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CRACK DEVELOPMENT IN CFRP REINFORCED MORTAR – AN EXPERIMENTAL STUDY

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ABSTRACT

This paper reports from a research study, aiming to investigate the crack development of a CFRP grid-reinforced mortar member tested in uniaxial tension. This composition of CFRP together with the mortar forms the MBC (Mineral Based Composite) strengthening material and its application for strengthening concrete structures is being researched at the Technical University of Denmark (DTU). For the strengthening material, tendencies in behaviour with changing geometrical parameters and mortar compositions are detailed.

The actual tests described contribute to a larger ongoing project on Mineral Based Composites (MBC), which is a newly developed strengthening materials and system for existing concrete structures, where FRPs, mainly CFRP grids are externally bonded to the concrete surface by means of cementitious bonding agents, i.e. polymer-modified mortars. Here only the strengthening system itself has been tested, the FRP material and the bonding agent together under uniaxial tension. Crack formation, crack development in CFRP reinforced concrete and the interaction between CFRP reinforcement and mortars are documented and evaluated and different mortars and grids are compared.

KEYWORDS

Concrete, FRP Grid, Mortar, Engineered Cementitious Composites (ECC), Dog bone, Bond, Tensile Test

INTRODUCTION

The use of concrete has been widely spread over the world as it is one of the most important construction materials (if not the most) for structures. Now, many of those have reached the end of their planned service life. Thus, there is an increasing need to restore or strengthen civil engineering structures worldwide, in particular related to transportation because of ageing, deterioration, and misuse of facilities, lack of regular maintenance and repair, and the use of inappropriate materials, construction techniques or both. Increased or changing loads may also lead to a need of upgrading. This situation leads to the development of new structural solutions with improved durability and higher properties and speeds of construction. Upgrading or rehabilitating structural integrity by the addition of reinforcing materials is an economic option to new construction. On the material side, several investigations have been carried out with different strengthening materials. There exist several repair and strengthening methods that are applied on existing concrete structures for this purpose, such as increase of the cross section of critical elements, span shortening with additional supports, external/internal post tensioning, steel plates bonding or fiber reinforced polymer composites.

Externally bonded FRP (Fibre Reinforced Polymer) systems have been proven to be an effective strengthening method in repairing or strengthening structures. Since the end of the 1980-ties, the use of Fibre Reinforced Polymers (FRP) is being researched and applied increasingly for the rehabilitation of existing concrete structures. FRP composite materials have a number of advantages when compared to traditional construction materials such as steel, wood and concrete. FRPs offer excellent corrosion resistance to environmental agents as well as high tensile strength, light weight, and high modulus of elasticity. The use of FRP strengthening systems for rehabilitation of concrete structures must be considered successful. Nevertheless, the epoxy bonded systems exhibit some disadvantages. For example the diffusion closeness, poor thermal compatibility with base concrete, sensitive to moisture on the adherents at time for bonding, hazardous working environment for the manual worker and the problem of minimum temperature of assemble in cold climates. It is therefore of interest to replace the epoxy adhesive with a mineral based bonding agent, e.g. polymer modified mortar, with similar properties to those of the base concrete applicable in a more environmentally friendly way. In a recently developed innovative strengthening system, the traditional epoxy bonding agent is being replaced by cementitious matrices to bond the FRP material to the concrete surface.

Several tests have been carried out on MBC-systems, focusing on flexural strengthening (Wiberg, 2003) and (Becker, 2003) and, more recently, shear strengthening (Christiansen, and Jürgensen,, 2006), (Blanksvärd, 2007). Mineral Based Composites (MBC) is a combination of polymer modified mortar (PMM) or an engineering cementitious composite (ECC) and FRP, a composite material which is made by replacing part or all of the cement hydrate binder of conventional mortar with polymers which, by strengthening the cement hydrate binder with polymers, and with the addition of conventional FRP becomes a high performance external strengthening system for existing concrete structures. For a better understanding of the behaviour of the strengthening material itself used in the MBC system, and to identify the most successful material combinations for further investigation, as a simplification, a pure tensional test, dog-bone tests, has been performed with the MBC materials in different combinations and geometries. As bonding agent for the FRP, both pre-mixed polymer-modified mortars and ECCs have been used.

