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CONFINEMENT OF RC COLUMNS WITH CFRCM

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Textile reinforced concrete is becoming increasingly important in construction. Besides the application in new constructions, textile reinforcement can be used for the strengthening of plain and reinforced concrete structures in the form of fabric reinforced cementitious matrices (FRCMs). An effective and promising application of FRCMs is the confinement of RC columns. Even though great research efforts have been carried out recently, there are still some discrepancies in current prediction models. This paper presents an extensive experimental study on concrete compression members confined with carbon fabric reinforced cementitious matrices (CFRCMs). The experimental program consists of specimens with varying geometries, concrete strengths, and strengthening systems. The investigations showed the importance of a precise determination of the FRCM's material parameters. Furthermore, possible reductions of the FRCMs tensile strength due to the application in curved areas have to be taken into account. Finally, an empirical prediction model as well as recommendations for the experimental determination of the strengthening systems material properties and reduction factors is presented.

Keywords: Fabric reinforced cementitious matrices, Textile reinforced concrete, Strengthening, Reinforced concrete, Design model.

1 INTRODUCTION

The confinement of reinforced concrete (RC) columns with fiber reinforced polymers (FRPs) for upgrading and retrofitting purposes is gaining importance in construction. While there are many advantages, like low dead weights, the speed of application, and only insignificant changes of the cross-sectional dimensions, there are still some drawbacks. Besides the lack of fire resistance, mainly the epoxy resin's sensitivity to ultraviolet light as well as the high costs of the fiber material can limit the field of possible applications. For this reason, strengthening systems in the form of fabric reinforced cementitious matrices (FRCMs) or rather textile reinforced concrete (TRC) are increasingly being considered as alternative composite material for the confinement of RC columns. So far, a number of research programs concerning the load bearing behavior of FRCM-confined concrete have already been carried out, as described, for example, by Cascardi *et al.* (2017). The experimental investigations mostly include only a small amount of specimens and a limited variation of the used materials in each case. Predictive models for the determination of the peak stress and strain of FRCM-confined columns by the analysis of unified databases are available in literature, e.g., Ombres and Mazzuca (2017), Cascardi *et al*. (2017). However, these models show large scattering. Upon closer inspection, there seem to be systematic deviations regarding the various experimental programs, especially between the different strengthening systems and fiber types used. The reason for this may be the divergent definitions and methods for the determination of basic material parameters. Different approaches have variously interpreted especially the specification of the axial tensile strength of the FRCM-systems. Additionally, most of the programs lack the implementation of investigations for the used strengthening system's efficiency for the application as confining jacket. The results available so far can, therefore, hardly be merged to a collective database. To establish a basis for a consistent and extendable collection of test results, an experimental program of Carbon(C)FRCM-confined concrete specimens has been carried out, including the proper determination of all material properties relevant for design purposes.

2 EXPERIMENTAL INVESTIGATIONS

2.1 Experimental Program

A total of 54 confined concrete specimens have been tested. The program mainly focused on the geometrical variation including circular cross sections (C) with different diameters as well as square cross sections (S) with varying corner rounding. Furthermore, two cementitious matrices (P, M) and different numbers of textile layers (L) were applied. Table 1 shows the specifications of the tested specimens.

Table 1. Experimental program.

Series	**No. of spec.**	**No. of textile layers**	**Diameter**	**Side length**	**Corner rounding radius**	**Height**	**Thickness FRCM-jacket**
		n [-]	*d* [mm]	*a* [mm]	*r* [mm]	*h* [mm]	t_m [mm]
P-C-150-L1	3	1	150	-	-	300	15
P-C-150-L2	3	2	150	-	-	300	15
P-C-150-L3	3	3	150	-	-	300	15
P-C-200-L1	3	1	200	-	-	400	15
P-C-200-L2	3	2	200	-	-	400	15
P-C-200-L3	3	3	200	-	-	400	15
P-S-R25-L1	3	1	-	150	25	300	15
P-S-R25-L3	3	3	-	150	25	300	15
P-S-R37_5-L1	3	1	-	150	37.5	300	15
P-S-R37_5-L3	3	3	-	150	37.5	300	15
P-S-R55-L1	3	1	-	150	55	300	15
P-S-R55-L3	3	3	-	150	55	300	15
P-S-R62_5-L1	3	1	-	150	62.5	300	15
P-S-R62_5-L3	3	3	-	150	62.5	300	15
M-C-150-L3	3	3	150		-	300	15
M-S-R25-L3	3	3	-	150	25	350	15
M-S-R37_5-L3	3	3	-	150	37.5	350	15
M-S-R55-L3	3	3	-	150	55	350	15

