This is the peer reviewd version of the followng article:

Impregnated Carbon Fabric-Reinforced Cementitious Matrix Composite for Rehabilitation of the Finale Emilia Hospital Roofs: Case Study / Nobili, Andrea; Falope, FEDERICO OYEDEJI. - In: JOURNAL OF COMPOSITES FOR CONSTRUCTION. - ISSN 1090-0268. - STAMPA. - 21:4(2017), pp. 05017001-05017022. [10.1061/(ASCE)CC.1943-5614.0000780]

Terms of use:

The terms and conditions for the reuse of this version of the manuscript are specified in the publishing policy. For all terms of use and more information see the publisher's website.

06/05/2024 10:38

IMPREGNATED CARBON FABRIC REINFORCED CEMENTITIOUS MATRIX COMPOSITE FOR REHABILITATION OF THE FINALE EMILIA HOSPITAL ROOFS: A CASE STUDY

Andrea Nobili, Ph.D., P.E.¹ and Federico O. Falope, P.E.²

6 ABSTRACT

1

2

3

4

5

In this paper, the mechanical performance of concrete beams strengthened by an impreg-7 nated Carbon Fabric Reinforced Cementitious Matrix (CFRCM) composite is investigated. 8 The study is aimed at the rehabilitation of the Finale Emilia hospital roofs, severely damaged 9 by the 2012 Northern Italy earthquake. A 8-m-long concrete beam could be taken from the 10 building for reinforcement and testing in a beam test setup. The composite is designed to be 11 externally applied to the existing thin clay tile layer bonded to the concrete beam intrados. 12 Two lamination cycles are considered, which differ in the way the partially-organic adhesion 13 promoter is applied to the fabric. It is found that impregnation thorough fabric immersion 14 provides a 1.5-fold increase in the ultimate strength of the strengthened beam compared 15 to expedited impregnation with a brush. Besides, clay tiles make a very good supporting 16 substrate, to the extent that cohesive fracture at the tile/concrete interface takes place on 17 the verge of concrete failure near the hinge zone. Conversely, expedited impregnation of 18 the carbon fabric with the adhesion promoter is unable to provide adequate fabric/matrix 19 adhesion and leads to delamination failure. Estimates of the adhesion strength, of the opti-20 mal bonded length and of the composite as well as of the concrete strain at failure are also 21 provided. 22

¹Dipartimento di Ingegneria Enzo Ferrari, Università degli Studi di Modena e Reggio Emilia, via Vignolese 905, 41125 Modena, Italy. (Corresponding author) E-mail:andrea.nobili@unimore.it

²Dipartimento di Ingegneria Enzo Ferrari, Università degli Studi di Modena e Reggio Emilia, via Vignolese 905, 41125 Modena, Italy. E-mail:federicooyedeji.falope@unimore.it

Keywords: Fabric reinforced Cementitious Material, Structural Rehabilitation, Clay tile,
 Roof beam strengthening

25 INTRODUCTION

Reinforcement and rehabilitation of structurally deficient structures sets a difficult engi-26 neering challenge. Historically, jacketing with new concrete bond with surface adhesive or 27 epoxy bonded steel plates have long been the preferred options to retrofit flexural members 28 (Blanksvärd and Täljsten 2008). In more recent times, a number of different technologies 29 have been made available, ranging from glass fiber reinforced polymer (GFRP) composite 30 plates (Saadatmanesh and Ehsani 1991; Rahimi and Hutchinson 2001), carbon fiber rein-31 forced polymer (CFRP) composites (Norris et al. 1997; Mouring et al. 2001), high strength 32 composites (Ombres 2011a; Arboleda 2014). In particular, great attention has been re-33 cently drawn towards brittle inorganic cement-based matrix composites, as opposed to duc-34 tile polymeric-based ones, in light of some limitations of the organic binder (Bentur and 35 Mindess 2006; Toutanji and Deng 2007). The inorganic matrix may accommodate different 36 kinds of reinforcement, either in the shape of long fibers arranged in sheets or nets (fabric re-37 inforced cementitious matrix, FRCM, or textile reinforced concrete, TRC), such as polypara-38 phenylene benzobi-soxazole (PBO) (Ombres 2011b), glass or carbon fabric (Babaeidarabad 39 et al. 2014) or randomly dispersed short fibers, such as polypropylene (Lanzoni et al. 2012; 40 Nobili et al. 2013). Besides, reinforcement may be dry, in direct contact with the matrix, 41 or impregnated through some adhesion promoter, which enhances the bond with the binder 42 and hinders slippage. 43