TENSIONAL BEHAVIOUR OF CONSTITUENTS

Consider a steel reinforced concrete specimen submitted to uniaxial loading, the stresses will be distributed respectively between the matrix and the steel reinforcement, in proportion to their stiffness and bond between the matrix and the reinforcement. The bond is depending on the pre-crack stress distribution. When the stresses in the matrix reach the ultimate tensile strength of the concrete, cracks will occur. At the time the first crack occur tension-stiffening will prompt the energy in the bond between the matrix and the reinforcement relocates and the stresses will be distributed to the nearby reinforcement without cracking and at certain energy a new crack will appear. Three main states can be identified until the stress reaches the yield stress of the steel reinforcement: State I. uncracked state, State II. Cracking, and State III. Steel-yielding. In a similar way to the steel reinforced specimens, a concrete specimen reinforced with a FRP follows the same loading behaviour. However, the ductile deformation area, State III, cannot be expected because of the carbon fibre reinforcement has no plastic capacity. Thus the composite fails or slip when reaching the tensile failure strain of the reinforcement, (Hegger and Voss, 2004). From (Fischer an Li, 2006) it is shown that brittle matrices, such as plain mortar and concrete, lose their tensile load-carrying capacity almost immediately after formation of the first crack, see Figure 2.

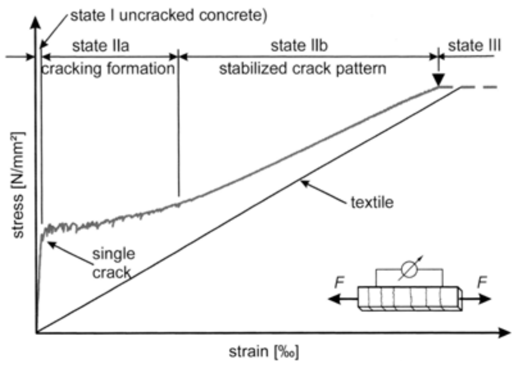


Figure 1. The tensioning stiffening, from (Hegger and Voss, 2004)

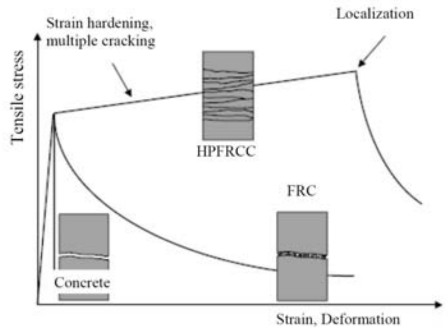


Figure 2. Stress-strain diagrams for FRC and ECC (HPFRCC) materials, from (Fischer and Li, 2006)

The addition of fibres in conventional fibres reinforced concrete (FRC) can increase the toughness of cementitious matrices significantly. However, their tensile strength and especially strain capacity beyond first cracking are not enhanced. FRC is therefore considered to be a quasi-brittle material with tension softening behaviour, i.e. a decaying load and immediate localization of composite deformation at first cracking in the FRC matrix. In contrary, HPFRCC (High-Performance Fibre-Reinforced Cementitious Composites) are defined by an ultimate strength higher than their first cracking strength and the formation of multiple cracking during the inelastic deformation process. In (Fischer and Li, 2006) it is described that the contribution of the cementitious matrix to the load–deformation response of reinforced concrete or ECC in uniaxial tension is generally described as tension-stiffening effect. Under axial loading, ECC materials tend to develop multiple cracking, in opposition to the regular brittle concrete. This is discussed more in detail below.

AIM AND SCOPE

The aim of the presented study was to investigate and document crack development behaviour in a CFRP-grid reinforced cementitious matrix, and the interaction between the CFRP-grid reinforcement and the mortar by comparing the test values of the specimens, fracture loads, crack loads, deflections and ultimate tensile strength, with different mortar mixes, CFRP-grids and grid orientations. For the test, a special dog bone specimen set-up has been developed. The presented test results will form a base for future studies in the field.

