FAILURE DUE TO DELAMINATION IN CONCRETE ELEMENTS STRENGTHENED WITH CEMENTITIOUS COMPOSITES

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Key words: FRCM, Fiber Reinforced Cementitious Matrix, Delamination, Characterization

Abstract: Failure due to delamination of fibre reinforced polymer (FRP) composites has been studied in a number of experimental investigations (see for e.g. [1]), with the aim of understanding its influence on structural behaviour at the ultimate limit state when applied as strengthening of reinforced concrete elements. Some studies have resulted in the first design guidelines for reinforced concrete structures strengthened with externally bonded FRP. American ACI 440-08 [2], European *fib*-T.G. 9.3 [3] and Italian Recommendations CNR DT-200/04 [4] are examples of such guidelines.
On the other hand very few information is available on bond behaviour between concrete and cementitious composite reinforcement particularly in relation to specific design code formulations. In this work an experimental study aimed at giving some insights on failure modes due to delamination in concrete elements strengthened with cementitious composites is presented. According to the results of this study, some elements about the estimation of the maximum bearing capacity of structural elements strengthened by means of composites with cementitious matrix can be obtained.

1 INTRODUCTION

In the last few decades the growing need of strengthening of existing reinforced concrete (RC) structures due to improper design or construction, change of the design loads, damage caused by environmental factors or seismic events, has resulted in the extensive research of new materials and techniques. The use of fibre reinforced polymers (FRP) externally bonded to the existing concrete structure by means of epoxy resin has gained an increasing diffusion due to its good behaviour against corrosion, flexibility and rapidity of application.

Strengthening of RC structures by means of high performance fibres bonded in a cementitious matrix (FRCM) is a recent and promising technique in the field of fibre composites [5-8]. High performance fibres are meant to transfer tensile forces whereas the cementitious matrix transfers compressive forces and realize the bond between the strengthening and the support. Compared with the FRP, FRCM (sometimes called TRC – Textile Reinforced Concrete – or TRM – Textile Reinforced Mortar) is a cost-effective technique since it is very easy to perform and do not demand skilled labour, has a good strength to fire and high temperature and it is not suitable to UV degradation.

A great number of experimental investigations on FRP strengthening applications are available in literature and some of them have resulted in the first design guidelines for concrete structures strengthened with externally applied FRP. American ACI 440-08 [2], European *fib*-T.G. 9.3 [3] and Italian Recommendations CNR DT-200/04 [4] are examples of such guidelines.

On the other hand, very few information are available about cementitious composite reinforcement and there are not guidelines or recommendations concerning its design and application.

This study aims to a better understanding of the behaviour of FRCM strengthened RC elements providing some experimental results on real scale beams and small specimens. Starting from the tests on four precast prestressed TT beam [9], some uniaxial tensile tests on FRCM specimens were performed to study the mechanical properties of such strengthening material. The indications of Jesse et al. 2009 [10] and Hartig et al. 2011 [11], were taken as basis for the setup adopted to carry out the tests.

According to the results of this study, some elements about the estimation of the maximum tensile strength of FRCM specimens and the bearing capacity of real scale structural elements strengthened by means of composites with cementitious matrix can be obtained.

2 EXPERIMENTAL RESULTS

2.1 Real scale precast prestressed TT beams

The experimental tests on real scale beams strengthened with FRCM composites have been partially described in [5] and they are here briefly recalled for the sake of clarity. Four precast prestressed TT beams belonging to an existing industrial building were reinforced with FRP and FRCM. One of them was taken as control unstrengthened beam (TT00) while the others were strengthened by means of various techniques, namely with a ply of carbon laminate bonded with epoxy resin (TTcl), a ply of steel fibres in a cementitious matrix (TTsf), and two layers of carbon fibres in a cementitious matrix (TTcf). The beams have a length of 1167cm and are 128.5cm wide. After a proper characterization of the basic materials, concrete was found to have a compressive average stress of 59.9 MPa and an elastic modulus of 41809 MPa. The reinforcing steel rebars have a value of the yield stress of 612 MPa and ultimate tensile stress of 647 MPa. The carbon laminate was found to have an elastic modulus, ultimate strength and ultimate strain of 168 GPa, 2539 MPa and 1.65%, respectively. The values provided by the manufacturer were used to characterize the carbon fibres for FRCM application which has a value of the elastic modulus, ultimate strength and ultimate strain of 240 GPa, 4300 MPa and 1.75%, respectively. The cementitious matrix was characterized by means of specimens with a cross section of 40x40mm and 160mm long. The average compressive strength was found to be 39.3 MPa. The steel fibres have an average ultimate strength value of 3322 MPa and an average ultimate strain of 2.25%.

