FRPRCS11
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Strengthening concrete structures using mineral based composites

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Keywords: CFRP; Grid; Mortar; Shear strengthening; Beams; Concrete.

SUMMARY
During the last two decades, strengthening concrete structures with epoxy bonded carbon fiber reinforced polymers (CFRP) has shown excellent results in increasing bearing capacity. However, there are some limitations with epoxy coated concrete surfaces, e.g.; low permeability which may provoke freeze/thaw problems, poor thermal compatibility to the concrete substrate which makes epoxy coating more sensitive to the surrounding temperature and regulations when it comes to the security and health (allergic reactions) of applicators and third party users. In this respect, using mineral based composites (MBC) may overcome some of these challenges associated with epoxy bonded strengthening systems. MBC, in this context, refers to high strength fibers bonded to the surface using a mineral based bonding agent. This study examines the cracking behavior and strain development of shear MBC strengthened RC beams. The results show that using MBC as shear strengthening postpones the formation of macro-cracks and that a considerable strengthening effect is achieved by using MBC.

1. INTRODUCTION

1.1 Background

As time changes so does society and its structures. Time dependent factors such as degradation have a significant impact on the life span of structures. When dealing with concrete structures and reinforced concrete (RC) structures the types of degradation listed in the European standard EN 1504-9 (2008) [1] categorize the causes of deficiencies into *defects in concrete* and *reinforcement corrosion*. All of these underlying reasons may ultimately result in concrete structures that have too low bearing capacity or multiple cracking enforcing it to be repaired or strengthened.

However, it is not only the degradation that may provoke strengthening measures. Other reasons might be; changes in structural use, the adoption of new design codes, safety etc.

When it comes to structural strengthening, the traditional ways include; adding or replacing embedded or external reinforcing steel bars, installing bonded rebars in preformed or drilled holes in the concrete, plate bonding, adding mortar or concrete, injecting cracks, voids or interstices, filling cracks, voids or interstices and prestressing (post tensioning). All of the above are part of principle 4 in the EN 1504-9 (2008) [1], for protection and repair of concrete structures.

1.2 Strengthening concrete structures

Plate bonding (method 4.3 in EN 1504-9 [1]) is a good alternative when it comes to strengthen concrete structures. Traditionally this has been done with epoxy bonded steel plates. This method requires heavy lifting and extensive mounting equipment due to the dead weight of steel. Another drawback when using steel is the corrosive properties which may reduce the life span of the strengthening system. During the last two decades a lot of research and development efforts have been made to develop strengthening systems utilizing fiber reinforced polymers (FRP). These FRPs are typically made of glass (G), aramid (A) and, most commonly in structural strengthening, carbon fibers (C). These fibers have a high strength/stiffness to weight ratio and are easy to apply.

These FRPs can be designed as laminates, sheets or bars mounted on the surface or as near surface mounted bars in the concrete cover [2], [3]. Although strengthening systems using epoxy as the bonding agent have shown good results in the form of bonding and application, there exist some drawbacks.

(a) There are regulations on how to handle the epoxy boding agents, based on the risk for eczema and toxicity of the components. (b) They have low permeability and diffusion of moisture out of concrete can be difficult, which for example can provoke freeze/thaw problems. (c) Poor thermal compatibility to the base concrete, which may cause unfavourable constraints. (d) The surface of the base concrete has to be free from water (dry) and the recommended temperature at the time of application and hardening should not be below 10 °C. (e) Depending on the amount of FRP coverage, it may also be difficult to assess the structure after strengthening.

Upgrading civil structures with mineral based composites gives a highly compatible repair and strengthening system with the base concrete. Mineral based composites (MBC) are in this paper used synonymously for upgrading with FRP materials together with a polymer modified or polymer reinforced cementitious bonding agent. Consequently, the use of these mortars should prevent some of the disadvantages with the organic resins such as epoxy.