TESTING

In the tests two different CFRP grid types and three different mortars have been used. The direction-dependent material properties for the grids and the mortars used are listed in Table 1 and Table 2. In table 1, tested values for the composite grid are shown together with material properties for the fibre given by the manufacturer. The G1 grid is referred to as the *small grid* and the G2 grid is in this paper referred to as the *medium grid*. Both grids are epoxy-coated, and the amount of the epoxy was quite extensive for the grids. This is also the reason why the material properties for the composite are so much lower than the pure fibres. A quick calculation give a volume percentage of 20 – 25 % fibre, the rest is epoxy matrix. Mortars used were two different pre-mixed mortars, M1 and M2 and one more ductile mortar ECC. The premixed mortars are high strength, quasi-brittle mortars. The ECC mortar contains long PVA-fibres embedded to improve ductility and a large portion of fly ash.

Table 1. Material properties for grids (fibres) used –, T-transverse, L-longitudinal

Grid – composite Tested values	Spacing L x T, [mm]	E_{Lc} [GPa]	E_{Tc} [GPa]	f_{Lc} [MPa]	f_{Tc} [MPa]	ε_{Lc} [‰]	ε_{Tc} [‰]
G1	24 x 25	62	39	782	533	12.5	14.0
G2	42 x 43	55	41	593	457	11.1	11.1
Grid – fibre Values from manufacturer	**Spacing L x T, [mm]**	**E_{Lf} [GPa]**	**E_{Tf} [GPa]**	**f_{Lf} [MPa]**	**f_Tf [MPa]**	**ε_{Lf} [‰]**	**ε_{Tf} [‰]**
G1	24 x 25	262	289	3950	4300	15.0	14.9
G2	42 x 43	284	253	3800	3800	13.4	15.0

Table 2. Material Properties for mortar used

Mortar	E_c [GPa]	f_{cc} [MPa]	f_{ct} [MPa]
M1	26.5	53.2	2.6
M2	35.0	77.0	2.8
ECC	19.0	60.0	3.0

The specimen geometry used in this paper has been developed specifically to these test series, with the intention of developing an effective test method to test CFRP-reinforced mortar/concrete in uni-axial tension. Uni-axial tension test, while simple in concept, requires attention to many test details. Amongst these are specimen alignment, and post-crack stability. The latter concern makes testing of concrete or tension-softening FRC particularly challenging, and a variety of methods of stiffening the machine and load-trains have been proposed. The final dimensions of the test specimens have been set to 160 x 160 x 980 mm as shown in Figure 3, with a test field of 400 x 160 mm. The carbon fibre grid was placed in the mid-plane in three different directions, longitudinal (L), transversal (T) and rotated (15°), see Figure 4. In the test self-centring anchor clamp's were used. The main purpose is to hold the test sample fixed and centred, and to transfer the tensile force form the test machine evenly into the specimen, with as little eccentric load as possible, in order to avoid any shear forces in the sample. On the clamped specimens elongations were measured by means of two LVDTs (Linear Variable Displacement Transducers) with extension arms on both sides of the test field of the specimens. The tests were carried out displacement-controlled with a loading rate of 0.6mm/min. Monitored parameters were load and global elongation by means of LVDTs. One specimen per series were equipped with strain gauges mounted on the grid. This test specimen was also monitored by the optical measurement system Aramis.

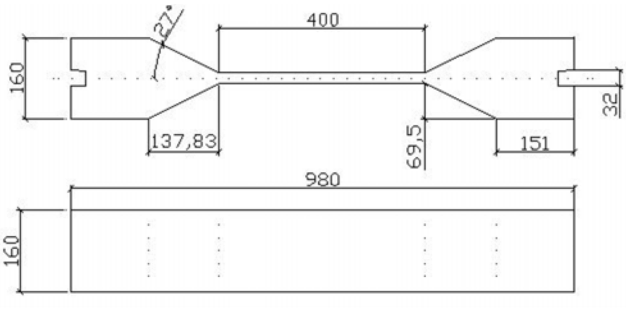


Figure 3. Test specimens used in the test

The Aramis system is a 3D optical measuring tool which analyzes, calculates and documents material deformations. It measures relative displacements within a pre-defined 3D measurement field by means of two high-resolution cameras.