In this paper, a Carbon Fabric Reinforced Cementitious Matrix (CFRCM) composite is designed and tested for the rehabilitation of the concrete-joist-and-hollow-block roofs of the "Ospedale Civile degli Infermi" (ICC-Evaluation Service 2013). This is a four-building hospital facility located in Finale Emilia, which had been severely damaged by the 2012 Northern Italy earthquake (Tertulliani et al. 2012). The main hospital building (coded H1) is a masonry unit which grew out of the former Santo Spirito church, whose conception dates

back to 1668. Although several literature contributions exist dealing with strengthening of 50 reinforced concrete (RC) beams by an externally applied FRCM composite (Triantafillou 51 and Papanicolaou 2005; Brückner et al. 2006; Al-Salloum et al. 2012; Loreto et al. 2013), 52 this paper investigates some novel and distinctive features. First, performance is assessed 53 in a beam test on roof beams taken from a case study application. Second, roof beams had 54 been cast onto a thin layer of clay tiles to provide material continuity with the hollow blocks 55 and an uniform substrate for plaster adhesion. Assessing the composite/tile/concrete bond 56 strength is crucial to developing a reliable reinforcement system directly applied onto the tile 57 surface. Indeed, mechanical removal of the tile layer prior strengthening is extremely costly 58 and time consuming, in light of the large area to be treated and of the extensive damage 59 this would cause to the underlying concrete. Besides, the clay tile provides a rough surface 60 suitable for direct lamination. Third, fabric is impregnated by a partially-organic adhesion 61 promoter and the extent of this impregnation deeply affects performance. 62

63

EXPERIMENTAL PROGRAM

⁶⁴ Application of the CFRCM composite

⁶⁵ A preliminary analysis of the main building found more than ten different types of roofs, ⁶⁶ for the largest part constituted by concrete beams with hollow blocks in between, with ⁶⁷ different slab thickness and orientation (Fig.1). A roof typical cross-section is shown in ⁶⁸ Fig.2. An impregnated CFRCM composite is considered to be bonded at the intrados of ⁶⁹ the concrete beams taken from the Finale Emilia hospital roof. The composite material is ⁷⁰ applied according to the following steps:

- 1. the substrate (i.e. the clay tile) is wetted and then a water-based liquid inorganic
 adhesion promoter is applied with a brush;
- ⁷³ 2. a first mortar bed, roughly 5 mm thick, is laid;
- cut-to-size pairs of uni-directional carbon fabric reinforcement sheets are impregnated
 by the adhesion promoter through immersion and then squeezed out to eliminate the

 $\mathbf{3}$

76

77

78

excess of impregnating agent (only for Cycle A, see Fig.3);

- 4. a first sheet of uni-directional carbon fabric reinforcement is placed onto the mortar bed and then rolled to dispense with trapped air bubbles (Fig.4);
- 79

5. a second sheet of the same uni-directional carbon fabric reinforcement is placed and then rolled;

81

80

6. a second and final mortar bed, roughly 5 mm thick, is laid on top.

Alongside this treatment, which is termed Cycle A, a simpler process is considered, named 82 Cycle B, which dispenses with step 3. According to this simpler application cycle, the liquid 83 impregnation agent is applied with a brush directly to the carbon fabric already placed on 84 the mortar bed, both after steps 4 and 5 (Fig.3). The reason for this second option is that the 85 expected performance decay could be weighted against the advantage of a more expedited 86 process and the lower cost it conveys. All materials adopted in the analysis are commercially 87 available and their main properties are gathered in Table 1 for the mortar and in Table 2 88 for the fabric. The mortar (coded B) and the impregnation agent are characterized as single 89 components in Nobili (2016). The main reason for adopting this fairly low-strength mortar is 90 compatibility with the clay tile mechanical properties. Besides, this mortar, in conjunction 91 with the adopted adhesion promoter, has proved very effective in developing a strong bond 92 with the carbon fabric. 93