1.3 Mineral Based Composites (MBC)

Fibers utilized in combination with cementitious bonding agents can be designed in different ways. Up-to-date, some of the commonly used designs of fiber are unidirectional dry fibers, [4], textiles in the form of meshes made from woven, knitted or unwoven rovings of fibers in different directions, [5];[6] or FRPs where the fibers are assigned as a grid with two orthogonal directions, [7]. The possibilities with the formability of the dry fibers and the textile meshes are much better than with an FRP grid where the fibers are embedded into a matrix. On the other hand, using dry fibers and non-impregnated textiles has shown poor bond properties to the cementitious bonding agent which leads to inferior strength capacities compared to the impregnation of dry fibers with polymers, e.g. epoxy. Impregnation in this respect will give a much higher bond strength to the cementitious bonding agent compared to the use of non-impregnated fibers. This is due to the low ability of the cementitious bonding agent to penetrate the dry fiber rovings, [8];[9]. Considering the bond, it is therefore advantageous to use impregnated fibers than using dry fibers. It is also shown in [10] that using epoxy impregnated carbon fiber grids outperforms the use of dry textile carbon fiber strengthening systems. In addition, there are also some uncertainties regarding the use of mortars as the bonding agent. These are primarily; (i) the bond in the transition zone between the mortar and the FRP and especially the bond between the base concrete and the mortar which can be influenced by drying shrinkage, (ii) Durability regarding fatigue. (iii) Influence on the structural performance regarding both micro and macro cracking of the structural system.

1.4 Chosen MBC system

Previous studies show that the use of MBC for shear strengthening reaches similar strengthening effects as the use of epoxy bonded carbon fiber sheets, [7]. The MBC system used in this research contains a cementitious binder, a CFRP grid and a concrete surface primer.

Generally, the surface of the base concrete needs to be roughened in order to remove the cement laitance to achieve a good bond between the base concrete and the mortar. Examples of roughening techniques are sandblasting or water jetting. In laboratory environments, or on smaller defined surfaces, a hand lay-up method can be used to apply the MBC. Prior to mounting the MBC system the base concrete surface has to be primed using a primer product to prevent moisture transport from the wet mortar to the base concrete. The hand lay-up technique used in this study basically consists of the following; first a layer of mortar is immediately applied to the primed surface, next, the CFRP grid is placed on the first layer of mortar followed by an additional layer of mortar applied on the grid. A graphical representation of the hand lay-up MBC method, after sandblasting, is shown in Figure 1. For larger in-situ cases then the system can also be applied by spraying. In this respect the application is done in three main steps. First, non-corrosive anchors and studs are mounted to the prepared concrete surface, these studs also acts as thickness gauges to ensure that the sought after thickness is achieved. Secondly, the CFRP grid is a mounted onto the studs and the grid are stretched to be leveled without any unevenness. Thirdly, the mortar is sprayed behind and onto the CFRP grid. The mortar is sprayed in such an amount that the sought after total thickness is achieved. When the outer layer of mortar has been sprayed then, where applicable, the mortar surface might be prepared into a desirable condition. Figure 2 is showing the three main steps for in-situ application of the MBC system together with a finishing surface treatment. The structure in Figure 2 is a silo which needed to be strengthened due to internal pressure from the silo content. In this case the silo was under reinforced and had significant cracking prior to strengthening with the MBC system. No cracks were visible after repeated loading and unloading of the strengthened silo. One advantage with the MBC system is that it is a transparent system when it comes to cracks inspected by eye. This study will also show crack propagation and monitoring tools for cracks and strains not visible to the naked eye.

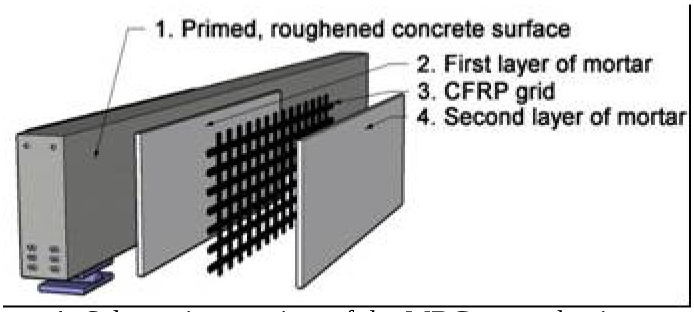

Figure 1: Schematic overview of the MBC strengthening system.

