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Strengthening of Concrete Beams in Shear with Mineral Based Composites Laboratory Tests and Theory

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ABSTRACT

Today, there are many different repair and strengthening methods that might be used to upgrade a concrete structure. One such method involves CFRP (Carbon Fibre Reinforced Polymer) bonding. This method has proven to be usable for many different types of retrofitting applications. Even so, there are some disadvantages while using epoxy resins as a bonding agent, i.e. diffusion closeness, thermal compatibility, working environment and the minimum temperature of assemble. It is therefore of interest to replace the epoxy adhesive with a mineral based bonding agent, e.g. polymer modified mortars with similar properties as the base concrete that also is more working environmental friendly. A combination between the polymer modified mortar and fibre reinforced polymers (FRP) can be used for repair and strengthening of civil structures. This paper presents a pilot study of RC beams strengthened in shear with mineral based bonding agents and CFRP grids. The project is a collaboration project among Luleå University of Technology, Norut Teknologi AS and Denmark Technical University and is also a part of the European funded project "Sustainable Bridges". The results so far show that comparable strengthening results as for epoxy bonded systems can be achieved with MBC strengthening systems. The strengthening effect of the beams was 40 – 100 % compared to the unstrengthened reference beam. The theoretical model describes the load carrying capacity fairly well.

KEYWORDS

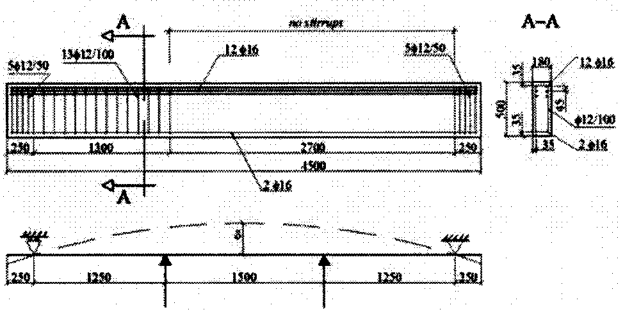
CFRP grids, Strengthening, Shear, Laboratory tests, MBC, Mineral Based Strengthening, Carbon Fibre

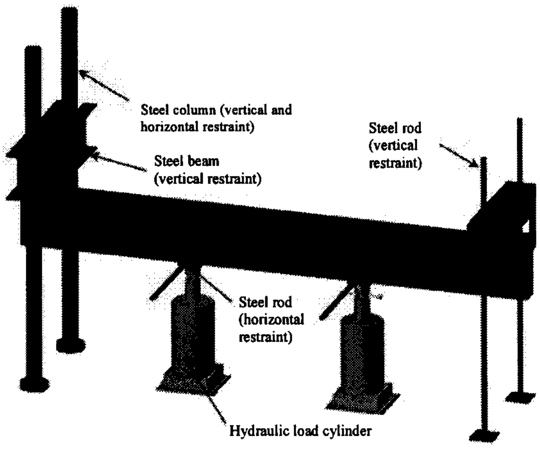
1. INTRODUCTION

Research with the use of short FRP fibres and cement based materials has been going on for some time now, see for example (Kesner et. al., 2003). However, experience with the use of long FRP fibres is limited. Research studying cement overlays with textiles of carbon fabrics embedded in cement based matrix to strengthen masonry walls has been carried out by (Kolsch, 1998). The strengthening system prevents partial or complete collapse of masonry walls in the critical out-of-plane direction during a seismic event. A study to improve the bond between carbon fibres and cementitious matrices has been done by (Badanoiu, 2001), where dry fibre fabrics were used. It was found that a pre-treatment with silica fume and high amounts of polymers improved the bond behaviour of carbon fibre to the cement. However, it was also stressed that more research is needed in this field. A very interesting pioneering work has been presented by (Wiberg, 2003). Large-scale tests of ordinary concrete beams strengthened with a cementitious fibre composite were reported. The composite used was made of polymer-modified mortar and a unidirectional sheet of continuous dry carbon fibres applied by hand. Both flexural and shear strengthening were tested. From the tests it was concluded that the method works, and that considerable strengthening effects can be achieved. In comparison with epoxy bonded carbon fibre sheets, the amount of carbon fibre needed to reach the same strengthening effect for the cementitious strengthening system was more than double. The reason for this is mainly due to problems with wetting the carbon fibre. This is also emphasised by (Badanoiu & Holmgren, 2003), where it was found that the load capacity of the cementitious carbon fibre composite is influenced by the amount of fibres in the tow. If the cementitious matrix can penetrate into the interior of the carbon fibre tow, a higher number of filaments will be active during loading, and this will lead to an increase in load carrying capacity. To overcome this problem use of CFRP grids and a cementitious matrix might be used. In this paper a brief presentation of the tests carried out at Technical University of Denmark is presented.

