COMPOSITE CARBON FIBRE EMBEDMENT DEPTH AND ANGLE CONFIGURATION INFLUENCE ON SINGLE FIBRE PULL-OUT FROM CONCRETE

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Abstract. Composite carbon fibres with different embedment depth in concrete matrix and angle configuration were used to investigate single fibre pull-out behaviour. Composite carbon fibres were manufactured by impregnating carbon fibre filaments with epoxy resin. Composite carbon fibres with diameter 1.77 mm and 50 mm length were used with smooth outer surface. Composite fibre diameterwas obtained by changing the carbon filament number (from 8 k to 24 k carbon fibre filaments). The fibre filament number used in this investigation was 24 k. The composite concrete matrices with compressive strength 40, 75 and 120 MPa, and very good flow ability were used for pull-out samples. Fibres were embedded in the concrete matrix with depths from 5 to 25 mm and angles configured in 0, 30, 45 and 60 degrees to the pull-out force. Single fibre pull-out tests were performed and force-displacement diagrams were obtained. Single fibre pull-out performanceandfibre failure mode was analysed. Fibre peak pull-out force for smooth fibres shows a steady and linear increase with the fibre embedment depth increase. Fibres with smooth surface show high performance and resistance to pull-out, when configured in the angles to the pull-out force.

Keywords: composite glass fibre, composite carbon fibre, composite fibre reinforced concrete.

Introduction

Fibre reinforced concrete (FRC) is a popular material in different civil engineering applications – slab on ground, raft foundation, wall, elevated slab and tunnel construction. It is relatively easy to produce and cast it in place, it shows high durability, integrity and impact resistance [1-3].

FRC is a composite material with short fibres and brittle concrete matrix. Traditionally it is considered that fibres are chaotically distributed in the concrete. FRC fabrication is similar to conventional concrete fabrication; short fibres are introduced to concrete at the mixing stage. It is commonly accepted that during mixing and placing fibre reinforced concrete into a mould, fibres are obtaining random spatial orientation [3]. Such material load bearing capacity in building elements is dependent on each single fibre pull-out process during concrete matrix cracking under applied external loading. Two main material groups are used to produce short fibres for fibre reinforced concrete: steel and polymer. In the present investigation a new type of composite fibres is under investigation (single fiber pull-out mechanics).

This investigation has to answer: is it possible to replace effectively steel or polymer fibres in the FRC structural elements? Composite fibres are fabricated impregnating industrially produced carbon fibre tows by epoxy resin. Diameters of industrially produced carbon fibre filaments are in microns and diameters of composite fibres are in millimetres. There are experiments with fibre filaments, which were embedded in concrete at different depth under the angle [5]. Single fibre diagram force – displacement is characterizingthe particular fibre load bearing mechanism. When these mechanisms are understood, there is a possibility to vary the number of fibres by changing the dosage and adjust the concrete matrix properties to design FRC having the necessary load-bearing mechanism at the cracking stage [1-8].

Methodology

Fibres

Straight smooth composite carbon fibres with 24 000 filaments were manufactured according to the technology described in paper [9]. Carbon fibre filaments were impregnated with epoxy resin and cured. Composite fibres were cut in 50 mm length. Fibre length to diameter ratio is 28.2 and average diameter 1.77 mm. Composite carbon fibres are shown in Fig. 1.

Fig. 1. **Composite carbon fibre with 24 000 filaments (*L* – 50 mm, *d* – 1.77 mm)**

Concrete compositions

Three concrete matrices were used with a mix design as described in paper [9]. Matrices were used to have three different concrete compressive strength levels – low, medium and high compressive strength. Concrete compressive strength is presented in Table 1.