2.2 Materials

The concrete specimens were produced in three series using different concrete mixtures. Each series was made of concrete from the same batch. All series used CEM II/A-LL 32,5 cement according to EN 197-1 and natural aggregates with a maximum grain size of 16 mm. The concrete mixtures were designed to meet the requirements of widely used normal strength concrete with a compressive strength class of C25/30 according to EN 206-1. After stripping, the top and bottom of the cylinders were grinded plane and parallel to assure uniform load distribution. The matrices used for the FRCM strengthening systems consist of two different high- performance concrete mixtures with fine grained aggregates (max. grain size ≤ 1 mm). All series were strengthened using a flexible heavy tow carbon textile with a mesh size of 12.7 mm in load bearing direction and a nominal thickness *t* of 0.125 mm. The mechanical properties of the FRCM-system were determined by tensile tests of the composite material according to the recommendations of RILEM Technical Committee 232-TDT (2016). The test setup as well as the single values of the tested specimens were discussed by Messerer *et al.* (2018). Table 2 shows the mechanical properties of the materials used for each series.

Table 2. Mechanical properties of the used materials.

Series	**Young's Modulus** core concrete	**Compressive strength** core concrete	**Flexural tensile strength** strength. concrete	**Compressive strength** strength. concrete	**Tensile strenght** FRCM composite
	E_c [GPa]	f_c [MPa]	$f_{ct,FRCM}$ [MPa]	$f_{c,FRCM}$ [MPa]	$f_{t,FRCM}$ [MPa]
P-C	30.70	32.2	6.6	84.9	2,180
P-S	32.57	35.5			
M	36.16	33.0	6.9	57.3	2,115

2.3 Test Procedure

The specimens were tested under uni-axial compression through monotonically applied loading 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 recorded using linear variable differential transformers (LVDTs). Strain gauges have been applied on the core concrete at mid height of the specimens prior to the strengthening process for the measurement of axial strains.

2.4 Test Results

The results of the tests are summarized in Table 3, giving the mean values over three specimens per series. The confinement ratio is defined by the maximum confining pressure f_{lu} provided by the FRCM jacket and the core concrete's compressive strength f_c.

Table 3. Test results.

Series	**Cross-sectional area (core)**	**Confinement efficiency factor**	**Confinement ratio**	**Peak stress (mean)**		**Absolute strength enhancement**
	A_c [mm²]	k_ε [-]	f_{lu} / f_c [-]	f_{cc} [MPa]	CV [%]	Δf_c [MPa]
P-C-150-L1	17,671	0.76	0.08	40.15	0.51	7.95
P-C-150-L2	17,671	0.67	0.14	47.18	3.00	14.98
P-C-150-L3	17,671	0.63	0.19	56.70	4.85	24.50
P-C-200-L1	31,416	0.80	0.06	34.54	8.61	2.34
P-C-200-L2	31,416	0.70	0.11	45.27	4.22	13.07
P-C-200-L3	31,416	0.66	0.16	54.87	2.76	22.67

Table 3. Test results (contd).