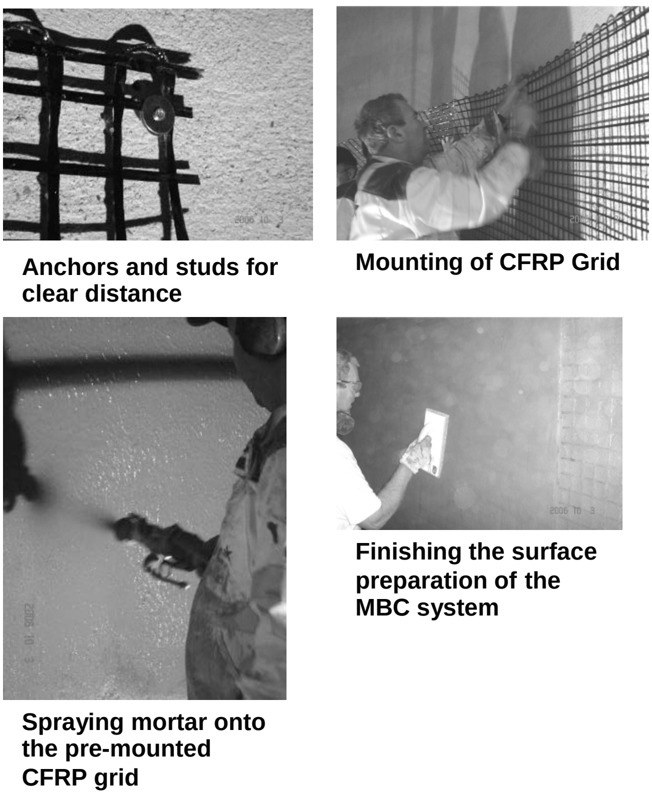

Figure 2: In-situ application of the MBC system.

1.4 Monitoring of cracks

It is off great interest to be able to monitor the composite action between the MBC systems and the concrete structure. One way of evaluating the composite action is to monitor the crack formations that progress in a shear strengthened structure during loading. However, monitoring the formation of cracks in concrete requires special monitoring tools. Firstly, the formation of cracks needs to be established. The formation of cracks does not start immediately but can be considered as an accumulation of micro-cracks while the load is increasing. When these micro cracks have created a certain level of damage, a macro-crack will form.

It is suggested in [11], based on experimental and theoretical investigations, that a non-linear process is preceding the formation of macro-cracks. It follows that the use of laser-interferometry and strain gauges on the stirrups can give an indication of the redistribution of forces before the appearance of macro cracks, by means of monitoring the linearity during the initial loading. Also for the post cracking behavior, it is shown that methods of photometric measurement make it possible to investigate the strain distributions prior to the formation of visible shear cracks [12];[13]. This paper will show the potential of postponing the formations of macro-cracks by the use of mineral based strengthening in shear.

2. EXPERIMENTAL PROGRAMME

2.1 Materials

The materials used in this investigation concern two different concrete qualities corresponding to C35 and C55 in EN 1992-1-1, flexural and shear steel reinforcement, ϕ16 and ϕ12 respectively, an orthogonal CFRP grid and a polymer modified mortar as bonding agent. Table 1 shows the compressive and tensile properties for the different constituents, note that all properties are given as ultimate values accept for the steel reinforcement which is given as yield values. The values of the concrete and mortar are tested according to [14]. Values for the properties of the fibers in the CFRP grid, were as provided by the manufacturer.

Table 1: Mechanical properties of the materials used.

	Tensile		**Compression**
Material	Stress [MPa]	Strain [‰]	Stress [MPa]
Concrete C35	2.8	-	48.9
Concrete C55	3.4	-	73.5
Mortar	3.0	-	65.6
Steel ϕ12	601	2.84	-
Steel ϕ16	555	2.79	-
CFRP grid	3800	15	-

2.2 Test set-up

In this investigation there were 11 reinforced concrete beams tested in total. All of the beams had a rectangular cross section. The chosen loading scheme for all specimens was 4-point loading, thus with two constant shear spans. All loading rates were deformation controlled to 0.01 mm/s. The experimental set-up, geometries and reinforcement scheme are recorded in Figure 3.

For monitoring convenience, the beam specimens were heavily shear reinforced in one span to ensure that the shear failure happened on the shear span with the lower shear capacity. Only one shear span was monitored and also strengthened. Common to all of the concrete beams is that they were heavily reinforced in flexure with 12 Ø16 mm steel bars at the bottom and two Ø16 mm at the top of the beam. The shear reinforcement constituted Ø10 mm stirrups with a distance 50 mm at the supports and Ø12 mm stirrups with the distance 100 mm in the heavily reinforced shear span. The densification of the shear reinforcement over the supports was designed to secure the anchorage of the longitudinal reinforcement. Further, the strengthened shear span of the beam specimens had three different designs of the shear reinforcement, which can be categorized as *no* shear reinforcement, stirrups with a distance *s = 350 mm* and stirrups with a distance *s = 250 mm*. The first category mainly distinguishes the behavior of the beam with no shear reinforcement and without the MBC system (reference beam). The other two mainly assess the influence of the interaction between the steel shear reinforcement and the MBC strengthening system.