Table 1

Concrete compressive strength for used matrices

Concrete Property	M1	M2	M3
Concrete compressive strength 28-day age, MPa	124.4	71.9	34.1

Samples

Single fibre pull-out experiments were carried out to investigate fibre resistance to pull-out from concrete matrix. Three different concretes wereused to investigate fibre pull-out behaviour in concretes with different strength levels. Two concrete opposite parts were cast and a plastic film was used to separate the concrete. Small opening in the plastic film allowed composite fibre to connect two concrete pieces. Seven samples for each configuration and the concrete matrix were manufactured (totally 210 pull-out samples).

Different mould sizes were used – Type A (40 x 60 x 30 mm) and B (80 x 100 x 30 mm) as shown in Fig. 2. The two concrete part sample type was chosen to enable a possibility to test single fibre pull-out at the configured angle and observe fibre pull-out from both sides of the concrete matrix, which exists in the real fibre reinforced concrete structure behaviour.

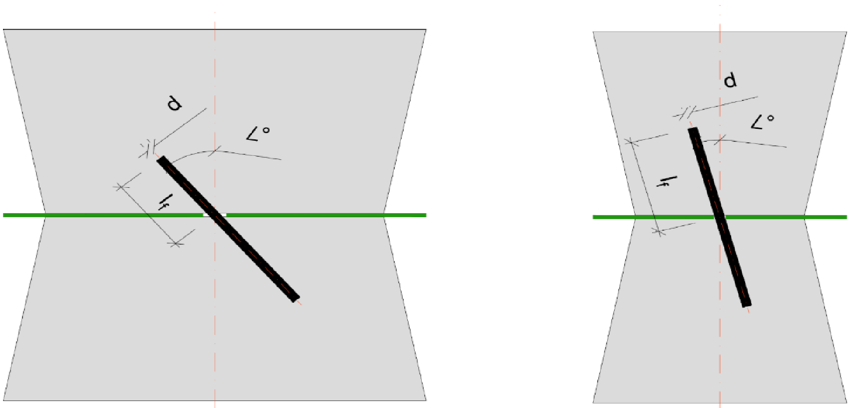

Fig. 2. **Sample geometry sketch:** Type A on the right, Type B on the left; fibre configurations – depth l_f = 25, 20, 15, 10 and 5 mm; and angle ∠ = 0º, 15º, 30º, 45º and 60º

Testing

All experimental tests were done at 28-day age. Concrete was cured in normal conditions RH > 95 % and 20 ºC. Concrete cube samples were tested in compression to control the compressive strength for the concrete mixes. Single fibre pull-out tests were done using the testing machine Zwick Z150. Pull-out displacement was measuredwith a non-contact video extensometer Messphysik. Loading rate at 5 mm·min^{-1} was applied for the test specimen in single fibre pull-out. Test specimens are made with a pre-made crack, configured in 5-25 mm depth for 0-degree angle and 20 mm depth for 0, 15, 30, 45 and 60-degree angle to pull-out force. The pre-made crack ensures that the fibre bridging force is going only through fibre between two concrete parts. Averagepull-out curves are calculated and presented in the paper. The calculation process is the following: displacements starting with displacement 0 mm are increased with 0.05 mm and average corresponding load is calculated.

Results and Discussion

Single fibre pull-out results for embedment depth and angle configurations are presented in Fig. 3 for M1, Fig. 5 for M2 and Fig. 6 for M3 concrete matrix. All three concrete matrices show a consistent peak force growth as the fibre embedment depth ranges from 5 to 25 mm.