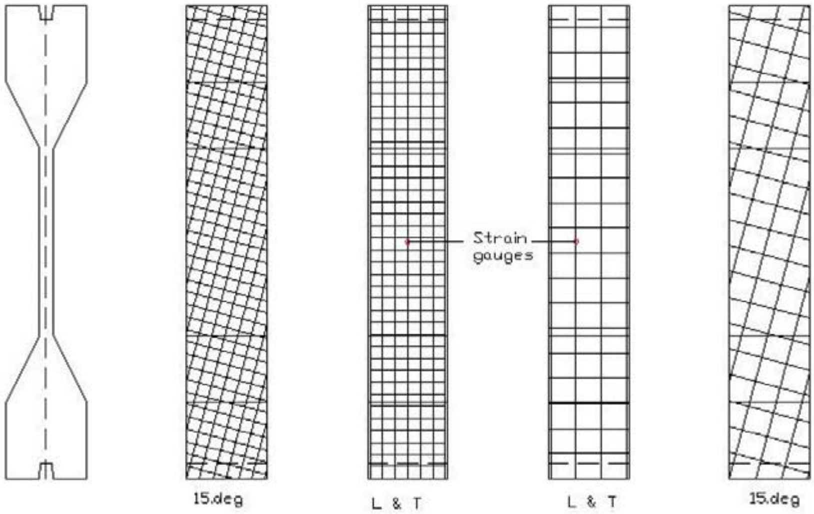


Figure 4. Drawings of specimens with grid a) Sideview of specimen b) Small grid 15° c) Small grid longitudinal–transversal d) Medium grid longitudinal-transversal e) Medium grid 15°

Test Matrix

With three different mortars (M1, M2, ECC), two different grids (medium and small), and three possible grid orientations (0° - longitudinally placed grid, 90° - transversally placed grid, 15° - rotated grid), the final test series consists of 13 different combinations, 3 specimens per each series, in total 39 specimens and 6 plain mortar dummies. Test matrix is shown in Table 3. All specimens had has at least 28 days of curing before testing.

Table 3. Test Matrix

Test Specimen	Mortar	Grid	Orientation	Referred to as
1	M1	---	---	M1 dummy
2	M2	---	---	M2 dummy
3	M1	small	90°	M1-90-small
4	M1	medium	90°	M1-90-medium
5	M1	small	0°	M1-0-small
6	M1	medium	0°	M1-0-medium
7	M1	medium	15°	M1-15medium
8	M2	small	90°	M2-90-small
9	M2	medium	0°	M2-0-medium
10	M2	small	15°	M2-15 small
11	M2	medium	15°	M2-15-medium
12	ECC	small	0°	ECC-0-small
13	ECC	medium	0°	ECC-0-medium