Series	Cross-sectional area (core)	Confinement efficiency factor	Confinement ratio	Peak stress (mean)		Absolute strength enhancement
	A_c [mm²]	k_ε [-]	f_{lu} / f_{c0} [-]	f_{cc} [MPa]	CV [%]	Δf_c [MPa]
P-S-R25-L1	21,963	0.43	0.03	31.50	8.63	-
P-S-R25-L3	21,963	0.36	0.07	42.49	5.37	6.99
P-S-R37_5-L1	21,293	0.52	0.04	30.65	11.11	-
P-S-R37_5-L3	21,293	0.42	0.10	46.84	6.00	11.34
P-S-R55-L1	19,903	0.63	0.06	35.77	3.96	0.27
P-S-R55-L3	19,903	0.52	0.14	49.93	5.87	14.43
P-S-R62_5-L1	19,147	0.68	0.06	35.47	6.81	-
P-S-R62_5-L3	19,147	0.56	0.15	51.37	4.27	15.87
M-C-150-L3	17,671	0.71	0.21	56.66	1.46	23.66
M-S-R25-L3	21,963	0.42	0.09	39.49	11.75	6.49
M-S-R37_5-L3	21,293	0.50	0.12	44.23	8.44	11.23
M-S-R55-L3	19,903	0.60	0.17	49.02	7.80	16.02

2.5 Determination of k_ε

Well-known from the confinement of concrete structures with FRP, confining jackets tend to fail prematurely compared to flat coupon tests (Lam and Teng 2003). Therefore, efficiency factors k_ε have been established. Similar observations had been made for the confinement with FRCMs by, for example, Ombres (2014) and Colajanni *et al.* (2014). The determination of such efficiency factors for FRCM jackets is inevitably more challenging. While measuring devices like strain gauges can be bonded directly onto the surface of FRP jackets, an application on textile meshes for FRCM strengthening systems is usually not possible. Indirect measurements on the top layer of the strengthening concrete have to be seen critically because of interferences due to cracking of the concrete and bond slip of the textile. Therefore, a new test method for the determination of k_ε has been developed. In a simple setup, two deflector rolls attached to a tensile testing machine pull apart a loop made of the considered FRCM strengthening system. Messerer *et al.* (2018) and Holschemacher *et al.* (2018) show detailed information on the setup and testing procedure. For the FRCM combinations used, tests on 83 loops with five different deflection radii and one to three layers of textile have been carried out. As a result, equations for the calculation of k_ε in dependence of the diameter of circular cross sections or rather the corner radius of rectangular cross sections as well as the number of applied textile layers could be defined, as seen in Table 4.

Table 4. Efficiency factors of the considered FRCM composites.

Series	Radius dependent efficiency factor		Layer dependent efficiency factor	Summed efficiency factor
	k_r [-]		k_n [-]	k_ε [-]
P	$6.65 \cdot 10^{-3} \cdot r[\text{mm}] + 0.266$	for $r < 80$ mm	$\frac{2.10 + n}{1.55 \cdot (n + 1)}$	$k_r \cdot k_n$
	0.798	for $r \geq 80$ mm		
M	$7.04 \cdot 10^{-3} \cdot r[\text{mm}] + 0.340$	for $r < 80$ mm		
	0.904	for $r \geq 80$ mm		

3 EMPIRICAL PREDICTION MODEL

The carried out experimental investigations are the basis for the determination of a peak-stress prediction model for FRCM-confined concrete. Focusing on a reproducible procedure, the following boundary conditions were defined. The axial tensile strength of the FRCM system has to be determined by tensile tests of the exact composite material rather than by using only the textile or the manufacturer's information. Significant discrepancies are possible, especially for flexible textile meshes, leading to distortions in modeling and design procedure. Furthermore, the efficiency factor k_ε has to be determined using appropriate instrumentation, e.g., fiber Bragg grating sensors, for compression tests or special material test setups.