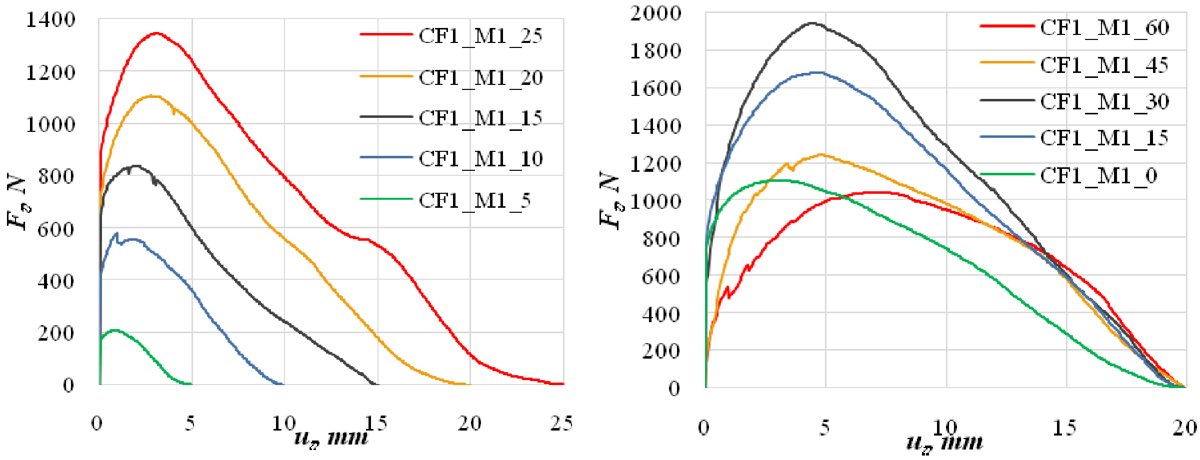

Fig. 3. **Average single fibre CF1 pull-out behaviour curves for concrete matrix M1, fibre configurations:** embedded in depth 25, 20, 15, 10 and 5 mm (on the left), angle configuration 0, 15, 30, 45 and 60 degrees (on the right)

From the figure (on the right) it is obvious that the fibre peak pull-out force is higher, when the inclination angle is 15 and 30-degree, 45-degree configuration has only slightly higher force. Only the angle 60-degree configuration has reduced the pull-out force. Both 45 and 60-degree angle configurations have significant slope reduction in beginning of the displacement (0-5 mm) due to deformations that occur by cracking the fibre channel corner. Slope reduction is higher for fibres in M1 matrix due to fibre filament longitudinal delamination. When delamination starts to occur, fibre rigidity reduces and the pull-out curve declines. Fibre before pull-out is shown in Fig. 4 (on the left); delaminated and separated fibre with 60-degree configuration in concrete matrix M1 is shown in Fig. 4 (in the middle and on the right).

Composite fibre after complete extraction has separated from the bottom part up to almost the end of the fibre. Delamination and separation starts from the crack plane and is getting deeper along the fibre. When the fibre has gained significant displacement, the pull-out force significantly reduces, delamination process decreases and does not happen completely to the fibre end.

There is very similar pull-out behaviour for composite fibre in M2 matrix compared to M1, only the resistance forces are smaller. Angle configurations 15 and 30-degree show higher pull-out resistance and 45 has similar maximum force, but decreased curve’s slope up to 0.5 mm displacement. Fibre with 60-degree configuration shows lower resistance and maximum pull-out force for approximately 110 N.

Average single fibre pull-out behaviour curves in concrete matrix M3 show that 15, 30 and 45-degree fibre inclinations have insignificant peak pull-out force increase. Fibre configured in 60-degree angle shows significantly smaller pull-out resistance and the pull-out peak force is at 10 mm of fibre displacement.

Fig. 4. **Composite fibre CF1:** before pull-out (on the left) and after complete extraction from concrete matrix M1, with configuration: embedded 20 mm, angle 60 degrees