94 Experimental setup

In order to avoid weakening an already poorly performing structure, only a single 8-mlong beam could be taken from the hospital roof (the original location of this beam is shown in Fig.1). For transportation convenience, the beam was cut into 5 pieces, between 1.2 to 1.4 m long. The roof beam is fitted with a variable-along-the-length longitudinal steel bar reinforcement, which roughly follows the bending moment diagram. Rebar surface is not patterned. The mid-span longitudinal reinforcement is given by $3\emptyset 16 + 2\emptyset 6$ mm and by $1\emptyset 16$ mm, respectively for lower and upper section reinforcement (see Fig.5). Conversely, the

beam end longitudinal reinforcement features $1 \not = 6 \text{ mm}$ (lower) and $1 \not = 12 \text{ mm}$ (upper section). 102 Table 3 gathers the cross-section inertial properties. It should be emphasized that the 103 longitudinal rebar distribution is incompatible with modern seismic design, for no provision 104 is taken against bending moment sign inversion. The beam pieces were further cut into a 105 total of 15 400-mm-long portions, each endowed with a different amount of longitudinal steel 106 rebars according to its location in the original joist. Transverse reinforcement is very weak 107 and only $1 \neq 6/500$ mm steel bar could be detected through pachometer testing. According 108 to the Italian Building Code (2008, §4.1.2.1.3.2), the theoretical ultimate shear strength 109 amounts to 110

111

$$V_{Rcd} = 22.4 \text{ kN.}$$
 (1)

In view of the high danger of brittle failure due to shear in a plain bending test, a beam test (alias traction-through-bending test) on pairs of beam portions joined together through a steel hinge was adopted (RILEM 1994). The test schematic is presented in Fig.6.

The joist pairs are joined together via removable mechanical connectors and then lami-115 nated according to either Cycle A or B. After 28-day curing, they are tested in a four-point 116 bending test arrangement, through a Metro Com Engineering 7170S02 machine. On the 117 overall, 7 joist pairs could be tested, 3 laminated according to Cycle A and 4 to Cycle B. A 118 Q-400 Dantec Dynamics Digital Imaging Correlation (DIC) system was adopted to monitor 119 the displacement field of the beam tests (Becker et al.). The beam concrete properties were 120 determined through crash testing of drilled concrete cores. Indirect measurement through 121 concrete hammer testing (PCE-HT-225A) was also pursued but it provided scattered results 122 around an unrealistically high mean. Finally, a qualitative indication of concrete carbonation 123 was obtained through phenolphthalein titration. 124

125 EXPERIMENTAL RESULTS

126 Beam tests

¹²⁷ Seven joist pairs, labeled from A1 to A7, were tested in a beam test through a four-point-¹²⁸ bending machine equipped with a 200 kN load cell. No provision was taken against shear ¹²⁹ failure on the grounds that laminate debonding was expected to take place prior to shear ¹³⁰ failure (the latter taking place much before bending failure). According to CNR DT200 ¹³¹ 2004, §4.1.1, the optimal bonded length, l_e , beyond which no increase of the load transferred ¹³² by the composite may be obtained, can be estimated as

$$l_e = \max\left(\frac{1}{\gamma_{Rd}f_{bd}}\sqrt{\frac{\pi^2 E_f t_f \Gamma_{fd}}{2}}, 200 \text{ mm}\right) = 245 \text{ mm}$$
(2)

where Γ_{fd} is the specific fracture energy which depends on the ultimate slip s_u (see also 134 D'Ambrisi et al. 2013 for a suitable choice of s_u for FRCM materials) and parameters are 135 given in Table 4. Clearly, for maximum performance, the bonded length l_b should exceed 136 l_e . Indeed, a bonded length $l_b = 300$ mm was considered with no special anchoring device 137 U-wrapped fabric, transverse bars, abrasive blasting of the substrate surface etc.). (e.g. 138 The bending test was carried out under displacement control at 1 mm/min knife speed. 139 Fig.7 gathers the results of the beam test while Fig.8 presents the failure mechanism for 140 each specimen. Failure in specimens A1–A3, treated according to Cycle A, is either due 141 to cohesive fracture in the thin tile layer, also known as intermediate debonding, or to 142 tensile failure in the concrete (for a brief description of the different fracture mechanisms see 143 CNR DT200 (2004)). Indeed, specimen A2 displayed clear evidence of tensile failure in the 144 concrete near the hinge, which was accompanied by mixed cohesive fracture at the laminate 145 interface. 146