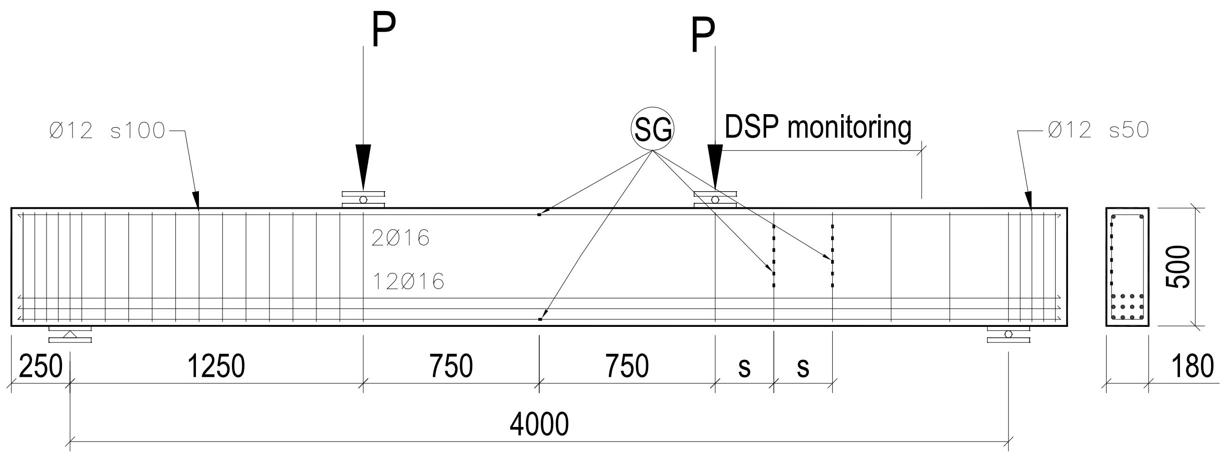

Figure 3: Test set-up including DSP and SG monitoring

2.3 Monitoring

A quite extensive measuring program was used to record the behavior of the tested beams. This includes monitoring the load with a load cell, Linear Variable Differential Transducers (LVDT) for measuring deflections and settlements, electrical foil strain gauges (SG) for local strain measurements and photometric strain measurement for global strain measurements. The loading was deformation controlled and the deformation rate was set to 0.01 mm/s, measured at the midpoint of the beam specimens. For a more detailed description of the experimental program the reader is referred to [7].

Strain gauge set-up

Two different types of SGs were used to measure strains on the CFRP grid and steel reinforcement. A gauge length of 5 mm was used (KFW-5-120-C1-11L3M2R) to measure strains on the steel reinforcement. In the case of measuring the strains on the CFRP grid the tows were quite narrow and a gauge length of 2 mm had to be used (KFWS-2N-120-C1-11L3M3R).

All beam specimens had SGs on the compressed and tensile longitudinal steel reinforcement at half span of the beam, see figure 3. Twelve SGs were applied on the two stirrups closest to the load for beam specimens with shear steel reinforcement in the weakened or strengthened shear span. The set-up for the SG assessment is recorded in figure 3.

To compare the CFRP strain to the strain in the steel stirrups, a similar assessment as for the SGs mounted on the stirrups was affiliated to the CFRP grid. By placing SGs on the steel stirrups, CFRP and using photometric strain measurement (see below) it was possible to compare strains in the steel stirrups (internal concrete) to strains in vertical CFRP tows (internal MBC) as well as strain fields obtained by the photometric strain measurements.

However, due to the design of the CFRP grid it was not possible to mount the SGs at exactly the same position as the steel reinforcement SGs. After casting the concrete beam specimens, the steel stirrups were located using a metal detector and the SGs were mounted onto the nearest vertical CFRP tow corresponding to the stirrup with SGs applied, leading to a maximum horizontal dislocation of 20 mm. The first SG on the stirrup and on the vertical CFRP tow was applied 170 mm from the bottom of the beam, just above the tensile reinforcement. The internal distance between the following SGs was then 50 mm, see also figure 3.