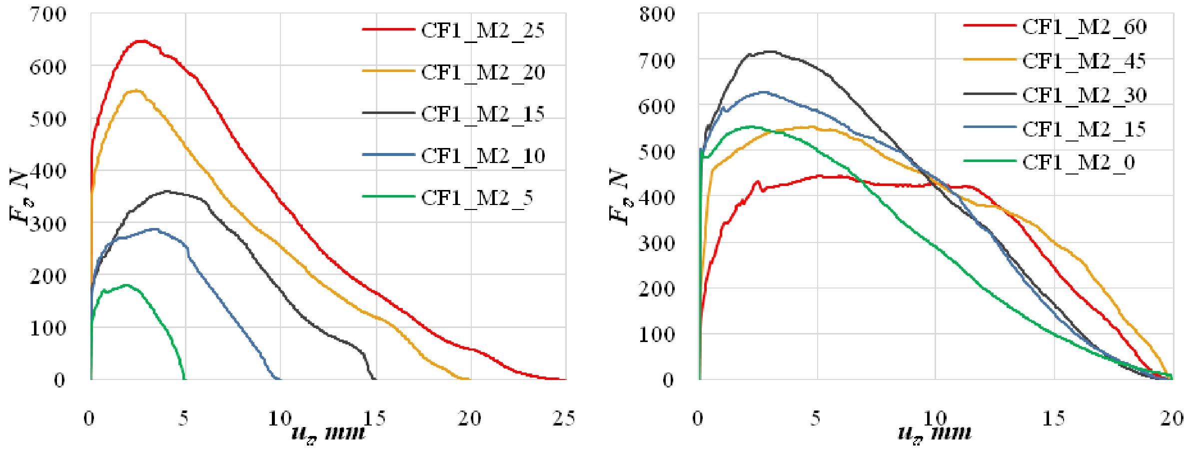

Fig. 5. **Average single fibre CF1 pull-out behaviour curves for concrete matrix M2, fibre configurations:** embedded in depth 25, 20, 15, 10 and 5 mm (on the left), angle configuration 0, 15, 30, 45 and 60 degrees (on the right)

Comprehensive research in steel fibres in concrete matrix comparable by strength to M2 shows that only corrugated steel fibres have the peak pull-out force at 600-700 N [10]. Other fibre types – smooth and with a hooked end have significantly less pull-out peak loads and resistance throughout the pull-out process.

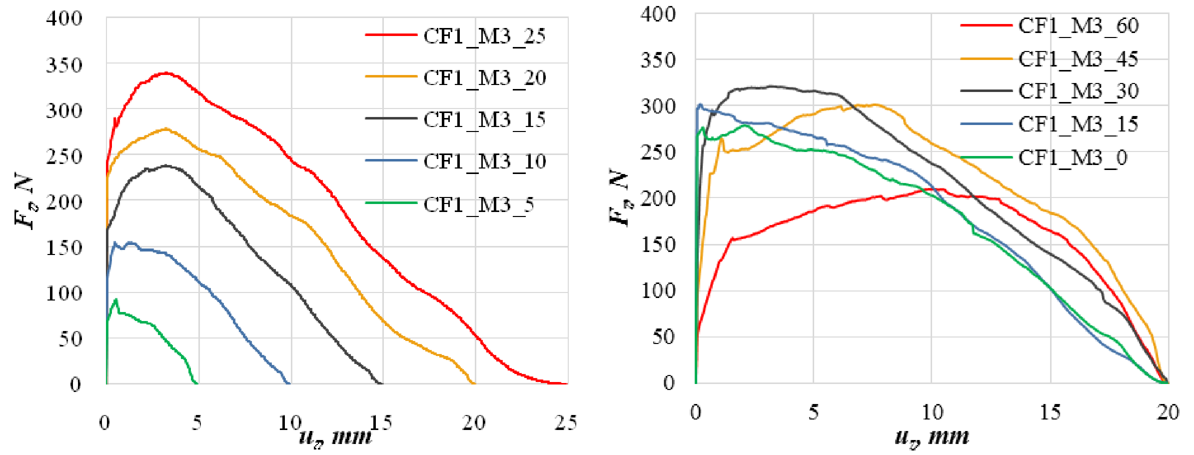

Fig. 6. **Average single fibre CF1 pull-out behaviour curves for concrete matrix M3, fibre configurations:** embedded in depth 25, 20, 15, 10 and 5 mm (on the left), angle configuration 0, 15, 30, 45 and 60 degrees (on the right)

Composite fibre CF1 after complete extraction with 45-degree configuration in concrete matrix M3 is show in Fig. 7.