¹⁴⁷ Conversely, delamination of the fabric with fracture taking place at the fabric/matrix ¹⁴⁸ interface is always met in specimens A4–A7, prepared according to Cycle B. The difference ¹⁴⁹ in the failure mechanism reflects itself in a sharp difference among the ultimate loads, which ¹⁵⁰ exceed 60 kN for Cycle A as opposed to well below 50 kN for Cycle B. It is observed that 151

ultimate loads within Cycle A were remarkably consistent (cfr. error bar in Fig.10).

152

Image Correlation results

A Q400 Dantec Dynamics Digital Image Correlation system was employed to acquire 153 the displacement field along the beam test through application to the specimen side of a 154 fine coarse speckle array. A preliminary zero-displacement data acquisition allowed assessing 155 a 20 μ m displacement background noise level (resolution). A technical problem prevented 156 recording displacement data of the A6 specimen. Two reference lines, named L and R157 for the left and right element, respectively, are drawn symmetrically about the hinge. The 158 deformation of such lines (i.e. longitudinal displacement with respect to the original position) 159 is displayed in Fig.9 for specimen A2 at 60% of the ultimate load and just prior to failure. 160 The symmetry of the left-right line displacement is remarkable and holds for all specimens. 161

162

Compression test of concrete cores

After bending, four concrete cores were drilled in the joist longitudinal direction out of 163 two joist pairs. Owing to the cross-sectional shape, cores were 50 mm in diameter and about 164 100 mm in height. After drilling, core specimens were regularized. Uni-axial compression 165 tests were performed through a Metro Com Engineering E7072C300 machine, equipped with 166 a 3000 kN load cell, under force control, at a loading rate of 0.5 MPa/s. Compressive strength 167 results are recorded in Table 5, together with their adjusted value, according to Kim and Eo 168 (1990) and Benjamin and Cornell (1970), to compensate for the non-standard specimen size. 169 Maximum aggregate size is about 15 mm. On the overall, results showed good consistency, 170 with a relative standard deviation (alias coefficient of variation, CV) of about 12%. A lon-171 gitudinal crack pattern consistently developed at failure, which agrees well with an uni-axial 172 compression failure mode (Neville and Brooks 1987). Indirect concrete hammer testing pro-173 duced scattered and unrealistically over-estimated results. Finally, phenolphthalein titration 174 provided little evidence of carbonation, as expected for a indoor structural element. 175

176 DISCUSSION

177

Theoretical flexural strength

The ultimate theoretical flexural strength of the unreinforced cross-section at mid-span 178 is, in the stress block approximation (Italian Building Code 2008, §4.1.2.1.2), $M_{Rd,midspan} =$ 179 32.2 kNm which, compared with the shear strength (1), shows that a plain bending test would 180 have been possible for a very long specimen, such that $l_A \ge 2.87 \text{ m} + l_F$. A similar calculation 181 shows that the beam end section unreinforced strength amounts to $M_{Rd,ends} = 20.5$ kNm and, 182 in a doubly built-in configuration, flexural failure still occurs at midspan. In this respect, the 183 existing longitudinal reinforcement provides adequate flexural strength and the composite 184 adds a comparatively small contribution to it. However, when considering bending moment 185 sign inversion, the beam end section appears exceedingly weak at the intrados, with an 186 ultimate theoretical strength of the unreinforced section of 12.6 kNm. Application of the 187 composite reinforcement leads to a theoretical strength of 21.9 kNm for the end section, 188 which warrants almost uniform flexural resistance for the beam in the case of bending moment 189 sign inversion. 190

¹⁹¹ Adhesion and laminate strength

The beam test setup easily lead to the evaluation of the ultimate load for the composite as

194

198

$$N_u = \frac{M_u}{d},\tag{3}$$

where $M_u = P(l_A - l_F)/4$ is the ultimate bending moment (Fig.6), d = 210 mm the lever arm and N_u the ultimate normal force conveyed through the hinge and the laminate. Once the normal force N_u is determined, the ultimate average shear stress easily follows

$$\tau_{av} = \frac{N_u}{A_b},\tag{4}$$

where $A_b = b_4 l_b = 39000 \text{ mm}^2$ is the bonded area and l_b the bonded length.