Photometric measurement set-up

Traditional strain measurements using strain gauges only measure local strains, while photometric strain measurements can indicate the global strain behavior of a specific surface. Photometric monitoring is a non-contact measurement by taking photos of the area studied. The photos were taken prior to loading (reference) and at certain load steps using a digital resolution camera (Canon EOS 5D). Photos were taken at load steps every 5 kN.

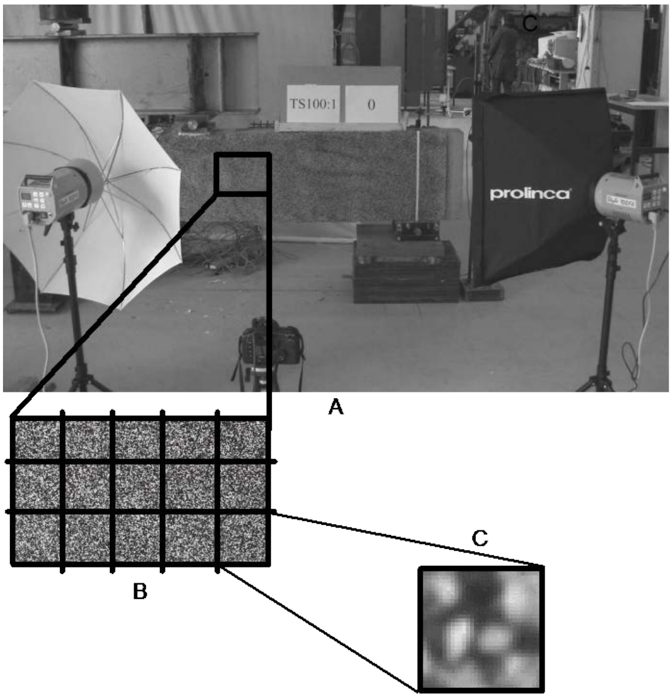

Figure 4: Set-up for the digital speckle pattern monitoring equipment. A) Equipment using camera and flashes, B) Part of the monitored surface, C) Sub-picture

The pictures were processed into a raw format grey scale) and trimmed so that only the investigated area remains. All photos were then analyzed by computer software based on speckle pattern correlation (DSP), developed at Luleå University of Technology [15];[16]. The photos were divided into different sub-pictures and their point of gravity was calculated, see figure 4. The centre of gravity was then calculated for all individual sub-pictures. The accuracy becomes higher if the sub-pictures are chosen to be large. A large number of pixels within the sub-picture will also increase the accuracy of the positioning. Speckle pattern correlation analysis will find the same sub-picture in the second loading condition even if the pattern has deformed or moved. The size and the distance of the sub-pictures can be chosen as desired.

The strains are calculated by correlating the sub-pictures during loading to the unloaded reference. For the software to work properly and give adequate results, the photographed area needs to be given pattern or divergent colors. In this case the strengthened area was given a random pattern by using an epoxy adhesive to adhere a mix of white and black sand.

Results from the speckle pattern correlation analysis can be plotted as shear strains, principal strains or strains in any arbitrary direction. In this study the accuracy of the strain measurements was 300 μstrain. The monitored surface was set to 880 x 500 mm, see figure 3 and figure 7.

3. RESULTS FROM EXPERIMENTS

The pre-cracking behavior of the strengthened and non-strengthened specimens was observed by the monitored strains with a SG in the midpoint of the stirrups. Figure 5 A and B shows the strain development in the stirrup 700 mm from the load for a beam specimen with concrete quality C35, without any strengthening system and having the MBC strengthening system. The first visual shear crack was formed at a shear force of 186 kN (without MBC) and 285 kN (with MBC). Figure 5 B shows the initial part of the strains at lower loads in order to get a more detailed overview of the initial