The following equations are based mainly on the design-oriented stress-strain model by Lam and Teng (2003) and modified for the use of FRCM. The maximum confining pressure f_{lu} of the FRCM jacket is given in Eq. (1) and Eq. (2),

$$f_{\mathrm{lu}} = \frac{2 \cdot t \cdot k_\varepsilon \cdot f_{\mathrm{t,FRCM}}}{D + t_\mathrm{m}} \qquad \text{for circular cross-sections} \tag{1}$$

$$f_{\mathrm{lu}} = \left(1 - \frac{(b-2r)^2 + (h-2r)^2}{A_\mathrm{c}}\right) \cdot \frac{(b + h + 2t_\mathrm{m})}{(b + t_\mathrm{m}) \cdot (h + t_\mathrm{m})} \cdot t \cdot k_\varepsilon \cdot f_{\mathrm{t,FRCM}} \qquad \text{for rectangular cross-sections} \tag{2}$$

where h and b are the side lengths of the rectangular cross section. The modeling is based on the absolute strength enhancement of the confined concrete Δf_c in relation to the confinement ratio f_{lu}/f_c. The transverse reinforcement of RC columns can be considered by addition of the confining pressure provided by the steel reinforcement as given by, for example, Pellegrino and Modena (2010).

A regression analysis of the experimental values leads to the following equation for the determination of the peak strength f_{cc} as seen in Eq. (3).

$$f_{\mathrm{cc}} = f_\mathrm{c} + \Delta f_\mathrm{c} = f_\mathrm{c} + 15.5 \cdot \ln\left(\frac{f_{\mathrm{lu}}}{f_\mathrm{c}}\right) + 46.6 \tag{3}$$

Figure 1 shows the best fitting curve for the experimental values ($R^2 = 0.927$) as well as its performance.

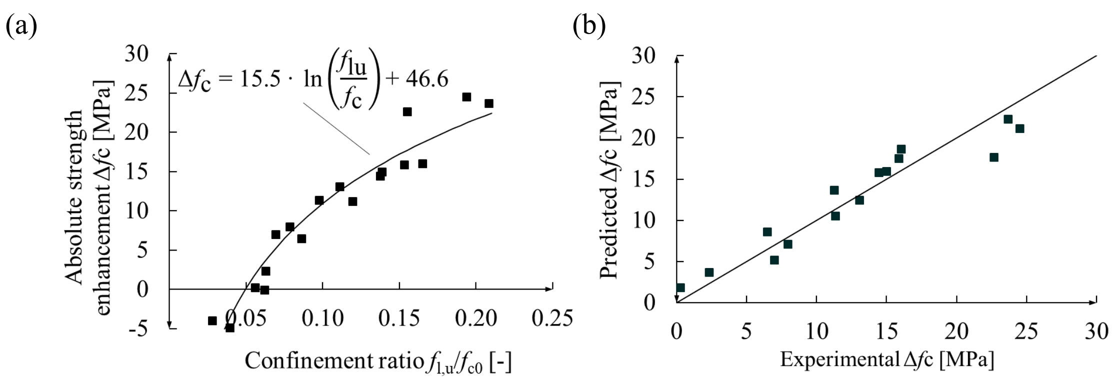

Figure 1. (a) Absolute strength enhancement Δf_c in relation to the confinement ratio f_{lu}/f_c; (b) Performance of the design equation.

4 CONCLUSIONS

The evaluation of the test results indicates that a significant increase in strength can be achieved by confining concrete columns with CFRCM. Yet, a minimum ratio of the confining pressure provided by the strengthening system and the core concretes compressive strength $f_{lu}/f_c \approx 0.05$ has to be reached. The experimental investigations enabled the development of an empirical model for the prediction of the peak strength of CFRCM-confined concrete. The use of the mechanical properties of the FRCM-composite rather than the characteristics of the separate components allows a better comparability between different strengthening systems. Furthermore, the tensile strength of the FRCM has to be reduced due to negative effects caused by the curved application for confinement. Therefore, reduction factors depending on the deflection radius as well as the number of applied textile layers have to be determined for the used strengthening system. The consideration of these effects in the modeling process may enable the development of a generally valid design model for FRCM-confined RC columns, independent of the material combination of the strengthening system.

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