Each beam was tested with a four point bending configuration. The ultimate load values reached by the FRCM strengthened beams were very closed to that obtained by the FRP strengthened beam (Figure 1).

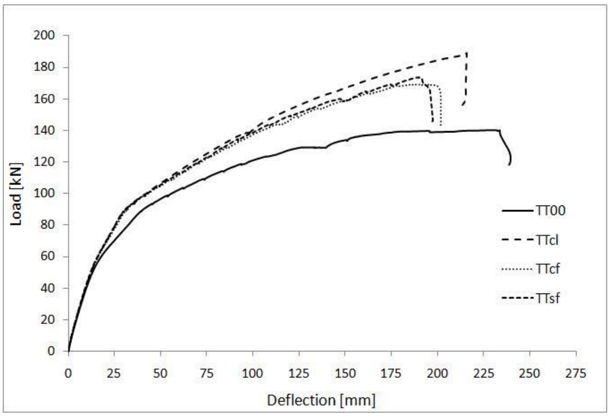

Figure 1: Load vs. deflection curve.

The observed failure modes were completely different (Figure 2): the FRP strengthened beam (TTcl) failed due to the delamination of the composite within the

Figure 2: Failure of the beam TT00 (a), TTcl (b), TTsf (c), and TTcf (d).

concrete substrate.

The beam strengthened with the steel fibre in the cementitious matrix (TTsf) failed due to delamination as well but in this case the delamination occurred between the fibre and the concrete matrix. In the case of carbon fibre in the cementitious matrix (TTcf) the failure occurred due to the rupture of the fibre at the midspan of the beam.

2.2 FRCM specimens

Once observed the behaviour of the real-scale beams a reliable procedure for characterizing FRCM composites was investigated. The FRCM composites, both with carbon and steel fibres, were tested by means of 20 uniaxial tensile tests, 10 made by concrete with carbon fibres and 10 made by concrete with steel fibres. The specimens were 500mm long, 60mm wide and 10mm thick (Figure 3).

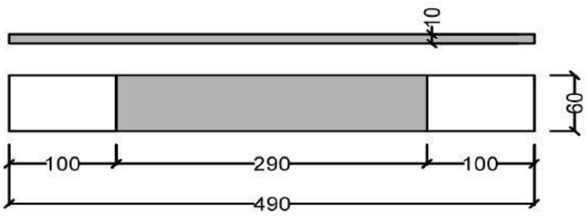

Figure 3: Geometry of the FRCM specimens (dimension in mm).

Based on the work of Jesse et al. 2009 [10] and Hartig et al. 2011 [11], the end of each specimens were smoothed by means of a thin layer of gypsum to avoid stress concentration due to the roughness of the concrete. Two steel plates were then applied to both ends and bolted with 6 bolts per end. A rubber layer was applied between the concrete and the steel plates with the aim of avoiding local failures (Figure 4). A strain transducer was applied at the middle of the specimen and a load cell registered the load evolution.

Figure 4: Setup of an FRCM carbon fibre specimen.

Some difficulties in obtaining significant results were found for the tests performed with FRCM carbon fibres because, once the cracks began to occur, the fibre began to slip inside the concrete matrix without any increase of the tensile force (Figure 5). On the contrary, the steel fibres have shown a better adhesion with the concrete matrix allowing more significant results (Figure 6).

Figure 5: Extraction of the carbon fibre from the cementitious matrix.

Figure 6: Cracking of the FRCM specimen with steel fibres.

In order to perform a better clamping of the specimens without inducing premature cracking, the concrete at both ends of the specimens was removed for about 40mm and the external fibres were bonded to two aluminium plates using epoxy resin. The final bonded length was of 80mm meanwhile the FRCM portion became 420mm long.

The tests on the FRCM composite with carbon fibres did not give reliable results also with this setup probably due to the effect of the external coating of the fibres that allowed fibre’s sliding into the concrete.

Instead the test of the FRCM composite with steel fibres provided good results. It has been observed the opening of several transversal cracks in the cementitious matrix (Figure 6), followed by the sudden failure of the steel strands (Figure 7). Although the cementitious matrix has been properly designed for FRCM applications, steel strands were very close one to each other and probably the penetration of the matrix into the fibres was poor. As a matter of fact some longitudinal splitting phenomena have been observed (Figure 7). The average ultimate load value was of 45945 N, whereas the maximum stress was of 3293 MPa.