The computed average shear stress, τ_{av} , for the specimens treated according to Cycle A is compatible with a clay tile failure mechanism and it is an important parameter to

design the roof reinforcement. Besides, evaluating the steel hinge net contact area with the 202 cross-section, $A_h = 8450 \text{ mm}^2$, the average compressive stress $\sigma = N/A_h \approx -4.09 \text{ MPa}$ 203 and the corresponding tensile stress (through Mohr's circle) $\sigma/2 \approx 2.04$ MPa, are easily 204 determined. In particular, the tensile stress far exceeds the ultimate tensile strength of 205 concrete $f_{ctm} \sim 0.46$ MPa, as evaluated according to Italian Building Code (2008, §11.2.10.2), 206 which fact may help explain heavy concrete damage incurred at failure for specimens A1, A3 207 and especially A2. Delamination at the fabric/matrix interface appears to be determined by 208 ineffective impregnation of the fabric reinforcement by the adhesion promoter in Cycle B. In 209 fact, all specimens treated according to Cycle B fail to provide consistent levels of ultimate 210 strength in the beam test. 211

²¹² Deformation at failure

The digitally acquired displacement field provides a discrete approximation of the strain 213 field both in the concrete and, with lower accuracy, in the composite. The mean concrete 214 compressive strain at failure (near the hinge) for specimens A1–A3 is 1.24% with CV =215 0.25%, while the corresponding (tensile) mean strain in the composite is 1.04% with CV =216 0.75%. It is interesting to observe that, introducing the concrete mean compressive strain 217 as the limiting deformation at failure in a stress block model, the theoretical strength of 218 the cross-section in a beam test, i.e. omitting the lower section rebars and assuming perfect 219 composite/substrate adhesion, amounts to 8.7 kNm (almost irrespectively whether it is mid-220 span or end section), which is 16% greater than the average ultimate bending moment, M_u , 221 as measured for specimens A1–A3 (see Table 6). However, the corresponding ultimate force 222 in the composite is 34.5 kNm, which differ very little (+1.4%) from the mean experimental 223 value. Finally, we note that the tensile mean strain in the composite at failure is very close 224 to the composite ultimate strain, ϵ_{fu} , which, according to ICC-Evaluation Service (2013), is 225 0.94% with CV = 0.19%. 226

227 CONCLUSIONS

228

In this paper, the mechanical performance of an impregnated Carbon Fabric Reinforced

Cementitious Matrix (CFRCM) composite is considered. The composite is intended to
strengthen the RC roof beams of the Finale Emilia hospital, severely damaged by the 2012
Northern Italy earthquake. The following conclusions can be drawn from the foregoing
analysis:

233 234

235

236

• A beam test, in the absence of anchoring devices, was found effective in assessing the composite strength, despite the variability of the longitudinal and the deficiency of the traversal steel bar reinforcement and despite the surprisingly poor mechanical performance of the concrete.

- External application of the composite to the thin clay tile layer onto which beams had been originally cast is safe and economic: cohesive fracture at the tile/concrete interface takes place at failure on the verge of brittle compressive failure in the concrete.
- Deformation data obtained from Digital Image Correlation give a tensile mean strain
 in the composite at failure around 1.04%, which is very close to the design strain, while
 the mean compressive strain in the concrete (near the hinge) is 1.24%, which is lower
 than expected (given that delamination occurs on the verge of concrete failure).
- Impregnation of the fabric needs be carefully considered. Indeed, impregnation through
 immersion provides a 1.5-fold increase of the ultimate strength with respect to expe dited impregnation. Furthermore, lack of adhesion due to insufficient impregnation
 consistently leads to fabric slippage in the matrix and, finally, debonding.
- Estimates of the composite strength, of the average shear strength at the composite/tile interface and of the optimal bonded length are given.
- Although the existing beam longitudinal steel bar reinforcement is adequate in a static
 analysis, composite strengthening at the intrados is required when considering seismic
 design and the possibility of bending moment sign inversion.