Fig. 7. **Composite fibre CF1 after complete extraction from concrete matrix M3, with configuration: embedded 20 mm, angle 45 degrees**

Composite fibre after complete extraction from concrete matrix M3 is deformed and is not straight, and it has some delamination or separation. Fibre internal damages cause significant pull-out resistance reduction.

Composite carbon fibre (CF1) peak pull-out forces from each fibre embedment depth and configuration angle are collected and plotted in Fig. 8 for three concrete matrices M1, M2 and M3.

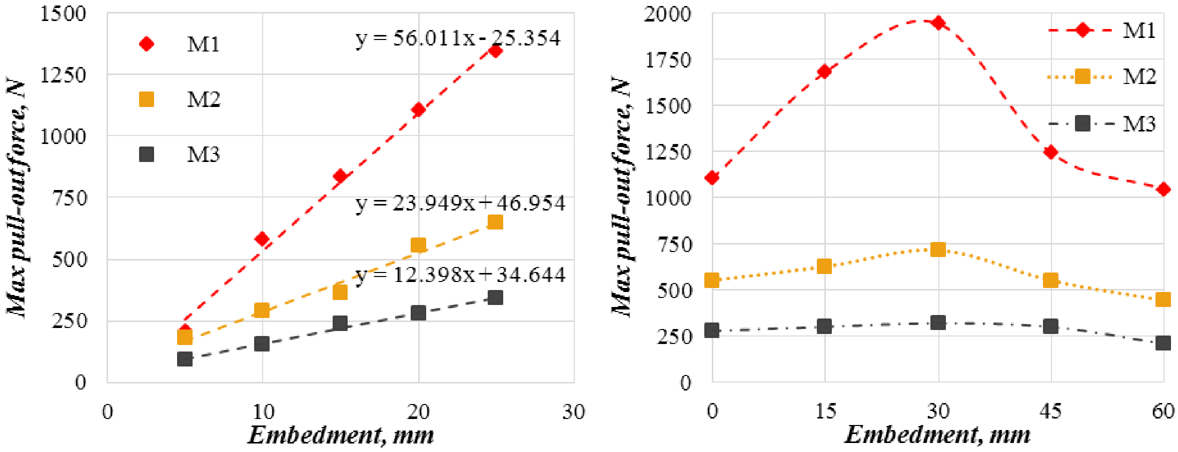

Fig. 8. **Single composite fibre CF1 peak pull-out force depending on fibre embedment depth (on the left) and fibre configuration angle (on the right) in three concrete matrices:** M1, M2 and M3

From the figure it can be seen that there exists linear relationship between the smooth carbon fibre (CF1) peak pull-out force and fibre configuration embedment depth. Composite carbon fibre peak pull-out force-embedment depth relationship is not parallel between the concrete matrices M1, M2 and M3. Fibre peak pull-out force is rising steeper with an increase of fibre configuration depth when concrete matrix becomes stronger. The fibre pull-out peak force increase trendline is almost twice steeper for M2 compared with M3, and for M1 compared to M2.

Conclusions

Pull-out experimental tests show that there is linear relationship between the fibre embedment depth and maximum pull-out force. Pull-out force is increasing faster in high strength concrete matrix compared to lower strength concretes, when the fibre embedment depth is incremented.

Composite fibre shows higher load bearing capacity during pull-out, when fibre is oriented at 15 and 30-degee angle in all three concrete matrices compared to configuration with 0-degree angle. Composite fibre oriented under 45-degree angle performance depends on the concrete matrix strength. Better performance is for fiberconcrete with lower concrete strength matrix. Composite fibre performance at degree angle configuration is lower due to fibre delamination, when the pull-out process is happening. Fibre is bent when pulled out from concrete, bending causes fibre delamination and even separation in some cases. Fibres with longitudinal defects significantly reduce fibre toughness and therefore the pull-out curve is reduced.

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