete jacket ε_j. Additionally, Figure 1 and 2 contain the axial strains of the concrete cylinder ε_c of series S1.

Table 3. Test results.

Series	**Specimen**	**Confinement pressure** $f_{l,j}$ [MPa]	**Confined concrete strength** $f_{cc,exp.}$ [MPa]	***CV*** [%]
S1-P	1	8.04	56.91	5.7
	2		54.36	
	3		58.84	
S1-U	1		57.10	
	2		54.84	
	3		56.42	
S1-S	1		49.28	
	2		53.85	
	3		51.25	
S2-P	1	8.04	58.57	7.1
	2		67.78	
	3		64.78	
S2-U	1		63.39	
	2		69.44	
	3		59.53	
S2-S	1		58.48	
	2		64.25	
	3		54.39	
S2-Pa	1		64.77	
	2		65.68	
	3		66.65	

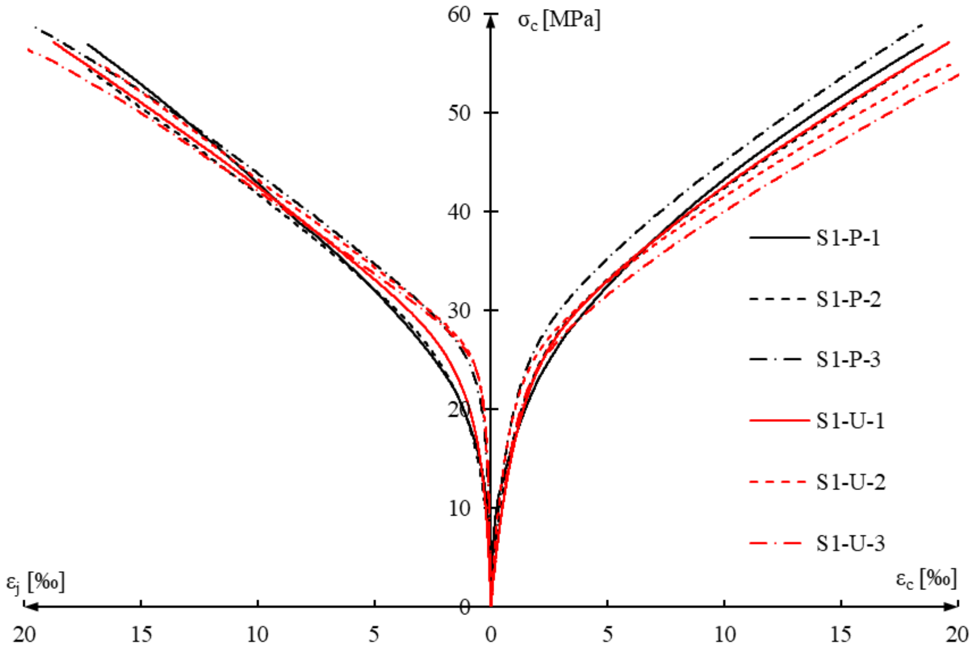

Figure 1. Stress-strain behavior of series S1-P and S1-U.