254 ACKNOWLEDGMENTS

10

This study was conducted in collaboration with Ardea Progetti e Sistemi Srl, Bologna, Italy, and with Studio Melegari, Parma, Italy. Financial support form the Fondazione Cassa di Risparmio di Modena, Pratica Sime nr.2013.0662, is gratefully acknowledged.

258 **REFERENCES**

- Al-Salloum, Y. A., Elsanadedy, H. M., Alsayed, S. H., and Iqbal, R. A. (2012). "Experimental and numerical study for the shear strengthening of reinforced concrete beams using textilereinforced mortar." *Journal of Composites for Construction*, 16(1), 74–90.
- Arboleda, D. (2014). "Fabric reinforced cementitious matrix (FRCM) composites for in frastructure strengthening and rehabilitation: Characterization methods." Ph.D. thesis,
 University of Miami, University of Miami. Open Access Dissertation. Paper 1282.
- Babaeidarabad, S., Loreto, G., and Nanni, A. (2014). "Flexural strengthening of RC beams
 with an externally bonded fabric-reinforced cementitious matrix." *Journal of Composites for Construction*, 18(5), 04014009.
- Becker, T., Splitthof, K., Siebert, T., and Kletting, P. Digital 3D-Correlation System Q-400.
 Dantec Dynamics. http://www.dantecdynamics.com.
- Benjamin, J. and Cornell, C. (1970). Probability, Statistics, and Decision for Civil Engineers.
 McGraw-Hill Publishing Company.
- ²⁷² Bentur, A. and Mindess, S. (2006). *Fibre reinforced cementitious composites*. CRC Press.
- Blanksvärd, T. and Täljsten, B. (2008). "Strengthening of concrete structures with cement
 based bonded composites." *Journal of Nordic Concrete Research*, 38, 133–153.
- Brückner, A., Ortlepp, R., and Curbach, M. (2006). "Textile reinforced concrete for strengthening in bending and shear." *Materials and structures*, 39(8), 741–748.
- CNR DT200 (2004). "Guide for the design and construction of an externally bonded FRP
 system for strengthening existing structures." *Italian National Research Council, Rome* R1/2013.
- D'Ambrisi, A., Feo, L., and Focacci, F. (2013). "Experimental and analytical investigation

- on bond between carbon-frcm materials and masonry." Composites Part B: Engineering,
 46, 15–20.
- ICC-Evaluation Service (2013). "Acceptance criteria for masonry and concrete strengthening
 using fiber-reinforced cementitious matrix (FRCM) composite systems." AC434.
- Italian Building Code (2008). "DM 14.01.2008: Norme tecniche per le costruzioni." Rome:
 Italian Ministry of Infrastructures and Transportation.
- Kim, J. K. and Eo, S. (1990). "Size effect in concrete specimens with dissimilar initial cracks."
 Magazine of Concrete Research, 42(153), 233–238.
- Lanzoni, L., Nobili, A., and Tarantino, A. (2012). "Performance evaluation of a
 polypropylene-based draw-wired fibre for concrete structures." *Construction and Build- ing Materials*, 28(1), 798–806.
- Loreto, G., Leardini, L., Arboleda, D., and Nanni, A. (2013). "Performance of RC slab-type
 elements strengthened with fabric-reinforced cementitious-matrix composites." *Journal of Composites for Construction*, 18(3), A4013003.
- ²⁹⁵ Mouring, S. E., Barton, O., and Simmons, D. (2001). "Reinforced concrete beams externally ²⁹⁶ retrofitted with advanced composites." *Advanced Composite Materials*, 10(2-3), 139–146.
- ²⁹⁷ Neville, A. M. and Brooks, J. J. (1987). *Concrete technology*. Longman Scientific & Technical.
- Nobili, A. (2016). "Durability assessment of impregnated glass fabric reinforced cementitious
 matrix (GFRCM) composites in the alkaline and saline environments." Construction and
 Building Materials, 105, 465–471.
- Nobili, A., Lanzoni, L., and Tarantino, A. (2013). "Experimental investigation and monitor ing of a polypropylene-based fiber reinforced concrete road pavement." *Construction and Building Materials*, 47, 888–895.
- Norris, T., Saadatmanesh, H., and Ehsani, M. R. (1997). "Shear and flexural strengthening
 of RC beams with carbon fiber sheets." *Journal of structural engineering*, 123(7), 903–911.
- Ombres, L. (2011a). "Flexural analysis of reinforced concrete beams strengthened with a cement based high strength composite material." *Composite Structures*, 94(1), 143–155.