elastic behavior. Here the strains behave linearly up to a shear force of 57 kN (without MBC) and 79 kN (with MBC). Thereby the formation of macro-cracks initiates long before the appearance of the first visual shear crack. Comparing a beam specimen with the MBC strengthening system and a specimen with no strengthening, it is clear that the strengthening reduces strain levels in the stirrup for low shear forces and continues to do so for higher load levels.
The linearity at low load levels becomes harder to detect when the shear reinforcement is increased due to low strain levels in the stirrups in the initial load levels. This is shown in figure 5 C for a beam specimen with higher concrete quality (C55) and shear reinforcement ratio (s=250 mm). Still, the strain in the stirrup for the MBC strengthened specimen has lower strains for the same shear load level compared to a non-strengthened one. Thus, indicating that utilizing the MBC strengthening system will reduce strains as the loading prevails. This behavior was noticed for all specimens with and without strengthening for different concrete qualities and different steel shear reinforcement ratios.
Shear strengthening of a beam with MBC will reduce the strains in the stirrups compared to a non-strengthened one. Thus, the vertical CFRP tows will attain and redistribute some of the above mentioned strains. Figure 6 shows the shear cracks and strains in the vertical CFRP tow at different shear loads. Here it is possible to see that there are strain concentrations in the vicinity of the formation of shear cracks.
The post cracking behavior and global strain distribution is monitored by the photometric measurement. Figure 7 shows the monitored principal strains at different load steps. The monitored area is shown in figure 7 for beam specimens with a stirrup distance of 350 mm and concrete quality C35 both with and without the MBC strengthening system.

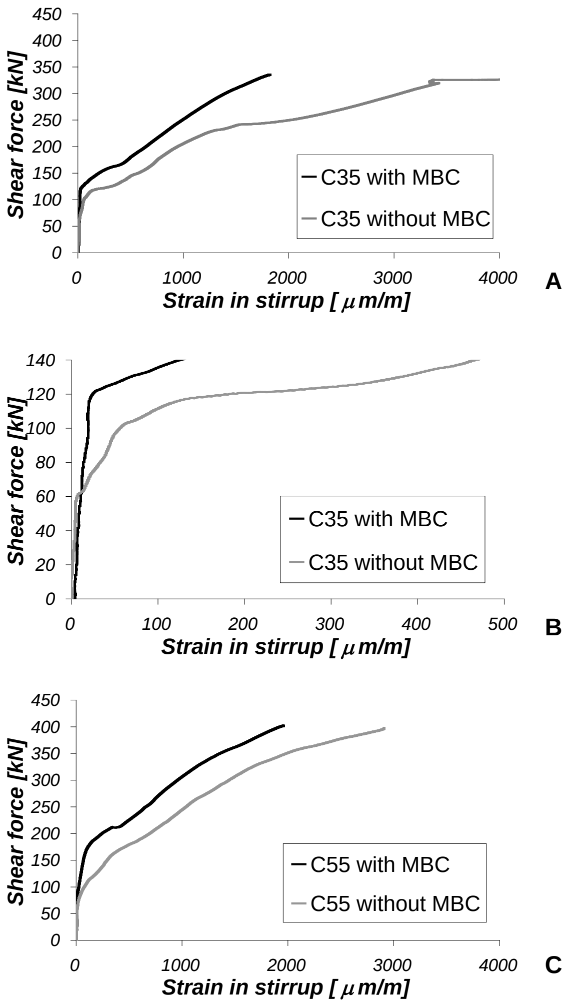

Figure 5: Strains measured in stirrup with and without MBC for specimens with A) Concrete C35 S=350 mm, B) Part of the initial strains in C35 s=350 mm, C) Concrete C55 s=250 mm

The load steps were taken at shear loads of 200 and 260 kN. By comparing the specimens with and without the MBC strengthening system, it is clear that the MBC system reduces the strains even for a load of 200 kN. When the load is increased the MBC system still reduces the principal strains at the load 260 kN compared to a non-strengthened specimen. Further, the photometric strain measurement indicated shear crack formations long before first visual appearance.
All of the recorded principal strains in figure 7 have the same scale. Only the direction and relative size are given, for values on the principal strain the reader is referred to [7].