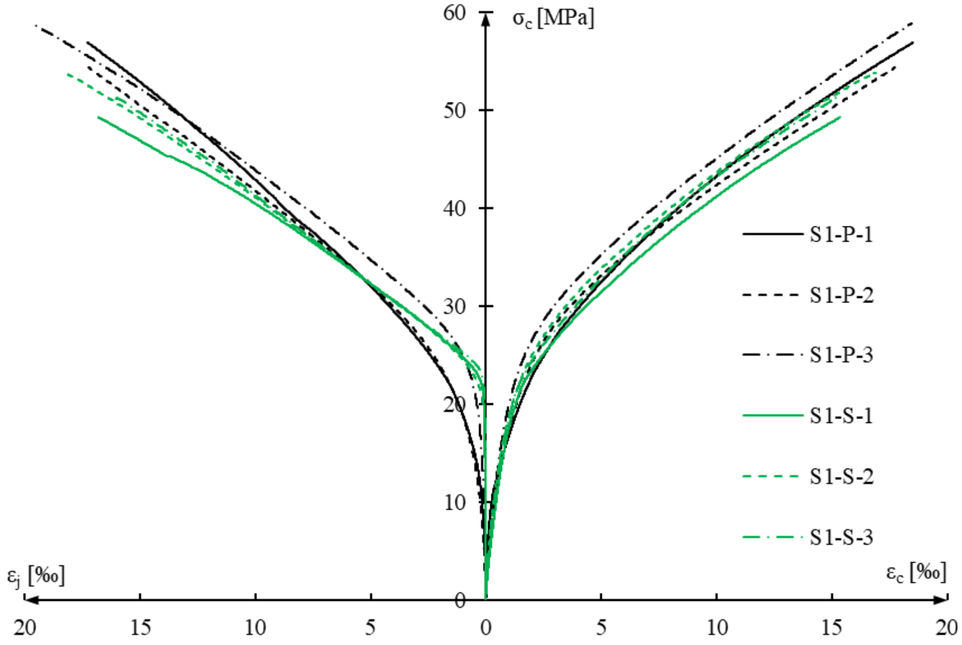

Figure 2. Stress-strain behavior of series S1-P and S1-S.

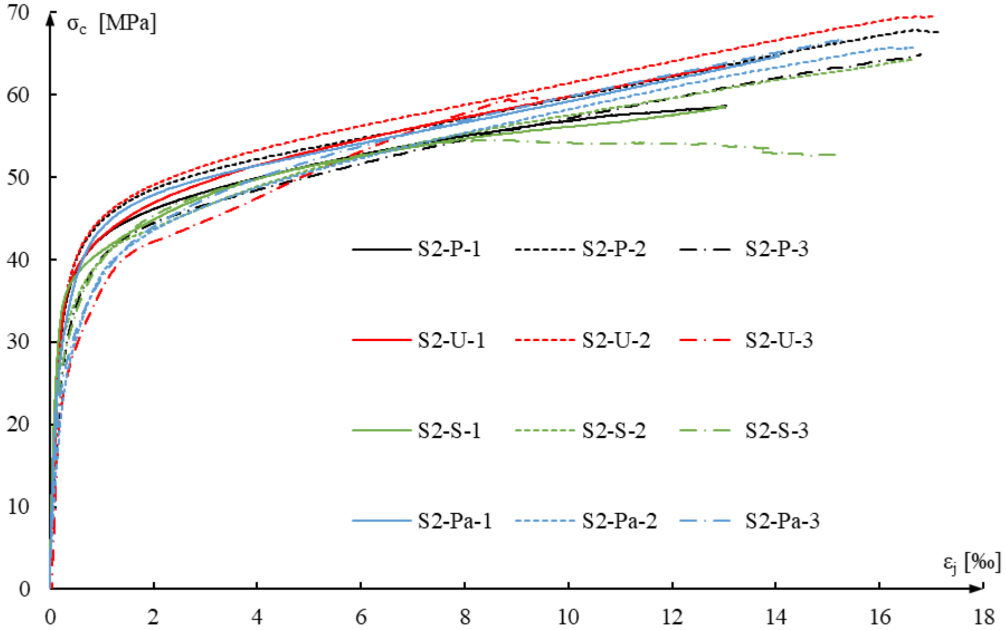

Figure 3. Stress-strain behavior of series S2.

With the exception of specimen S2-S-3, which can be seen as a negative outlier, the test result showed no significant discrepancies between the different preparation methods. Solely the specimens of series S1-S seem to underperform slightly. This could be due to the minimal gap occurring by the application of the lubricating layer.

3 CONCLUSIONS

The experimental results correlate with further findings of Li (2006), Mirmiran *et al.* (1998) and Shahawy *et al.* (2000), suggesting no significant influence of the substrate condition or rather the interfacial bond on the load bearing behavior of FRP confined concrete. Therefore, the recommendations of ACI 440.2R (2017) can be seen as the most advanced concept considering the FRP confinement as a “contact-critical” application with lower requirements for the preparation of the concrete surface prior to strengthening. Following this approach, the FRP confinement of RC columns can be implemented more efficiently, reducing the expenses of the pretreatment processes.

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