2. TEST SET-UP

The test set up for the beam test is shown in Fig. 1. Five beams with the same geometry, concrete quality (average compressive strength 38 MPa), and steel reinforcement (average tensile strength 517 MPa for the rebars and 530 MPa for the stirrups) were tested, four of them strengthened with CFRP grids, while the first beam served as reference beam without CFRP strengthening. The properties of the grids are given in Fig. 1. The load was applied by two cylinders standing on the floor therefore the beams were turned upside down. Each of the cylinders provided a load of maximum 500 kN. The load was increased by approximately 10 kN/min/cylinder and the tests were load controlled. The pressure was translated into voltage by the data-logger and the optical measuring equipment. The measuring equipment comprised of transducers, strain gauges (on DTU2 and DTU5) and photogrammetric strain measuring equipment to measure the strains and crack propagation on the strengthened surfaces of each test beam. At failure, both data-logger and photo equipment were stopped, and the failure load was recorded. Numerous pictures were taken with a digital camera to keep track on the crack development during loading. However, due to limited space this is not presented in this paper. A great amount of longitudinal steel reinforcement ensured that the beams would not fail in bending. All the beams had a steel reinforcement for shear only in one side. The CFRP grids were applied using two types of mortars in two layers with a thickness of 10 mm on both sides of the beams. The CFRP grid was placed between the two layers of the mortar. Before applying the first layer of mortar a primer was applied to the sandblasted concrete surface to optimize the bond between concrete and mortar. In Fig. 1 the material properties for the mortar and CFRP grid used are presented.





MBC strengthening materials:
Mortar modulus of elasticity:

Cement I. E_1=26.5 GPa, with short glass fibres
Cement II. E_2=18.0 GPa

CFRP Grid properties (x: horisontal, y: vertical):

Grid I. 70x72 mm; 230 g/m^2,
E_x = 341 GPa, ε_{ux} = 1.3%, E_y = 390 GPa, ε_{uy} = 0.8 %
Grid 2. 24x25 mm; 150 g/m^2,
E_x = 281 GPa, ε_{ux} = 1.3%, E_y = 380 GPa, ε_{uy} = 1.4 %
Grid 3. 42x43 mm; 390 g/m^2,
E_x = 407 GPa, ε_{ux} = 1.1%, E_y = 417 GPa, ε_{uy} = 1.1 %

Beam	CFRP	Mortar
DTU1 Ref.	-	-
DTU2	Grid 3	Cement I
DTU3	Grid 2	Cement I
DTU4	Grid 1	Cement II
DTU5	Grid 1	Cement I

Figure 1. Test set-up

3. EVALUATION

3.1. Theory

Studies on the shear strengthening of a RC beam by bonding FRP composites have been carried out since the early 1990's (Chen & Teng, 2003). In the early studies the shear capacity of the FRP strengthening was based on a very simplified stress distribution. In recent years a more advanced theory has been developed (Carolin & Täljsten, 2005). The theory provides a more detailed specification of the strain distribution in the bonded FRP. This is, of course, a decisive factor in the study since the strains in the CFRP material are proportional to the stresses. A well adopted approach for shear design is to use the truss or strut and tie model:

$$V_n = \underbrace{V_c}_{Concrete} + \underbrace{V_s}_{Steel} + \underbrace{V_f}_{FRP} \tag{1}$$

The derivation of V_c and V_c refers often on national codes or standards. For the term V_f the same approach as for the truss analogy may be used, with special consideration to the compatibility relationships for the studied FRP system. In this paper a simplified theory is presented for the contribution of the CFRP grid. A CFRP grid usually consists of a vertical and a horizontal tow. Both these tows contribute to the load carrying capacity, which in this paper is presented as a result vector, see Fig. 2.

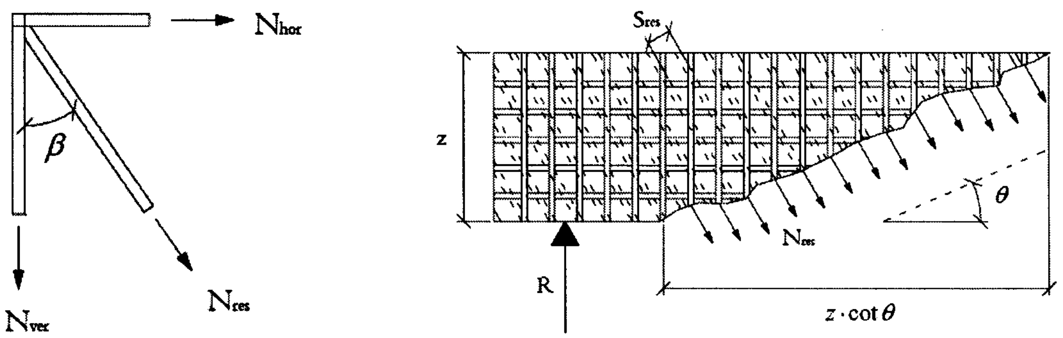


Figure 2. Relation between vertical and horizontal tow - left. The truss model - right