308	Ombres, L. (2011b). "Structural performances of PBO FRCM-strengthened RC beams."
309	Proceedings of the ICE-Structures and Buildings, 164(4), 265–272.
310	Rahimi, H. and Hutchinson, A. (2001). "Concrete beams strengthened with externally
311	bonded FRP plates." Journal of composites for construction, 5(1), 44–56.
312	RILEM, T. (1994). "RC 5 Bond test for reinforcement steel. 1. Beam test, 1982." RILEM
313	Recommendations for the Testing and Use of Constructions Materials, 213–217.
314	Saadatmanesh, H. and Ehsani, M. R. (1991). "RC beams strengthened with GFRP plates.
315	I: Experimental study." Journal of Structural Engineering, 117(11), 3417–3433.
316	Tertulliani, A., Arcoraci, L., Berardi, M., Bernardini, F., Brizuela, B., Castellano, C.,
317	Del Mese, S., Ercolani, E., Graziani, L., Maramai, A., et al. (2012). "The Emilia 2012
318	sequence: a macroseismic survey." Annals of Geophysics, 55(4).
319	Toutanji, H. and Deng, Y. (2007). "Comparison between organic and inorganic matrices for
320	RC beams strengthened with carbon fiber sheets." Journal of Composites for Construction,
321	11(5), 507-513.
322	Triantafillou, T. C. and Papanicolaou, C. G. (2005). "Textile reinforced mortars (TRM)
323	versus fiber reinforced polymers (FRP) as strengthening materials of concrete structures."
324	Proceedings of the 7th ACI International Symposium on Fibre-Reinforced (FRP) Polymer

Reinforcement for Concrete Structures, American Concrete Institute, 99–118.

326	List of	Tables	
327	1	Mortars properties	15
328	2	Fabric properties in the principal direction	16
329	3	Cross-section inertial properties	17
330	4	Parameters for the evaluation of the optimal bonded length l_e	18
331	5	Compression results	19
332	6	Beam test results; FM=Failure mechanism: (c) cohesive in the brick layer, (t)	
333		traction in the concrete, (d) delamination at the fabric/matrix interface	20

Characteristic	Unit	Value
Mean compression strength after 28 days	MPa	6.5
Mean flexural strength after 28 days	MPa	3
Support adhesion strength after 28 day	MPa	1
Water content	%	23
Aggregate maximum size	mm	0.7
Longitudinal elastic modulus	GPa	11
Water vapor permeability, μ	-	12

TABLE 1. Mortars properties

Characteristic	Unit	Value
Density	g/cm^2	160
Elastic modulus, E_f	GPa	210
Ultimate strength, f_{uf}	GPa	≥ 2.0
Ultimate strain, ϵ_{uf}	%	≥ 2.1
Cross-section area/unit width	$\mathrm{mm}^2/\mathrm{cm}$	0.88

TABLE 2. Fabric properties in the principal direction

Inertial property	Unit	Value
Area, A	mm^2	19500
Center of mass, x_G	mm	0
Center of mass, y_G	mm	119
Principal moment of inertia, I_{x_G}	mm^4	12391
Principal moment of inertia, I_{y_G}	mm^4	1358

TABLE 3. Cross-section inertial properties

Parameter	Unit	Value
γ_{rd}	-	1.25
k_b	-	1
k_G	-	0.037
FC	-	1.2
Γ_{fk}	$\rm N~mm^{-2}$	0.118
f_{bd}	$\rm N~mm^{-3}$	2.36
s_u	mm	0.1