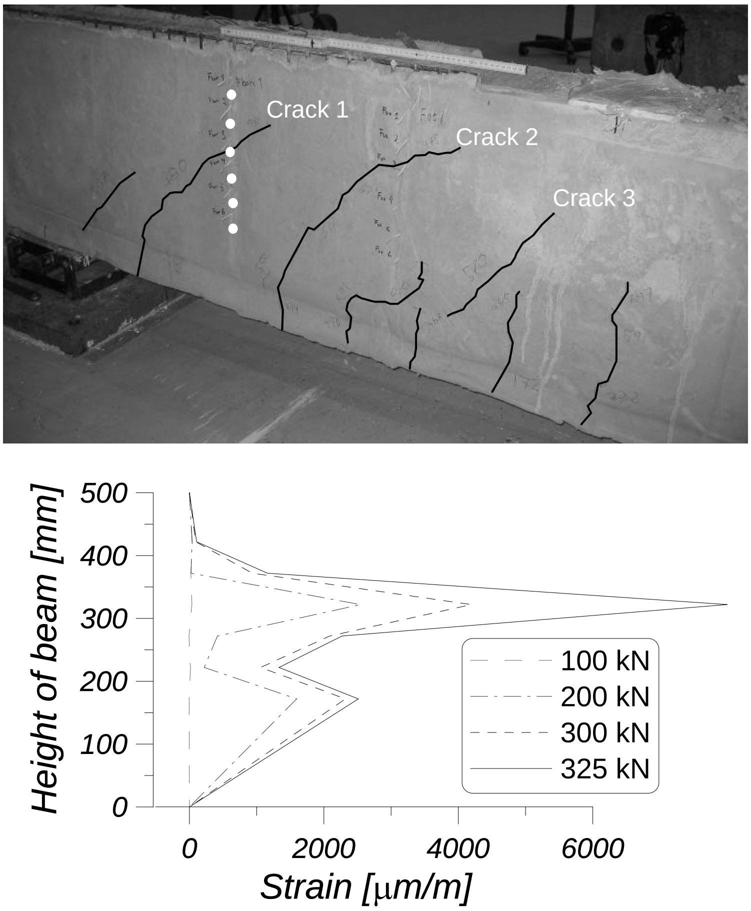

Figure 6: Above, shear crack propagation, white dotes indicates the location of the SGs on the CFRP grid. Under, strains monitored in the vertical CFRP tow located at 680 mm from the load.

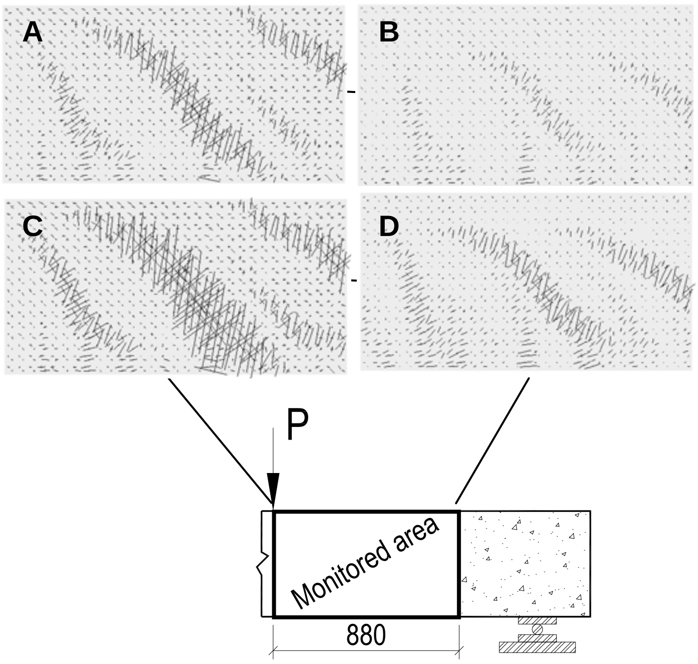

Figure 7: Photometric measurement of the principal strains for concrete quality C35 and s=350 mm. A) Without MBC at 200 kN, B) With MBC at 200kN, C) Without MBC at 260kN, D) With MBC at 260 kN.

4. CONCLUSIONS

In the pre-cracking stage, macro-cracks preceded the formation of visual shear cracks. The formation of macro cracks appear at 31 % of the first visual shear crack load for non-strengthened specimens and 28 % for strengthened specimens, when studying strains in the stirrups. Compared to a non-strengthened specimens, MBC strengthening increased the macro-crack formation by 38 % for specimens with concrete quality C35 and s=350 mm and 35-67 % for all C55 specimens. MBC had a better reduction of macro-cracking for specimens with low shear reinforcement ratios, most likely due to the close spacing of the carbon fibre tows in the CFRP grid. High reinforcement ratios transferred tensile stresses in a more continuous manner during the macro-cracking. This is explained by low strain levels in the stirrups in the initial load levels which made the transition between micro- and macro cracking less distinguished.