RESULTS

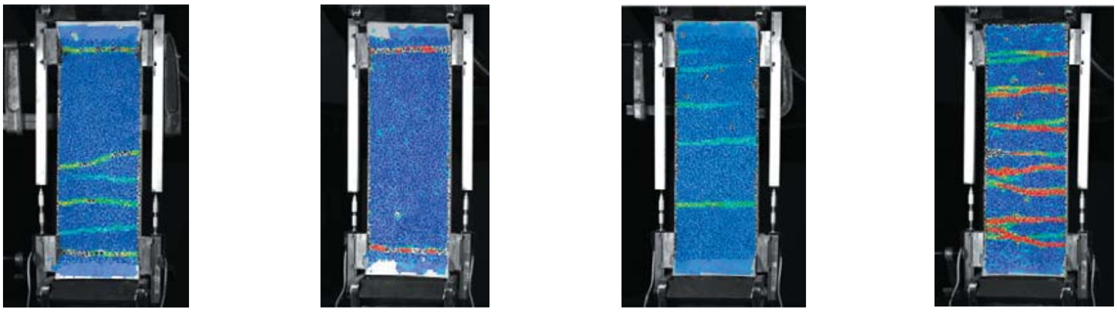
In order to build up a comparative analysis all M-grid specimens were placed in longitudinal direction, for the three different mortars (M1-0-medium vs. M2-0-medium and ECC-0-medium). Two S-grids were placed in longitudinal direction with a ductile and a quasi-brittle mortar (ECC-0-small vs. M1-0-small). The specimens have been compared in their load-deformation behaviour, illustrated with stress-strain plots, by crack widths documented by Aramis, and listed values for comparison. The load-deflection response of the ECC specimens is as expected ductile, and the amount of cracks more numerous than of the quasi-brittle mortars M1 and M2. The crack widths of the ECC specimens are significantly smaller, ranging from 0.2 mm to 0.4 mm of the medium grid and 0.1 mm to 0.6 mm for the small grid, compared to the 0.75 mm to 1.5 mm of the M2-medium, and the 0.2 mm to 0.8 mm of the M1-small. It is furthermore observed that the cracks of the ECC specimens are not fully developed, as there is fibre bridging over the PVA-fibres in the matrix until fracture of the specimen occurs. The initiation of the first crack starts at a slightly later load level on the ECC specimens than of the M1 and M2 specimens. Because of the smooth transition between the uncracked and the cracked stage, it is difficult to determine, even from the test data, when exactly the actual cracks form. Studying the load-deflection graphs of

the ECC specimens, and applying tendency lines between the pre and post cracking stages, the load can be approximated.
These reveal that the initial cracking of the ECC does in fact occur at a later stage than for the M1 and M2 specimens leading to a conclusion that the tensile strength of the ECC mortar is marginally higher than the M1 and M2 mortar. As seen in Table 4 the ultimate tensile strength of the ECC specimens is far greater than the M1 and M2, having an load carrying capacity of approximately 60-100 %. Table 4 summarizes numerical results for selected series.

Table 4. Failure loads, loads at first cracking, and mean number of cracks
Comparative values for series, mean values, for all grid orientations

Test Specimen	Load at failure [kN]	Load at first crack [kN]	Mean no. of cracks
M1-0-medium	8.9	7.2	2.5
M2-0-medium	11.9	6.8	2.3
ECC-0-medium	15.0	8.3	10+
M1-0-small	8.3	7.5	2.7
ECC-0-small	17.3	9.7	10+
M1-15-medium	6.5	5.7	1.3
M2-15-medium	8.5	7.1	1.7
M1-90-medium	15.9	6.6	4.0
M1-90-small	8.9	7.4	4.3
M2-90-small	9.0	5.9	6.0

On the ECC specimens cracks were smaller and more numerous than of M1 or M2. ECC graphs show a characteristic ductile crack pattern as the other two mortars show typical brittle failure, see Figure 5.



M1-90-small M2-90-small ECC-0-medium ECC-0-small

Figure 5. Crack patterns illustrating the mean number of cracks until failure for different combinations, recorded by Aramis