The direction and strength properties of the grid resultant are depending on the properties of each tow direction. This is expressed in equation (2)-(5).

$$N_{hor} = \frac{\varepsilon_{hor} \cdot E_{hor} \cdot A_{hor}}{s_{hor}} \tag{2}$$

$$N_{ver} = \frac{\varepsilon_{ver} \cdot E_{ver} \cdot A_{ver}}{s_{ver}} \tag{3}$$

$$N_{res} = \sqrt{N_{hor}^{\ 2} + N_{ver}^{\ 2}} \tag{4}$$

$$\beta = arc\tan\left(\frac{N_{hor}}{N_{ver}}\right) \tag{5}$$

Based on these considerations some of the existing design models can be used to determine the contribution from the CFRP grid, (Täljsten & Carolin, 2005). This equation is rewritten with the properties of the resulting tow, using $\eta = 0.4$ as the modification factor due to the parabolic for of the strain contribution over the section:

$$V_{FRP} = \frac{2 \cdot \eta \cdot N_{res} \cdot z}{s_{res}} \cdot \frac{\cos(\theta - \beta)}{\sin\theta} \tag{6}$$

$$s_{res} = s_{ver} \cdot \cos\beta = s_{hor} \cdot \sin\beta \tag{7}$$

3.2. Results from tests

The load deflection curves from the tests are shown in figure 3 together with the calculated and experimental values, the calculation is carried out at a strain level of 10 ‰.

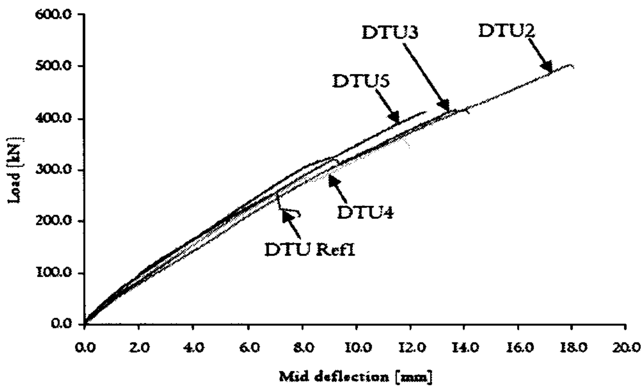


Figure 3a. Load-Deflection curves

Beam	Exp. [kN]	Calc. [kN]	V_{exp}/V_{cal}
DTU2	54	58	0.93
DTU3	54	42	1.29
DTU4	58	67	0.87
DTU5	54	45	1.20

Figure 3b. Experimental and calculated values

4. SUMMARY AND CONCLUSIONS

All five beams failed in shear. The strengthening effect was significant, the increase in load carrying capacity for the strengthened beams was approximately 40-100 % compared to the reference beam. The largest increase was achieved using the grid with the densest fibre area per cross-section and the mortar with short glass fibres. The theoretical approach gave a reasonable estimation of the shear strengthening effect, however it was difficult to exactly measure the strain in the tows and the scattering was large, therefore the theoretical evaluation is imperfect and further laboratory research together with more detailed analytical and numerical analysis is needed to improve the design model. Furthermore, a large test series is now ongoing at Luleå University of Technology in collaboration with Technical University of Denmark and Norut Teknologi A/S in Norway. Here we are not only investigating the structural behaviour of the strengthening system but also the effect of shrinkage and temperature.

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REFERENCES

Badanoiu A., 2001, Improvement of the bond between carbon fibres and cementitious matrices, Technical report 2001:1, Concrete Structures, ISSN 1404-8450, Royal Institute of Technology, Department of Structural Engineering, 100 44 Stockholm, Sweden, p 44.

Badanoiu A. and Holmgren J., Cementitious composites reinforced with continuous carbon fibres for strengthening of concrete structures, Journal of Cement & Concrete Composites, vol. 25, 2003, pp 387-394.

Carolin A. and Täljsten B., Theoretical Study of Strengthening for Increase Shear Capacity, Journal of Composites for Construction, November/December 2005, pp 497-506.

Chen, J. F. and Teng, J. G. (2003) Shear Capacity of Fiber-Reinforced Polymer-Strengthened Reinforced Concrete Beams: Fiber Reinforced Polymer Rupture, Journal of Composites for Construction, ASCE / May 2003, pp 615-625.

Kolsch H., 1998, Carbon fibre cement matrix (CFCM) overlay system for masonry strengthening, Journal for composites for construction, Vol. 2, No. 2, May 1998, pp105-109.

Kesner K.E., Billington S.L and Douglas K.S., 2003, Cyclic Response of Highly Ductile Fibre-reinforced Cement-Based Composites, ACI Materials and Journals - Technical Paper, September -October 2003, pp 381-390.

Wiberg A., 2003, Strengthening of concrete beams using cementitious carbon fibre composites, Doctoral Thesis, ISSN 1103-4270, Royal Institute of Technology, Structural Engineering, 100 44 Stockholm, Sweden, p 140.