It as also noted from the strain gauge monitoring on the CFRP grid that there were high strain concentrations in the vertical tows close to the forming shear cracks. The strain concentrations in vertical CFRP tows in the vicinity of shear cracks indicates a good bond between the CFRP and the mortar. This bond-slip behavior will be the subject of future research.

The post cracking behavior was monitored by using photometric strain measurement. It was noted that strengthening with MBC reduces the principal strains for all load steps in comparison to a non-strengthened specimen. It was also possible to detect shear crack formations before they were visually apparent.

Measurements from both traditional strain gauges together with photometric strain monitoring were in agreement. Using the photometric monitoring tools is an easy way to obtain useful strain fields on the surface not detectable by traditional strain gauges.

ACKNOWLEDGMENTS

The research presented in this paper has been funded by several organizations. The Swedish National Road Administration, The Development Fund of the Swedish Construction Industry, Skanska AB and Sto Scandinavia AB.

REFERENCES

[1] EN 1504-9: 2008. Products and systems for the protection and repair of concrete structures – Definitions, requirements, quality control and evaluation of conformity – Part 9: General principles for the use of products and systems, 2008.
[2] Oehlers, D.J., Rashid, R., and Seracino, R. "IC debonding resistance of groups of FRP NSM strips in reinforced concrete beams". Journal of composites for construction, 11(4), 401-409 (2007).
[3] Nordin, H., and Täljsten, B. "Concrete beams strengthened with prestressed near surface mounted CFRP". Composites for Construction, 10(1), 60-68 (2006).
[4] Wiberg, A. Strengthening of concrete beams using cementitious carbon fibre composites. Doctoral Thesis, Royal Institute of Technology, Structural Engineering, 100 44 Stockholm, Sweden, p 140. ISSN 1103-4270, 2003.
[5] Triantafillou, T.C., and Papanicolaou, C.G. "Shear strengthening of reinforced concrete members with textile reinforced mortar (TRM) jackets". Materials and Structures, 39, 85-93, 2006.
[6] Brückner, A., Ortlepp, R., and Curbach, M. "Textile reinforced concrete for strengthening in bending and shear". Materials and Structures, 39, 741-748, 2006.
[7] Blanksvärd, T. 2007. *Strengthening of concrete structures by the use of mineral based composites*. Licentiate thesis 2007:15, Luleå University of Technology, Division of Structural Engineering.
[8] Raupach, M., Orlowsky, J., Büttner, T., Dilthey, and U., Schleser, M. "Epoxy impregnated textiles in concrete – Load bearing capacity and durability". Proc., the 1st international RILEM symposium: Textile reinforced concrete, RILEM, Aachen, Germany, 55-66, 2006.
[9] Shilang, X.U., and He, L.I. "Bond properties and experimental methods of textile reinforced concrete". Journal of Wuhan University – Materials Science Edition, 22(3). 529-532, 2007.
[10] Blanksvärd, T. Strengthening of concrete structures by the use of mineral-based composites – System and design models for flexure and shear. Doctoral thesis, Luleå University of Technology, Division of Structural Engineering, 2009.
[11] Hegger, J., Sherif, A., and Görtz, S. "Investigation of pre- and postcracking shear behavior of prestressed concrete beams using innovative measuring techniques". ACI Structural Journal, 101(2), 183-192, 2004.
[12] Lee, T.K., and Al-Mahaidi, R. "An Experimental investigation on shear behaviour of RC T-beams strengthened with CFRP using photogrammetry".Composite Structures, 82, 185-193, 2008.
[13] Sonnenberg, A.M.C., and Al-Mahaidi, R. "Investigation of dowel shear in RC beams using photogrammetry". Magazine of Concrete Research, 59(9), 621-626, 2007.
[14] DIN EN 196-1. Methods of testing cement - Part 1: Determination of strength, 2005.
[15] Carolin, A., Olofsson, T. Täljsten, B. "Photographic Strain Monitoring for Civil Engineering". Proc. in, FRP Composites in Civil Engineering, CICE 2004, Adelaide, Australia, 593-600, 2004.
[16] Svanbro, A. Speckle interferometry and correlation applied to large-displacement fields. Doctoral thesis 2004:05, Luleå University of Technology, Division of Experimental Mechanics, 2004.