The load-deflection behaviour of the different mortars has been parted into the behaviour of the quasi-brittle mortars (M1 and M2), and the behaviour of the ductile ECC mortar. In terms of load-elongation curves, this behaviour is shown on Figure 6. The ECC specimens, after the first crack, show a definite raising tendency until the peak load, which gives the failure load. These curves are smooth which means there is no hidden crack formation with sudden decrease of energy. The quasi brittle mortars M1 and M2 are “jumping”and have a decrease in load carrying capacity right after the first crack. Compared to the theoretical stress-strain values of the bare CFRP-grid, (Blanksvärd, 2006), the increase in the strengthening effect is almost identical for the three mortars up to the point of the first crack. Loading further, after having reached the ultimate tensile strength of the CFRP, the load-elongation curves differ significantly depending on the mortar´s ductile or quasi brittle characteristics. For the ductile mortar, a significant tension-stiffening effect is recorded, resulting in a maximum of 100% increase in the tensile capacity, when compared to that of the quasi brittle mortars. This fact seems to confirm that the increased ductility of the ECC mortar has a positive effect on the interaction with the CFRP, hence increasing the uniaxial tensile strength of the ECC composite specimens. To our experiences, in case of the quasi-brittle M1 mortar, the medium grid performs about 60% better in transversal direction than in longitudinal direction. In contrary, in combination with the ductile ECC mortar, the S-grid has given about 15% higher results. Two possible reasons for the better performance of the medium grid when transversally placed are the anchorage and the possibility of the joint to deform and to carry load up to failure. The 15° orientated specimens, compared to the longitudinally placed reinforcement, do not develop as many cracks and have a reduced tensile strength. Cracks developing here tend to follow the grid. The numerical values are shown together with other grid orientations in Table 4.

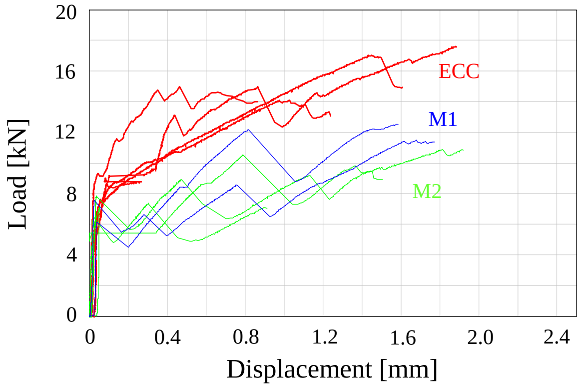


Figure 6a. Load-deflection curves for medium grid

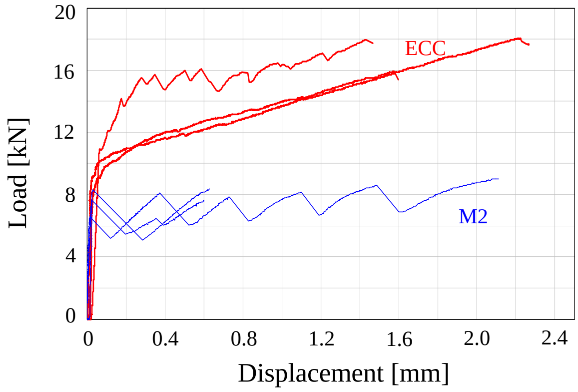


Figure 6b. Load-deflection curves for small grid

DISCUSSION AND CONCLUSIONS

Due to the bridging effect of the long PVA-fibres embedded in the ECC mortar, together with the multiple cracking behaviour, it seems that stresses are reduced both in the CFRP grid and in the grid-mortar interface. By reducing and redistributing these interfacial bond stresses, the ECC mortar "helps" the grid by preventing premature failure in the joints of the grid from local stress concentrations and bond slip. Multiple cracking and a significant tension stiffening behaviour was observed when applying a ductile, PVA-reinforced ECC as bonding agent. Recorded peak values in the load-elongation curves characterize a much more "balanced" behaviour for these M1 specimens. The same plots for the quasi brittle mortars are "jumping", indicating a more uneven stress distribution and possible local failures in the grid joints. Typical brittle failure and corresponding crack patterns were recorded in case of the quasi brittle M1 and M2 pre-mixed mortars.

Differences in the tensile capacity for the same material combinations but longitudinally or transversally placed grids are more significant in case of the medium grid. The medium grid when transversally placed "over performed" with 64%. The small grid performed alike in both directions. One possible reason to premature failure of the CFRP grid may be that the bond between mortar and grid is insufficient, so that local slippage occurs in the longitudinal fibre bundles causing a bond stress redistribution within the longitudinal and transversal fibre bundles. As a consequence, the joints are weakened by the emerging shear forces, hence reducing the tensile capacity of the CFRP.

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