TABLE 4. Parameters for the evaluation of the optimal bonded length l_{e}

	Cylinder strength [MPa]			
Core	Raw	Adjusted		
		(Kim and Eo 1990)	(Benjamin and Cornell 1970)	
C1	9.89	10.78	10.81	
C2	8.48	9.34	9.26	
C3	8.00	8.75	8.75	
C4	10.36	11.28	11.32	
mean	9.18	10.03	10.03	
std. dev.	1.12	1.18	1.22	
rel.std. dev. $[\%]$	12.20	11.83	12.20	

TABLE	5.	Compression	results
-------	----	-------------	---------

Specimen	FM	M Cycle	M_u	N_u	$ au_{av}$	$ au_{av}$ mean	Std.dev
			[kNm]	[kN]	[MPa]	[MPa]	[MPa]
A1	с	А	7.11	33.88	0.86		
A2	c+t	A	7.25	34.56	0.88	0.88	0.02
A3	с	А	7.4	35.25	0.90		
A4	d	В	5.4	25.74	0.66		
A5	d	В	4.02	19.16	0.49	0.57	0.00
A6	d	В	4.27	20.35	0.52	0.37	0.08
Α7	d	В	5.09	24.26	0.62		

TABLE 6. Beam test results; FM=Failure mechanism: (c) cohesive in the brick layer, (t) traction in the concrete, (d) delamination at the fabric/matrix interface

334 List of Figures

335	1	Roof system at ground floor for the hospital main building (H1) \ldots .	22
336	2	Roof typical cross-section (dimensions in mm) $\ldots \ldots \ldots \ldots \ldots \ldots$	23
337	3	Application of the liquid impregnation agent to the cut-to-size carbon fabric:	
338		(a) impregnation through immersion (Cycle A), (b) application with a brush	
339		to the carbon fabric already placed on the mortar bed (Cycle B)	24
340	4	The roof concrete beam is placed upside down for lamination (clay tile on top,	
341		steel hinge for the beam test at the bottom)	25
342	5	Concrete beam mid-span (a) and beam end (b) cross-sections (clay tile at the	
343		bottom) and reference system	26
344	6	Schematic of a beam test: $l_F = 300 \text{ mm}, l_A = 900 \text{ mm}$	27
345	7	Beam test results - solid curves belong to Cycle A, dashed curves to Cycle B	28
346	8	Failure modes: cohesive fracture (specimen A1 and A3), tensile failure in the	
347		concrete (A2), delamination (A4,A5,A7)	29
348	9	Location of the reference lines L and R (a) and their axial displacement w vs.	
349		cross-sectional height y at 100% (solid) and at 60% (dashed) of the ultimate	
350		load for specimen A2 (b). Reference system as in Fig.5	30
351	10	Ultimate load N and one-standard deviation bar	31



FIG. 1. Roof system at ground floor for the hospital main building (H1)



FIG. 2. Roof typical cross-section (dimensions in mm)



FIG. 3. Application of the liquid impregnation agent to the cut-to-size carbon fabric: (a) impregnation through immersion (Cycle A), (b) application with a brush to the carbon fabric already placed on the mortar bed (Cycle B)



FIG. 4. The roof concrete beam is placed upside down for lamination (clay tile on top, steel hinge for the beam test at the bottom)



FIG. 5. Concrete beam mid-span (a) and beam end (b) cross-sections (clay tile at the bottom) and reference system



FIG. 6. Schematic of a beam test: $l_F = 300$ mm, $l_A = 900$ mm



FIG. 7. Beam test results - solid curves belong to Cycle A, dashed curves to Cycle B



FIG. 8. Failure modes: cohesive fracture (specimen A1 and A3), tensile failure in the concrete (A2), delamination (A4,A5,A7)



FIG. 9. Location of the reference lines L and R (a) and their axial displacement w vs. cross-sectional height y at 100% (solid) and at 60% (dashed) of the ultimate load for specimen A2 (b). Reference system as in Fig.5



FIG. 10. Ultimate load \boldsymbol{N} and one-standard deviation bar