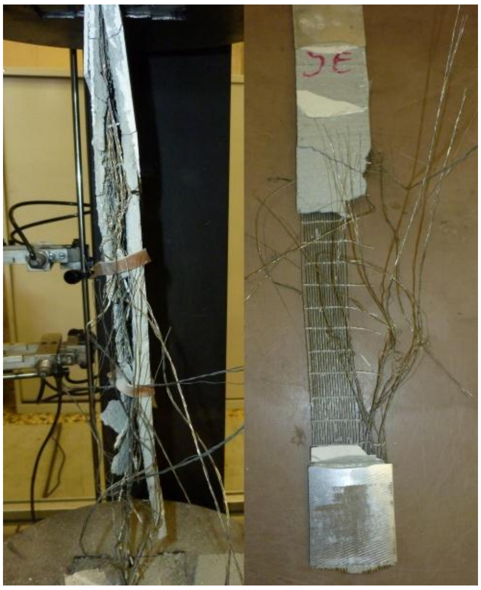

Figure 7: Splitting of the FRCM steel fibre net specimen

Furthermore, the steel fibres have been tested in tension to compare their ultimate stress with that obtained from FRCM specimens. The average ultimate tensile stress value was of 3346 MPa with a corresponding ultimate strain of 2.25%.

3 DISCUSSION

The experimental tests of the precast prestressed TT beam strengthened with both FRCM and FRP composites can be coupled with the experimental tests on FRCM specimens and those deriving from tensile tests on the fibres alone to draw some preliminary observations.

The ultimate tensile strain for the steel fibres was 2.25% whereas for the carbon fibres the value provided by the manufacturer was 1.75%. Using simple equilibrium equations and assuming perfect bonding between the fibres and the cementitious matrix, the ultimate load for the PRC TT beams has been obtained and listed in Table 1 (the theoretical value of the beam TTcl, strengthened with FRP, was obtained following the indications of CNR DT-200/04 [4]).

Table 1: Experimental and theoretical values of the ultimate load for the PRC TT beams.

	TT00	TTcl	TTcf	TTsf
$P_{max,exp}$ [kN]	140.0	189.1	169.2	173.6
$P_{max,theor}$ [kN]	137.2	155.9	159.6	175.9

Theoretical predictions obtained using equilibrium equation for beams strengthened with FRCM composites and assuming the failure of the beams due to the rupture of the fibres, are rather good. The difference between the experimental and theoretical value for the case with FRCM and carbon fibres (TTcf) and steel fibres (TTsf) are 5.6% and 1.3%, respectively. Despite the experimental test on the beam TTsf showed a failure mode with delamination, it has been chosen to preliminarily assume the perfect bond between the fibre and the cementitious matrix due to the complete absence of analytical indications on how to take into account the possibility of a delamination failure. Nevertheless the theoretical value is close to the experimental one.

Instead, the predictions of the CNR DT-200/04 [4] seems to be too conservative [12] leading to a difference between experimental and analytical ultimate load of 17.5%.

4 CONCLUSIONS

The use of composites for strengthening of existing RC structure has gained a growing importance in the last few decades but, despite a large number of experimental and analytical studies on FRP strengthening are available in literature, very few works have been carried out on the use of FRCM composites. This paper aims at increasing knowledge about that technique through the experimental investigations on 4 precast prestressed TT beams coupled with 20 FRCM small specimens.

The results showed that the use of FRCM composite as strengthening of RC structures is able to significantly increase the ultimate load capacity (Figure 1).

The FRCM specimens used for the characterization of the composite were made following the indication of Jesse et al. 2009 [10] and Hartig et al 2011 [11] obtaining quite good results only for steel fibres whereas the specimens with carbon fibres showed the sliding of the fibres into the cementicious matrix.

Theoretical predictions, obtained using equilibrium equation for beams strengthened with FRCM composites and assuming the failure of the beams due to the rupture of the fibres, are fit experimental results quite well despite the observed failure of the beam strengthened with FRCM composites with steel fibres was due to delamination of the composite. Instead, the predictions of the CNR DT-200/04 [4] for FRP strengthening seem to be too conservative.

These conclusions are valid only for this experimental campaign, since the works available in literature are too few to allow a generalization of the results. Furthermore, being these PRC TT beams quite long, the hypothesis of reaching the ultimate tensile strength of the fibres seems to be reasonable since there is a long bonding surface. The same hypothesis could be not valid for shorter beams, suggesting further studies on the effective bond length for structural elements strengthened with FRCM composites.

FRCM composites seem to be a promising

technique for strengthening of existing RC structures but further studies are needed to reach a deep knowledge of the behaviour of this kind of composites, particularly aimed to a better understanding of the delamination process and to define a shared test setup for their characterization which allows a reliable repeatability (a shared test setup is also needed for bond behaviour of FRP composites).

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